A STUDY OF HEAT TREATMENT OF ALUMINIUM WHEEL CASTINGS

Southern Aluminium Pty Ltd

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B. E. (Mech.) Hons.

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ABSTRACT

Continual attempts are made to improve production techniques in modern manufacturing industries to cater for value added products and optimised processing time. Southern Aluminium Pty Ltd (SAPL), a subsidiary of Comalco Aluminium Ltd, established in 1989, is a manufacturer of automobile wheels, having to meet production in excess of fifty thousand wheels per month for the world automobile industry. SAPL produces a variety of wheel types and offer a complete package in design right from inception stage through development, casting, heat treatment, machining and finishing of aluminium alloy wheels. All wheels at SAPL are produced using commercial aluminium alloy 601 which is predominantly an aluminium-silicon-magnesium material. A detailed analysis of product flow at SAPL has shown that heat treatment occupies the majority of value added wheel processing time. Heat treatment at SAPL is the controlled process of heating and cooling the alloy wheels in order to improve their mechanical properties and enhance their performance. It is essentially a three stage manufacturing process involving solution treatment, quenching and aging. The improvement in mechanical properties of the alloy during heat treatment is significantly influenced by the degree of heat treatment time and temperature used. A preliminary investigation carried out at SAPL has encouraging results to reduce heat treatment time without affecting the mechanical properties of the alloy. This work proposes a modified heat treatment process and the associated product flow which results is substantial time savings. The current processing techniques in use at SAPL could not be sufficiently adapted to accommodate the proposed changes to the heat treatment process. Hence, it was necessary to develop a system that would provide a means of incorporating the proposed changes into the alloy wheel manufacturing process. The development of this system involved a preliminary design of an experimental heat treatment cell followed by numerous experimental investigations to study the functioning of the cell. A number of experimental investigations were completed in order to investigate the behaviour of aluminium alloy 601 during heat treatment, and in particular, the effect of varying solution treatment time and temperature on the mechanical properties of the alloy. The procedure leading towards the experimental investigation has necessitated the development of various testing rigs, temperature analysis and mechanical tests. The process is simulated on a smaller scale to check the proposed changes. A significant outcome of the experimental investigation completed was that solution treatment for the alloy could be reduced from the standard condition of four and a half hours at 540°C to a significantly improved condition of twenty two minutes at 570°C. A comparison of the proposed optimised method with the customer specifications and the existing heat treatment method is carried out using statistical routines. A quantitative substantiation using statistical methods has shown that the optimised method is not significantly different to the existing method of heat treatment. The optimum solution treatment developed did not affect the hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance of the alloy. In addition, the machinability and painted finish of the alloy wheels using the optimised method is also found to be extremely satisfactory. The project has shown that productivity improvements at SAPL were possible through a substantial reduction in processing time of a major manufacturing stage in the production cycle without affecting the quality of the final product. The product cycle when implemented would result in significant cost savings for the company.

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INTRODUCTION

Manufacturing is the backbone of any industrialised nation. Its importance is emphasised by the fact that, as an economic activity, it comprises approximately one third of the value of all goods and services produced in industrialised nations[1]. The economic health of a country is directly related to its level of manufacturing activity. The higher the level of manufacturing activity in a country then, generally, the higher is the standard of living of its people. So, what is manufacturing? Manufacturing can be broadly defined as the process of converting raw materials into useful products. Manufacturing changes the form of materials, using various processing techniques, to create useful products. As a result of the number of changes in form of the raw material during processing, the manufactured product has a value greater than that of the raw material. At each stage of the manufacturing process, in which the usefulness of the raw material is improved, the value of the item increases. For example, raw materials needed for the production of steel wire have a certain value when mined. As the raw materials are processed into steel wire a useful product is created with a value higher than that of the raw materials. Further processing of the steel wire into nails or coat-hangers increases the value of the product again.

A manufacturing system coordinates elements of input, process and output. Input in a manufacturing system includes consumer demand, material, money, energy, human resources and education, whilst process includes design, production and management. A combination of input and process in a manufacturing system result in output. Examples of output include; goods, capital goods, satisfaction, quality and cost effectiveness. As consumer demand is an input into manufacturing systems it makes sense that for a manufacturer to remain viable it must satisfy consumer demand or be left behind as those demands are met by other manufacturers. One particular example of consumer demand is more rapid fulfilment of customer orders, ie. reduced lag time between an order being placed and a quality final product being received. Most factories use a push system approach to plan and build products to fill customer orders. A push system approach is to build to order, which means that when an order arrives at the company it creates a demand to manufacture the product according to how the customer wants it. This type of manufacturing approach creates a long lead time for delivering the product because manufacturing does not commence until after the customer has placed the order. In order to reduce the time between commencement of manufacturing and delivery to the customer, it is necessary to reduce the amount of time that a product spends in process. This can be achieved through reducing the processing time of the product at individual stages of manufacturing. Improvements in productivity can be described as changes in operating cycles and processes that result in the production of more items at equivalent or lower cost or the production of the same amount of items at a lower cost[1]. This also extends to changes in operating cycles and processes to ensure a better quality product at the end of production. Ultimately, the objective of productivity improvements is the production of more items with higher quality at a lower cost. This particular objective is something that modern manufacturing organisations endeavour to achieve.

Two parameters that have a substantial influence on productivity improvements within a manufacturing organisation are process planning and product flow. Planning of manufacturing activities is necessary for a manufacturing operation to be efficient. Process planning determines the required operations and necessary facilities to manufacture a part or product. It is concerned with selecting methods of production, tooling, fixtures and machinery, sequencing of operations and assembly. Two aspects of process planning are specification of a suitable production schedule and determining production speeds for minimum cost and maximum production rate. Process planning determines product flow within a manufacturing system. Product flow is the flow of product throughout the manufacturing system from initial to finished product. Factors that influence product flow are the sequencing of necessary production operations to give the most efficient process, plant layout and the ordering of operations such that necessary tasks are completed in the correct order of processing. Product flow analysis assists in achieving the most economical use of floor space and is used to assess sequencing of operations to determine the optimum arrangement of equipment. In its broadest sense, product flow is used to analyse products flowing through a plant and assess the most appropriate paths and sequencing of events. The study of product flow within a manufacturing environment involves the optimisation of a problem by analysis of all the options and alternatives within the problem. It is very important that the focus of the problem remains the desire for an increase in productivity. There is a need for understanding product flow and process planning as a part of controlling and optimising overall production time and production rate. Without efficient product flow productivity cannot be optimum. Improvements that arise from product flow analysis contribute to the productivity improvements of the operation. Flow of materials and components throughout a manufacturing system is greatly affected by plant layout. The arrangement of production machinery and material handling equipment should be orderly and efficient. Factors that need to be considered when choosing a material handling method for a particular manufacturing operation include shape, weight and characteristics of parts; types of movement and distances involved and the position and orientation of parts during movement and at their final destination; condition of the path along which parts are to be transported; degree of automation and control desired and integration with other systems and equipment; operator skill required and economic conditions[1].

Due to the increasing desire to improve productivity in manufacturing systems automation is becoming increasingly popular. Automation is the process of following a predetermined sequence of operations with little or no human labour, using specialised equipment and devices that perform and control manufacturing operations. This is achieved with various devices, sensors, actuators, techniques and equipment that are capable of observing the manufacturing process, making decisions concerning the changes that should be made in the process and controlling all aspects of the processing operations. The major goals of automation in manufacturing facilities are to integrate various operations to improve productivity, increase product quality and uniformity, minimise cycle times and effort, reduce labour costs, reduce possibilities of human error and raise the level of safety for personnel. The basic areas of activity in manufacturing plants that are subject to automation include manufacturing processes such as machining, forging and grinding; inspection of parts for quality, dimensional accuracy and surface finish; assembly of parts and final product; and packaging[2]. In addition, material handling and material movement are also popular areas subject to automation in manufacturing plants. During manufacturing operations materials and parts are moved from storage to machines, from machine to machine, and from machines to shipment. Time is required to move materials and parts, either manually or mechanically. Idle time and the time required for transporting materials and parts between operations usually occupies the majority of time a part spends in process. There is a need to develop optimum material handling times between processes and during each process in order to reduce total processing time and consequently reduce in-process inventory. As inventory sits in queues no value is added, yet it costs money to the company, thus it makes sense to reduce the time that inventory is in process to as low as practicable. Manufacturing systems with many individual operations, require a large amount of material handling for the transfer of parts between various stages of completion. Automation of material handling also has benefits not immediately recognisable as productivity improvements. For example, operations involving human beings can be unpredictable, unreliable and also unsafe for the operator depending on the conditions under which the operations are being carried out. For this reason, automated material handling is advantageous. Automated material handling also leads to the desired effects of improved repeatability and lowered labour costs.

A study of a modern manufacturing organisation such as the one detailed in the following literature is useful to highlight the need for productivity improvements in a manufacturing system and emphasise the extent to which automation can accompany these improvements. A study of product flow and processing time within this manufacturing system is necessary for understanding the mechanisms for improving production rate. It will become evident that the project being completed here is targeting productivity improvements within the manufacturing system through a significant reduction in processing time at a particular stage of product flow.

ALUMINIUM WHEEL PRODUCTION AT SOUTHERN ALUMINIUM PTY LTD

Southern Aluminium Pty Ltd (SAPL), a subsidiary of Comalco Aluminium Ltd, is a manufacturer of automobile wheels, having to meet production in excess of fifty thousand wheels per month for the world automobile industry. SAPL is situated in Bell Bay, Tasmania, Australia and is one of only three major wheel manufacturing companies in Australia. Its customers include well established automobile manufacturing companies such as Nissan, Mazda and Ford. SAPL commenced production in 1989 and produce a variety of wheel types and offer a complete package in design right from inception stage through development, casting, heat treatment, machining and finishing of aluminium road wheels. The company has developed a consistent theme of quality awareness throughout the plant and a philosophy of process control and quality assurance. Improvements at SAPL have advanced through consideration of productivity improvements, workforce safety and environmental aspects. All wheels at SAPL are produced using commercial aluminium alloy 601. The constituents added to aluminium to produce aluminium alloy 601 are approximately by weight 6.6% silicon, 0.3% magnesium, 0.12% iron, 0.01% titanium and 0.005% strontium, making the alloy predominantly an aluminium-silicon-magnesium material. Aluminium alloy 601 is used as the work material at SAPL due to its consistent mechanical properties and structural integrity in permanent mold castings. An excellent resistance to corrosion in the environment expected for an automobile wheel, achievement of adequate strength through heat treatment and lack of brittleness or susceptibility to stress-corrosion cracking makes it an ideal work material for automobile wheels. The properties that aluminium alloy possess make it the most suitable material for all stages of the automobile wheel manufacturing process, including casting, heat treatment, machining, finishing and service life. The use of aluminium alloy wheels improves tyre safety and wear and also the braking characteristics of vehicles[3]. Their lightness in comparison with traditional steel wheels requires less braking effort and they are easier to handle[3]. Turbulent air flow caused by holes and fins cast into most aluminium wheel designs has an important cooling effect on brakes. Alloy wheels also have a double safety hump incorporated into their rim which helps keep the tyre on the rim in the event of a sudden 'blow-out'[3].

Molten aluminium is delivered to SAPL, as it is needed, from a nearby aluminium smelting plant, Comalco Aluminium Ltd. It is delivered in large crucibles that maintain the molten temperature of the metal during transportation. The molten aluminium is kept in a large holding furnace in the first instance and then fed into smaller mobile crucibles, known as 'transfer crucibles', periodically where the above mentioned alloying elements are added in respective proportions to produce the required alloy mixture. The molten aluminium is held in the transfer crucibles and treated until required for casting, at which stage the molten aluminium is fed from the transfer crucibles into the individual casting machine crucibles. Treatment of the molten metal in the transfer crucibles involves 'degassing' the metal to remove excess hydrogen and consequently reduce wheel porosity during casting. It is useful to mention here that the transferring of molten aluminium from the transfer crucible to the casting machine crucible is known as a 'metal transfer' as it will be referred to later. Following on from the initial molten metal preparation and filling of the casting machine crucibles there are four major operations that contribute to the manufacturing of a wheel at the plant. These are casting, heat treatment, machining and finishing. Each of these four major operations involve a series of smaller individual operations. Figure 1 shows product flow, involving these four major stages of production, through the plant, from which it can be seen that the first major stage in the wheel manufacturing process is casting. Wheels are cast using a low pressure die casting technique, the principles of which are discussed later. The plant has eight low pressure die casting machines in total which are grouped together as four pairs. A single operator is responsible for the operation of one casting machine. Each casting cycle is initiated by a human operator pressing the appropriate buttons on the casting machine control panel. A casting cycle involves filling of the dies with molten aluminium, solidifying the aluminium in the dies, ejecting the solidified castings from the dies, quenching the castings to a temperature close to room temperature and delivering the castings to the operator for further processing. When running at full capacity, each casting machine is capable of producing two castings simultaneously approximately every six minutes. Each metal transfer into the casting machine crucible yields enough volume of metal for the production of approximately sixty wheels. The operator that initiates the casting cycle is responsible for some further wheel processing operations. These operations include the stamping of each cast wheel with a melt number stamp, manually removing any visible marks from the front face of each wheel, manually removing excess aluminium from the top and bottom rim of each wheel and finally, checking the castings for distortion using a distortion gauge. A melt number stamp is essential on each casting so that the alloy content of the wheel can be identified if needed. Each time the casting machine crucible is filled an alloy sample is taken from the crucible and examined spectrographically to determine alloy composition. The alloy composition is recorded along with the corresponding melt number.

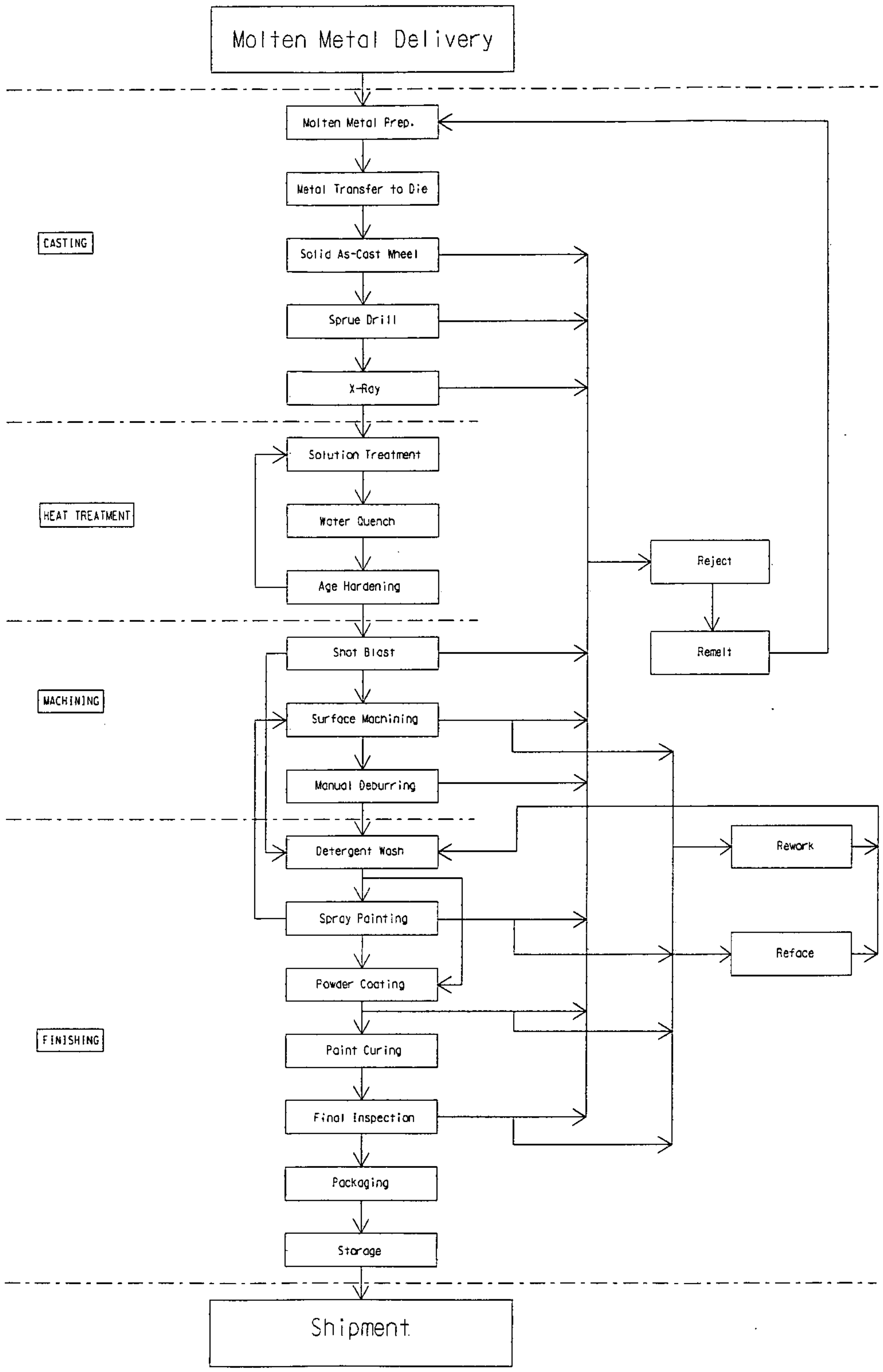


Figure 1: Product Flow Through Southern Aluminium Pty Ltd

The melt number on each cast wheel can then be related to an exact alloy composition. A distortion gauge placed on the front face of each wheel informs the operator of the wheels distortion. A wheel that is badly distorted, greater than plus or minus half a millimetre out of plane, is rejected immediately as it cannot be repaired and is unsuitable for use on a motor vehicle.

As mentioned previously, a low pressure die casting technique is adopted at SAPL for wheel production. The particularities of low pressure die casting will be discussed in detail later, however, it is worth noting at this stage some brief detail of the process. During casting molten metal is fed at low pressure from the casting machine crucible through a tube into the centre of the bottom die and continues to be fed into the die until sufficient metal has entered to fill the cavity. A fine steel wire mesh is placed into the centre of the bottom core of each die prior to initiating the casting cycle to prevent impurities entering the casting. Any impurities in the molten aluminium present in the casting machine crucible become caught in the wire mesh during the casting cycle and solidify. The solidified form stays attached to the casting as it is removed from the die. This solidified form, containing impurities and the fine steel wire mesh, is referred to as a 'sprue' and is removed from each casting using an automated drilling operation. During this operation, a wheel is fed automatically from the casting machine, via a conveyor, into a drilling machine. Inside the drilling machine the wheel is clamped automatically, drilled to remove its sprue and machined across the back of the rim to remove excess flashing. The wheel is then automatically delivered to another conveyor where it travels to the x-ray machine. At the x-ray machine, the wheel undergoes x-raying to determine porosity content and other possible defects. An operator observes the wheel as it is x-rayed and determines at the end of the x-raying cycle whether or not the wheel must be rejected by comparing the wheel porosity content with a sample showing the maximum porosity size and scattering allowed. X-raying is the final operation in the casting section of the plant. Material handling between processes is highly automated in the casting section of the plant due to the fact that conditions in the casting area can be unsafe for human operators to handle wheels between casting operations and automation of wheel handling between casting operations reduces the labour involvement in the area. The high degree of automated wheel handling also means that there is much faster and more consistent transfer of wheels between subsequent processes than there could possibly be without automated material handling.

The requirements of a wheel, such as acceptable surface finish and associated mechanical properties are specified by the customers of SAPL. The mechanical properties specified for aluminium alloy 601 include hardness (HB), yield strength (YS), ultimate tensile strength (UTS), percentage elongation (ε) and impact resistance. These mechanical properties, as specified by Nissan, Mazda and Ford, are shown in Table 1 and are representative of the mechanical properties required of an aluminium alloy wheel for use on passenger vehicles. It is impractical to highlight the specifications for impact resistance at this point as they are many and varied. Impact resistance and the appropriate specifications will be referred to later as they are required.

TABLE 1 - Customer Specifications for Mechanical Properties of Aluminium Wheels

Mechanical Property	**Ford**	**Nissan**	**Mazda**
Hardness (500/10)	63-90	64.6-85.7	64.6-85.7
Yield Strength (MPa)	≥120	No Spec.	No Spec.
Ultimate Tensile Strength (MPa)	≥220	≥ 245	≥ 245
Elongation (%)	≥7	≥ 5	≥ 5

The hardness and strength properties of a wheel directly after casting are not sufficient to meet with the customer specifications shown. Typical mechanical properties of aluminium alloy wheels in the 'as-cast' condition are shown in Table 2, from which it can be seen that the 'as-cast' hardness and tensile properties are significantly less than those specified in Table 1. However, the 'as-cast' mechanical properties of a wheel can be improved by subjecting the wheel to a suitable heat treatment process. It follows then that heat treatment is the next necessary major processing operation after casting. Heat treated aluminium alloys are recognised under a temper designation system. It is useful to reproduce this designation system here, Table 3, to show the range of heat treatment processes used for improving the mechanical properties of aluminium alloys.

TABLE 2 - Typical 'As-Cast' Mechanical Properties of Aluminium Wheels at SAPL

Mechanical Property	Measured Value
Hardness (500/10)	40
Yield Strength (MPa)	93
Ultimate Tensile Strength (MPa)	190
Elongation (%)	14

TABLE 3 - Temper Designation System for Aluminium Alloys[4]

Temper	Definition
F	As fabricated
O	Annealed
H1	Strain-hardened only
H2	Strain-hardened and partially annealed
H3	Strain-hardened and stabilised
T1	Cooled from an elevated-temperature shaping process and naturally aged to a substantially stable condition
T2	Cooled from an elevated-temperature shaping process, cold worked and naturally aged to a substantially stable condition
T3	Solution heat treated, cold worked and naturally aged to a substantially stable condition
T4	Solution heat treated and naturally aged to a substantially stable condition
T5	Cooled from an elevated-temperature shaping process and artificially aged
T6	Solution heat treated and artificially aged
T7	Solution heat treated and stabilised
T8	Solution heat treated, cold worked and artificially aged
T9	Solution heat treated, artificially aged and cold worked
T10	Cooled from an elevated-temperature shaping process, cold worked and artificially aged

The heat treatment method adopted at SAPL is T6 in the temper designation system for aluminium alloys, which involves solution treatment, quenching and artificial aging. The particular heat treatment conditions used at SAPL are as follows:

I. Solution treatment: 4.5 hours at 540°C

II. Quench: 80 seconds at 80°C (using water as the quenchant), and

III. Aging treatment: 4.5 hours at 140°C

It is evident from the details given of the heat treatment process used at SAPL that heat treatment consumes approximately nine hours of wheel production time. The principles of heat treatment will be discussed in detail later, however, it is useful to note at this stage that solution treatment and artificial aging processes involve heating a metal to an elevated temperature and holding it at that temperature long enough to form a desired crystal structure in the metal. Aging can also be carried out successfully at room temperature, referred to as natural aging, for some aluminium alloys but takes much longer than artificial aging.

An explanation of the heat treatment process used at SAPL is aided by showing the existing heat treatment system and the associated heat treatment equipment, Figure 2, and discussing its method of operation. It can be that there are three main ovens used for the heat treatment of aluminium wheels at SAPL. The two ovens to the right are both solution treatment ovens and are marked on Figure 2 as (a) and (b). The third oven to the left, marked as (c), is the age oven. Wheels are fed through either of the two solution ovens for the process of solution treatment, are quenched on completion of solution treatment in large tanks at the back of the solution ovens, then fed through the age oven for the process of age hardening. It can be seen that wheels travel through the ovens in large steel baskets which each have a maximum capacity of twelve wheels. The two types of baskets used are; i) horizontal baskets: these have four layers which hold three wheels per layer and wheels are placed horizontally in each basket, and ii) vertical baskets: these have two layers which hold six wheels per layer and wheels are placed vertically in each basket. In Figure 2, a semi-loaded horizontal basket can be seen exiting the age oven whilst fully loaded vertical baskets can be seen at the ends of either of the two solution treatment ovens. Apart from manually loading and unloading wheels from the heat treatment baskets the heat treatment process is fully automated.

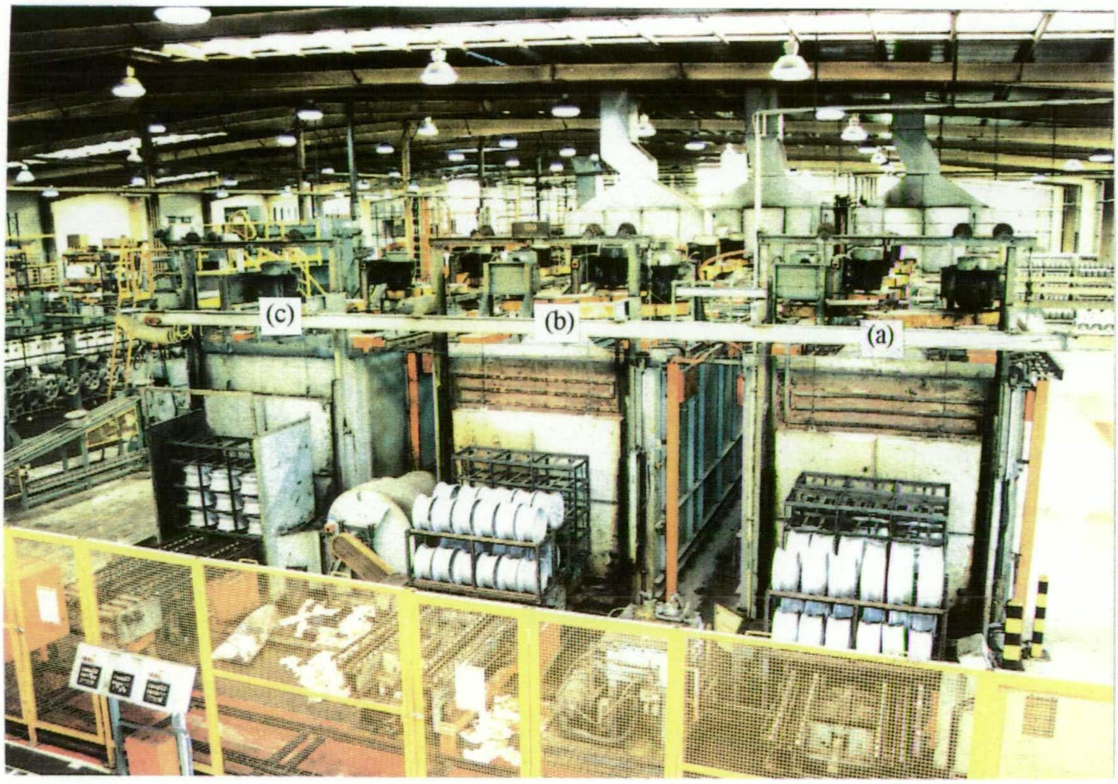
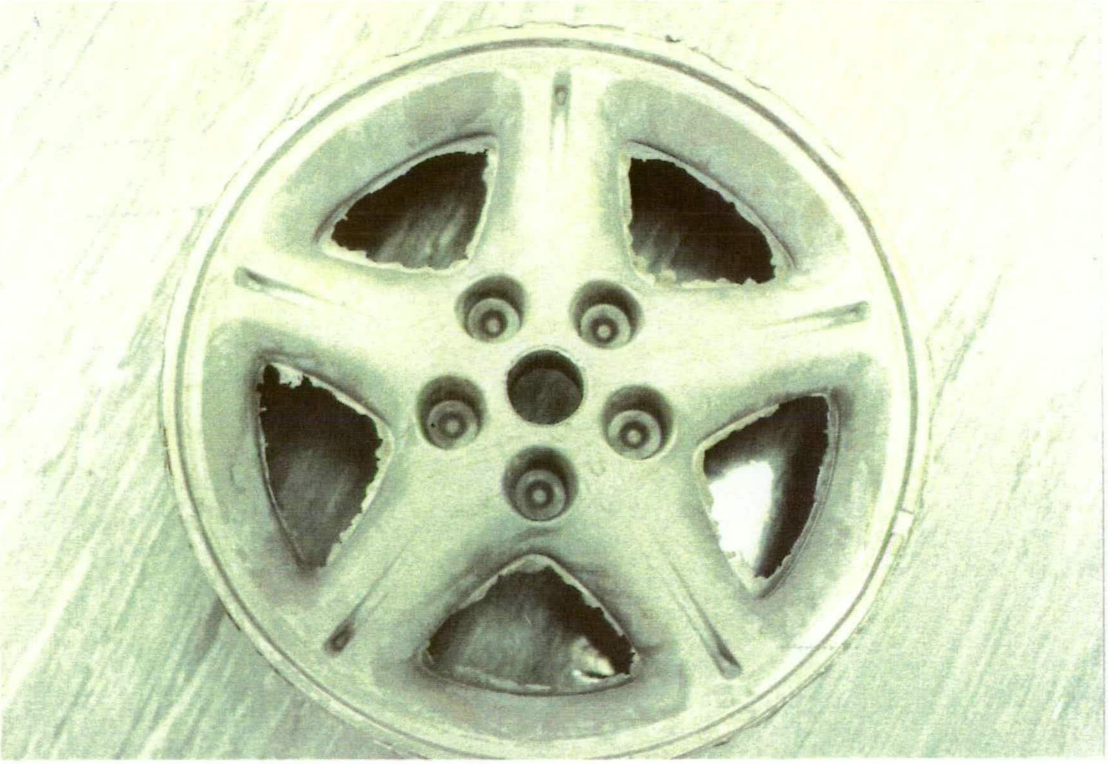


Figure 2: Existing Heat Treatment System and Associated Equipment at SAPL

The manufacturing stage following heat treatment is machining. As heat treatment is such a time consuming process it takes a minimum of nine hours for a wheel to transfer from casting to machining operations. This large lag time between casting and machining is highly undesirable for reasons that will be discussed shortly. If a reduced heat treatment time could be used to achieve the desired mechanical properties in the alloy then the lag time between casting and machining could be significantly reduced.

Nevertheless, the first operation in the machining stage of the plant is recognised as 'shot blasting' and is used to give each wheel face a predetermined surface texture. During shot blasting wheels are struck repeatedly at high speed and force with small steel balls, referred to as shot, of less than one millimetre diameter. An impression is left on the front face of the wheel after each strike of the shot. This results in a desired surface finish on the wheel that improves its visual appearance and aids in paint adhesion during painting operations carried out later in the processing cycle. Excess aluminium is removed from the wheel as a desirable secondary action during shot blasting due to the high speed and force at which the shot strikes the wheel. Surface machining of the wheel follows directly from shot blasting. Machining of wheels is a necessary step in the wheel manufacturing process as an 'as-cast' wheel is not of a satisfactory standard for commercial use. Machining is used to shape wheels to a specified form and dimension, remove burrs and sharp edges remaining after casting and give the wheel a predetermined texture and surface finish. A comparison between an 'as-cast' wheel and a machined wheel is shown in Figures 3(a) and (b) from which it can be seen that a machined wheel is of a much better form and surface finish than an 'as-cast' wheel. Each of the objectives of surface machining are executed as different operations but are carried out inside any one of the five automated machining cells at the plant. Each machining cell can be set-up to machine any one wheel type at any given time. Due to the varying shape and size of each wheel type it is necessary to specify to the machining cell which wheel type it will be machining. Each machining cell is programmed to cater for each wheel type produced at the plant and is interchangeable to adapt to any wheel type at any given time. As there are five individual machining cells it is possible to carry out machining operations on five different wheel types at any one time. With this automated surface machining process, the only human intervention is the manual stacking of wheels at the entrance to the machine lines. Once stacked at the entrance, a material handling system delivers a wheel to each of the individual stages inside the machining cell. To process a wheel through each of the machining operations mentioned earlier takes approximately two to three minutes from start to finish. All machining operations are carried out automatically inside the machining cells and machined wheels are delivered to the operator at the end of the machine line ready for further processing. The machining cells are the most advanced automated processing equipment in the plant and are an excellent example of how automation can save time, effort and money in a manufacturing system. Wheels delivered to the operator at the end of the machine lines are subject to a 'leak test' which involves immersing an air tight wheel completely underwater and observing the water for escaping air bubbles from the wheel rim section. Air bubbles escaping from a wheel indicates a defect in the wheel rim and thus the wheel must be rejected.



(a)

(b)

Figure 3(a): 'As-Cast' Aluminium Alloy Wheel, and (b) Machined Aluminium Alloy Wheel

The air leak test is a vital component of the wheel manufacturing process as wheels must not be allowed to leave the plant if they fail this test. Most of the tyres used in conjunction with aluminium wheels are tubeless, meaning that a wheel with an air leak fitted to a vehicle can be detrimental to passenger safety.

The final stage of wheel processing at the plant is finishing. The primary operations that fall into the category of finishing are detergent washing, spray painting, or wet painting, powder coating and paint curing of wheels and inspection and packaging of wheels for storage and shipment. Detergent washing of the wheels is necessary to ensure that they are completely free from contaminants before painting. Wheels are delivered to the detergent washing centre on vertical hangers which support two wheels only. The vertical hangers are contained on a continuous chain that runs through the detergent washing, powder coating and paint curing sections of the plant. The operations of detergent washing, powder coating and paint curing are completely automated once the wheels are manually stacked on the vertical hangers by operators from the finishing area. After detergent washing, wheels travel through a drying oven for twenty five minutes, set at 140°C, to ensure they are thoroughly dry before painting commences. Wheels that require spray painting are manually taken from the vertical hangers and fed onto a horizontal chain that runs through the spray painting centre. Spray painting is also an automated process that requires human involvement only for the stacking and removing of wheels from the horizontal chain and the initial setting up of the spray painting guns. Once spray painted, wheels are returned to the vertical hangers from which they were taken. Wheels then continue through to the powder coating and paint curing operations. Powder coating is an operation that covers the surface of each wheel with a thin layer of powder form paint. To harden the powder on the wheel it is necessary to subject the wheel to a paint curing operation. During paint curing, wheels travel through a two zone oven with temperature settings of nominally, 200 to 245°C for the first zone and 140 to 150°C for the second zone. The time taken for the wheels to travel through the paint cure oven is approximately twenty five minutes per zone, hence making the paint cure operation a fifty minute process in total. During paint curing the powder forms a hard, clear coating on the wheel. After paint curing the wheels are manually removed from the vertical hangers, stacked onto pallets and stored until required for final inspection.

Some wheel types, depending on their shape, may require painting directly after shot blasting and prior to machining. Wheels that do require spray painting before machining are still powder coated and inspected after machining, as demonstrated on the product flow chart in Figure 1. Final inspection of the wheels involves an operator visually examining each wheel and deciding whether or not the wheel can be shipped depending on its condition. At final inspection, wheels may be rejected or sent for rework or reface if they are not of an acceptable standard to send to the customer. Some common problems that cause a wheel to be rejected or sent for rework or reface at final inspection include paint or machining defects, discovery of defects not noticed earlier during processing or damage to the front face of the wheel.

With the discussion of the particular processing techniques used at SAPL completed it is now interesting to mention the methods by which reject wheels are detected and dealt with during manufacturing. The product flow chart of Figure 1 shows that each individual wheel undergoes approximately eighteen to twenty different operations during processing from raw material to final product. There is human handling and inspection of wheels between most operations and the possibility of discovering a reject wheel is facilitated throughout most of the manufacturing cycle. It is, however, more desirable to discover a reject wheel early in the manufacturing process rather than later as there are less costs tied up in the wheel after only a small amount of processing than there are after a large amount of processing. That is, for every step of successful processing that a wheel undergoes it will increase in value to the company until such time that it reaches maximum value is ready for shipment. For example, to reject a wheel after painting or machining is much more costly to the company than to reject a wheel at the casting stage. All reject wheels are remelted at the plant and reused for casting. Reworking and refacing of wheels are alternative options to rejection for some wheels and involve re-machining or sanding the front face of a wheel to remove microporosity or minor defects. Rework and reface of wheels is possible only on suitable wheels that are not too badly damaged and are recoverable by use of these operations. Reworking and refacing are again costly and undesirable operations but are sometimes necessary and are cheaper options to rejecting a wheel. Reworked and refaced wheels need only undergo a few reprocessing operations before they are ready for shipment whereas a reject wheel must be melted and totally reprocessed. SAPL is a quality accredited company that strives for quality but the production of some reject wheels is inevitable. To achieve one hundred percent quality in the manufacturing process and eliminate tasks not on the critical path of processing, such as reject, rework and reface, is an ultimate goal of every company in theory but is, however, unlikely to be achieved in practice due to uncontrollable variation in some processes. Continual improvement and reduction of rejects as a result of research and development is an ongoing task at SAPL.

In an attempt to minimise the reject rate at the plant a variety of quality control procedures are adopted. They are used to ensure such things as correct metal specification, control of manufacturing processes and also that non-destructive and destructive testing levels are maintained. Apart from essential quality control requirements stipulated by SAPL's customers, the company institutes a number of additional internal quality control procedures to minimise work-in-progress scrap throughout the manufacturing cycle. It is useful here to introduce the control points for quality inspection throughout the plant, starting with the material entering SAPL through to finishing operations.

Material: Molten metal delivered to the plant is inspected to examine metal weight and metal chemistry. Metal weight is examined using heavy duty scales and metal chemistry is determined from a supplier certificate that accompanies the metal delivery.

Melts: Metal temperature and cleanliness are monitored during metal holding in the transfer crucibles. Spectrographic analysis of the metal determines the alloy content to be added to the melt. Following alloy additions, another spectrographic analysis is completed to inspect the conformity of the metal to alloy specifications. Hydrogen content is also measured during metal holding in the transfer crucibles to ensure conformity with the specifications.

Casting: Before casting commences, die temperature, die filling pressure, air cooling times and air cooling flow rates are all set to predetermined values. These parameters are then measured frequently throughout the casting process and adjusted if necessary.

Front face distortion of castings is measured periodically using a distortion gauge and an x-ray check to evaluate porosity size and scattering is completed on castings at a frequency specified by the customer. Wheel surface appearance is visually inspected on each casting to ensure a tolerable appearance is being achieved. Dies are modified accordingly if the casting surface appearance is not acceptable.

Dimensional checks are carried out on castings using a 'Coordinate Measuring Machine' (CMM) each time a die is put into production to ensure that the die is producing wheels within specification.

Heat Treatment: Parameters to be controlled during heat treatment include furnace temperature, cycle times and quench temperature. Furnace temperature and quench temperature are controlled using programmable logic controller (PLC) equipment and cycle time is predominantly determined by the amount of product flow and breakdown time.

Hardness of castings exiting the heat treatment oven is measured periodically, nominally every two hours, using a non-destructive test. Test results are recorded on a process chart with the upper and lower control limits marked. Any wheels not within the control limits are sent for a second heat treatment to improve their condition.

Shot Blast: Frequent comparison of the visual appearance of wheels with a customer approved wheel is carried out on wheels exiting the shot blast machine to ensure the correct shot striking force and pattern is being used.

Machining: Dimensional checks are completed on machined wheels regularly using the CMM to ensure conformity with drawing specifications. A full dimensional check is completed at the start of a machine line set-up and then every six hours to ensure the machine is operating correctly. If wheels are determined to be dimensionally incorrect then the machine lines are adjusted accordingly.

Air Leak Test: An air leak test is completed on every wheel after machining. Wheels that have been leak tested and passed are marked and sent for further production. The leak test mark is viewed at final inspection to ensure that all wheels leaving the plant have passed a leak test. If wheels have not been marked then they are sent back to the leak test machine for testing.

Finishing: Wheel painting is the main process to be controlled in the finishing section of the plant. A small number of wheels are painted and examined for paint colour, adhesion, hardness, appearance and film thickness before a large batch of production wheels are painted. Curing oven air temperature is also monitored frequently to ensure the correct curing temperature is being used. Furthermore, a visual inspection is completed on all wheels at final inspection to ensure that only acceptable wheels leave the plant.

Destructive testing: Destructive tests including fatigue tests, tensile tests, impact tests and paint tests are carried out on wheels at sufficient frequency to ensure that consistent quality is being maintained. Wheels that have been subjected to these performance tests are destroyed.

Fatigue Tests: A Dynamic Radial Fatigue Test and a Rotary Bending Fatigue Test are used to test the fatigue resistance of the wheel. A Dynamic Radial Fatigue Test is an analysis of the ability of the wheel rim to withstand the loads upon it by constant flexing of the tyre under load and under high life cycle conditions. A Rotary Bending Fatigue Test is a measure of the ability of the wheel spoke assembly to stay attached to the wheel rim by creating a bending force on the wheel hub and spoke assembly. Both tests are a simulation of extreme vehicle operating conditions.

Tensile Tests: Destructive tensile tests are completed periodically on samples taken from heat treated wheels in order to establish yield strength, ultimate tensile strength and percentage elongation of the alloy and conformity with the appropriate specifications.

Impact Tests: Impact testing is used to evaluate the resistance of the wheel and rim to impact and also the strength of the rim to the wheel centre attachments. This test is completed by releasing a specified weight onto a wheel at a specified height and angle.

Paint Tests: A range of destructive tests are carried out periodically on wheels to evaluate paint resistance. The tests include the measure of corrosion, heat, acid, alkali, alcohol, gasoline, window washer fluid, grease, guard wax, salt water, chip and oil resistance and also thermal shock, paint hardness and adhesion.

This concludes the description of the manufacturing processes and techniques used at SAPL including product flow through the plant and the quality procedures used to minimise scrap or wastage. It was necessary that this information was given in order to aid in the understanding of the project being completed here. It is now necessary to document the particularities of the project being completed and provide a rationale for undertaking this particular experimental investigation. The particular project being completed in this instance involves an investigation into the optimisation of the heat treatment of aluminium alloy wheels at SAPL. The objective and expected outcome of the project is to create productivity improvements at the plant as a result of reducing the processing time of a significant stage of the manufacturing cycle. The rationale for selecting heat treatment as the process to be optimised is evident from the time study shown in Table 4. The time study was completed several times and the values given in Table 4 are averages of the trials completed. It can be seen from the values given that heat treatment in practice takes approximately ten and a half hours. Although the heat treatment process used at SAPL has been previously documented as a nine hour process theoretically it takes longer in practice due to equipment breakdowns and variation in product flow. It is evident from the values given in Table 4 that heat treatment is the most significant contributor to total wheel processing time. In fact, it represents approximately sixty nine percent of total value added processing time. It is necessary to note that the times shown in Table 4 are for direct processing operations and include direct material handling time only. They do not include time spent for wheels sitting idle in queues waiting to be processed. Direct processing time of a wheel from casting to finished product is considerably less than the actual time a wheel spends in production. The time spent by a wheel waiting to undergo further processing is a significant contributor to the total time that a wheel spends in the plant. Reducing the time taken for wheels to undergo processing would consequently mean that wheels spend less time in the plant. It follows then that there would be a direct reduction in the amount of inventory in the plant as a result of reducing wheel processing time. This would ultimately result in cost savings for the company. Reducing the time a wheel spends in the plant through a reduction in processing time results in faster product flow and an improved production rate. Hence, the heat treatment process is the greatest contributor to total processing time and significant benefits exist if the time of this particular process could be significantly reduced.

TABLE 4 - Processing Times for Aluminium Wheels at SAPL

Process	Time (s)	Time (hrs mins s)
Casting	3,111	00hrs51mins51s
Heat Treatment	37,666	10hrs27mins46s
Machining	2,023	00hrs33mins43s
Finishing	12,180	03hrs38mins33s
Total Processing Time	54,980	15hrs16mins20s

The driving force behind this project is that 'production cost is proportional to production time' and consequently in this instance, a reduction in production costs is achievable through a reduction in production time. In addition, there are also other important secondary benefits achievable. Firstly, defect detection time will be improved if heat treatment time is reduced. Due to the nature of certain defects in wheels, defects are sometimes not recognisable until after the wheel has been machined. An example of this is microporosity which is formed during solidification of the alloy during casting. Small micrporosities are impossible to detect by x-ray examination but normally become visible after fine machining or polishing. Wheels with microporosity defects have to be rejected, or reworked if possible, as microporosity causes surface bubbles after painting. With the existing process cast wheels do not reach machining until a period of at least nine hours has lapsed. This means that a defect present in a wheel is not detected until nine hours after the wheel has been cast. During this nine hours further wheels are cast with the likelihood that they too will have the same defect. Hence, it is not uncommon for a large batch of wheels to be produced with a common detrimental defect. If it were such that there was a significantly shorter time period between casting and machining then it would consequently mean that wheel defects would be recognised faster and the cause could be remedied prior to the production of a large batch of wheels. This particular possibility for the faster realisation of defects in wheels introduces the possibility of significant cost savings due to a lower reject rate. A further foreseeable benefit obtainable through the reduction of heat treatment time is that overall plant power costs can be reduced. The existing heat treatment system consumes approximately forty percent of total plant power. It is anticipated that an optimised system would use significantly less power due to the lower capacity requirements of the associated heat treatment equipment. A saving in floor space is also anticipated, again due to the lower capacity requirements of the associated equipment. Both power and floor space savings translate directly into cost savings for the company.

This investigation is aimed at developing innovative methods to substantially reduce wheel heat treatment time and hence significantly improve product flow rate as a result. An understanding of the behaviour of aluminium alloy under various processing conditions helps to build more effective product flow lines. This work is a step towards understanding the behaviour of aluminium alloy and the effect of a reduction in heat treatment time on production flow rate. However, an initial investigation is necessary to determine whether the existing heat treatment process at SAPL can be modified and improved without affecting the quality of the aluminium wheel produced in terms of both mechanical properties and surface finish. The following section deals with an introduction to aluminium alloys, their importance and characteristics and highlights associated processing techniques. The following literature survey is carried out with a view to addressing the above mentioned issues.

CHAPTER ONE

LITERATURE SURVEY

1.1 INTRODUCTION TO ALUMINIUM ALLOYS

Pure aluminium has a range of characteristics that make it a very useful material. Some of the most outstanding characteristics are its light weight, excellent electrical and thermal conductivity and corrosion resistance. Aluminium has a density of 2700kg/m^3 and weighs only approximately one-third as much as the same volume of steel, copper or brass. It has high resistance to corrosion in atmospheric environments, in fresh and salt waters, and in many chemicals and their solutions. No coloured salts are formed to discolour or stain adjacent materials or products with which aluminium comes into contact with and it has no toxic reactions[5]. Among the commercial metals, aluminium is second to iron in consumption, on a weight and volume basis, for most production activities[6]. Aluminium and many of its alloys can be worked readily into any form needed, be cast by all foundry processes and accept a wide variety of attractive, durable and functional surface finishes[5].

The unique combinations of properties provided by aluminium and its alloys make aluminium one of the most versatile, economical and attractive metallic materials for a broad range of uses from soft, highly ductile wrapping foil to demanding engineering applications[5]. Most of the applications of aluminium products require properties or characteristics that cannot be obtained using purity aluminium. Alloying with other elements to produce a series of materials with improved properties and characteristics is necessary. The mechanical properties of purity aluminium are inadequate compared to those of steel but can be improved through both alloying and heat treating to produce alloys with higher strength than that of structural steel[5]. The tensile yield strength of super-purity aluminium in its annealed (softest) state is about 10MPa whereas the tensile yield strength of some commercial high strength aluminium alloys exceeds 550MPa[5]. The main reason for alloying aluminium is to increase the materials strength and hardness and resistance to wear, creep, stress relaxation and fatigue[7]. The improvement in mechanical properties of the alloy is dependant on the different alloying elements used and the combinations of them.

Aluminium alloys are grouped in terms of their major alloying elements. A system comprising of a four digit numerical designation incorporating a decimal point is used to identify aluminium alloys in the form of castings and foundry ingots. The first digit in the designation indicates the alloy group, as shown in Table 1.1.

TABLE 1.1 - Aluminium Alloy Designation System[4]

Major Alloying Element	Designation
None (≥ 99.0% Aluminium (Al))	1xx.x
Copper (Cu)	2xx.x
Silicon (Si), with added copper and/or magnesium (Mg)	3xx.x
Silicon	4xx.x
Magnesium	5xx.x
Zinc (Zn)	7xx.x
Tin (Sn)	8xx.x
Other	9xx.x
Unused series	6xx.x

For 2xx.x through 8xx.x alloys, the group is determined by the alloying element present in the greatest percentage, except in cases in which the composition being registered qualifies as a modification of a previously registered alloy[5]. If the greatest percentage is common to more than one alloying element, the alloy group is determined by the element that comes first in the sequence shown above[5].

The second two digits identify the specific aluminium alloy and the last digit, separated by a decimal point, indicates the product form, whether casting or ingot, designated as 0 or 1 respectively[5]. A modification of an original alloy is indicated by a serial letter preceding the numerical designation[5]. An example of an aluminium casting number is A514.0 in which A indicates it is the first of what may be a series of the same type of aluminium, 5 indicates it is a magnesium alloy, 14 indicates aluminium purity and .0 indicates the product form is casting. Commercial aluminium alloy 601 is designated as alloy A356 by the Aluminium Association as it belongs to the 3xx.x series of alloys. From herein any reference made to alloy A356 can also be recognised as a reference to aluminium alloy 601 as they are essentially the same alloy.

Aluminium alloys can be divided into two groups; those that are heat-treatable (commonly aluminium-copper, aluminium-copper-nickel, aluminium-magnesium-silicon and aluminium-lithium systems) and those that are non heat-treatable (commonly aluminium-manganese, aluminium-magnesium and aluminium-silicon systems)[4]. Those that are non heat-treatable may be strengthened through either cold working operations or annealing whilst age hardening treatment, or precipitation treatment, is used to strengthen heat-treatable alloys[4].

The applications of aluminium alloys are many and varied due to their high versatility through varying alloying elements and the great range of properties and characteristics available. Aluminium alloys find use in many domestic, commercial and industrial applications. A few examples of each are shown in Table 1.2.

TABLE 1.2 - Applications of Aluminium Alloys

Domestic	**Commercial**	**Industrial**
Foil for packaging	Aircraft structural components	Aluminium smelters
Saucepans	Lawn mower housing	Boat manufacturers
Cutlery	Street lamp housing	Wheel manufacturers
Refrigerator parts	Outboard motor parts	Shaping plants
Ornamental pieces	Roofing, panelling and scaffolding	Processing plants
Architectural fittings	Food and drink containers	
	Automobile road wheels	

Selecting an alloy for an application is purely a matter of meeting the required properties and characteristics of the alloy for that specific application. For example, unalloyed 1xx.x aluminium compositions can be used for applications where very high electrical conductivity is essential[8]. For marine and salt water exposures, where high corrosion resistance is required, the 5xx.x aluminium-magnesium alloys are applicable, while the 2xx.x series are used where high strength is a predominant requirement[8].

The 2xx.x aluminium-copper group includes compositions capable of developing the highest strengths and hardness among all casting alloys[5]. Development of high strength in 2xx.x alloys is achieved through heat treatment. Heat treatment is a process that rearranges the alloy microstructure to improve its mechanical strength and is discussed in detail later. The 7xx.x aluminium-zinc-magnesium alloys are notable for their combinations of good finishing characteristics, good corrosion resistance and ability to develop high strength through natural aging without heat treatment[5]. Alloys of the 3xx.x and 4xx.x groups have higher silicon content and are thus better suited for casting than alloys of the 2xx.x, 5xx.x, 7xx.x and 8xx.x groups. High surface and internal quality castings in the form of intricate designs and with large variations in section thickness can be cast using alloys of high silicon content[5]. Castings are the main use of aluminium-silicon alloys while some sheet and wire is also made for welding and brazing and some piston alloys are extruded for forging stock[6]. Copper free alloys are used for low-to-medium strength castings with good corrosion resistance and those with copper are used for medium-to-high strength castings where corrosion resistance is not critical[5]. Due to the excellent castability of aluminium-silicon alloys it is possible to produce reliable castings even where complex shapes are concerned and obtain higher mechanical properties than in castings made from higher-strength but lower-castability alloys. The highest volume usage alloys are those in the 3xx.x group which, in addition to silicon, contain magnesium or copper, or both[4]. Alloys in this group are commonly aluminium-silicon-magnesium, aluminium-silicon-copper and aluminium-silicon-copper-magnesium systems. Cast aluminium-silicon-magnesium alloys are used extensively in a wide variety of applications requiring a high strength-to-weight ratio. This alloy system possesses excellent castability, good fatigue properties and corrosion resistance. In addition, aluminium-silicon-magnesium castings can be heat treated to obtain an optimum combination of strength and ductility. They find wide commercial use as extrusion alloys because they provide an excellent combination of extrudability, strength, corrosion resistance, finishing characteristics and ready weldability[5]. The aluminium-silicon-magnesium system of alloys are used extensively in the automotive industry as they posses excellent tensile and fatigue properties and good corrosion resistance[9]. The addition of silicon in the alloy produces excellent castability and resistance to hot-tearing[10]. Shrinkage defects in castings are also reduced as silicon increases in volume during solidification[11]. The presence of magnesium also offers the ability to heat treat the alloy to high strength levels[12].

In the 'cost effective' approach to the problem of material selection, the only valid basis for choosing a particular material is that it will perform all required functions at the lowest overall cost. The material chosen may be the most cost effective due to one or more of the following reasons; i) it is the lowest in initial cost and provides service and durability at least equal to those offered by any alternative material, ii) it is the most economical in the long run due to its low operating or maintenance cost, or iii) it has special characteristics not matched by any other material[5]. It is because of the latter reason, *ie. it has special characteristics not matched by any other material,* that commercial aluminium alloy 601 is used as the working material at SAPL for producing road wheels. The combination of properties available with this particular aluminium alloy are unmatched by any other commercially available materials. The particular range of properties available with aluminium alloy 601 that make it a suitable and desirable material for the production of road wheels have been given previously.

1.2 EXTRACTION OF ALUMINIUM FROM 'THEN' BAUXITE

Direct-current electrolysis of aluminium oxide dissolved in a molten sodium fluoride-aluminium fluoride bath at temperatures of 940 to 980°C is used to produce primary aluminium. In this process pure alumina is dissolved in a bath of molten cryolite (sodium- aluminium-fluoride) in large electrolytic furnaces called reduction cells, or 'pots'. By means of a carbon anode suspended in the bath, electric current is passed through the bath mixture causing metallic aluminium to be deposited on the carbon cathode at the bottom of the cell. The heat generated by passage of this electric current keeps the bath molten, so that alumina can be added as necessary to make the process continuous. At intervals aluminium is siphoned from the pots, and the molten metal is transferred to holding furnaces for either alloying or purification. It is then cast into ingots, billet or block of various sizes for further fabrication[2]. Figure 1.1 shows a flow chart[13] of aluminium production at Comalco Aluminium Ltd (Bell Bay) from which it can be seen in pictorial form the essential aspects of the process by which alumina is smelted into primary aluminium. Shown on the flow chart are the various raw materials and operations that are required for the production of primary

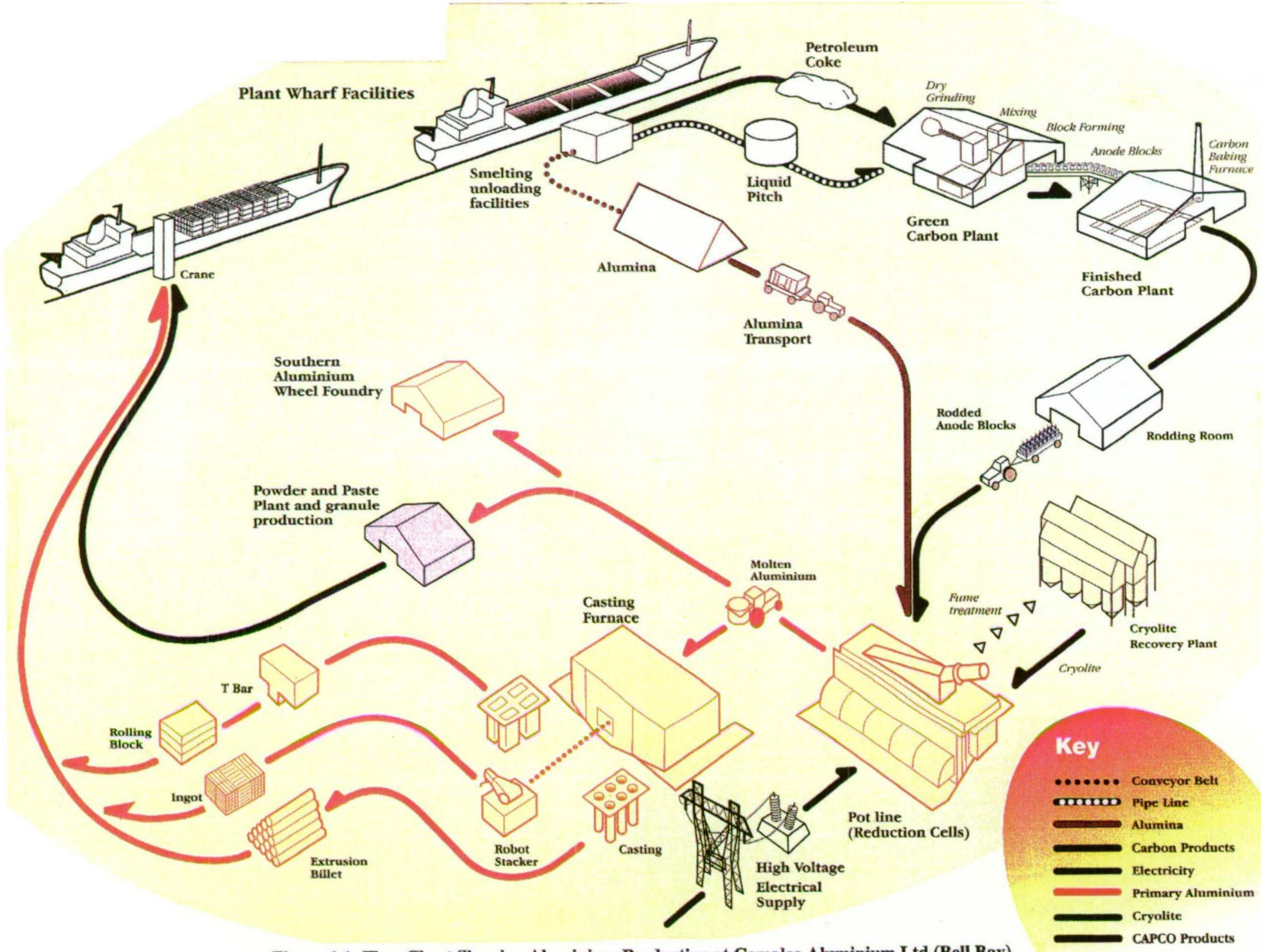


Figure 1.1: Flow Chart Showing Aluminium Production at Comalco Aluminium Ltd (Bell Bay)

aluminium. It is interesting to note on the flow chart that SAPL is shown as a consumer of the molten aluminium produced. The principal current source of aluminium is the mineral bauxite, from which aluminium oxide, or alumina, is extracted and prepared for the smelter by crushing, grinding, chemical processing and calcination[5]. Although aluminium ores are widely distributed in the earth's crust, only bauxite has proved economical as a source of ore from which the metal can be smelted[2].

Iron and silicon are the major impurities present in primary aluminium and vary from 0.05 to 0.6% and 0.04 to 0.3% respectively. Other impurities present in primary aluminium, of less than 0.1% each, are copper, manganese, nickel, zinc, sodium and titanium[5]. These impurities derive from residual impurities in the smelter grade alumina and in the petroleum coke used in producing anodes and linings for the electrolytic cells. Metal from smelting cells is frequently analysed and graded as impurities are present from a variety of sources and in varying amounts. High purity smelter grades, which have preferred characteristics for certain uses, are usually higher priced than base grades and are available in smaller quantities as purity increases.

Secondary aluminium is recovered from scrap and is an important contributor to the total metal supply. Scrap may be recovered from either plants making end products or metal that has been previously used by consumers and is denoted by either new or old scrap respectively. Recycling of scrap metal is important from an economic point of view. The energy required to remelt secondary aluminium in preparation for reuse is only five percent of that required to produce new aluminium. The insignificant energy content involved in 'reworking' and 'reprocessing' aluminium has encouraged many aluminium industries to develop their own processing units.

1.3 PROCESSING TECHNIQUES USED FOR ALUMINIUM ALLOYS

The range of methods used for the processing of aluminium alloys can be divided into the following classifications; i) casting, ii) bulk deformation processes, iii) machining, iv) fabrication and finishing, and v) heat treatment. Each method is a major field of research in manufacturing processes. Only a brief explanation is given here to familiarise each of these five processing methods.

Casting of Aluminium Alloys

Casting processes are classified as either expendable mold or permanent mold casting. Expendable mold casting involves molds made of either sand, plaster or ceramic which are broken up to remove the casting once it has solidified. Molds are used once only in this type of casting. There are a range of casting processes that come under the family of expendable mold casting. These include sand casting, shell-mold casting, plaster-mold casting and full-mold casting. Each of these processes involve the filling of a formed mold with molten metal and solidifying the metal in the shape of the mold. All molds in these processes are broken up to remove the casting and are thus discarded after only one casting. This type of casting is suitable for low production runs as the molds are costly and set-up time is long. Permanent mold casting uses molds made of metals that hold their shape and strength at high temperature so they can be used repeatedly for casting. This type of casting can be automated for large production runs. Various permanent mold casting techniques include die casting, hot-chamber casting, cold-chamber casting and low pressure die casting. All these processes involve the directing of molten metal into permanent molds and solidifying the metal in the shape of the mold. Solidified shapes are then removed from the mold, without damaging either the casting or the mold. Molds are used repeatedly to produce castings of the same shape and size. Permanent mold casting is commonly used for casting aluminium, magnesium and copper alloys because of their generally lower melting points[2]. In particular, the permanent mold casting technique of die casting is used for the casting of aluminium wheels at SAPL. It is useful here to give some detail on die casting in order to familiarise the process.

Die Casting: Die castings are produced by forcing molten metal under pressure into permanent steel dies (molds). The process of die casting involves the following steps. Firstly, the die is closed and locked in position. Molten metal is then fed into the die cavity, induced by the application of pressure. Sufficient metal is delivered to the die to fill the die cavity. The metal remains in the die for a predetermined period of time under pressure for solidification. To aid solidification of the metal, some type of cooling is usually applied to the die. Once the casting has solidified the die is opened and the casting is ejected. While the casting die is open, it is cleaned, cooled and lubricated as required. The die is then closed and locked in position and the process is repeated. The process of die casting can be computer driven, with minimum human involvement to the extent of starting the process and carrying out die maintenance as required. The main advantages of die casting compared to other casting and forming processes are[2]:

- Because the dies are filled by pressure, castings with thinner walls, greater length-to-thickness ratio, and greater dimensional accuracy can be produced by die casting than by most other casting processes.
- Production rates are higher in die casting, especially when multiple cavity dies are used, than in other casting processes.
- Dies for casting can produce many thousands of castings without significant change in casting dimensions.
- Some aluminium alloy die castings can develop higher strength than comparable sand castings.

Bulk Deformation Processes for Aluminium Alloys

Aluminium alloys may be formed using bulk deformation processes which induce shape changes on the workpiece by plastic deformation under forces applied by various tools and dies. Bulk deformation processes are classified as either primary working or secondary working and can be carried out at cold, warm or hot temperatures. The purpose of primary working bulk deformation processes is to start with a solid piece of metal from a cast state, such as an ingot, and break it down into shapes such as slabs, plates and billets. The types of processes used include forging, rolling and extrusion. Secondary working involves further shaping the primary worked metal into forms such as bolts, sheet, metal parts and wire. Bulk deformation processes fall into the four main categories of; i) forging, ii) rolling, iii) extrusion, and iv) drawing.

Forging: Forging is used for the production of discrete parts with a set of dies. It is usually performed at elevated temperatures and the associated die and equipment costs are high. Operator skill also needs to be moderate to high. Some finishing operations are usually required after forging is completed. Many aluminium alloy components are produced using forging techniques due to their high ductility and ability to form well in dies[14].

Rolling: Rolling can be either flat or shape. Flat rolling is used for the production of flat sheet, plate and foil in long lengths whereas shape rolling is used for the production of various structural shapes, such as I-beams. A common product produced using flat rolling techniques is aluminium alloy wrapping foil for domestic use and aluminium panelling.

Extrusion: Long lengths of solid or hollow products with constant cross-section are produced using extrusion techniques. The long lengths produced are then cut to desired useful lengths. Extrusion is usually carried out at elevated temperatures. Aluminium alloy billet can be produced using extrusion. Aluminium scaffolding tubing and hollow-ware is also produced using this technique.

Drawing: Drawing is used to produce long sections of rod and wire with round or various cross-sections and smaller cross-sections than extrusion products. Good surface finishes result from drawing. Aluminium alloy rod and wire is produced using this technique.

Machining of Aluminium Alloys

Machining is a mechanical operation designed to remove material from a workpiece to generate a shape. This is achieved by means of cutting tools which are used to shape the workpiece. The three basic elements of machining are; i) the cutting tool, which is used for removing excess material from the workpiece, ii) the workpiece or component to be shaped, and iii) the machine tool, which supports the cutting tool and the workpiece and provides the required interference, relative motion, power and associated forces to sustain the interference (cut) and generate the component final shape and size[15]. Machine tools are precision items of equipment which can be driven and controlled by computers. The development of numerically controlled machine tools has formed the basis for improved productivity through 'programmable automation' whereby different components can be made by changing computer programmes[15]. Machining operations can produce components with high geometrical accuracy and very good surface finish[12].

The ease or difficulty with which a machining operation can be performed is referred to as machinability. The major process variables that influence machinability of aluminium are tool material properties, tool geometry, work material properties, cut geometry, cutting speed, machine tool variables, cutting fluids used, cost and time variables and component dimensions[15]. The process variables influence various performance aspects such as aluminium surface finish, cutting tool life, tool wear, temperatures and power[16]. These performance measures and their ideal criteria are listed in Table 1.3.

TABLE 1.3 - Machining Performance Measures and Their Criteria[15]

Technological Performance Measures	**Level of Criteria**
Type of Chip Formation	Steady (Continuos)
Tool Wear	Minimum to Nil
Tool Life	Maximum to Infinity
Metal Removal Rate	Maximum to Infinity
Forces	Minimum to Nil
Power	Minimum to Nil
Size Variations	Minimum to Nil
Surface Finish or Roughness	Minimum to Nil
Economic Performance Measures	**Level of Criteria**
Production Rate (component/time)	Maximum to Infinity
Profit Rate ($/time)	Maximum to Infinity
Cost/component	Minimum to Nil

Aluminium alloys can be machined at high speeds as most of the heat generated during cutting is removed with the chip. Chip temperatures developed during machining operations range from 250°C to 500°C[2]. Due to the fact that heat is removed with the chip,. tool surfaces are not subject to excessive heat which causes rapid tool wear and loss of tool hardness.

A property of aluminium that makes it a desirable choice for use in production processes is the ease with which it can be shaped compared to other useable metals. Basic cutting drilling and finishing operations can be carried out manually with ease. The machinability of aluminium alloys in comparison to other commonly machined metals is shown in Table 1.4. Magnesium alloy has been given a rating of unity with an increase in rating indicating a more difficult, slower or more costly machining operation. It can be seen from the machinability factors given that the aluminium alloys rate highly amongst other commonly machined metals. Their excellent machining characteristics result from the high rates of metal removal possible, while maintaining adequate tool life and good surface finish[10].

Table 1.4 - Machinability Factors of Commonly Machined Metals[16]

Magnesium alloys	1.0	Gray cast iron	2.4
Aluminium alloys	1.3	Mild steel	3.3
60/40 Brass	1.4	Copper	4.5

The properties of aluminium which are particularly relevant to its machinability are its thermal conductivity and elastic and shear properties. Heat generated during machining operations is rapidly conducted away from the tip of the cutting tool due the high thermal conductivity of aluminium alloys. This means that working speeds can be increased without risk of damage to the cutting tool due to overheating[10]. Machining energy required is also reduced due to the ease with which aluminium alloys can be machined. This is due mostly to their low impact strength and low resistance to penetration[10]. Another property of aluminium that gives rise to its good machinability is its modulus of elasticity. The modulus of elasticity of aluminium is lower than that of most commonly machined metals, ie. only 70GPa for aluminium alloy compared to 103GPa for gray cast iron, 117GPa for copper and 200GPa for mild steel[17].

Fabrication and Finishing of Aluminium Alloys

Fabrication processes include a host of joining operations such as welding, brazing, soldering and mechanical fastening operations such as bolted and screwed joints, riveting and adhesive bonding. Finishing processes are used to enhance the physical appearance of components without changing their geometry. These processes include washing, polishing, chrome plating, powder coating, painting and paint curing. Fabrication and finishing operations, when applied to aluminium alloys, generally do not play a role in changing the mechanical properties of the alloy. The exception to this is the finishing operation of paint curing. It has been mentioned earlier that paint curing involves the hardening of powder paint on an item by subjecting the item to an elevated temperature for a predetermined period of time. For aluminium alloys, the elevated temperature used for paint curing, nominally in the range of 140 to 190°C, is enough to slightly enhance the mechanical properties of the alloy in terms of both hardness and tensile strength.

Heat Treatment of Aluminium Alloys

The most effective method of strengthening metal alloys is by means of heat treatment processes. Heat treatment is the controlled heating and cooling of metals to change their properties to improve their performance or to facilitate processing[18]. The hardness and strength of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix, accomplished by an appropriate heat treatment[17]. This process is called precipitation hardening because the small particles of the new phase are termed 'precipitates'. Pure metals possess atoms of the same size, so heat treatment of pure metals is not an option for improving strength.

A phase diagram facilitates an explanation of the heat treatment process. It is simplified by reference to a binary system, even though in practice many heat treatable alloys contain two or more alloying elements. The phase diagram is of the form shown in Figure 1.2 for the hypothetical A-B system. Two requisite features must be displayed by the phase diagrams of the alloy systems for precipitation hardening; i) an appreciable maximum solubility of one component in the other, of the order of several percent, and ii) a solubility limit that rapidly decreases in concentration of the major component with temperature reduction[17]. Both these conditions are satisfied by the hypothetical phase diagram. The maximum solubility corresponds to the composition at point M[17]. In addition, the solubility limit boundary between the α and the $\alpha + \beta$ phase fields diminishes from this maximum concentration to a very low B content in A at point N[17]. Furthermore, the composition of a precipitation hardenable alloy must be less than the maximum solubility[17]. These conditions are necessary but not sufficient for precipitation hardening to occur in an alloy system[17].

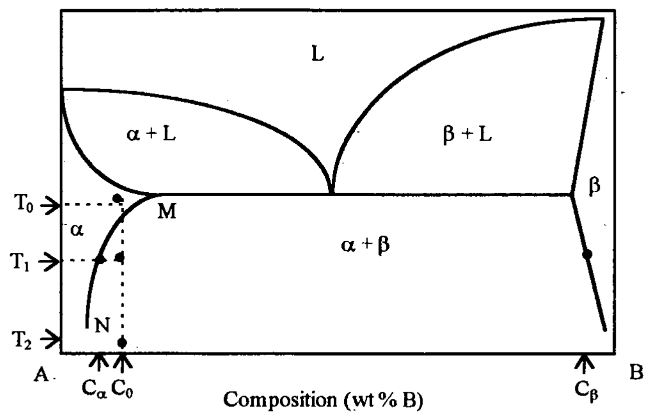


Figure 1.2: Hypothetical Phase Diagram for a Precipitation Hardenable Alloy of Composition C_0[17]

Those alloys which react most positively towards heat treatment are steel alloys and aluminium alloys[19]. Aluminium alloys are commonly heat treated by a three step process involving:

I. Solution Treatment - Dissolution of soluble phases
II. Quenching - Development of supersaturation
III. Aging (or Precipitation Hardening) - Precipitation of solute atoms either at room temperature (natural aging) or an elevated temperature (artificial aging)

These three processes of heat treatment are represented on a temperature-versus-time plot to aid in their understanding, Figure 1.3. An explanation of the plot is given in the literature that follows.

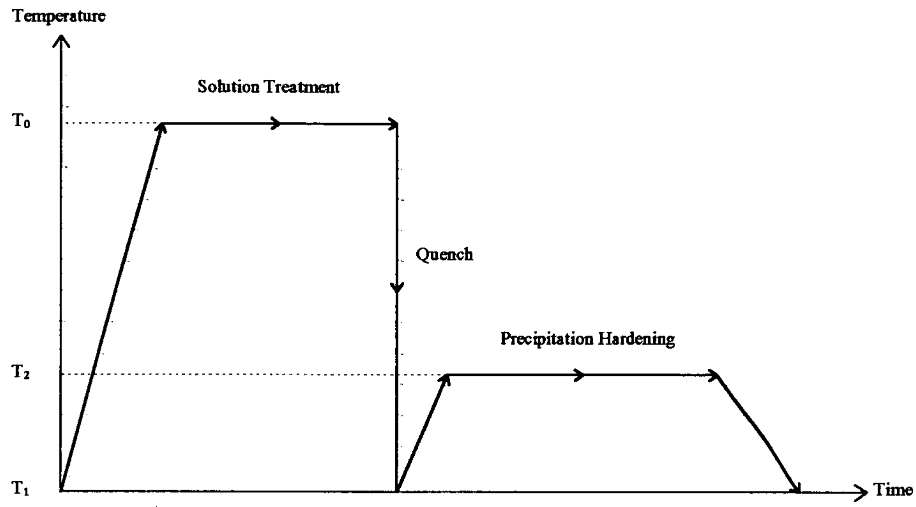


Figure 1.3: Schematic Temperature versus Time Plot Showing Solution Treatment and Precipitation Hardening[17]

<u>Solution Treatment</u>: To get maximum benefit from precipitation hardening it is necessary first to produce a solid solution in the alloy. This is accomplished through solution treatment. The purpose of solution treatment is to take into solid solution the maximum practical amounts of the soluble hardening elements in the alloy. For aluminium-magnesium-silicon casting alloys, the function of solution treatment is three fold; i) dissolution of magnesium silicide, Mg_2Si, particles which form during solidification and subsequent slow cooling, ii) homogenisation of solutes in the aluminium matrix, and iii) spheriodisation and coarsening of the eutectic silicon particles[20]. The process consists of soaking the alloy at a temperature sufficiently high and for a time long enough to achieve a homogeneous solid solution. Homogeneous in its broadest sense means 'the same'. For alloy castings the term homogeneous means the alloy content of the casting is the same throughout the entire structure. That is, a number of samples could be taken from any part of a homogeneous alloy casting and the same alloy content should be observed in each sample. After casting and before heat treatment, the alloy content in the casting is not necessarily the same throughout. Alloying elements may be grouped together in isolated regions of the casting. Hence, a function of solution treatment is to distribute alloying elements evenly throughout the alloy structure. The solution treatment temperature is determined by the composition limits of the alloy and the time for which an alloy is exposed to the solution treatment temperature (soak time) is a

function of the microstructure prior to heat treatment[5]. The solid solution formed during solution treatment must be quenched rapidly enough to produce a supersaturated solution at room temperature, which is the optimum condition for precipitation hardening.

The process of solution treatment is further explained through consideration of Figures 1.2 and 1.3 for an alloy of composition C_0. The treatment consists of heating the alloy to a temperature within the α phase field, say T_o, and waiting until the β phase that may have been present is completely dissolved[17]. At this point the alloy consists only of an α phase of composition C_0 [17]. This procedure is followed by rapid cooling or quenching to temperature T_1 to the extent that any diffusion and the accompanying formation of any of the β phase is prevented[17].

Quenching: Quenching follows directly from solution treatment and is necessary to avoid those types of precipitation that are detrimental to mechanical properties and corrosion resistance[5]. Quenching ensures that the mechanical properties of the alloy that are improved during solution treatment are maintained by keeping the microstructure of the body in the solution heat treated form. The most common method of quenching is by immersion of the part in cold water, or for complex shapes, immersion in water at a temperature of 65 to 80°C. The time between the alloy leaving the solution treatment oven and immersion in the quench tank must be short enough to avoid slow pre-cooling into the temperature range where very rapid precipitation occurs and the volume, heat absorption capacity and rate of flow of the quenching medium must be such that no precipitation occurs during cooling[5]. The function of quenching after solution treatment is to retain the maximum amount of solutes in the aluminium matrix for subsequent precipitation during aging. If the quench rate is not sufficiently high, precipitation may occur at high temperatures during cooling, reducing the quenched-in level of solute supersaturation in the matrix. This results in a lower volume fraction of fine precipitates forming during aging, leading to lower strength, since the precipitates formed during quenching are normally too coarse to make any significant contribution towards matrix hardening[20]. Although from a metallurgical point of view a high quench rate is essential for achieving optimum properties in the alloy, in many cases, such quench rates cannot be used due to problems of producing high internal stresses and distortion. This is especially true for cast components which often have complex shapes and thin sections. It is a widely used practice in foundry to quench castings in hot or boiling water to minimise the possibilities of distortion[20]. If heat is rapidly extracted at the part surface by the quenchant, the high conductivity of aluminium results in rapid temperature losses in thin sections and large temperature differences between thin and thick sections of the part. Large temperature differences create thermal stresses that cause plastic deformation and distortion[21]. If heat is extracted more slowly, the high metal conductivity aids in maintaining temperature uniformity within the part[21]. The practical difficulty lies in establishing just how fast a part of a particular alloy needs to be quenched to retain sufficient hardening elements and compounds in solution in order to achieve an acceptable age hardening reaction, while not cooling so fast that plastic deformation occurs that causes distortion of the part[21]. It has been established in much literature[22-26] that polymer additives can be added to water to provide a quenchant medium that will aid in the minimisation of distortion during heat treatment. Polymer quenchants work in such a way that a fine film of the product surrounds the casting once it is immersed in the quenchant, providing a heat transfer barrier between the casting and the quenchant, causing a uniform rate of heat transfer from both thin and thick sections of the casting. The uniform rate of heat transfer means that thermal stresses in the part are reduced or eliminated, thus reducing distortion in the part.

Aging (or Precipitation Hardening): The third step in the heat treatment process is aging. Aging the solution treated and quenched alloy is necessary to ensure that a finely dispersed precipitate forms in the alloy[27]. The formation of a finely dispersed precipitate that provides higher strength and hardness in the material is the objective of aging. The fine precipitate in the alloy impedes dislocation movement during deformation by forcing the dislocations to either cut through the precipitated particles or go around them[27]. By restricting dislocation movement during deformation, the alloy is strengthened. An alloy that has been subject to an aging process in which the alloy has achieved maximum hardness, or peak hardness, is classed as peak-aged. If the alloy has not been subject to a sufficient aging process to allow the achievement of maximum hardness then the alloy is classed as under-aged.

Precipitation hardening can also be further explained through consideration of Figures 1.2 and 1.3. For precipitation hardening, the supersaturated α solid solution is ordinarily heated to an intermediate temperature T_2 within the $\alpha + \beta$ two-phase region, at which temperature diffusion rates become appreciable[17]. The β precipitate phase begins to form as finely dispersed particles of composition C_β[17]. After the appropriate aging time at T_2 the alloy is cooled to room temperature, normally this cooling rate is not an important consideration[17].

A factor influencing the mechanical properties of an alloy attained through heat treatment is pre-aging. Pre-aging is the period when as-quenched castings are stored at room temperature or slightly higher prior to the commencement of artificial aging. The time of pre-aging typically ranges from a few minutes to several days depending on each individual foundry's process arrangements. If the 'as-quenched' castings are stored at room temperature then the process is effectively natural aging. The effect that natural aging has on the strength properties of A356 alloy prior to artificial aging has been documented by Shivkumar et al[28] in which it is shown that during natural aging, two factors need to be considered; i) formation of clusters, and ii) supersaturation of the matrix. If the clusters formed during the natural aging process are stable, or have attained a critical radius, then during artificial aging a large nucleation density is obtained and the strength properties increase[28]. However, if the clusters have not attained a critical radius, the supersaturation in the matrix diminishes and the size at which the clusters become stable during artificial aging increases[28]. In this case, Shivkumar et al[28] have stated that the clusters may dissolve during artificial aging until some of them are stabilised by the increased level of solute in the matrix. Shivkumar et al[28] state in their work that this behaviour may explain the observed decrease in strength properties in A356 alloys when they are subject to natural aging. It is worth noting at this point that the improvement in mechanical properties in aluminium alloys is determined by the temperature and duration of the solution treatment and aging processes and also by the quenching technique used.

It is now useful to document specific detail regarding the effect that heat treatment has on the mechanical properties of aluminium alloys. This literature survey covers research findings on the relationship between varying alloy content in aluminium and heat treatment of the alloy and specific detail about the effects that solution treatment and aging have on the mechanical properties and machinability of aluminium alloy 601 in particular. A number of important conclusions have been drawn and they show that substantial progress has been made in understanding the effect of heat treatment process parameters on microstructure, mechanical properties and machinability of this important aluminium casting alloy. Determining how varying alloy content effects the microstructure, mechanical properties and machinability of aluminium alloy 601 is also necessary to understand the role that varying alloy content plays in the process of heat treatment. The 'as-cast' microstructure has an influence on the response of A356 alloy to heat treatment[29]. Both treatments, ie. modification of the alloy and heat treatment, can be used in conjunction with each other to produce the desired properties in the casting[29]. There is reason to believe that some shortening of the standard heat treatments to reach the same properties is possible with modified alloys and this could result in some energy savings[29]. A basic tenet of materials science is that the mechanical properties exhibited by metals are greatly influenced by their microstructure[18]. Firstly then, it is useful to provide some detail on the significance of alloying elements present in aluminium alloy 601.

Iron (Fe) is a common element added to aluminium alloys for the purpose of increasing tensile strength[10]. The effect of iron content on the 'as-cast' properties of aluminium-silicon alloys has been documented by Tsukuda et al[30], which shows that yield strength and ultimate tensile strength increase slightly with iron contents up to 0.5% by weight in A356 alloy, but ultimate tensile strength is reduced for iron levels above this. Tsukuda et al[30] have shown that low levels of iron content in the alloy have a damaging effect on its elongation and impact strength. Other studies in this area by Sinfield et al[31] have shown that although there is not an appreciable change in yield strength and ultimate tensile strength with increasing iron content in A356 alloy, there is a significant reduction in the ductility and corrosion resistance of the alloy. Similar studies on the effects of iron on the mechanical properties of A356 alloys have been conducted by Closset and Gruzleski[32]. Their work has shown that varying amounts of iron content in alloy A356 have significant effects on mechanical properties. It is shown that yield strength and ultimate tensile strength decrease significantly at higher iron levels, approximately 250 and 322MPa respectively at

0.15% iron content to 236 and 294MPa respectively at 0.36% iron content. It is also shown that elongation of A356 alloy decreases from 12.7% at iron levels of 0.1% to an elongation of 3.8% at iron levels of 0.36%. This decrease in elongation directly reduces the ductility of the alloy. These findings are in agreement with the findings of Tsukuda et al[30] and Sinfield et al[31]. High tensile strength without sufficient ductility will lead to a low fracture toughness in the alloy[33]. For this reason and also because aluminium wheels produced at SAPL must have high corrosion resistance, it is important that low iron content be maintained in the alloy mix. Hence, efforts are often made to keep iron content in the alloy as low as possible. Efforts that can be made to reduce iron content in the alloy include starting with a low iron charge in the original melt, minimising iron pickup during melting and holding of the alloy and making suitable additions to the melt. Metals such as cobalt, chromium, manganese, molybdenum and nickel can be added to the melt as a corrective for iron and also to improve the alloys strength at high temperature[34]. Copper can be added to alloy 601 to improve strength and fatigue resistance but it has detrimental effects on the corrosion resistance of the alloy[9]. Due to this decrease in corrosion resistance it is not practical to add copper to aluminium alloy 601 for the purpose of strength improvements during wheel manufacturing at SAPL.

With aluminium alloys for casting silicon is the main alloying element. Its intrinsic ability to give high fluidity and low shrinkage, results in good castability and weldability of the alloy[10]. Silicon also decreases the coefficient of thermal expansion of aluminium alloys, resulting in reduced internal stresses, due to contraction of a casting as it cools[10]. Both yield strength and ultimate tensile strength increase rapidly with silicon additions of up to about 7% by weight of the alloy, while ductility decreases[9]. With silicon concentrations greater than 7% by weight the rate of increase in strength properties decreases significantly. Tsukuda et al[30] have shown that elongation and impact strength decrease rapidly in aluminium-silicon alloys with a silicon content greater than 6 to 8% by weight which means that the ductility and impact resistance of the alloy are reduced. Magnesium combines with silicon in the alloy to form magnesium silicide, an age hardening compound that improves mechanical strength during heat treatment. Magnesium alone has very little effect on the 'as-cast' properties of the alloy[35].

Trent[36] has shown that silicon particles are highly abrasive and thus increase cutting tool wear during machining processes. Trent[36] has shown that the size and shape of silicon particles in the alloy play an important role in determining the quality of its machined surface. This work provides a direct relationship between the heat treatment and the machinability of aluminium alloys with significant silicon content, such as aluminium alloy 601. In the work completed by Trent[36] it is shown that alloys with fully spheroidised silicon particles finely dispersed throughout the alloy structure achieve much better surface finish after machining than alloys with non-spheroidised, large silicon particles. To create an alloy with a finely dispersed structure of fully spheroidised silicon particles it is necessary to subject the alloy to a suitable heat treatment process. During initial heat treatment of aluminium alloys the silicon particles begin to spheroidise in the alloy structure. With continuing heat treatment, silicon particles achieve full spheroidisation and disperse throughout the alloy structure as fine particles[37]. Trent[36] suggests that the poorer surface finish obtained with alloys having large non-spheroidised particles is due to the particles being torn from the alloy surface during machining. This is in agreement with the work completed by El-Azim et al[38] in which it is suggested that the rough surface finish associated with a coarse distribution of primary silicon particles is due to the silicon particles being torn out of the material. To eliminate the coarse distribution of primary silicon particles and hence improve surface finish, it is necessary to subject the alloy to a suitable heat treatment process that will result in a finely dispersed structure. The work completed by Trent[36] and El-Azim et al[38] has provided a direct relationship between the heat treatment and machinability of aluminium alloys by documenting the finding that silicon particle size and shape, determined by heat treatment, significantly influence the machinability of the alloy. The addition of strontium (Sr) in A356 alloy increases the spheroidization rate and lowers the coarsening rate of silicon particles during heat treatment[37]. Although porosity is increased with the addition of strontium, the 'as-cast' and heat treated mechanical properties of the alloy are improved[37].

Research[39] conducted using the major research laboratories of Comalco and the availability of research material has investigated the effect of varying solution treatment time and temperature on the tensile properties of unmodified and 0.01%Sr modified and 0.02%Sr modified aluminium alloy 601. This research has shown some interesting relationships between heat treatment and modification of the alloy. The research laboratories used were very well equipped with the necessary instrumentation and personnel expertise to carry out the investigation. It is worthwhile noting that whilst the solution treatment condition was varied during the investigation a fixed aging treatment of 4.5 hours at 140°C was maintained. The first part of the investigation involved a study of the effect that varying solution treatment time and temperature has on the yield strength of 0.01%Sr modified alloy. From research[39] it is shown that with a solution heating time of fifteen minutes for a sample of 0.01%Sr modified aluminium alloy 601 at a maximum solution treatment temperature of 518°C, the yield strength obtained in the alloy is 135MPa. With a heating time of fifteen minutes and a maximum temperature of 532°C, the yield strength remains almost unchanged. With a heating time of twenty minutes and a maximum temperature of 536°C, the yield strength increases slightly to 147MPa. Further increase in heating time to thirty minutes at a maximum temperature of 540°C increases the yield strength to 155MPa. The yield strength corresponding to the standard T6 heat treatment process used at SAPL (solution treatment for 4.5 hours at 540°C and aging for 4.5 hours at 140°C) for a 0.01%Sr modified alloy is 175MPa. The variation in ultimate tensile strength of the alloy with varying solution time has also been studied in research[39]. It is shown that the ultimate tensile strength of 0.01%Sr modified alloy initially decreases slightly in the first fifteen to twenty minutes of heating and then increases with increased heating time to a maximum of 240MPa after thirty minutes at 540°C. Research[39] has shown a comparison between the yield strength and ultimate tensile strength of unmodified and 0.01%Sr modified alloy as a function of solution heating time. It is shown that for a zero to thirty minute heating cycle at 540°C the unmodified alloy has a higher yield strength but lower ultimate tensile strength throughout the cycle, Figure 1.4. It can be seen that after a solution treatment condition of thirty minutes at 540°C the maximum yield strength and ultimate tensile strength of the unmodified alloy are 165 and 225MPa respectively compared to the maximum yield strength and ultimate tensile strength of the 0.01%Sr modified alloy of 155 and 240MPa respectively.

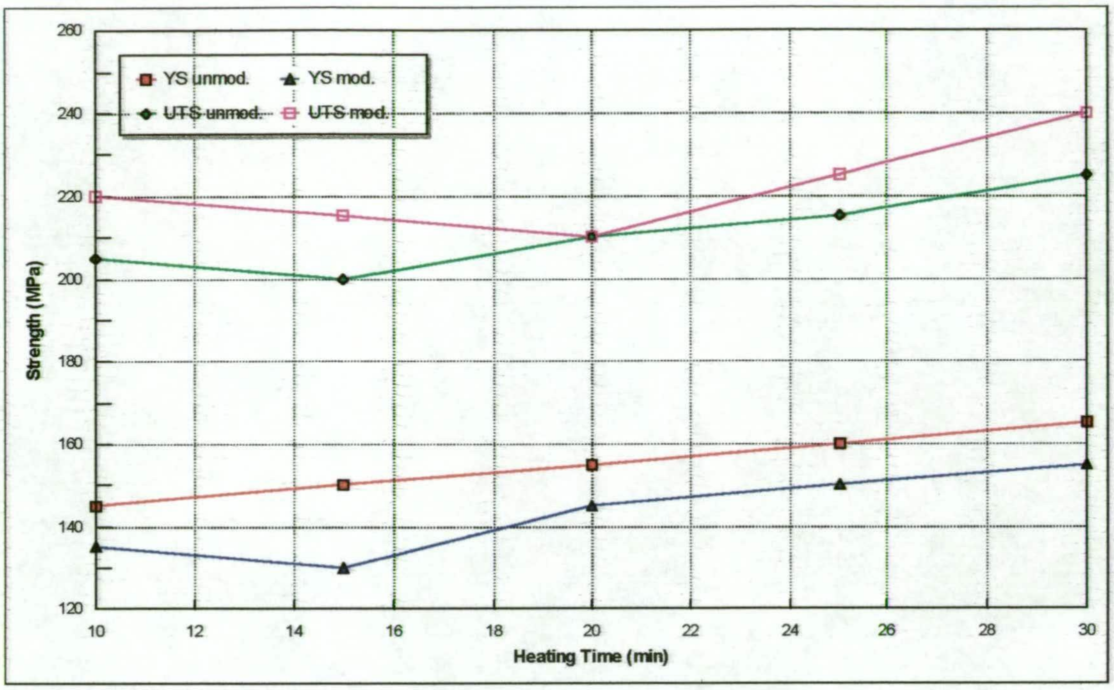


Figure 1.4: Strength of Unmodified and 0.01%Sr Modified Aluminium Alloy 601 as a Function of Solution Heating Time at 540°C[39].

The effect of varying solution time on the elongation of 0.01%Sr modified alloy has also been studied in research[39] using a maximum solution temperature of 540°C. It is shown for 0.01%Sr modified alloy that as heating time increases from ten to twenty minutes, the elongation of the alloy initially decreases from 8% to 4% and then increases to 8.5% as heating time increases to thirty minutes. It is also shown that the elongation of the unmodified alloy is in the range of 2 to 3% for a heating time of thirty minutes. This is shown graphically in Figure 1.6. Elongation is 10.5% with the standard T6 heat treatment process used at SAPL for 0.01%Sr modified alloy. The results indicate that the addition of 0.01%Sr to aluminium alloy 601 gives the effect of reduced yield strength but increased ultimate tensile strength and elongation during solution treatment.

The effect of varying solution treatment time and temperature on the yield strength of 0.02%Sr modified aluminium alloy 601 has been shown in research[39] to be similar to that of the 0.01%Sr modified alloy. For 0.02%Sr modified alloy it is shown that with a solution heating time of ten minutes at a maximum solution temperature of 514°C, the yield strength in the alloy is 125MPa, increasing to 130MPa with a heating time of thirteen minutes at a maximum solution temperature of 529°C. Further increase of the heating time to twenty minutes and a maximum temperature of 540°C increases the yield strength to 150MPa. The same temperature with a heating time of thirty minutes gives a decrease in yield strength to 135MPa. It is also shown that ultimate tensile strength increases with heating time up to a maximum of 230MPa after thirty minutes at 540°C but remains unchanged after thirty minutes. With the standard T6 heat treatment process used at SAPL for 0.02%Sr modified alloy the yield strength and ultimate tensile strength are 158MPa and 251MPa respectively. As mentioned earlier, the yield strength corresponding to a standard T6 heat treatment for 0.01%Sr modified alloy 601 is 175MPa, thus indicating that an increase in strontium in aluminium alloy 601 from 0.01% to 0.02% significantly reduces the alloys yield strength during heat treatment. A relationship between strontium content and yield strength of the alloy is shown in Figure 1.5 for both a standard and shortened heat treatment process. The standard heat treatment process consists of solution treatment for 4.5 hours at 540°C and aging for 4.5 hours at 140°C whilst the shortened heat treatment process consists of solution treatment for thirty minutes at 540°C and aging for 4.5 hours at 140°C. It is evident in both cases that the addition of strontium to the alloy causes a significant decrease in yield strength.

Research[39] has also shown the effect that strontium modification has on the elongation of 0.02%Sr modified alloy for varying solution treatment times. It is shown in Figure 1.6 that the elongation of 0.02%Sr modified alloy at a solution temperature of 540°C decreases from 8% to 6% as heating time increases from ten to fifteen minutes and then increases gradually to 8.5% as heating time increases from fifteen to thirty minutes. With the standard T6 heat treatment process used at SAPL for 0.02%Sr modified alloy the elongation is 11%, which is slightly higher than the elongation of 10.5% mentioned previously for 0.01%Sr modified alloy 601 heat treated using the standard T6 condition. Again it is evident that the addition of strontium to the alloy improves its elongation.

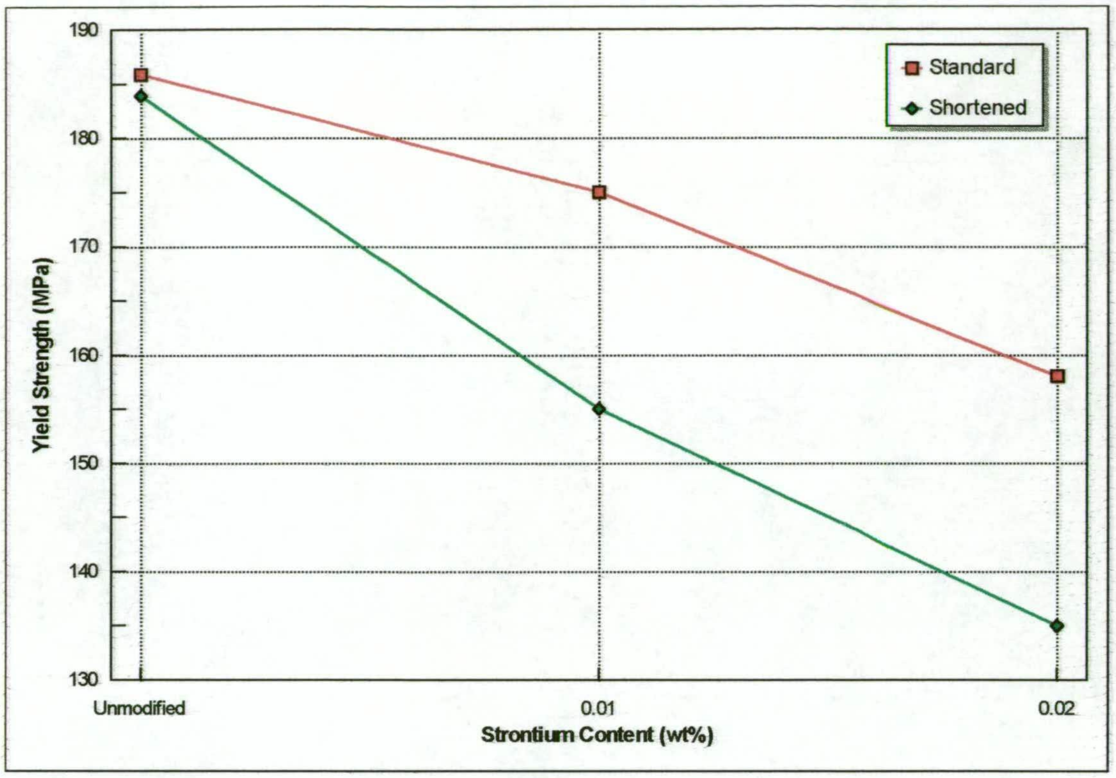


Figure 1.5: Yield Strength of Aluminium Alloy 601 as a Function of Strontium Content for Both a Standard and Short Solution Heat Treatment[39]

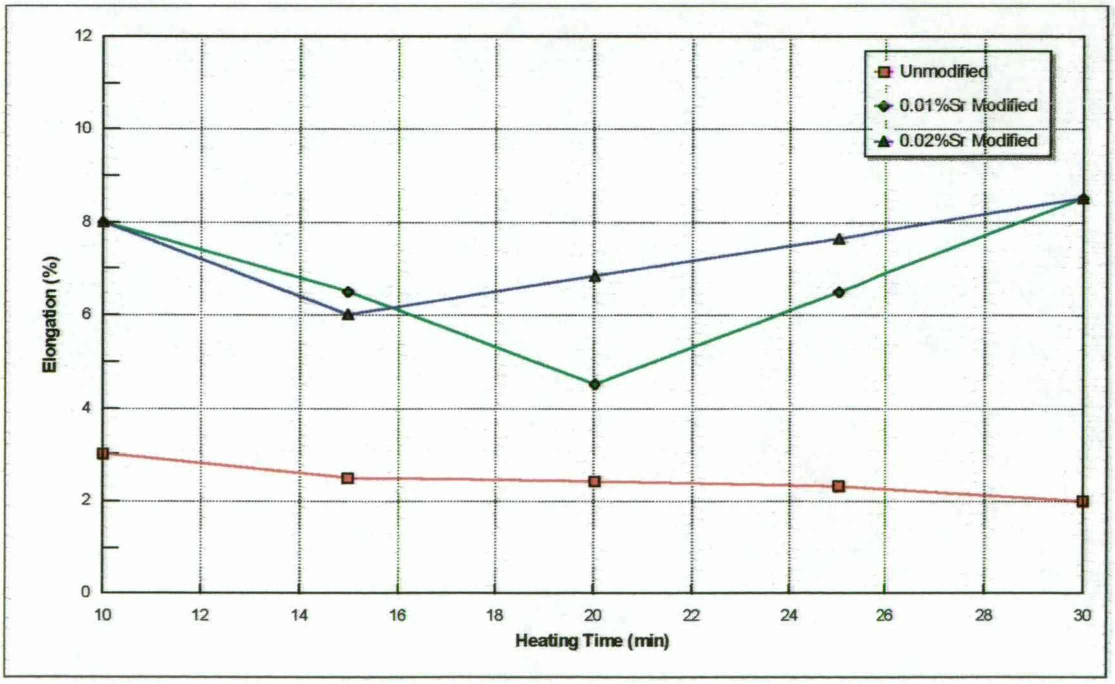


Figure 1.6: Elongation of Unmodified and Strontium Modified Aluminium Alloy 601 as a Function of Heating Time at 540°C[39]

Hence, a major finding from research[39] is that the addition of strontium to alloy 601 causes a decrease in yield strength but an increase in both ultimate tensile strength and percentage elongation. With both a standard and shortened solution treatment process, the decrease in yield strength caused by strontium addition is evident. Addition of strontium to aluminium alloy is essential to achieve full modification of the silicon eutectic phase in order to obtain sufficient ductility in the alloy, but the amount of strontium addition needs to be minimised in order to prevent a significant reduction in yield strength[37]. In the current practice at SAPL 0.005% strontium by weight is added during the melt. This amount has been documented in research[39] as being sufficient to cause full modification of the eutectic silicon phase and thus achieve sufficient ductility in the alloy.

Further work on the effect of solution treatment on aluminium alloy 601 has been completed by Shivkumar et al[28] who have investigated the effects of solution treatment parameters on permanent mold castings of A356 alloys. Unmodified and 0.02%Sr modified test bar samples of A356 alloy were used in their investigations to examine the influence of selected variables on the tensile properties of the alloy. The test bars were subject to the following heat treatment cycle:

I. Solutionize at 540°C for 25, 50, 100, 200, 400 and 800 minutes
II. Quench in water at 60°C for 7 seconds
III. Natural age at room temperature for 24 hours
IV. Age at 171°C for 4 hours

Heat treated samples were subject to tensile tests from which yield strength, ultimate tensile strength and percentage elongation were all determined. The results from their investigations have shown that strontium modification of the alloy causes a decrease in 'as-cast' yield strength but a slight increase in yield strength during and after solution heat treatment. It is shown that yield strength of the modified A356 alloy increases with solution treatment time and reaches a maximum after about one hundred minutes. It is also shown that ultimate tensile strength increases with solution treatment time and reaches a maximum after about fifty minutes. This is shown graphically in Figure 1.7 from which it can be seen that yield strength and ultimate tensile strength are slightly greater in the modified alloy than in the unmodified alloy.

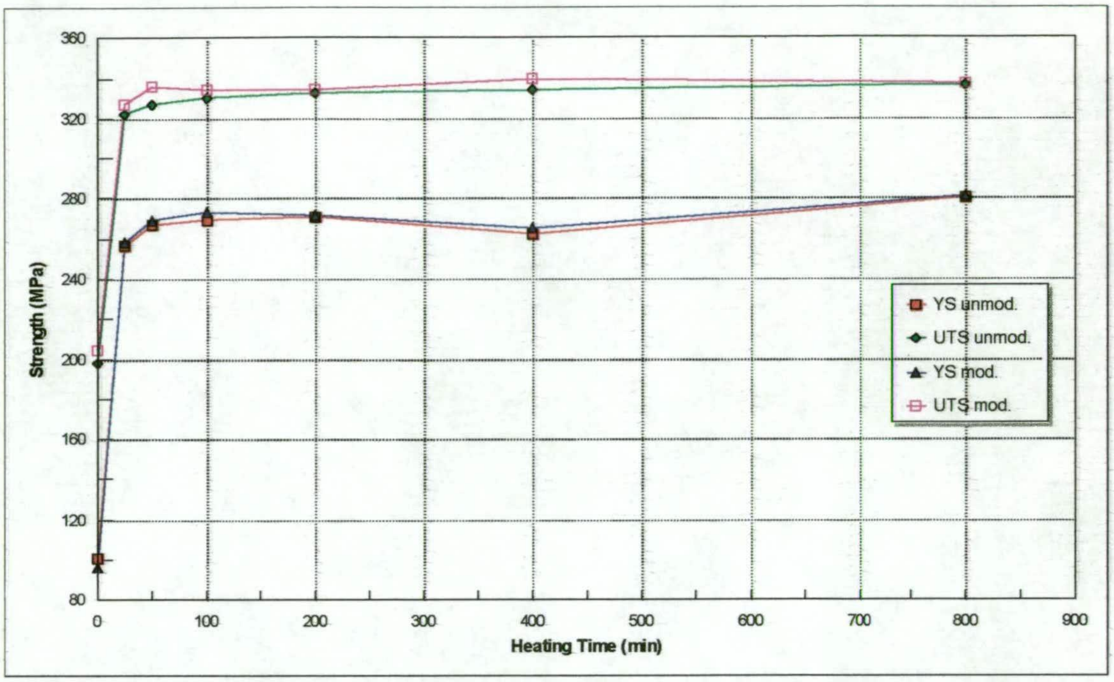


Figure 1.7: Tensile Properties of Unmodified and 0.02%Sr Modified A356 Alloy as a Function of Solution Heating Time[28]

It is shown in the work by Shivkumar et al[28] that the property most affected by strontium modification is elongation. The relationship between strontium modification and elongation is shown in Figure 1.8. It can be seen from this that strontium modification of the alloy causes a significant increase in elongation during solution treatment. These findings are in agreement with the findings detailed previously from research[39] for 0.02%Sr modified alloy other than the effect that strontium modification has on the yield strength of the alloy. Shivkumar et al[28] have shown that the modified alloy has a slightly higher yield strength than the unmodified alloy which differs to the findings from research[39] that has shown yield strength to be lower in the modified alloy. The reason for the discrepancy between the findings of either party is unclear at this stage.

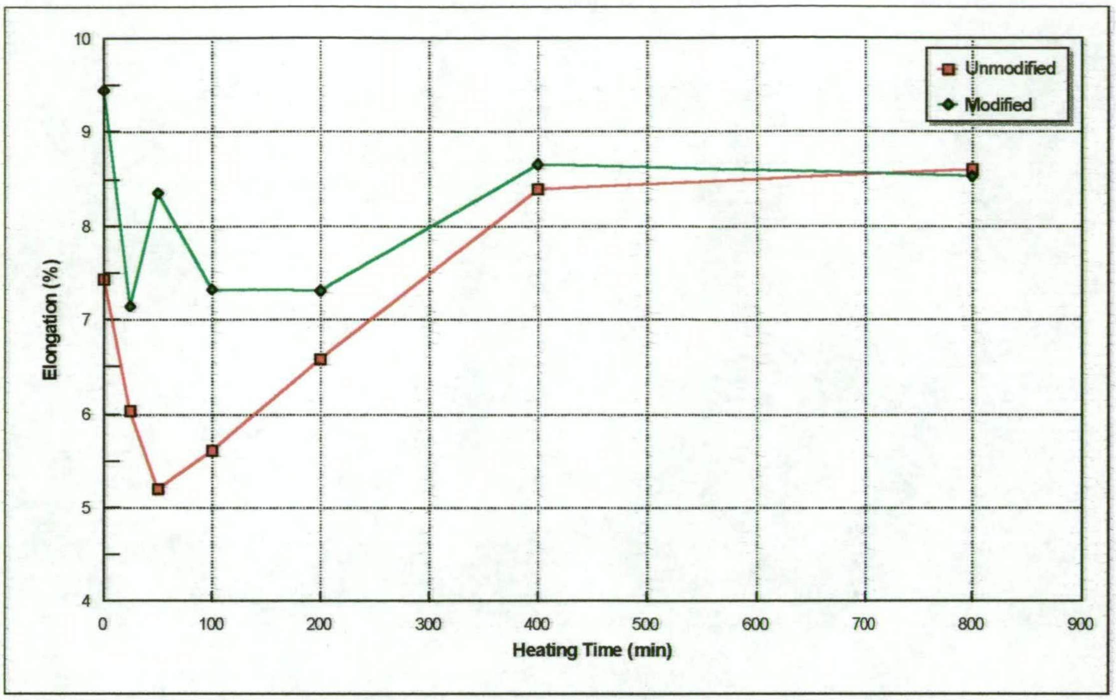


Figure 1.8: Elongation of Unmodified and 0.02%Sr Modified A356 Alloy as a Function of Solution Heating Time[28]

Although the findings given by Shivkumar et al[28] are encouraging it should be noted that modification of aluminium alloy 601 can have some adverse effects. One of the major problems associated with chemical modification of the melt is the tendency of the modifier to increase porosity levels in the casting[40]. The enhancement in mechanical properties attainable after modification can easily be offset by the presence of porosity in the cast part. The presence of porosity in aluminium alloy castings induces tensile transverse stresses in silicon particles and at the particle matrix interface[41]. These stresses promote crack initiation at the particle-matrix interface and thus lower mechanical properties. However, Shivkumar et al[28] have shown in their work that strontium modification of permanent mold test bars of A356 alloy does not have an appreciable effect on porosity, Table 1.5. The presence of some porosity due to modification of the alloy is evident from the slightly lower density of the modified alloy. Shivkumar et al[28] have shown that, despite the presence of some porosity, modified samples exhibit higher tensile properties than unmodified alloys.

TABLE 1.5: Density of Unmodified and 0.02%Sr Modified A356 Alloy Test Bars[28]

0.02%Sr Modified Alloy		**Unmodified Alloy**	
Sample	Density (g/cm^3)	Sample	Density (g/cm^3)
1	2.6853	1	2.6867
2	2.6854	2	2.6862
3	2.6851	3	2.6858

The effect of solution treatment time on the hardness of unmodified and 0.02%Sr modified A356 alloy has also been shown by Shivkumar et al[28] for a maximum solution temperature of 540°C. It is shown in Table 1.6 that hardness increases in the unmodified alloy with solution treatment time up to a Rockwell hardness value of 93.2 after twenty five minutes and remains almost unchanged as solution time increases. Rockwell hardness increases in the modified alloy up to a maximum of 94.9 after one hundred minutes and then decreases as solution time increases. It is evident from the work completed by Shivkumar et al[28], as shown in Table 1.6, that strontium modification has a damaging effect on the hardness of the alloy when short solution treatment times only are used.

TABLE 1.6: Rockwell (F) Hardness Values of Permanent Mold Test Bars[28]

Solution Time (min)	**Hardness (Unmodified)**	**Hardness (0.02%Sr Modified)**
As-Cast	58.2	59.6
25	93.2	86.6
50	93.9	91.9
100	93.0	94.9
200	93.8	90.5
400	93.7	92.3
800	91.0	93.7

It has been shown in further work by Shivkumar et al[42] that aging, the third component of the T6 heat treatment process, of A356 alloy has a significant influence on tensile properties. Their investigations involved subjecting test bars of unmodified and 0.02%Sr modified A356 alloy to the following heat treatment cycle:

I. Solutionize at 550°C for 50 minutes

II. Quench in water at 60°C for 7 seconds

III. Natural age at room temperature for times varying from 0 min to 72 hr

IV. Age at temperatures ranging from 145°C to 201°C for times varying from 0 min to 100 hr

Their research has shown that the yield strength, ultimate tensile strength and percentage elongation of A356 alloy is directly affected by aging time and temperature. The major findings from the work by Shivkumar et al[42] are summarised in Tables 1.7 and 1.8 for unmodified and 0.02%Sr modified alloy respectively from which it can be seen that the general trend is increasing aging time or temperature improves the strength properties of the alloy but lowers its elongation. At aging temperatures less than 181°C, yield strength and ultimate tensile strength increase gradually with aging time and reach a maximum value after about ten to twelve hours. For temperatures above 181°C, yield strength and ultimate tensile strength are observed to be notably high after only two to four hours of treatment. It is also shown that elongation initially decreases with aging time for temperatures below 181°C. Shivkumar et al[42] have shown in their work through a comparison between tensile strength and elongation for the unmodified and 0.02%Sr modified alloy that strontium modification does not have any detectable influence on precipitation kinetics.

TABLE 1.7: YS and UTS of Unmodified Alloy During Aging[42]

Temperature (°C)	Time (hr)	YS (MPa)	UTS (MPa)	Elongation (%)
161	2	204.6	323.1	9.5
	6	320.4	363.1	5.3
	10	303.8	368.6	4.3
	12	294.8	366.5	3.7
	18	327.3	370.6	5.7
171	2	258.3	345.2	8.9
	4	296.9	353.4	4.1
	6	317.6	367.9	5.8
	10	332.8	359.6	4.9
	12	321.1	357.6	5.4
181	2	265.9	314.8	10.4
	6	311.4	358.9	8.4
	10	324.5	354.1	5.4
	12	303.8	338.3	6.7
	18	315.5	361.0	5.0
191	2	309.4	338.3	3.2
	6	345.2	361.0	5.8
	10	305.9	338.3	3.3
	12	303.1	338.3	3.1
	18	315.6	346.6	4.2
201	2	299.0	330.7	3.2
	4	303.8	325.9	4.9
	6	305.9	336.9	6.1
	10	328.6	337.6	1.4
	12	312.8	343.1	9.6
	100	128.2	155.0	25.6

TABLE 1.8: YS and UTS of 0.02%Sr Modified Alloy During Aging[42]

Temperature (°C)	Time (hr)	YS (MPa)	UTS (MPa)	Elongation (%)
161	2	222.5	317.6	7.8
	6	306.6	371.3	6.0
	10	319.6	343.1	1.5
	12	305.9	365.8	3.6
	18	338.2	358.9	2.6
171	2	252.8	344.4	8.6
	4	298.2	353.4	5.5
	6	297.6	354.1	5.4
	10	325.1	371.3	4.8
	12	314.8	366.4	5.3
181	2	262.5	338.9	13.6
	6	281.8	357.5	4.9
	10	314.8	352.0	3.9
	12	333.4	363.0	5.1
	18	339.6	366.4	6.5
191	2	290.0	332.0	2.7
	6	321.7	371.3	6.6
	10	344.4	361.7	4.4
	12	314.8	355.5	6.6
	18	305.2	336.2	6.6
201	2	306.5	334.1	4.7
	4	287.3	310.0	7.0
	6	298.3	328.6	8.3
	10	345.1	354.7	2.3
	12	345.8	355.3	9.6
	100	107.5	148.8	26.7

If it were possible to significantly reduce solution treatment time without affecting the quality of the casting produced there would be significant benefits obtainable for many manufacturing plants. In particular, aluminium alloy wheel manufacturing time at SAPL could be significantly reduced as a result of a significant reduction in a major manufacturing process such as heat treatment. In research[39] it has been shown that a solution treatment condition of thirty minutes at 540°C is sufficient to achieve a high level of yield strength in cast unmodified aluminium alloy 601. Referring back now to the previously documented work completed during research[39] it has been shown that with a short solution heating time of thirty minutes at 540°C, where the sample is initially at room temperature, it is possible to achieve a yield strength in unmodified aluminium alloy 601 that is comparable to the yield strength normally obtained with a standard solution treatment condition of 4.5 hours at 540°C. It is shown in research[39] that the alloy sample reaches a temperature of 540°C after eight minutes of heating and a yield strength of 135MPa is achieved at that point. After two minutes of holding at 540°C, a yield strength of 145MPa is achieved. Further holding for another twenty minutes at 540°C increases the yield strength to 183MPa. This yield strength is very close to the maximum yield strength of 187MPa achieved in the alloy in the underaged condition using the standard T6 heat treatment process, which suggests that an isothermal solution treatment time longer than twenty two minutes of holding at 540°C offers no real benefit in terms of improved yield strength. Hence, a total solution treatment time of thirty minutes, consisting of eight minutes heat-up period and twenty two minutes holding period, is sufficient to achieve a high level of yield strength in aluminium alloy 601. The elongation of unmodified aluminium alloy 601 has also been studied in research[39] for varying solution treatment times. It is shown that as the sample temperature reaches 540°C, elongation starts to increase with solution treatment time. It is shown that an isothermal holding time at 540°C beyond three to four minutes is favourable for the improvement of ductility. The hardness of alloy samples for various heating times has also been documented in research[39]. It is shown in Figure 1.9 for a maximum solution treatment temperature of 540°C that hardness of the alloy initially decreases within the first four minutes of heating and then increases with heating time from four to thirty minutes.

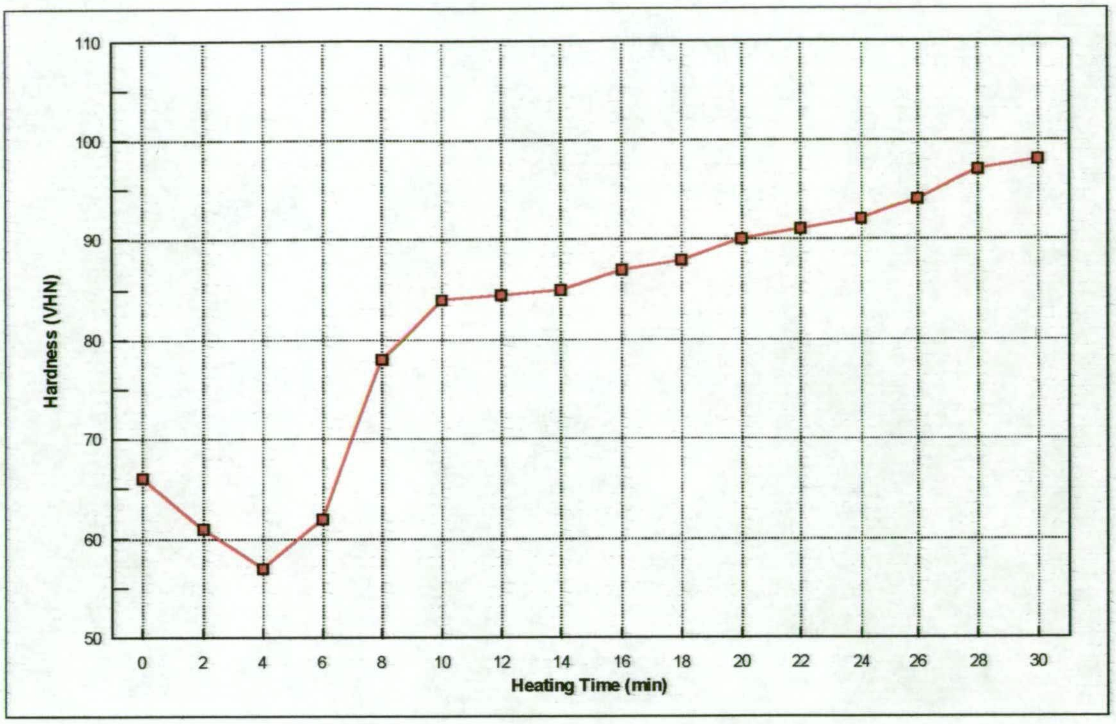


Figure 1.9: Hardness of Aluminium Alloy 601 as a Function of Heating Time During Solution Treatment at 540°C[39]

It is useful now to introduce the concept of a combined casting and solution treatment process. With the standard T6 heat treatment process used at SAPL a casting is solution treated only after being quenched to room temperature from the casting machine. This differs significantly from a combined casting and solution treatment process in which the casting is solution treated immediately after casting whilst the casting is still at an elevated temperature. For a combined casting and solution treatment process the heat-up time needed to get the casting up to the maximum solution treatment temperature is significantly reduced as the casting is already close to the maximum solution temperature when it leaves the casting machine. This in turn ultimately reduces the total solution treatment time needed as a significant portion of solution treatment time involves heating a casting up to the maximum solution treatment temperature. The solution treatment condition of thirty minutes at 540°C suggested in research[39] as being sufficient to achieve a high level of yield strength may be reduced even further for a combined casting and solution treatment process, in which samples are initially heated from an elevated temperature. When a casting is at an elevated temperature (nominally 400°C directly after casting for aluminium wheels at SAPL) prior to solution treatment, a reduction in heating time is possible since the time taken to heat castings from room temperature to 400°C doesn't play an important role in determining final yield strength, ultimate tensile strength or percentage elongation. This is confirmed in research[39] from the results of both tensile tests and analysis of the alloy microstructure after heat treatment. However, research[39] has shown that for short solution treatment times, the heating rate from approximately 400°C to the maximum solution treatment temperature and selection of the maximum solution treatment temperature are critical for determining the final yield strength of the alloy. It is shown that for a set heating time of ten minutes, with varying heating rates and solution treatment temperatures the corresponding yield strength in the alloy varies significantly. The yield strength corresponding to a slow heating rate and low maximum solution temperature is only 115MPa, which is significantly lower than the yield strength of 145MPa corresponding to a high heating rate and high maximum solution temperature. Hence, it is critical for achieving a high level of yield strength that a high heating rate be used and a maximum solution temperature be correctly established for an optimised solution treatment process.

Information on the change in microstructural features during the initial stage of solution treatment is crucial in understanding the mechanisms which control the change of mechanical properties with short solution treatment time and temperature. Research[39] has shown the results of using a 'Differential Scanning Calorimeter' to study the microstructure of aluminium alloy 601 during solution treatment. It is shown in the results that the solution treatment process is almost complete within two to three minutes of reaching a solution temperature of 540°C and also that the maximum solute content is sensitive to the solution temperature. However, it is not shown to what extent the matrix composition of aluminium alloy 601 is homogenised using a short solution treatment time or how homogenisation of the matrix affects the mechanical properties of the alloy. This has, however, been shown in research[43] in which measurements of silicon and magnesium contents and their distribution in aluminium dendrites were taken using an electron microprobe analysis technique. This research involved a quantitative metallographic examination of the microstructure of aluminium alloy 601 solution treated for different times in the range of two to thirty minutes at 540°C to establish the extent to which spheroidisation of the silicon eutectic particles during solution treatment was improving the ductility of the alloy.

Research[43] was again conducted in the major research laboratories of Comalco using specialised equipment. The main aim of the investigation was to determine the effect of short solution treatment times on the tensile properties of unmodified aluminium alloy 601. Again, it is important to note that a fixed aging condition of 4.5 hours at 140°C was used during testing.

The chief outcome of research[43] is that an isothermal solution treatment condition of four to six minutes at 540°C and an aging condition of 4.5 hours at 140°C is necessary and sufficient to achieve a level of yield strength and ultimate tensile strength in unmodified aluminium alloy 601 close to those obtained with the standard T6 heat treatment process used at SAPL. As a result of research[43] it has been shown that the yield strength of aluminium alloy 601 increases rapidly to approximately 160MPa and ultimate tensile strength increases to approximately 250MPa with a short isothermal solution time of four to six minutes at 540°C. It is shown that a longer holding time of thirty minutes only leads to a slightly higher yield strength and ultimate tensile strength in the alloy of 165 and 270MPa respectively. A standard solution treatment of 4.5 hours at 540°C for the same alloy gives a yield strength and ultimate tensile strength of 175 and 275MPa respectively. It has been shown in research[43] that a solution treatment time of less than four minutes holding at 540°C gives the effect of lowering the yield strength of the alloy dramatically. It is suggested in research[43] that this is due to the magnesium content in some regions of the wheel being lower than necessary for less than four minutes of isothermal solution treatment. A composition analysis of the alloy completed in research[43] has shown this to be true. An electron microprobe composition analysis of the alloy conducted in research[43] has shown that with a short solution treatment condition of four to six minutes at 540°C the magnesium content in the matrix is approximately 0.25% by weight, which is very close to the maximum of 0.3% by weight allowed by the alloy composition, and that the distribution of magnesium particles is fairly homogeneous. This indicates that a high degree of completeness of the solution and homogenisation process are achieved with a short solution treatment of four to six minutes at 540°C. When a longer solution treatment of ten minutes at 540°C is used it is shown in research[43] that almost complete solution and homogenisation are achieved. The confidence of achieving a high degree of the maximum yield strength and ultimate tensile strength through using a short solution treatment is reflected by the results of the composition analysis as tensile strength is related to the degree of the homogenisation process[43].

In addition it is shown in research[43] that for a fixed aging condition of 4.5 hours at 140°C an isothermal solution time of ten to twelve minutes at 540°C is necessary and sufficient to achieve a level of elongation in aluminium alloy 601 close to the maximum value of 10.3% obtained with the standard T6 heat treatment used at SAPL. It has been shown that elongation starts to increase after six minutes of solution treatment at 540°C and then becomes constant after approximately ten to twelve minutes of being held at 540°C. The resulting elongation is shown to be approximately 10.0%. This reinforces confidence in using a shorter solution treatment time as the results obtainable are consistent and comparable to those obtained using the standard solution treatment process.

Furthermore, research[43] has shown that the fraction of spheroidised silicon particles and the average silicon particle size in aluminium alloy 601 increase rapidly in the first ten minutes of solution treatment at 540°C, and then the rate of increase reduces significantly. The spheroidization of eutectic silicon particles during solution treatment helps to improve the ductility of aluminium alloy 601[37]. This is consistent with findings documented in research[43] where it has been shown that the change in elongation of the alloy with solution treatment time matches well with the change in morphology and size of the eutectic silicon particles. It is shown that the percentage of spheroidised eutectic silicon particles increases significantly as solution time increases from two to ten minutes and then the rate of increase becomes much lower during further solution treatment. It is also shown that the average silicon particle diameter increases dramatically in the first ten minutes of solution treatment and then the rate of increase becomes much slower. The correlation between the change of elongation and the change of silicon particle morphology and size suggests that spheroidisation and coarsening of silicon particles are dominant factors controlling ductility in the alloy.

Further work completed in research[43] has shown that the strength and ductility of aluminium alloy 601 improves with increasing solution temperature from 500 to

550°C, but no benefit is gained by increasing the solution temperature above 550°C. Figure 1.10 shows that for a fixed solution treatment time of one hour, both the yield strength and ultimate tensile strength increase with increasing solution treatment temperature from 500 to 550°C, and then there is no significant increase in yield strength for solution temperatures above 550°C.

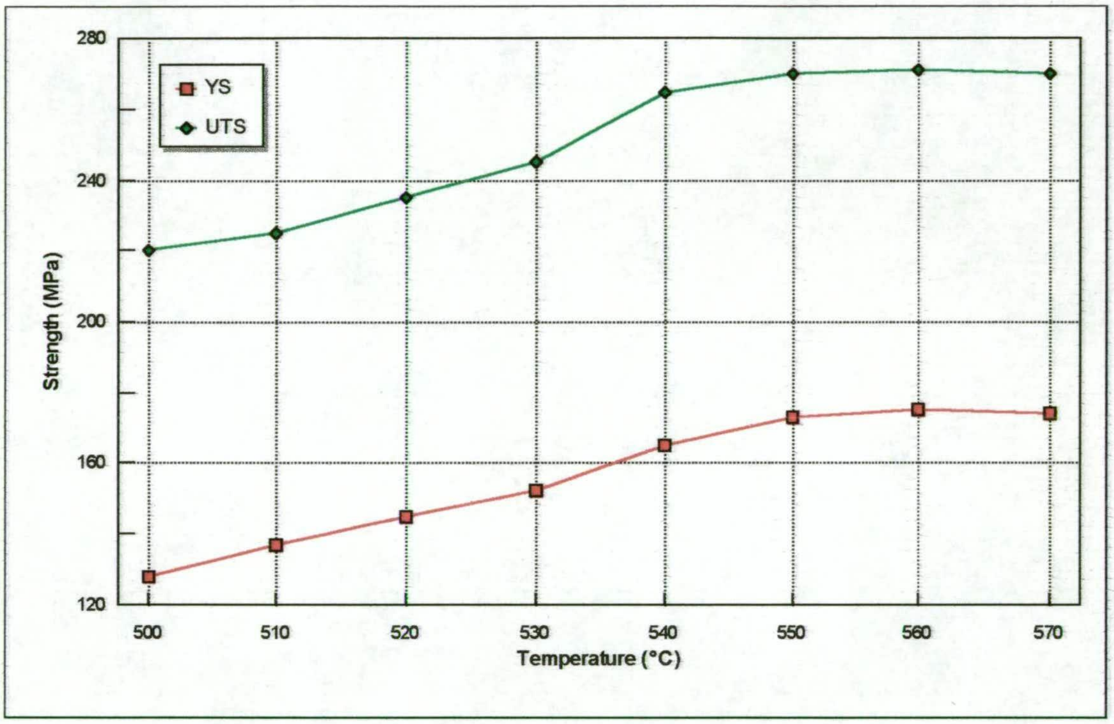


Figure 1.10: Yield Strength and Ultimate Tensile Strength of Aluminium Alloy 601 as a Function of Solution Temperature for a Fixed Solution Time of One Hour[43]

It is shown in research[43] that a solution treatment condition of one hour at a temperature of 500°C is not sufficient to dissolve all magnesium compounds or achieve sufficient homogenisation, leading to low strength in the alloy. It is shown that as solution temperature increases to 525°C, homogenisation is achieved within one hour, but the magnesium content in the matrix is still significantly lower than the maximum amount allowed by the alloy composition, indicating that the solution process is not complete. It is shown in research[43] that both homogenisation and solution process are complete within one hour when a solution temperature of 540°C or a higher is used, resulting in improved strength and ductility in the alloy. Although yield strength and ultimate tensile strength increase in the alloy with increasing solution temperature from 540 to 550°C for a one hour solution time, previous findings from research[43] have shown that for a short solution treatment condition of four to six minutes or even ten to twelve minutes, a solution temperature of 540°C is sufficient to achieve high yield strength, ultimate tensile strength and percentage elongation and that no real benefit exists in increasing solution temperature above 540°C when a short solution treatment time only is used. Figures 1.11 and 1.12 show graphically that for increasing solution temperature from 540 to 550°C there is no significant gain in yield strength, ultimate tensile strength or elongation for a short solution time between two and thirty minutes. In fact, the graphs show that yield strength and ultimate tensile strength are slightly higher when a solution temperature of 540°C is used for short solution treatment times.

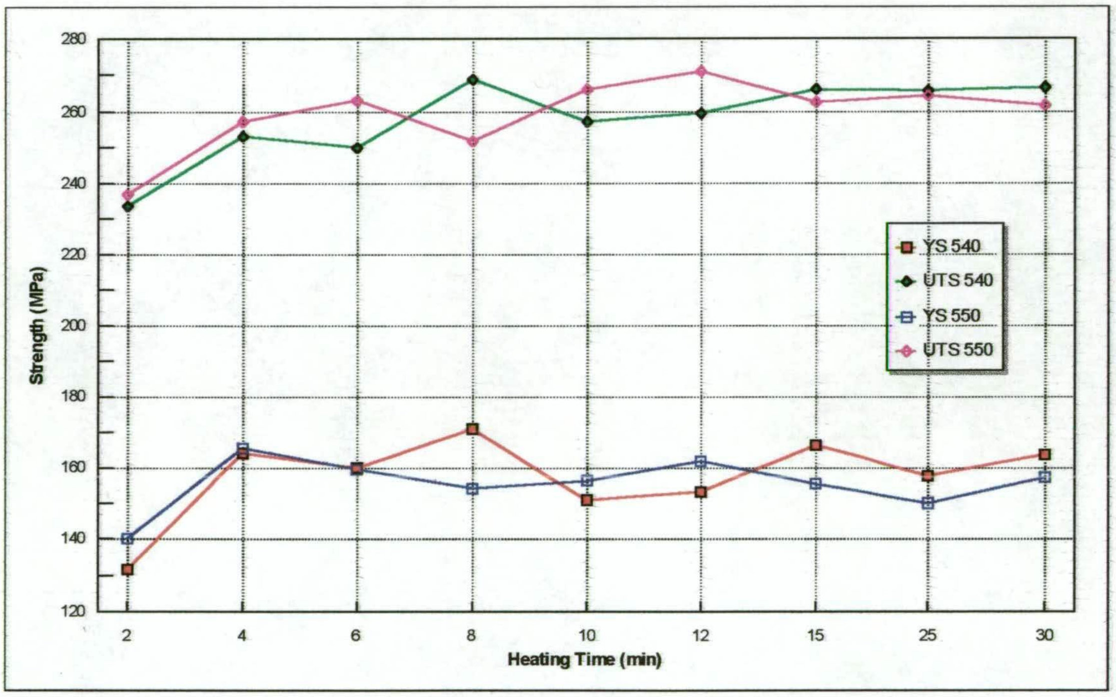


Figure 1.11: Comparison of Yield Strength and Ultimate Tensile Strength in Aluminium Alloy 601 as a Function of Solution Treatment Temperature [43]

The findings given in research[43] have significant implications on the heat treatment process used at SAPL. In particular, the findings given show that when a fixed aging condition of 4.5 hours at 140°C is used it is possible to achieve a high level of tensile strength in the alloy using only a short solution treatment time of four to six minutes and a high level of elongation using a short solution treatment time of ten to twelve minutes. The desirable solution treatment temperature to use to achieve the high level of mechanical properties is shown to be 540°C.

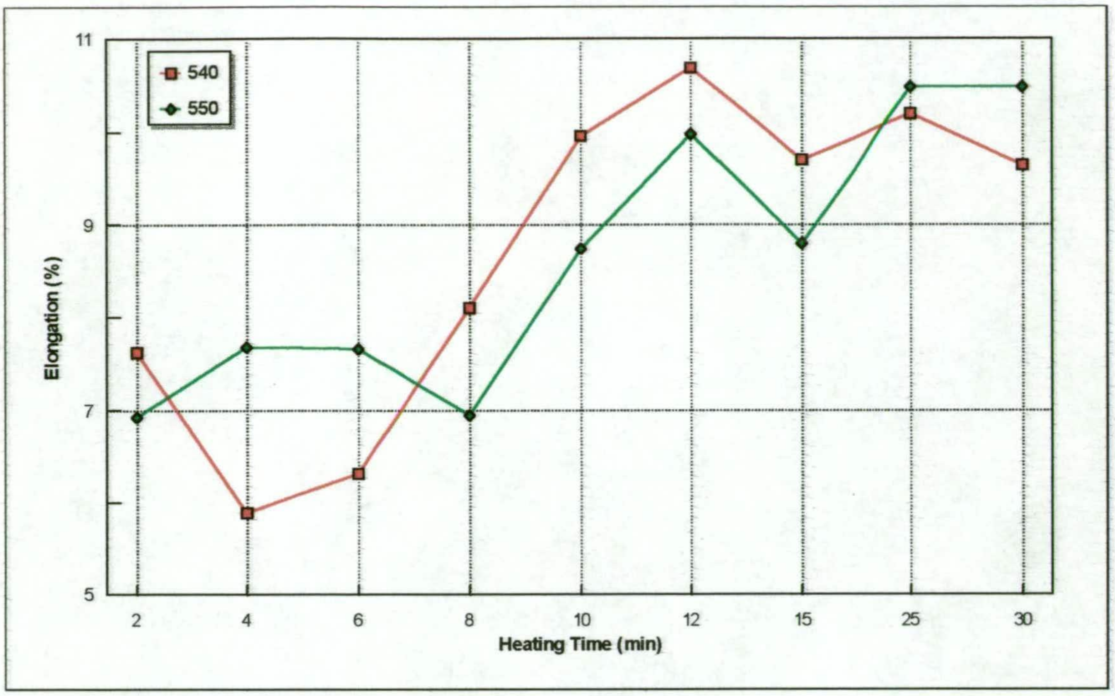


Figure 1.12: Comparison of Elongation in Aluminium Alloy 601 as a Function of Solution Treatment Temperature [43]

While it is interesting to note the behaviour of aluminium alloys with varying alloy content and heat treatment conditions, it is also necessary to understand the effect that these parameters have on aluminium alloy 601 as it undergoes further processing. The machinability of aluminium casting alloys is affected by the following four material related factors; i) alloy composition, microstructure and properties, ii) casting method used, iii) treatments which alter the microstructure, such as heat treatment, and iv) metallic and non-metallic impurities[12]. The effect that heat treatment has on the machinability of aluminium alloy 601 is of particular interest as almost all aluminium castings require some form of machining during processing. Many aluminium casting alloys are machined after heat treatment and therefore the effect on machinability of microstructural changes due to heat treatment needs to be investigated. In particular, the role that heat treatment conditions play in determining the machinability of aluminium alloy wheels needs to be understood. A common measure of machinability for aluminium alloys is surface finish, or surface roughness. The internationally adopted standard measure for surface roughness is the 'arithmetic mean value' (Ra). Ra is defined as the arithmetic average deviation of the surface from a mean line or centreline, expressed in micrometres[1]. Measuring surface roughness is important because it influences the fit between mating surfaces, function of certain parts, fatigue and notch sensitivity, electrical and thermal contact resistance, corrosion resistance, subsequent processing, appearance and cost of manufacture[1].

Research into the effect of heat treatment on the machinability of aluminium alloys has been completed by Jocumsen[44] who has shown some significant results. Jocumsen[44] has studied the effect that heat treatment has on the machinability of aluminium alloy 601 by machining samples of the alloy that had been subject to the following heat treatment process:

I. Solution treatment at 505°C for 8 hours
II. Quench in water at 60 to 80°C
III. Under age at 140°C for 4 hours
IV. Peak age at 165°C for 8 hours

A significant finding of Jocumsen's work is that the surface roughness of aluminium alloy 601 decreases dramatically from the 'as-cast' condition to the 'under-aged' condition and then decreases even further to the 'peak-aged' condition. This is shown graphically in Figure 1.13 for varying cutting speeds.

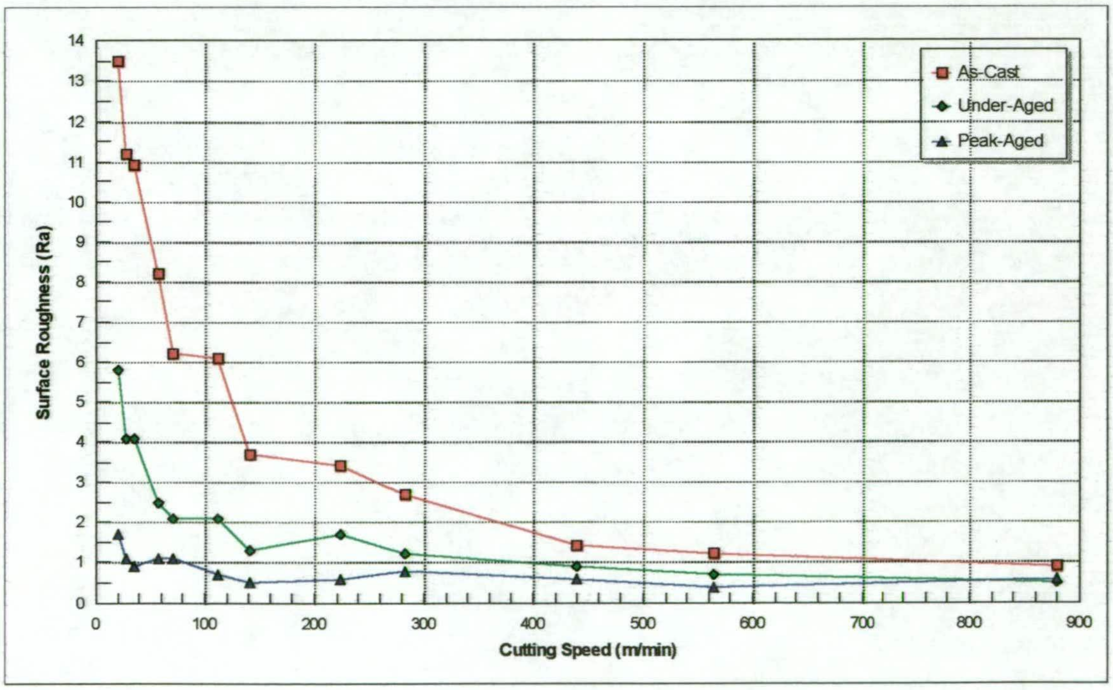


Figure 1.13: Surface Roughness of Aluminium Alloy 601 as a Function of Heat Treatment[44]

Jocumsen suggests in his work that the decrease in surface roughness of the alloy from the 'as-cast' to the 'under-aged' condition and then further to the 'peak-aged' condition may be due to an increase in the hardness of the alloy. Jocumsen has shown in his work that the hardness of alloy 601 increases from a Brinell hardness number of 53 in the 'as-cast' condition to 59 in the 'under-aged' condition and then increases further to 88 in the 'peak-aged' condition.

The decrease observed in surface roughness for the different heat treatment conditions used in Jocumsen's work indicates that heat treatment has a significant influence on the machinability of the alloy. It is shown that solution treatment and under-aging of the alloy cause a dramatic improvement in surface finish from the 'as-cast' condition, corresponding to a reduction in the formation of built-up-edge (BUE). BUE describes the build up of work material on the tool tip during cutting. It directly affects the ability to achieve desired dimensional and surface finish control. Aluminium alloys readily form BUE and it is this which often makes obtaining a desired surface finish difficult. Jocumsen suggests in his work that the reduction in the formation of BUE is due to a combination of precipitation hardening of the matrix and the spheroidisation of silicon particles during heat treatment. It can be seen from Figure 1.13 that the surface roughness of the alloy continued to climb exponentially as the cutting speed decreased. This suggests that the dominant effect on surface finish for aluminium alloy 601 may be the 'tearing' and 'ploughing' of the material rather than the formation of BUE.

This concludes the literature survey conducted into the area of the heat treatment of aluminium alloy 601 and its effects on microstructure, mechanical properties and machinability. To fully understand the process of heat treatment many aspects have been considered in this literature survey, including alloy content, solution treatment and aging effects on mechanical properties and the influence of heat treatment on the machinability of the alloy. The data obtained from this literature survey has given some encouraging results towards optimising the heat treatment process at SAPL.

1.4 CONCLUDING REMARKS

The importance of manufacturing and its relation to the economic health of a country has been established early in this chapter. Likewise, the importance of productivity improvements have been established and shown to be directly influential on the economic health of a manufacturing organisation. Productivity improvements have been identified as being obtainable through implementing techniques to achieve optimum product flow and reduce processing time. An investigation of a modern manufacturing plant, Southern Aluminium Pty Ltd, revealed that productivity improvements for the plant are achievable through a reduction in processing time of a major processing operation. Heat treatment was identified as being the greatest contributor to total wheel processing time and thus seen as being the operation that would create the most significant productivity improvements if optimised. Heat treatment has been shown to be a necessary operation in the production of aluminium wheels to improve their mechanical properties from the 'as-cast' condition and prepare them for use on passenger vehicles.

A literature survey conducted to investigate the process of heat treatment and its effect on the mechanical properties of aluminium alloy 601 gave some interesting results towards the optimisation of the heat treatment process. Some important conclusions were drawn from the literature survey which show that substantial work has been completed to date in understanding the above mentioned issues. The literature survey has shown that varying alloy content and heat treatment time and temperature significantly influence the mechanical properties of aluminium alloy 601 during heat treatment. Firstly, considering the role that varying alloy content plays in the process of heat treatment, much work has been completed to understand the effect that the addition of strontium has on the mechanical properties of the alloy. Most of the research in this area was comparatively similar and suggested that with the addition of strontium the 'as-cast' and mechanical properties of the alloy are improved. Mechanical properties were shown to be optimum for a silicon content in the range of 6 to 8% by weight. Iron additions have been shown to improve the mechanical strength of aluminium alloys but must be kept low in aluminium alloy wheels due to its detrimental effect on corrosion resistance.

A significant finding to come from the literature survey in relation to optimising the heat treatment process at SAPL is that an isothermal solution treatment time of four to six minutes at 540°C is necessary and sufficient to achieve a high level of yield strength and ultimate tensile strength in the alloy. Although with a short isothermal solution treatment time of four to six minutes, the completeness of solution and homogenisation is such that a high percentage of the optimum strength can be achieved the size and morphology of the silicon particles in the alloy are not sufficiently changed for good ductility. This mismatch results in lower ductility being obtained with a short solution time of four to six minutes. The mechanical property requirements for a cast aluminium alloy wheel are obviously a well balanced combination of suitable high strength, ductility, impact resistance and good fatigue properties. It has been shown that high strength and hardness without sufficient ductility will lead to a low fracture toughness in the alloy. For this reason a solution treatment time of only four to six minutes should be avoided, thus making the best short solution time ten to twelve minutes, as ten to twelve minutes of solution treatment at 540°C has been shown to be sufficient for achieving a high level of elongation in the alloy.

The behaviour of aluminium alloy 601 during aging treatment has been shown in some detail in the literature survey. The general trend is that increasing aging time or temperature improves the strength properties of the alloy but lowers its elongation.

An important parameter shown in the literature survey to be affected by heat treatment is the machinability of the alloy. The major documented finding is that the machinability of the alloy improves with heat treatment from the 'as-cast' condition and furthermore, a significant improvement is noticed from the under-aged to the peak-aged condition. It is suggested that the improvement in machinability is closely related to the degree of spheriodisation of the eutectic silicon particles in the alloy.

The intention now is to develop a system at SAPL that will allow for the heat treatment of wheels using a shortened heat treatment cycle in a combined casting and heat treatment process in order to match and compliment the findings given in the literature survey. In the first instance, this will involve the solution treatment of wheels using a ten minute isothermal solution treatment time at a temperature of 540°C. In the first instance, an isothermal solution time of ten minutes will be used, in preference to twelve minutes, as it represents the minimum time that can be used in the solution treatment process. Aging treatment will be carried out using the standard condition of 4.5 hours at 140°C. Wheels heat treated under this new heat treatment process will then be tested for hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance. As there is no existing practical process for the determination of the mentioned mechanical properties of the alloy using a combined casting and heat treatment process incorporating the mentioned optimised heat treatment conditions then it is necessary to develop an experimental heat treatment cell to allow an investigation to be completed. The design and development of the heat treatment cell required for the experimental investigation is documented in the following chapter.

CHAPTER TWO

DESIGN OF EXPERIMENTAL APPARATUS

For the purpose of testing wheels using an optimised solution treatment condition in a combined casting and heat treatment process it was necessary to design a heat treatment cell, housing the necessary experimental equipment required for testing. The design of the experimental cell involved the visualisation of various systems and mechanisms that could be used to perform the necessary heat treatment operations. Consideration of the options available led to the selection of a satisfactory system that could be incorporated into the manufacturing cycle at the plant. The design of the system was complex as it was not allowed to interfere with current processing operations and there was limited space available for the situation of the necessary equipment, such as a solution treatment oven and quench tank. The heat treatment cell designed is a simulation of a heat treatment process that may be used in future if the mechanical properties using the shortened heat treatment process are proved to be sufficient. The cell designed in this instance would need to be incorporated on a larger scale with some minor technical changes if it was to be used as a permanent production process, however, the simulation in this preliminary stage will prove useful for the purpose of obtaining wheel mechanical properties and proving wheel handling capability at high temperature. The cost of simulating the process on a small scale is only a fraction of the cost of setting up a full scale modified heat treatment process and it is due to this latter reason in particular that a small scale simulation heat treatment cell was used in the first instance.

2.1 DESIGN AND DEVELOPMENT OF EXPERIMENTAL TESTING EQUIPMENT

The experimental cell designed needed to be such that wheels were able to be removed at very high temperature from the casting machine, in which they were cast, and placed directly into a solution treatment oven. As stated earlier, in a combined casting and heat treatment process a casting is removed from the casting machine and immediately subject to the solution treatment process whilst the casting is still at an elevated temperature. The best practice for removal of castings, to take advantage of their high temperature immediately after casting, is to take them from the casting machine transfer trolley, immediately after casting. A transfer trolley is a mechanical device used to remove castings from the casting machine dies. An explanation of the operation of a transfer trolley is useful at this point. Each casting machine has its own transfer trolley. Once a casting has solidified in the die, the die separates, and the top die with the casting attached, moves upwards. When the top die is fully retracted the transfer trolley moves underneath it at which stage the castings are released from the top die onto the transfer trolley. The transfer trolley and castings then move clear of the die and come to rest for a short period. During this rest period it is possible to remove castings from the transfer trolley by an external source. It is at this point that it is most practical, and convenient, to remove castings and subject them to the shortened solution treatment process. This will be carried out by transferring castings from the transfer trolley directly to a solution treatment oven. The time delay between castings leaving the transfer trolley and entering the solution oven will be sufficiently low enough to ensure that the castings enter the solution oven with a temperature very close to that with which they leave the die. After solution treatment, it is necessary that wheels be quenched and subject to further processing. In order to complete the tasks mentioned it was necessary to design and manufacture a heat treatment cell that could be placed in front of a casting machine as required. A heat treatment cell was designed to satisfy the above criteria, consisting of a manoeuvrable platform that housed a solution treatment oven, quench tank, wheel placement table and robot. The development of this heat treatment cell involved a major design exercise right from inception stage to completion of the experimental test rig. The development of the experimental heat treatment cell involved the conceptual layout of the system, selection and design of experimental test equipment and implementation of the conceptual design to a fully operational physical system. The layout and particularities of the designed heat treatment cell and wheel position on the transfer trolley, just prior to being taken for solution treatment, are shown schematically in Figures 2.1 and 2.2 on the following pages. From these it can be seen that each of the individual cell components play a significant role in the heat treatment process. It is interesting to list here each item of experimental equipment used in the cell and give a description of their purpose and the process of their design.

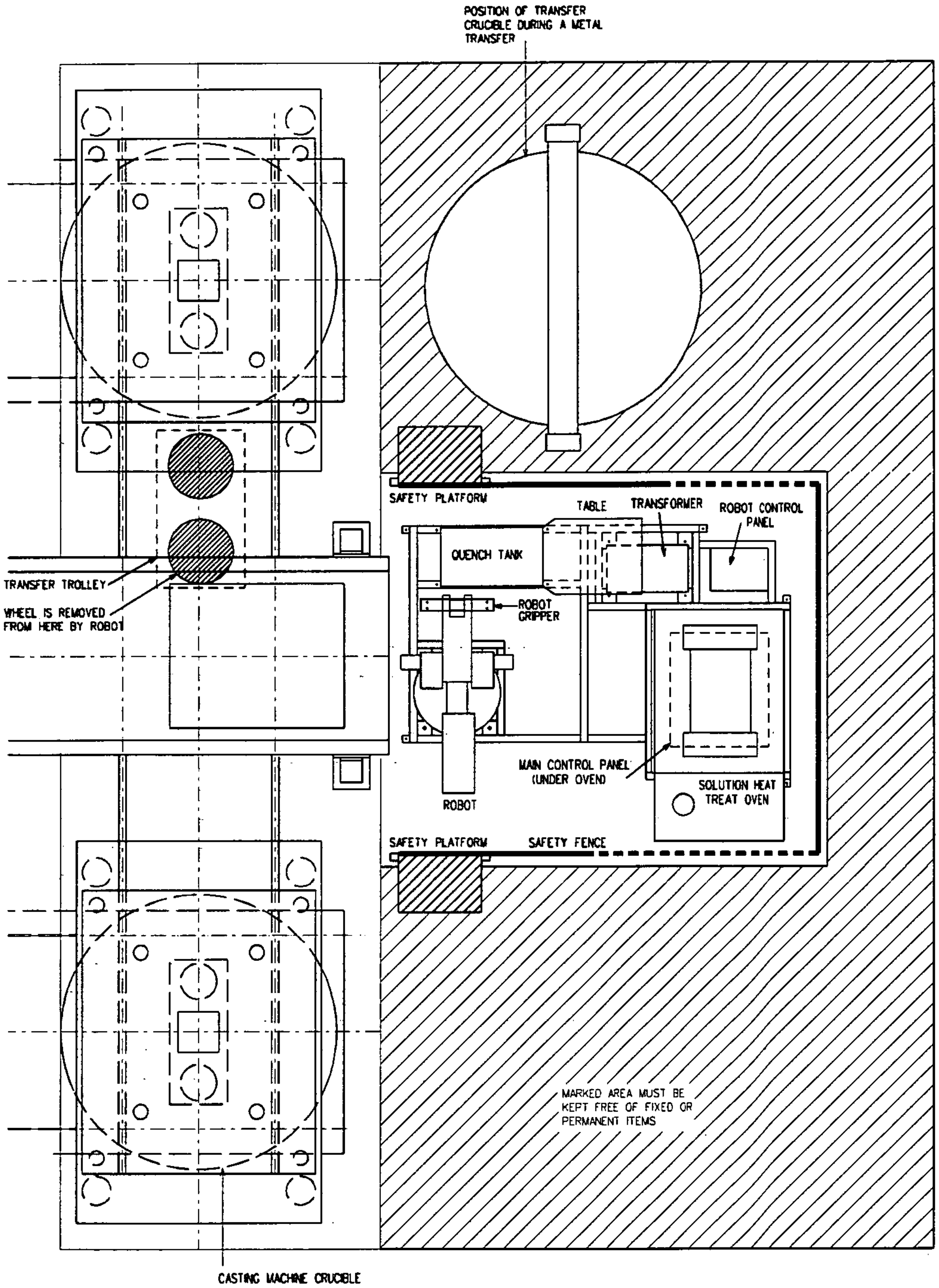


Figure 2.1: Top View of Experimental Heat Treatment Cell and Casting Machine Set-Up

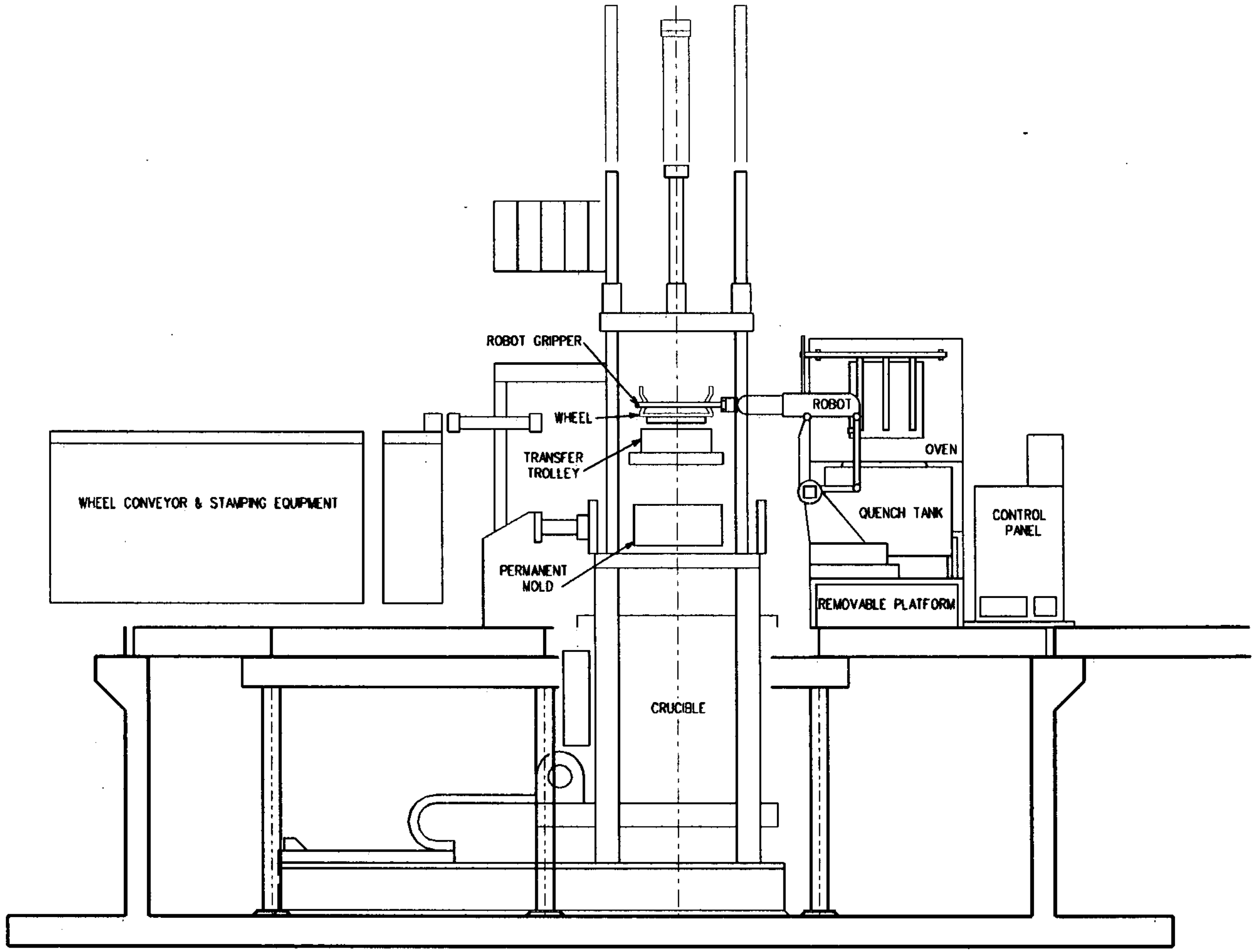


Figure 2.2: Side View of Experimental Heat Treatment Cell

Solution Treatment Oven: A suitable solution treatment oven was the first major piece of experimental equipment required for the heat treatment cell. Earlier work to date documented in the literature survey has suggested that a solution treatment temperature of 540°C is necessary and sufficient for the optimised heat treatment process and in addition, a high initial wheel heat-up rate is preferred for increasing the tensile strength of the alloy. Hence, the criteria that the solution treatment oven had to satisfy were; i) it had to be capable of quickly heating a casting to 540°C, and ii) it had to be able to maintain a uniform temperature of 540°C. Furthermore, the solution treatment oven, and consequently, the entire platform structure, had to fit within the limited floor space available in front of the casting machine. It can be seen from Figure 2.1 that available floor space in front of the casting machine is limited due to activity in the area during metal transfers. The transfer crucible featured in Figure 2.1 must be able to be positioned directly in front of the casting machine crucible during metal transfers. The width and length of the experimental cell, as it is shown in Figures 2.1 and 2.2, is the maximum physical size that it can possibly be without interfering with production activities in the casting area. The existing solution treatment ovens could not be used for the experimental investigation being completed in this instance as they were needed for the standard solution treatment process that had to continue and were also unsuitable for placement in the area near the casting machines in which the heat treatment cell was required. Hence, a suitable solution treatment oven was selected from an appropriate manufacturer and commissioned to the heat treatment cell. It was necessary to make some modifications to this oven in order to prepare it for use in the cell. The modifications were directed at automating the oven door opening and closing operations. The oven door, as it was, required manual control for opening and closing. This was considered unsuitable for the ovens new task as it would be both unsafe and impracticable for human operators to be operating the oven door during solution treatment operations. Hence, a design yielded the modifications that could be made to the oven that would allow the oven door opening and closing operations to be fully automated. Computer Aided Drawing (CAD) played a significant role in this particular design process. With the aid of CAD it was possible to design the system and test the function of the modifications prior to their physical implementation. The solution treatment oven used and resulting oven modifications are shown schematically, in detail, in Figure A.1, attached in Appendix A, and visually in Figure 2.3.

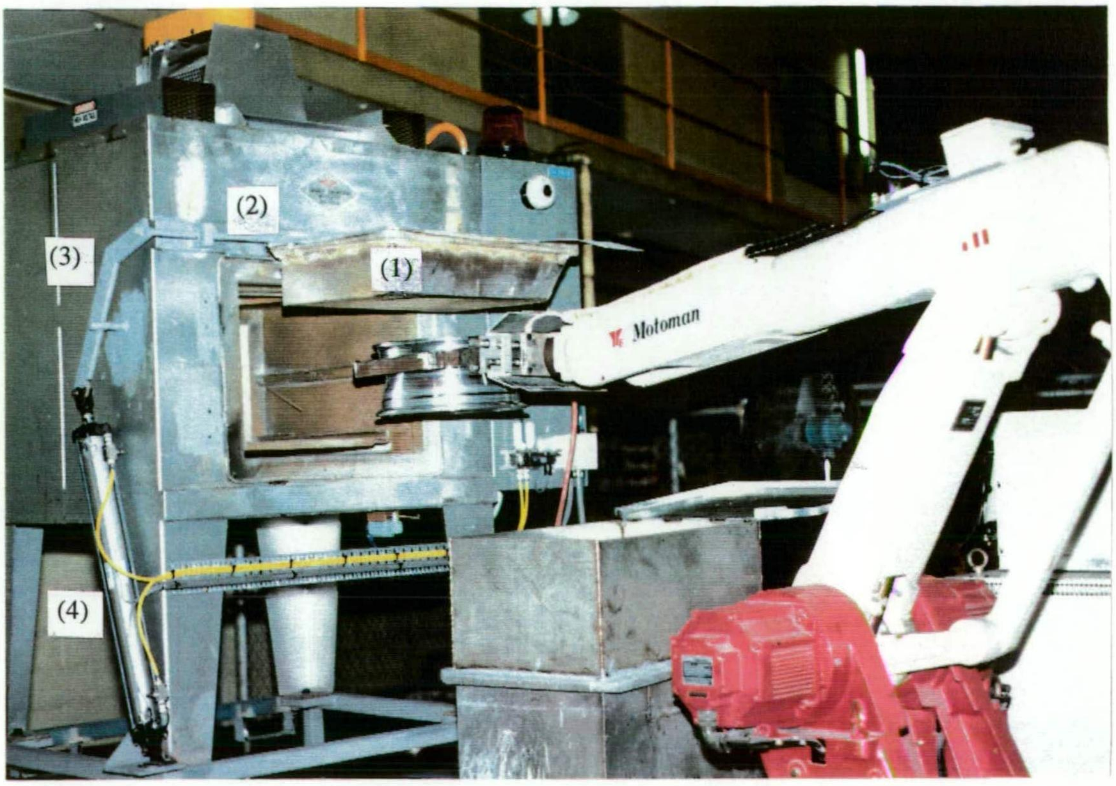


Figure 2.3: Solution Treatment Oven Used for Experimental Cell with Oven Door Modifications Shown

It can be seen that a pneumatic cylinder and lever type system were used for automation of the oven door operations. The modified system involved support of the oven door (1) by a series of brackets which were connected to a shaft (2) above the oven door which was connected to a metal bracket in the form of a bent arm (3). The arm then was connected to a pneumatically controlled linear operating cylinder (4). Full retraction of the cylinder caused the oven door to open whilst full extension of the cylinder caused the oven door to close with a seal tight enough to ensure minimum heat loss from the oven chamber whilst the oven was in operation. The pneumatic cylinder control and ultimately, operation of the oven door, was executed through robot programming using a hand on/off command, thus allowing for automated oven door operation. The nature of the robot program and hand on/off command is discussed in detail in the robot programming text attached in Appendix B, *Robot Program Used For Solution Treatment Process*.

Quench Tank: Following wheel solution treatment it was necessary to quench each wheel as soon as it left the solution oven. It has been mentioned previously that the lower the delay between a wheel leaving the solution treatment oven and entering the quenchant then better are the mechanical properties developed in the alloy. It is common practice in many wheel manufacturing industries to use a quenchant temperature of 80°C following directly from solution treatment. A quenchant temperature of 80°C is used in the existing quenching process at SAPL as this temperature has been proven, through many 'in-house' investigations, to give the best 'trade-off' between mechanical properties and distortion effects. Hence, a quenchant temperature of 80°C was used for the shortened solution treatment process which meant that the quench tank required for the experimental cell needed to be able to hold a volume of quenchant at a maintained temperature of approximately 80°C. To meet this requirement a stainless steel quench tank was designed and water was selected as the quenchant fluid. The design of the quench tank was, in part, based on the findings of some preliminary experimental investigations. As solution treatment is to be performed at an elevated temperature of 540°C and consequently wheel temperature directly before quenching is 540°C then it was anticipated that the quench tank temperature of initially 80°C would increase steadily for every wheel quench. An experimental investigation was conducted to investigate this. The aim of the investigation was firstly, to obtain a quenchant temperature profile to determine the quenchant cooling period and secondly, to determine the time taken to quench a wheel from solution treatment temperature to equilibrium with the quenchant temperature, ie. from 540°C to 80°C. The experimental investigation was carried out using the solution treatment oven detailed previously and a simulation quench tank. K-type thermocouples were used to monitor the wheel and quenchant temperature during testing. K-type thermocouples are commonly used for contact temperature measurement as they provide reliable results. It is worth showing here the details of the particular thermocouple used in this instance as this type of thermocouple will be utilised frequently throughout this project for various temperature measurements, Figure 2.4.

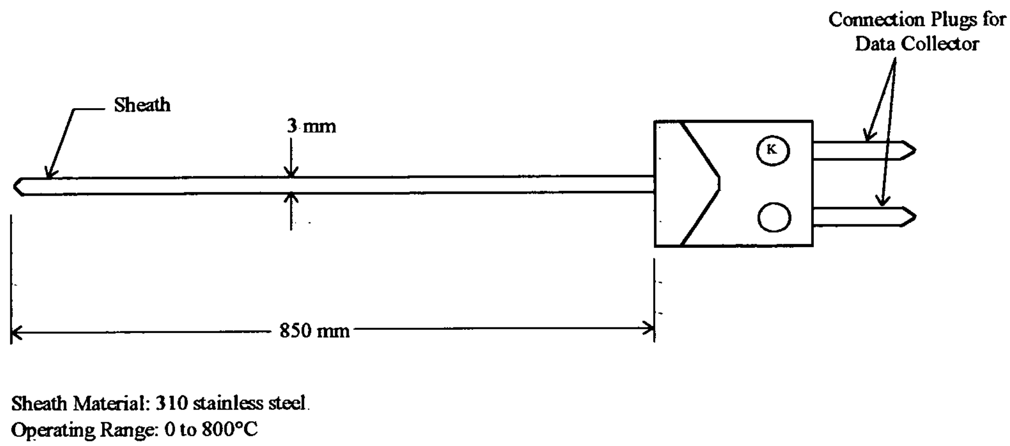
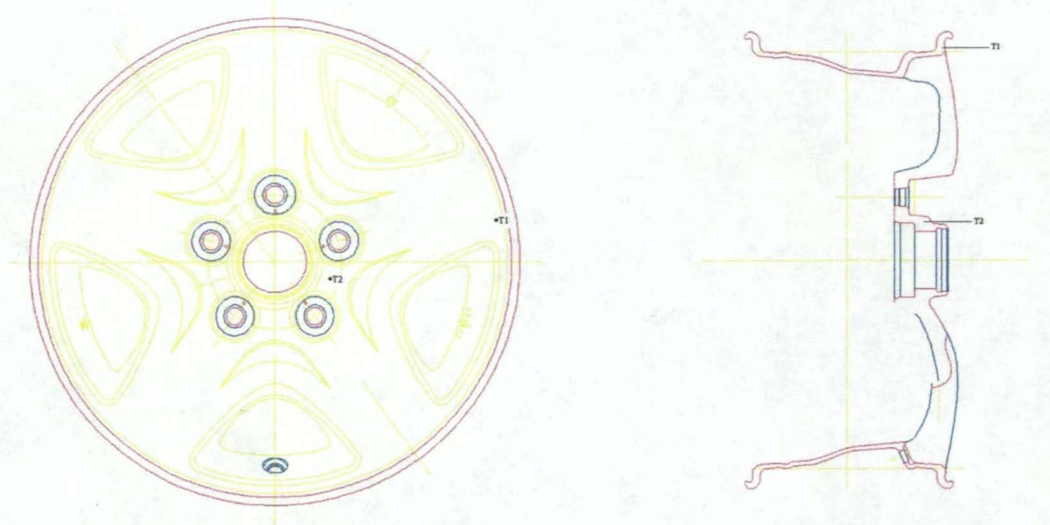


Figure 2.4: K-Type Thermocouple used for Temperature Measurements

The J15 wheel type was chosen as the test specimen for this particular investigation as it is a wheel of medium mass. The J15 wheel type has an 'as-cast' mass of approximately 10.9kg compared to 8.6kg for the lightest wheel type and 12.2kg for the heaviest wheel type produced at the plant at the time of testing. The purpose of studying this particular medium mass wheel was to determine a cooling time during quenching that could be applied to all wheel types produced at SAPL. Hence, the J15 wheel type, being of average mass, would provide a good indication of the general cooling time required. Two thermocouples were inserted into the front face of the J15 wheel type, one near the edge of the wheel (T1) and one near the centre of the wheel (T2), Figure 2.5. These particular positions were chosen on the wheel for thermocouple placement as they represented both a thin and thick section of the wheel. The purpose of measuring wheel temperature in both these positions was to investigate the effect that the varying cross-sectional area had on the cool down rate of the wheel during quenching.



Front Face View

Cross-Sectional View

Figure 2.5: Thermocouple Placement in the J15 Wheel Type

Two thermocouples were placed in the quenchant, one on both the left and right hand sides of the quench tank. A series of trials were completed in this experimental work, which consisted of heating the J15 wheel type to 540°C in the solution treatment oven and quenching the wheel at this temperature in a body of water maintained at 80°C. The temperatures of both the wheel and the quenchant were measured and recorded using a programmable Anritsu AM-7002 data collector which was compatible with the k-type thermocouples used. This particular data collector, or data logger, has a six channel input, meaning that a maximum of six individual temperature measurements can be recorded at any one time. The operating temperature of the Anritsu-7002 data collector is of the range -200 to 1370°C. Temperature measurements recorded and stored on the data collector were down loaded to a Microsoft Windows software package, Lotus 1-2-3 (Version 5), and then viewed numerically and graphically to evaluate temperature profiles for the wheel and quenchant.

The temperature profiles for the wheel and quenchant obtained from this work are shown graphically in Figures 2.6 to 2.9. Figures 2.6 to 2.8 show clearly the wheel temperature profile for three subsequent wheel quenches from 540°C to 80°C. It can be seen from these graphs that a quench time of approximately fifty seconds is necessary to cool a wheel from the maximum solution temperature (540°C) to equilibrium with the quenchant temperature (80°C).

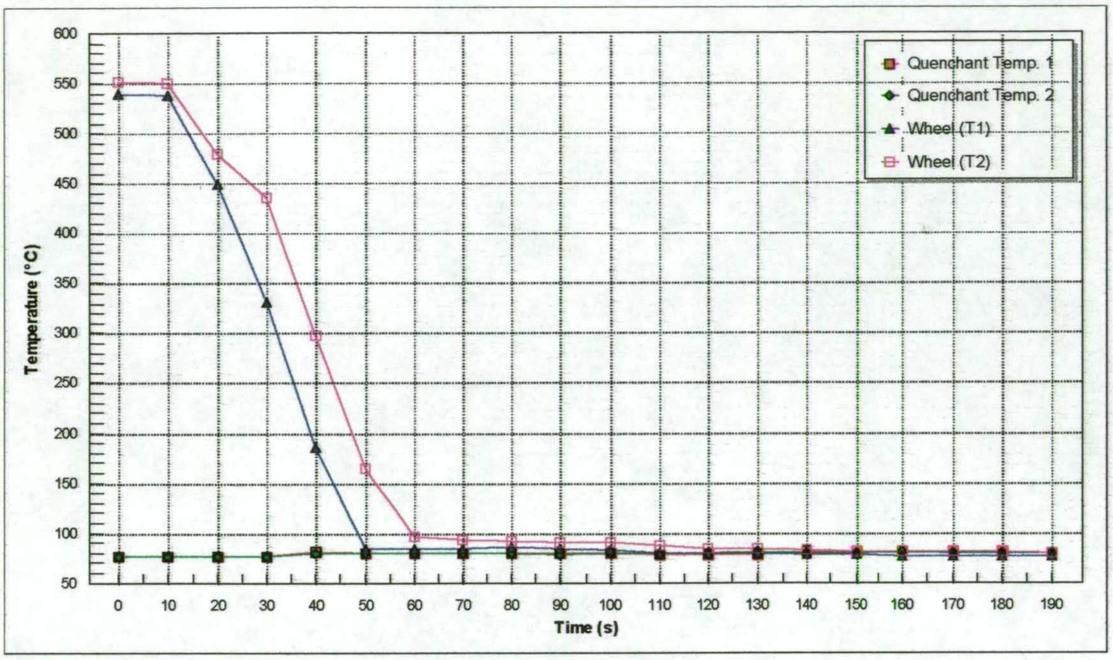


Figure 2.6: Wheel Temperature Profile During Quenching (Profile 1)

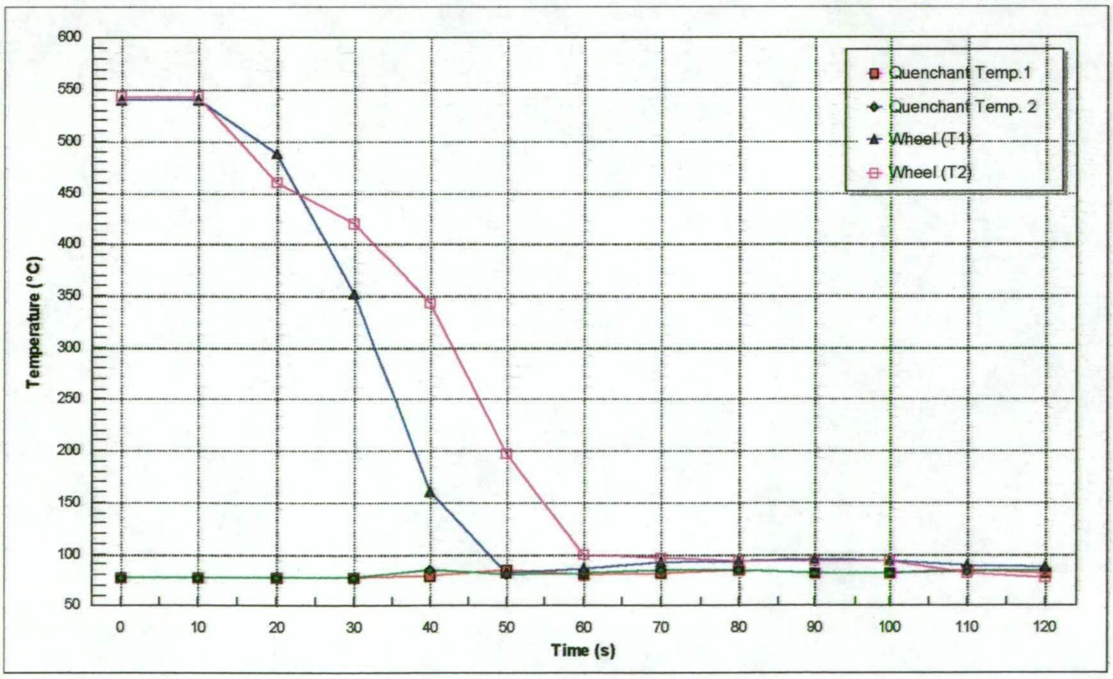


Figure 2.7: Wheel Temperature Profile During Quenching (Profile 2)

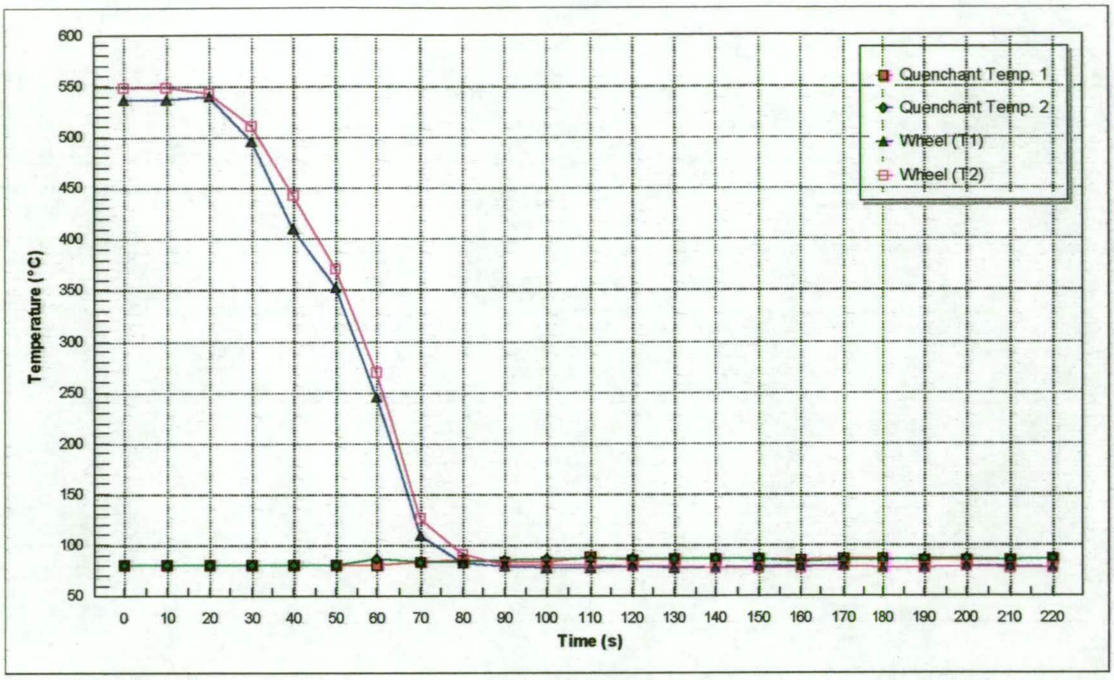


Figure 2.8: Wheel Temperature Profile During Quenching (Profile 3)

An interesting feature of the temperature profiles obtained for the J15 wheel type is that the thinner section of the wheel, represented by T1, had a more rapid cooling curve than the thicker section of the wheel, represented by T2. This is particularly evident in Figures 2.6 and 2.7 from which it can be seen that the thicker section of the wheel took approximately ten seconds longer than the thinner section of the wheel to achieve equilibrium with the quenchant temperature. The principles of heat transfer suggest this behaviour to be common and will be discussed in detail later.

Figure 2.9 shows the quenchant temperature profile that was obtained during the three subsequent wheel quenches. The first quench took place at approximately twenty two minutes, the second at approximately forty five minutes and the third at approximately seventy minutes. It was estimated at this stage of the project that the approximate time between quenches during normal operation of the experimental cell would be twenty minutes at least, including handling of the wheel, heating of the wheel and isothermal holding of the wheel. Hence, a period of twenty minutes or more was left between each quench.

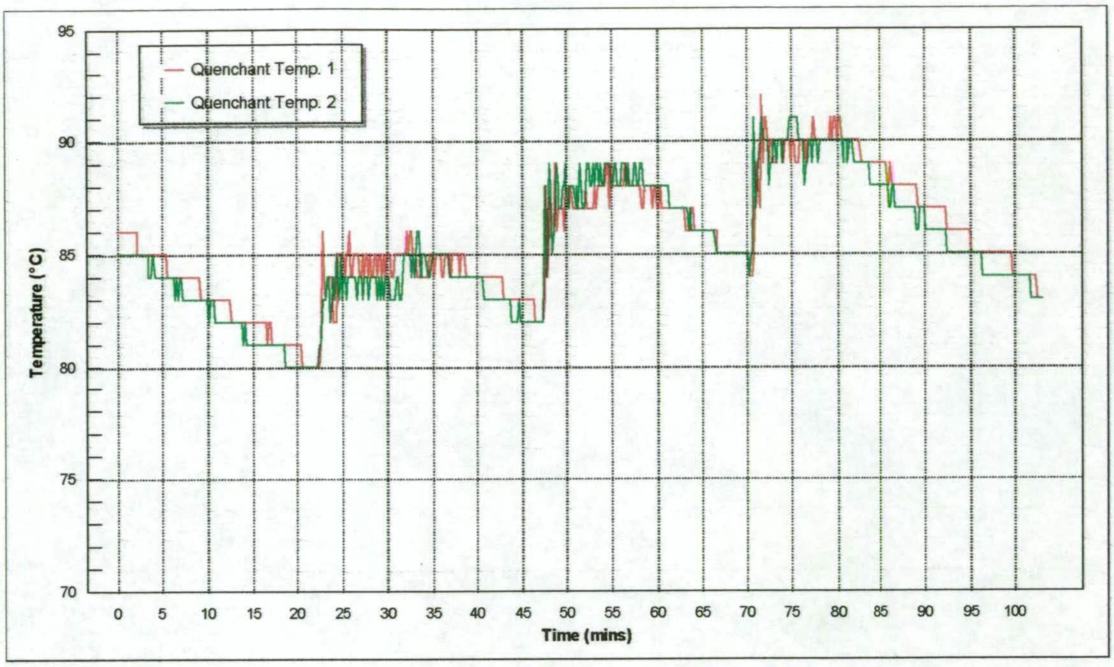


Figure 2.9: Quenchant Temperature Profile for Three Subsequent Wheel Quenches

From Figure 2.9 it can be seen that the quenchant temperature increased immediately after each quench and did not cool sufficiently back to 80°C between each quench. It was found from the quenchant temperature profile that as each quench took place the quenchant temperature slowly increased by 4 or 5°C and did not cool back to 80°C prior to the next quench. It can be seen from Figure 2.9 that at the start of the first quench the initial quenchant temperature is 80°C and rises to approximately 86°C immediately after the first quench. At the start of the second quench the initial quenchant temperature is 82°C, rising to 89°C on completion. For the third quench, the quenchant temperature is initially 84°C and rises to approximately 92°C on completion. If quenching had continued under the observed trend then for the tenth quench, say, the initial quenchant temperature would be approximately 98°C which is extremely high considering a quenchant temperature of 80°C is required. To overcome this problem it was necessary to design and develop a cold water recirculation system for the quench tank. The designed system consisted of a temperature control unit and a thermocouple and some pipe work for water flow. The cold water supply for the tank was from existing facilities on the casting machine. An overflow drain was developed on the quench tank to prevent water spillage due to overfilling, which again connected to existing facilities on the casting machine. The cold water recirculation system worked on the principle that when a quenchant temperature of greater than 80°C was realised in the quench tank, through thermocouple and temperature control equipment, cold water would be directed into the bottom of the tank and any excess water would drain away through the overflow pipe in the top of the tank until the quenchant temperature decreased back to the desired 80°C.

It was also established during the quench tank experimental testing that a heater system would be required for initialising a water temperature of 80°C prior to commencing the heat treatment cycle. Tests were completed without heaters in the quench tank, using a hot wheel at 540°C as the heating source for the water. The quenchant, originally at 12°C (room temperature), needed to be subjected to twenty seven wheel quenches at 540°C before it heated to the required quenching temperature of 80°C. To use this process as a means of heating the tank in a production situation is not wise or efficient for two dominating reasons; i) to use only one wheel as the heating source by continuously heating the wheel to 540°C and quenching was found to take three to four hours, which makes this a time consuming method as the wheel must be heated from the quenchant temperature to 540°C each time, and ii) if a high number of hot castings, initially at 400°C after casting, are used from the casting machine as the quenchant heating source, then wheel heating time is reduced, and consequently heat-up rate of the quenchant is increased, but a high number of wheels may be rejected as they are quenched at a temperature below the necessary 80°C. Wheels quenched at less than 80°C are likely to be distorted and hence may be rejected. Thus, a heater system was designed to be incorporated into the quench tank. This heater system consisted of two 10kW immersion heaters, installed in the bottom of the tank.. To protect the immersion heaters from accidental collision with wheels during quenching, a metal grid was designed and positioned inside the quench tank above the heaters. Details of the designed quench tank are shown schematically in Figure A.2, attached in Appendix A.

Wheel Placement Table: It can be seen from Figure A.2 that a table is attached to the quench tank. This table allows intermediate wheel placement during heat treatment cell operations. The design of the cell was such that once a wheel had been removed from the casting machine and placed in the solution treatment oven, a wheel from the table that had been solution treated and quenched using the optimised process would be returned in its place. This method enabled further processing of the solution treated wheels through the existing process without the need for human involvement in the form of taking wheels from the cell after quenching to the next processing point. The wheel placement table was constructed from a thin section of stainless steel plate. Stainless steel was selected as the quench tank and wheel placement table material to avoid the rust problems associated with the necessary environment and a lip was designed around the edge of the table to minimise water spillage. The wheel placement table was also slightly angled to direct any excess water from the quenched wheel back into the quench tank.

Robot: A method of transferring wheels from the casting machine into the solution treatment oven, from the solution treatment oven to the quench tank, from the quench tank to the wheel placement table and from the wheel placement table back to the casting machine was required. It was determined that a robot would provide the best material handling system for this process due to the flexibility requirements. A Motoman YASNAC ERC K30S robot with a maximum handling capacity of 30kg, featured in Figure 2.3, was commissioned to the experimental test rig. This robot was programmed for the task of wheel handling within the heat treatment cell. Determination of a robot program flow chart was the first step in robot programming to establish a methodical sequence of events that would enable the required wheel handling operations. A total of eight individual jobs were programmed into the robot, involving wheel removal from the casting machine, wheel placement and removal from the solution treatment oven, wheel quenching and placement on the table and returning of the solution treated and quenched wheel back to the casting machine. Each of the eight jobs were programmed individually with a main job, or master job, used to call and execute them in the sequence required for successful operation. To ensure that collisions between the robot and casting machine moving parts did not occur during wheel removal and return to the casting machine it was necessary to incorporate a number of input and output signals into the main program to act as a communication system between the two parties. As mentioned previously, the robot program is attached in Appendix B, *Robot Program Used For Solution Treatment Process*, to aid the reader in understanding the process by which wheels are to be solution treated and quenched using the shortened method and also to highlight the steps and instructions used for robot programming. The robot program flow chart and technical particularities of the robot are shown in Figure 2.10.

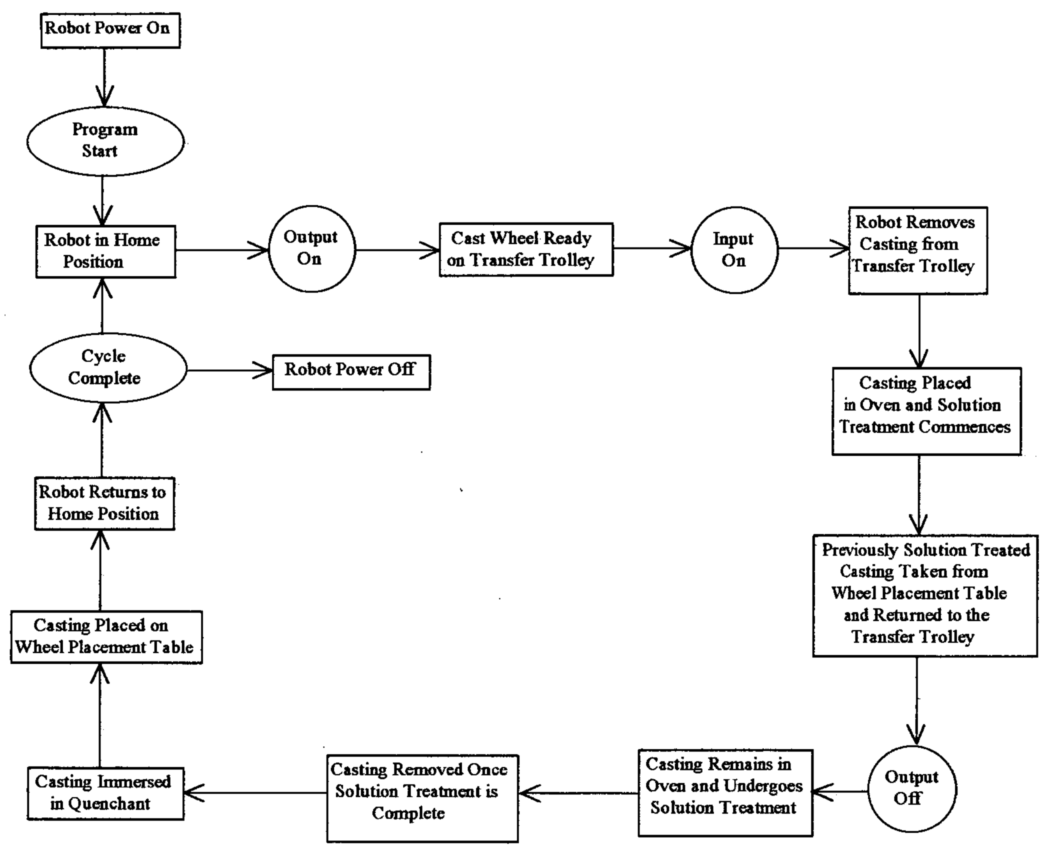


Figure 2.10: Robot Program Flow Chart

In preparation for wheel handling it was necessary to select a set of grippers and design a pair of gripper arms for the robot. The variation in diameter of wheels produced at SAPL range from thirteen to seventeen inches, meaning that the gripper needed to have a large operating span. The maximum opened width of the gripper needed to be such that there was enough clearance to pass either side of a seventeen inch wheel and the maximum closed width of the gripper needed to be such that a thirteen inch wheel could be sufficiently gripped. A gripper suitable for this task was selected and connected to the robot. Figure A.3, attached in Appendix A, shows the selected gripper and the designed gripper arms. It can be seen from this that the gripper is essentially a pair of pneumatically controlled cylinders operating in parallel. Control of the grippers was possible through use of some necessary control equipment and robot programming commands similar to those used to control the oven door. A pressure switch was connected to the grippers to allow them to operate effectively with the large variation in wheel diameters. The switch worked in such a way that once a certain grip pressure was applied to a wheel then the supply of air to the gripper would cease with enough pressure maintained in the gripper to ensure a sufficient grasp of the wheel. This meant that the robot could grip a wheel of any diameter in the range of thirteen to seventeen inches and apply the same gripping pressure to each wheel. The gripping pressure applied to each wheel needed to be set specifically to allow a substantial grip of the wheel but not to great as to cause excessive distortion of the wheel during heat treatment and quenching. Through a series of wheel dimensional checks, completed after quenching, using the CMM, it was determined that a gripping pressure of 400kPa applied to the wheel was sufficient enough to ensure a good grasp of the wheel and not to excessive as to cause distortion. The type of distortion caused by gripping the rim of the wheel during handling is termed as 'Out of Round', OOR. This type of distortion causes the circular shape of the wheel to become more of an oblong shape. During machining the machining cells detect the non-circular shape of the wheels and consequently are unable to machine the wheels sufficiently. Hence, badly distorted wheels due to OOR are rejected. Design of the gripper arms was reasonably complex as they had to suit the criteria of being able to grip a small thirteen inch wheel satisfactorily but also angled sufficiently as to be able to accommodate a large seventeen inch wheel. The gripper arms also had to have a good surface contact area on the wheel rim during handling to ensure a sufficient grip. An optimum arm design was achieved that allowed the sufficient grip of any wheel in the thirteen to seventeen inch diameter range.

To attach the gripper to the robot end effector a connection plate was designed and fabricated. This plate, shown in Figure A.4, attached in Appendix A, was simply a section of steel plate with holes drilled in the appropriate positions as to allow attachment of the plate to the robot end effector and attachment of the gripper to the plate. Furthermore, it was also necessary to design a shield for the grippers to protect them from radiant heat as the grippers were required to go inside the solution treatment oven during wheel handling. Shielding of the grippers was necessary to reduce exposure to the elevated temperature inside the oven which could consequently result in gripper damage and failure. The final design for the protective shield is shown in Figure A.5, attached in Appendix A, and consisted of a section of thin aluminium sheet folded in a manner as to direct heat away from the gripper during movements inside the solution treatment oven. Aluminium was chosen as the gripper material for two dominating reasons; i) the lightness of the material meant that there would be minimum extra weight on the robot arm, and ii) the shiny surface of the material ensured that heat would be readily reflected away from the gripper. To provide an overview of the robot assembly, the robot gripper (1), gripper arms (2) and protective heat shield (3) are shown assembled and attached to the robot in Figure 2.11.

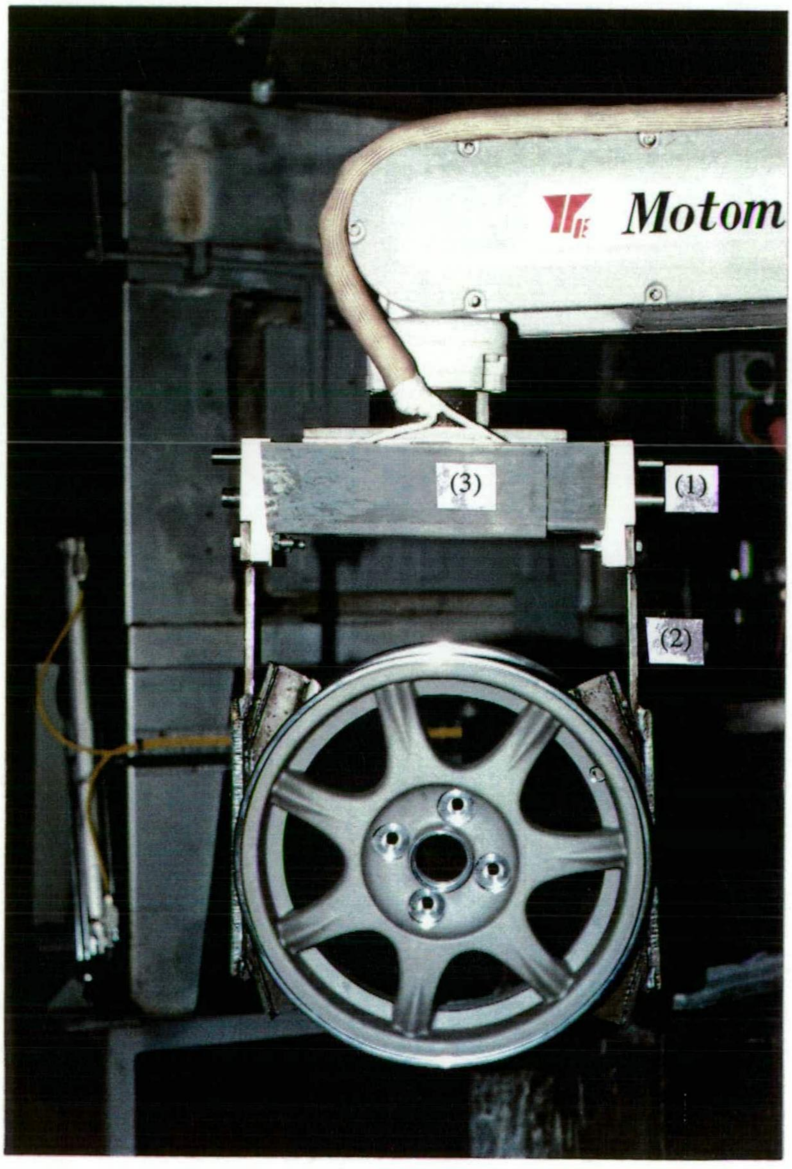


Figure 2.11: Robot Gripper, Gripper Arms and Protective Heat Shield

Control of the robot was through an external programming unit and the associated robot wiring was contained in an external control panel. The control panel and programming unit needed to be incorporated into the heat treatment cell as they were critical items of experimental equipment. To minimise space consumption it was determined that the control panel be placed under the solution treatment oven and the programming unit be placed, at eye level, behind the quench tank and table. In addition, having these two components in these positions meant that they were not exposed to robot movements, which ultimately meant that they were protected from unexpected or accidental collision with the robot.

Each of the cell components, ie. solution treatment oven, quench tank, wheel placement table and robot, were placed on a common base, so they could act as a single heat treatment cell. The common base used acted as a platform that could be manoeuvred around the plant as necessary. The platform design was dependant on three main criteria; i) robot flexibility and handling skills, ii) the size of the items to be placed on the platform, and iii) available floor space in front of the casting machines. Each item of experimental equipment to be placed on the platform was set up and tested on the plant floor, and the casting machine dimensions were taken, in order to determine the most feasible platform design. To allow for the manoeuvrability of the heat treatment cell around the plant it was necessary to keep the platform weight to a minimum. With this criteria it was decided to construct the platform base, shown schematically in Figure A.6, attached in Appendix A, from steel hollow section (50 X 50 RHS) using a skeleton type frame only. To enable the cell to be moved around the plant it was necessary to design the platform as two separate sections. One section for the solution treatment oven and the other section for the robot, quench tank, wheel placement table, programming unit and control panel. This enabled the cell to be moved as two separate sections and joined together at the required destination. To ensure that the layout and positioning of the two platform halves, relative to each other, did not vary, locating pins were placed on the platform base. The platform was designed in such a way that it could be easily transported using the mechanical lifting equipment on site.

2.2 SAFETY ISSUES INCORPORATED INTO THE EXPERIMENTAL HEAT TREATMENT CELL

As the heat treatment cell was to be used in a hazardous environment then there were a number of safety issues that had to be considered. It is shown in Figure 2.1 that there is a safety fence surrounding the heat treatment cell. This safety fence acts as a protective device for workers from the robot as well as a protective device for the robot from workers. Firstly, the safety fence provided a barrier between the robot working area and the working area of employees to prevent collision between the robot and workers in the area. The robot may move suddenly and unexpectedly so it is critical that a guard be in place to prevent injury to employees. Secondly, as there is heavy movement of large objects in the area, transfer crucibles and forklifts for example, then the safety fence also provided a barrier of protection for the heat treatment cell from collision with these large objects. During a metal transfer from the transfer crucibles to the casting machine crucible there is an opportunity for the transfer crucible to collide with the cell. If a collision should occur, the safety fence prevents any serious damage to the cell. The safety fence was painted bright yellow to promote awareness of the experimental cell's existence. The safety fence is shown visually in Figure 2.12 which shows the heat treatment cell situated next to a casting machine.

A further safety issue that was incorporated into the experimental cell was that of safety platforms. The need for safety platforms on the experimental cell will become evident after consideration of the metal transfer process. During a metal transfer there may be molten aluminium leakage from the transfer crucible onto the surrounding floor. It is necessary during a metal transfer for one worker to stand on either side of the transfer crucible. As the heat treatment cell occupies a large amount of floor space then during a metal transfer the worker closest to the cell has limited room to move. This means that if there were a metal leakage onto the floor the worker trapped between the transfer crucible and the experimental cell would have a high risk of sustaining hot metal burns to the feet and lower legs. To overcome this situation, a safety platform on which workers could stand during a metal transfer was attached to either side of the cell, as shown in Figure 2.1. The safety platform was simply a sheet of steel decking elevated above the ground and hinged and supported by a steel frame and heavy duty chain but was sufficient enough to prevent serious injury to employees.

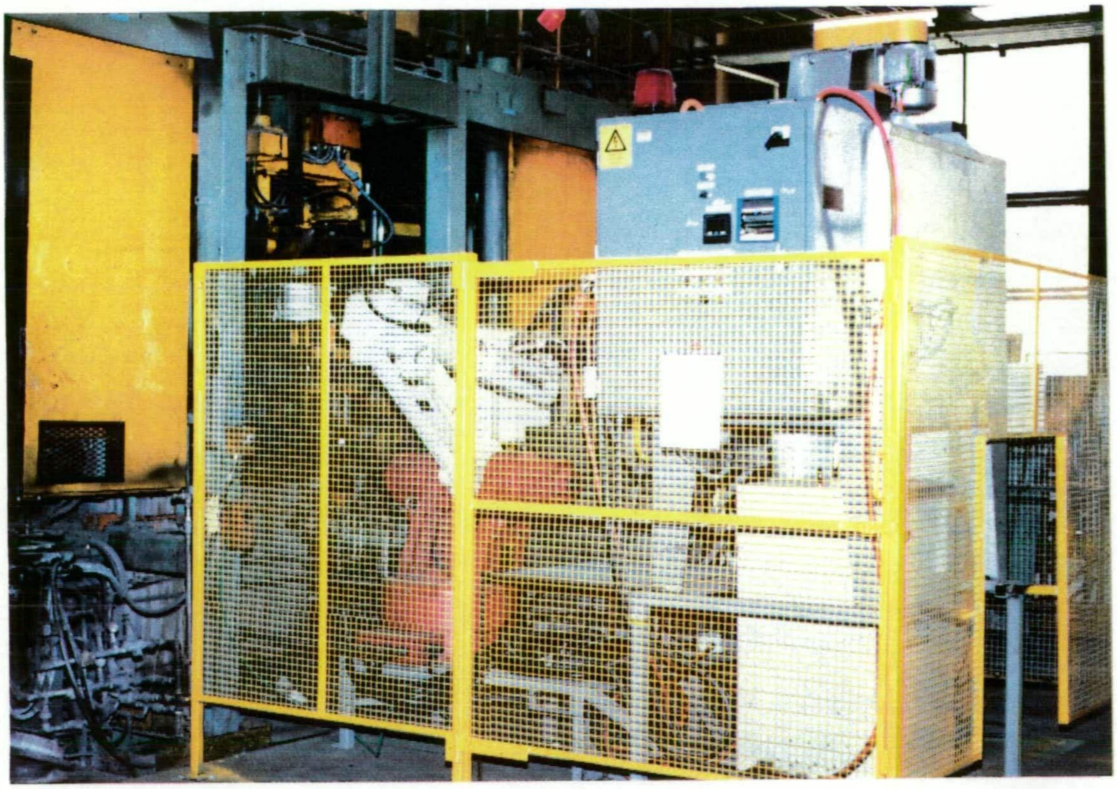


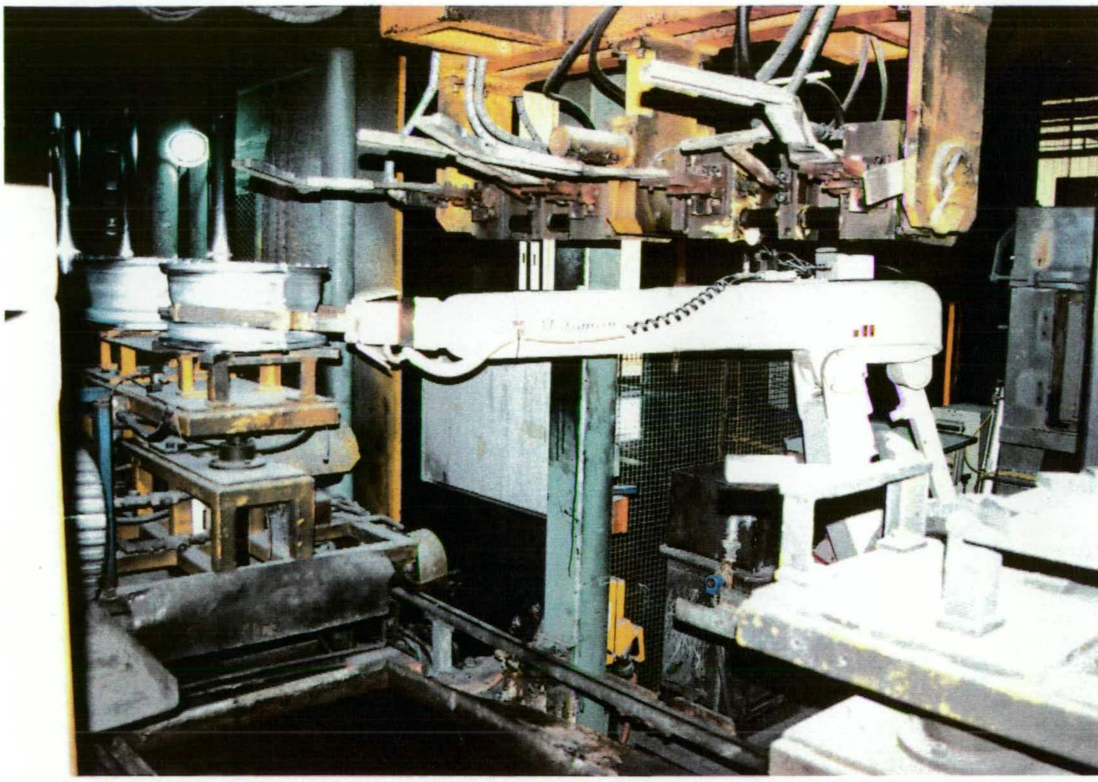
Figure 2.12: Experimental Heat Treatment Cell Showing Safety Fence and Situation Near a Casting Machine

Furthermore, protection of electrical wiring and air supply lines inside the experimental cell was necessary. Many electrical wiring and air supply lines for the heat treatment cell were situated on the ground directly under the solution treatment oven door. As castings, at elevated temperatures, are frequently moving in and out of the oven then it was necessary to apply some type of protection to the electrical and air supply lines. The accidental dropping of a casting onto these lines would initially result in damage to the lines with the possibility of injury to individuals, due to leaking air lines and exposed live electrical wires, as a secondary action. To prevent castings coming into contact with the wiring, a metal grid and supporting frame were constructed around the immediate assembly. This can be seen in the lower section of Figure 2.12 between the robot and solution treatment oven. The grid covers all wiring and is angled to direct dropped castings to clear ground.

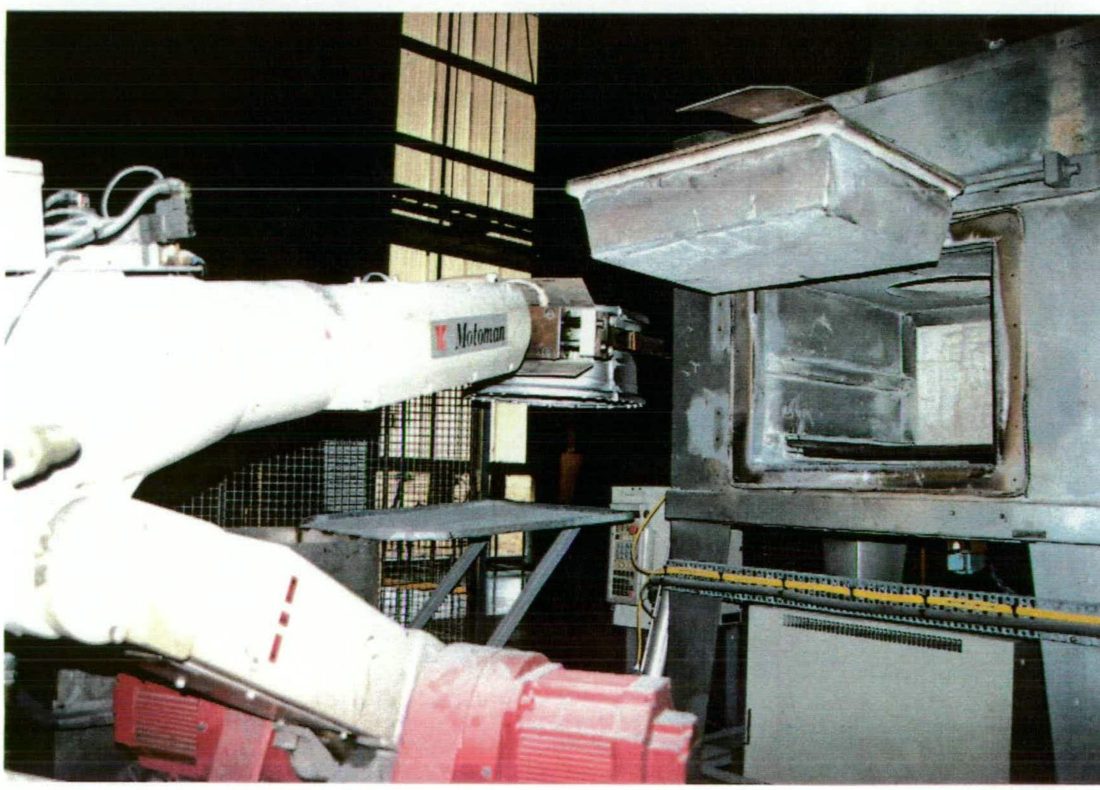
2.3 DETAILED EXPLANATION OF THE OPERATION OF THE EXPERIMENTAL HEAT TREATMENT CELL

Although some understanding of the operation of the experimental cell has been obtained through the given discussion of the various items of equipment used in the cell, it is useful to describe in detail its operating procedure. An explanation of the procedure of operation of the developed experimental heat treatment cell is simplified with the use of sequential photos which show visually the execution of one program cycle, and also through consideration of the robot program flow chart shown in Figure 2.10. It can be seen from the robot program flow chart that before robot movement commences there are some initial requirements that need to be satisfied. These requirements are that the robot is in its home position and also that the casting is ready to be removed from the transfer trolley. Communication signals between the robot and the casting machine indicate the status of these initial requirements. Once these initial requirements are satisfied the first manoeuvre of the robot is to remove the casting from the transfer trolley. This particular step is highlighted in Figure 2.13(a). From this position the casting is taken directly to the solution treatment oven, Figure 2.13(b). The oven door opens for the minimum time possible whilst placing the casting in the oven to minimise heat loss from the oven chamber. The casting is then left in the oven to undergo solution treatment. Whilst the casting is in the oven undergoing solution treatment the robot executes another step of the program cycle. This step involves returning a previously solution treated casting to the transfer trolley in replace for the recently removed casting. This step is carried out by taking the casting from the wheel placement table, Figure 2.13(c), and returning it to the transfer trolley. Placing of the returned casting on the transfer trolley is the same as that shown in Figure 2.13(a) for removal of the casting. Upon completion of this step the robot returns to its home position and waits whilst the casting in the oven continues to be solution treated. On completion of solution treatment the oven door opens and the robot moves in and grips the casting. The robot then removes the casting from the oven and places it immediately into the quenchant, Figure 2.13(d). On completion of quenching the casting is placed on the wheel placement table in the position shown in Figure 2.13(c). The robot then returns to its home position ready to repeat this cycle. The description given here represents one execution of the program cycle only and involves the solution treatment of one wheel only using the optimised process.

Solution treatment of many wheels is achieved by allowing the robot to continue operation for as long as required. This optimised solution treatment process is fully automated with human intervention required only by the casting machine operator for the purpose of marking the optimised solution treated castings such that they can be distinguished from other normal production wheels.

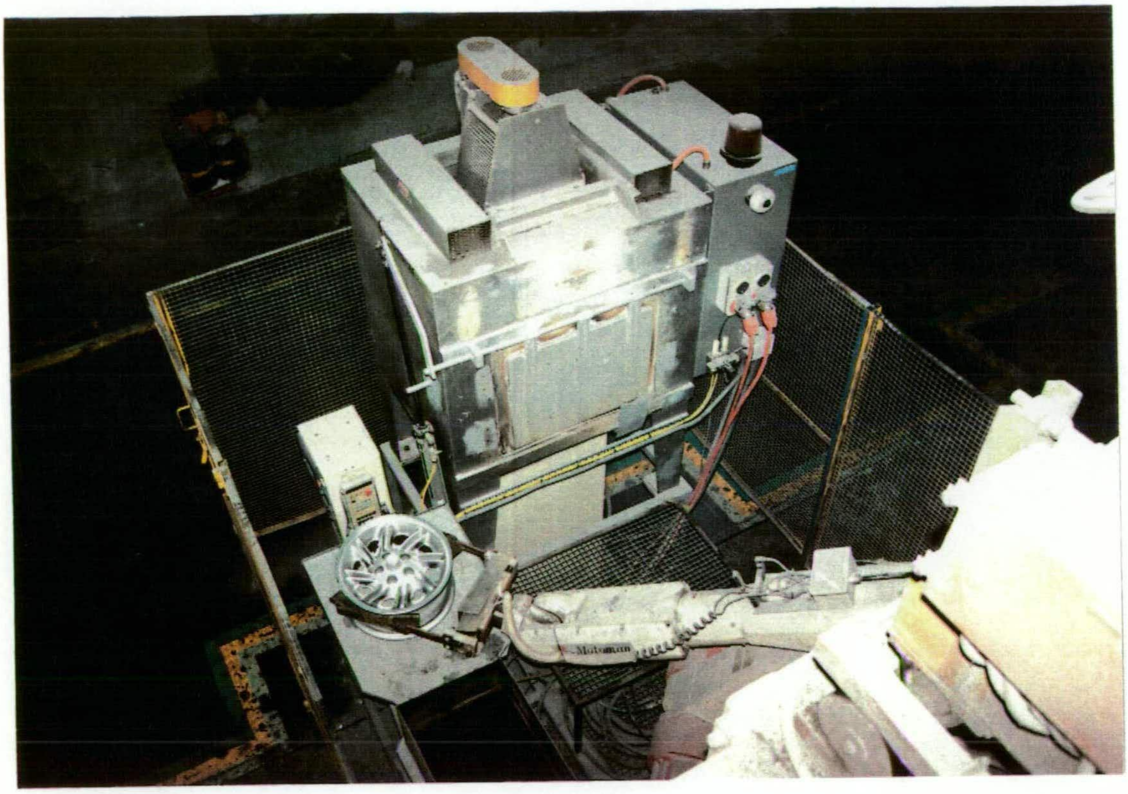


(a)

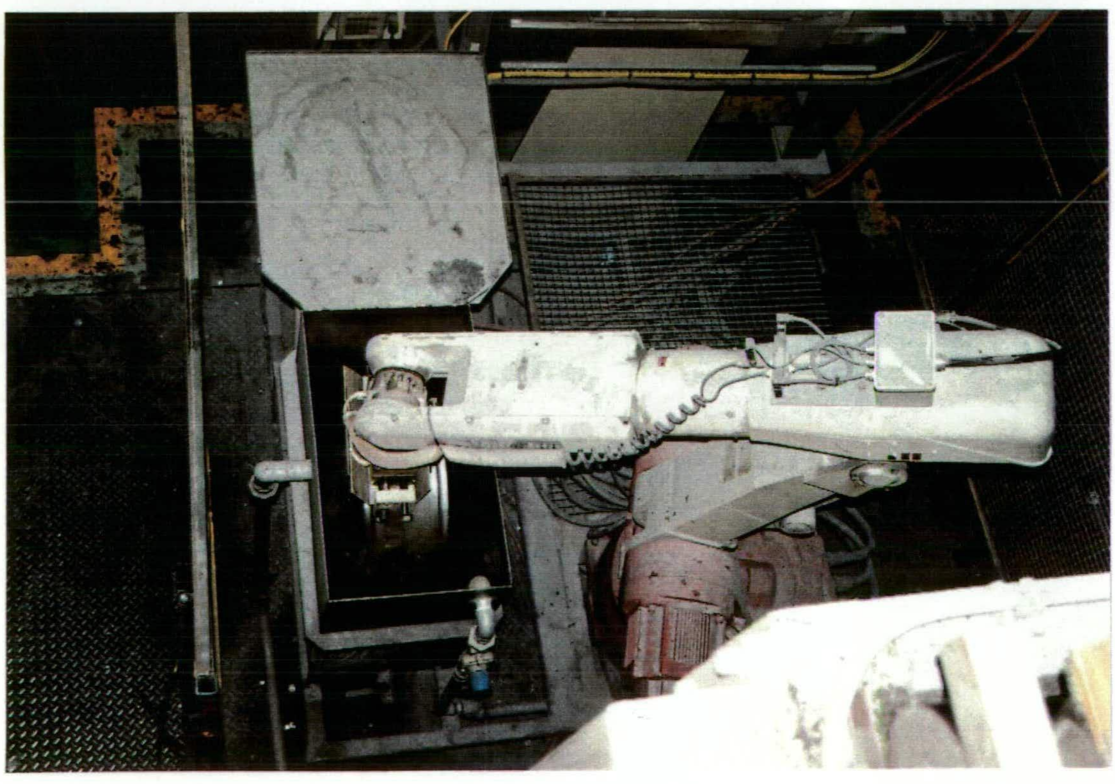


(b)

Figure 2.13(a) Removal of a Casting from the Transfer Trolley, and (b) Placement of the Casting in the Solution Treatment Oven



(c)



(d)

Figure 2.13(c) Casting Removed from Wheel Placement Table, and (d) Quenching of the Solution Treated Casting

2.4 CONCLUDING REMARKS

The intention now is to use the experimental heat treatment cell to investigate the effect that solution treatment has on the development of mechanical properties in aluminium alloy wheels and consequently determine an optimised heat treatment process that can be used effectively at SAPL. Two important features of the testing procedure, quenching time and quenchant temperature, have been investigated during the development of the experimental rig. It has been shown that a quench time of approximately fifty seconds is required to sufficiently cool castings from the solution treatment temperature to equilibrium with the quenchant temperature. Furthermore, it has been shown that a constant quenchant temperature of 80°C will be maintained during normal operation of the experimental cell due to a cold water recirculation system that has been incorporated into the operation of the quench tank. Hence, through development of the experimental cell detailed here a system is now available that can be used to trial an optimised solution treatment cycle in a combined casting and heat treatment process. The designed experimental cell is of particular value as it is versatile and practical. The designed cell can be easily adapted to accommodate varying solution treatment times and temperatures, varying wheel diameters and finally, varying quenching times and temperatures if necessary. Due to the versatility of the experimental cell it can be seen that many aspects of solution treatment can be studied using the described set-up.

However, before the major investigation can commence it is necessary to complete some preliminary experimental investigations to study the functioning and behaviour of the experimental equipment and also to obtain some specific information relevant to the particular wheel types to be used as test specimens for the major investigation. The particular details of the preliminary experimental investigations required are given in the following chapter.

CHAPTER THREE

PRELIMINARY EXPERIMENTAL INVESTIGATIONS

Before the proposed experimental investigation could commence it was necessary to confirm some specific detail about the experimental apparatus and its general working condition. A preliminary investigation on the operation and function of the experimental equipment will reinforce the reliability of the results that are to be obtained. Furthermore, a preliminary experimental investigation is necessary to determine some specific detail about the alloy wheels that are to be used as test specimens in the major investigation. Consideration of the existing heat treatment process at SAPL highlights the need for carrying out the mentioned preliminary investigation.

Solution treatment of wheels at SAPL is essentially a two stage process. The first stage is a heating process in which wheels undergo a particular heating curve. This involves heating wheels from their initial temperature, nominally room temperature, to the maximum solution treatment temperature of 540°C. The second stage is an isothermal holding period which involves holding the wheels at the maximum solution temperature of 540°C for a predetermined period of time. The proposed optimised solution treatment process that is to be trialed as part of the major investigation is not dissimilar to the existing solution treatment process in this respect. The optimised solution treatment process will still incorporate the two stage process of firstly, heating wheels to the maximum solution temperature and secondly, holding wheels at the maximum solution temperature. This is further explained with the aid of a temperature-time plot, Figure 3.1. Section A of the graph represents the heat-up curve for the wheel during solution treatment. This is the

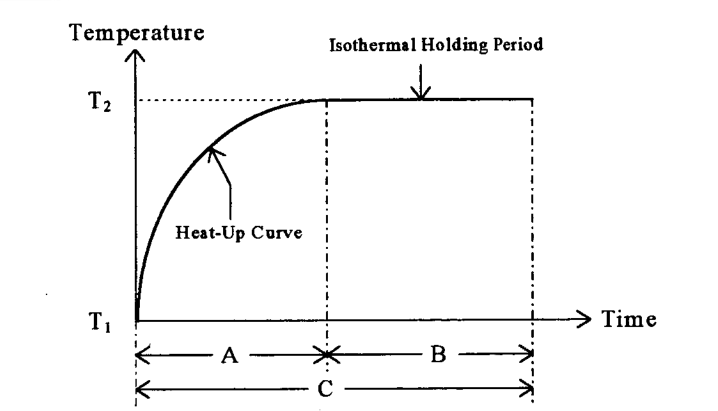


Figure 3.1: Temperature-Time Plot for Solution Treatment

first stage of the solution treatment process. During this period the wheel is heated from its initial temperature, T_1, up to the maximum solution treatment temperature, T_2. This is then followed by a period in which the wheel temperature is maintained uniformly at the maximum solution treatment temperature, T_2, for a predetermined time, section B. This is the second stage of the solution treatment process. It can be seen then that total solution treatment time, represented by C, is the sum of A and B.

It has been previously documented that some experimental investigations[43] have shown that an isothermal solution treatment condition of ten minutes at 540°C can be used as an optimised solution treatment process to achieve a high level of tensile strength and elongation in the alloy. This suggested ten minute solution treatment process represents the second stage only, section B in Figure 3.1, of the total solution treatment process. In order to establish the total optimised solution treatment time required it is necessary to determine the time taken to heat a wheel to the maximum solution treatment temperature, ie, establish the first stage, section A in Figure 3.1, of the solution treatment process. It is this first stage of the solution treatment process that is unknown at this point and therefore must be determined to allow an optimised solution treatment process to be trialed.

Figure 3.2 shows in block diagram form the information that is required to establish an optimised solution treatment process. It can be seen from this that the information required to establish the optimised solution treatment process consists of; i) an isothermal holding time, ii) a solution treatment temperature, and iii) wheel heat-up time. The first two items have been given by research[43] whilst the third item is to be

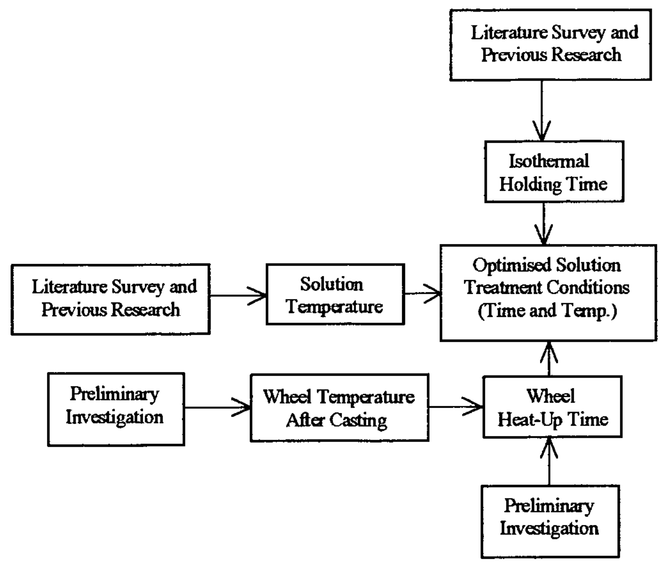


Figure 3.2: Block Diagram Representation of Required Information for the Determination of Suitable Solution Treatment Conditions

determined using a preliminary experimental investigation. It can be seen from the block diagram representation that the wheel temperature after casting must be known in order for a heat-up time to be determined. In order to find the time taken to heat a wheel from its initial temperature up to the maximum solution treatment temperature it is necessary firstly that the initial temperature of the wheel be determined. The initial temperature of the wheel is effectively its temperature when entering the solution treatment oven.

For the optimised solution treatment process being trialed in this instance the experimental heat treatment cell is designed to remove individual wheels from the casting machine as required, immediately after casting, and place them into the solution treatment oven. It can be seen then for this process that the temperature of the wheel at the start of solution treatment can be determined by establishing the temperature of the wheel immediately after casting and subtracting any heat losses during wheel handling between the casting machine and the solution treatment oven. Hence, the first stage of the preliminary investigation will strive to determine the initial temperature of the wheel immediately prior to solution treatment.

3.1 PRELIMINARY EXPERIMENTAL INVESTIGATION TO DETERMINE WHEEL TEMPERATURE IMMEDIATELY PRIOR TO SOLUTION TREATMENT

This investigation is used to determine wheel temperature immediately after casting and consequently establish the initial wheel temperature at the commencement of solution treatment. The results from this will then be used in conjunction with the second part of this investigation to determine wheel heat-up time and hence, establish an optimised solution treatment process that can be trialed as part of the major investigation. Wheel heat-up time in this instance is defined as the time taken to heat a casting from its temperature immediately prior to solution treatment, close to casting temperature, up to the maximum solution treatment temperature. The temperature profile after casting differs for each wheel type, as the cooling and casting conditions in different dies vary with wheel type. Firstly, before wheels are released from the dies in the last stage of the casting process they are subject to a cooling process, using air as the cooling fluid. The purpose of air cooling the wheels whilst still in the dies is to increase their solidification rate, and consequently increase production rate, compared to wheels produced at a rate when cooling is not used. The solidification of castings is increased due to air cooling rather than allowing the castings to solidify naturally, ie. no external cooling. Secondly, different wheel types are also cast at different temperatures depending on their design. For these reasons, different wheel types leave the casting dies at different temperatures. Once removed from the die and placed on the transfer trolley there is no external cooling provided for the wheels. The only source of heat loss from the hot castings is through heat conduction to the transfer trolley itself, as it is at a much lower temperature than the casting, or through natural convection and radiation from the casting to the surrounding air. These sources of heat loss cause the temperature of the casting to reduce whilst being transferred from the casting die to the solution treatment oven, via the transfer trolley. These sources of heat loss, although only minor, are undesirable as they reduce the temperature of the casting before solution treatment. Wheel heat-up time increases significantly as the difference between initial temperature of the wheel and maximum solution treatment temperature increases. However, for the purpose of the major investigation these heat losses will be measured and tolerated rather than attempting to eliminate them. Hence, the procedure followed for this part of the preliminary investigation will be firstly, to determine the time taken to transfer a wheel from the casting machine to the solution treatment oven, ie. determine handling time, secondly, to establish the temperature of the wheel immediately after casting and measure any heat losses over a set time period, ie. establish a cooling curve for the wheel, and finally, determine the temperature of the wheel at the commencement of solution treatment by studying the cooling curve for the period equal to the handling time determined.

In order to investigate the temperature variations mentioned earlier that are present amongst different wheel types it was considered useful to measure the 'after-casting' temperature of two different wheel types in this particular investigation. The first wheel type, the Mazda MX5, was chosen as it was known at this stage of the project that this particular wheel type would be used as the test specimen for the major investigation. Hence, it was necessary to obtain specific information relevant to the MX5 wheel type at this stage of the project. The MX5 wheel type, having an 'as-cast' mass of approximately 8.57kg, was also the lightest wheel type being produced at the plant at the time of testing. The second wheel type, the Nissan A32, was chosen as it represented the heaviest wheel type used at the plant at the time of testing and would thus provide a comparison between two wheel types at the extremities of the mass scale. The 'as-cast' mass of the A32 wheel type is approximately 12.12kg.

Handling time for transferring the test specimen (wheel) from the casting machine to the solution treatment oven was determined using a series of trials conducted for the purpose of ascertaining the function and behaviour of the experimental heat treatment cell and determining this time lag. These trials were aimed at proving the wheel handling capability of the robot and measuring specific times taken for the robot to complete various tasks, ie. time taken for the robot to remove a wheel from the casting machine and place it in the solution treatment oven and the time taken for the robot to remove a wheel from the solution treatment oven and place it in the quench tank. The trials completed showed the experimental apparatus to have the necessary wheel handling skills and proved the ability of the experimental apparatus to be used as a successful set-up for the major investigation. Furthermore, it was determined from the trials completed that the time lag between a wheel leaving the casting machine and entering the solution treatment oven was approximately sixty seconds, or one minute. During this sixty second period, the operations that take place include the transferring of a wheel from the die to the transfer trolley, the moving of the transfer trolley to its rest position and the moving of a wheel, by the robot, from the transfer trolley to the solution treatment oven. In other words, the casting takes approximately sixty seconds to be transferred from the die to the solution treatment oven. In order to take maximum advantage of the elevated temperature of the wheel immediately after casting it is critical that the wheel be transferred to the solution treatment oven in the quickest time possible. The sixty second period determined represents the quickest time possible. The robot program was optimised to achieve this short transfer time.

Temperature measurements of the castings were taken using thermocouple techniques and associated data acquisition. These techniques are found to be highly reliable and comparable to infra-red thermography. A high temperature k-type thermocouple, as detailed in Chapter Two, was used as the temperature measuring instrument to monitor wheel temperature following immediate release from the casting machine die.

Temperature measurement recording over a set time period was possible through use of a data collector. An Anritsu AM-7002 data collector, also detailed in Chapter Two, was selected for this role. The wheel temperature was recorded every two seconds during this investigation whilst constant surface contact was maintained between the thermocouple and the wheel. Due to the high temperature of the wheel and the die immediately after casting it was not possible in this situation to make the appropriate holes in the wheels for the insertion of a thermocouple below the wheel surface. However, measuring the wheel surface temperature is a satisfactory and viable option in this instance and the surface temperature measurements taken will prove useful towards indicating the wheel temperature immediately after casting. Figure 3.3 shows schematically the method by which surface temperature measurements were taken during this investigation. An explanation of this diagram aids in the understanding of the temperature measurement process. When the transfer trolley is in Position 1 the wheels have just been released from the die. It is at this point that the thermocouple is placed on the wheel surface as shown and temperature measurement commences. The transfer trolley, and wheels, then move to Position 2, enabling the dies to close and continue with further production. Thermocouple contact with the wheel and temperature measurements continued whilst the transfer trolley moved from Position 1 to Position 2. In Position 2 the transfer trolley remains stationary for a set period of time before the wheels are transferred to the subsequent process. Temperature measurements continued during this set period of time, finishing only when the wheels moved to the subsequent process. It is shown later that this temperature measuring time period is sufficient for obtaining a satisfactory cooling curve for the wheel.

Two separate temperature measurements were completed for each wheel type so that two temperature profiles were obtained for each of the two wheel types tested. Figure 3.4 shows the two temperature profiles obtained for the MX5 wheel type (lightest wheel). It can be seen from this that the temperature of the MX5 wheel type immediately after casting is approximately 405°C and reduces to 390°C after remaining stationary on the transfer trolley for sixty seconds. Assuming heat loss from the casting is approximately the same during wheel handling from the transfer trolley to the solution treatment oven as it is for the casting remaining stationary on the transfer trolley then it can be seen that the initial temperature of the MX5 wheel type at the commencement of solution treatment will be approximately 390°C. This is a very significant finding as it means it is now possible to complete a further investigation to determine the heat-up time for the MX5 wheel type during solution treatment.

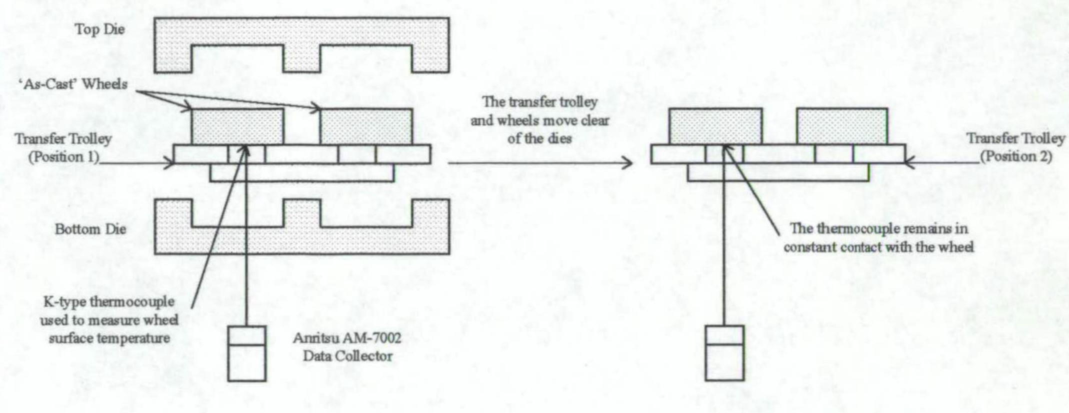


Figure 3.3: Method of Measuring 'As-Cast' Wheel Temperature on the Casting Machine

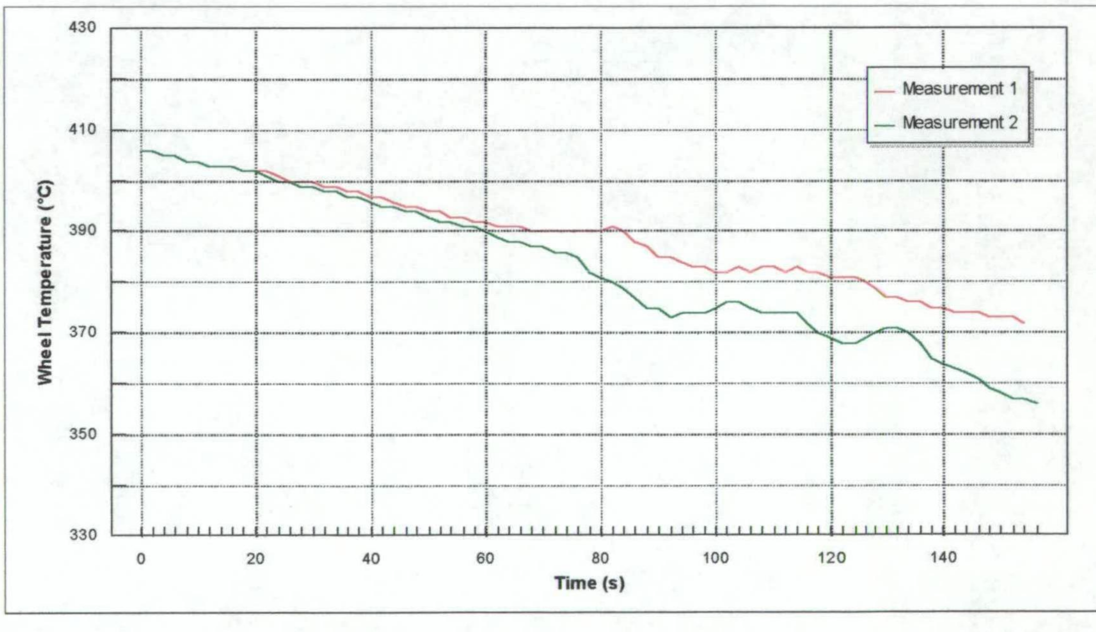


Figure 3.4: MX5 Wheel Type Temperature Profile Immediately After Casting

Figure 3.5 shows the two temperature profiles obtained for the A32 wheel type (heaviest wheel). For both measurements, the A32 wheel type exhibited a very similar profile. The wheel temperature immediately after casting is shown to be approximately 460°C. This reduces to approximately 455°C after sixty seconds. Using the same assumption as for the MX5 wheel type, then it can be seen that the temperature of the A32 wheel type at the commencement of solution treatment will be approximately 455°C.

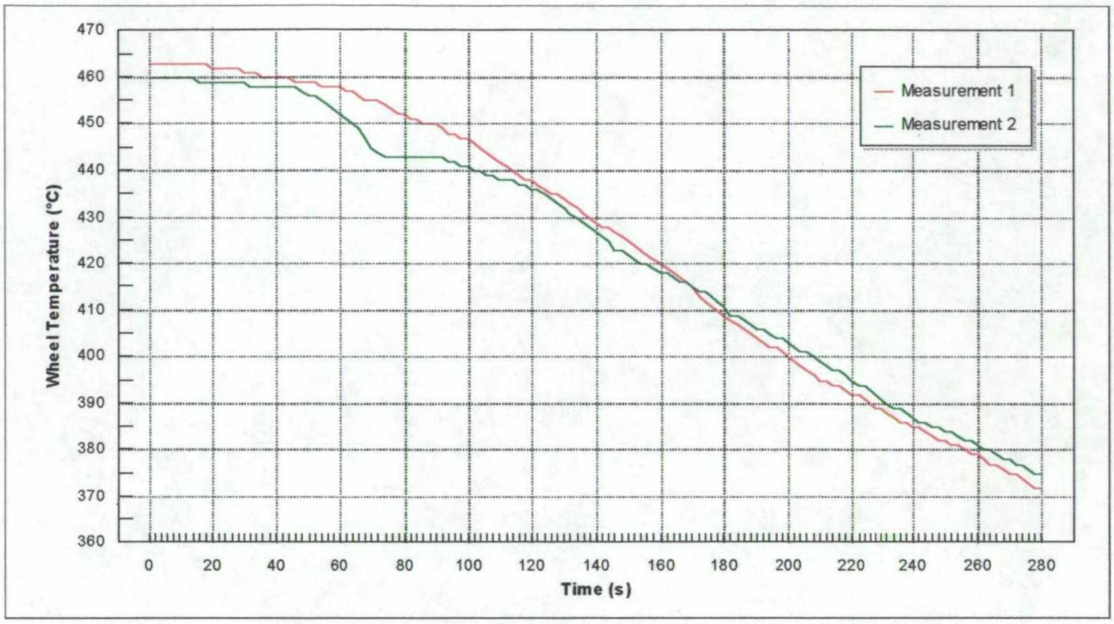


Figure 3.5: A32 Wheel Type Temperature Profile Immediately After Casting

This investigation has proved useful for determining wheel temperature immediately prior to solution treatment for the two wheel types tested and was necessary in order to complete the second part of this investigation which aims to determine wheel heat-up time during solution treatment. The determined wheel temperatures immediately prior to solution treatment will be used in conjunction with the following investigation to determine the time taken to complete the heat-up stage of the solution treatment process. The significant findings of this part of the investigation are that the temperatures of the MX5 and A32 wheel types immediately prior to solution treatment are approximately 390 and 455°C respectively.

A comparison of initial temperatures for wheels at the extremities of the mass has shown that the heavier wheel type, the Nissan A32, has a significantly higher initial temperature compared to the lighter wheel type, the Mazda MX5. The significance of the difference in initial temperature between wheels of different mass will become apparent at the conclusion of the following investigation.

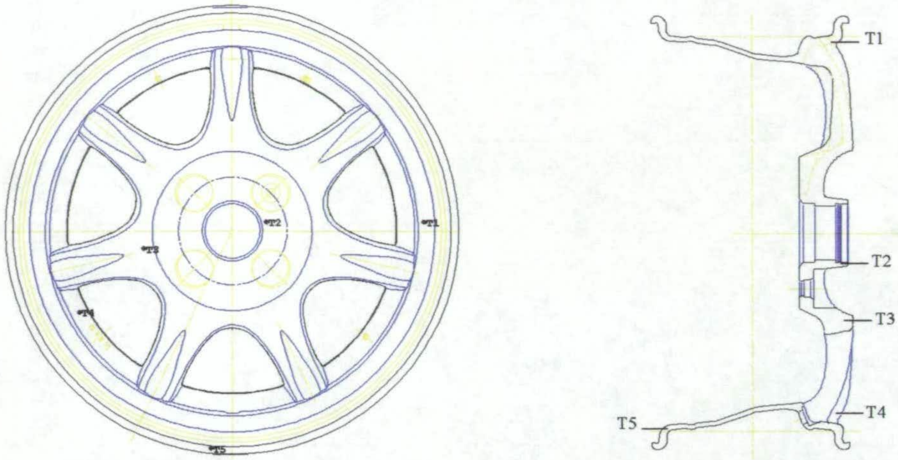
3.2 PRELIMINARY EXPERIMENTAL INVESTIGATION TO DETERMINE WHEEL HEAT-UP TIME DURING SOLUTION TREATMENT

This next stage of the preliminary experimental investigation is used to determine the time taken to heat a wheel from the initial temperature with which it enters the solution treatment oven, determined in the previous investigation, to the maximum solution treatment temperature. As mentioned earlier, solution treatment is a two stage process consisting of; i) heating the wheel to the maximum solution treatment temperature, and ii) holding the wheel at that temperature. The 'time to hold' at solution temperature part of the process has been determined from an earlier investigation[43]. The heating part of the process will be obtained using this experimental investigation. This stage of the preliminary investigation will also prove useful for studying the uniformity of heat distribution in the alloy wheel during solution treatment. The procedure followed for this part of the preliminary investigation is firstly, to expose the wheel to the maximum solution treatment temperature of 540°C and monitor its heating curve, and secondly, determine the heat-up time for the particular wheel type by studying the heat-up curve obtained.

As information is known already on the initial temperature of both the MX5 and the A32 wheel types at the commencement of solution treatment, then these two wheel types will be utilised further for the second part of this investigation. The 'as-cast' mass of the MX5 and A32 wheel types have been listed previously as being 8.57 and 12.12kg respectively and they represent the lightest and heaviest wheel types produced at SAPL at the time of testing.

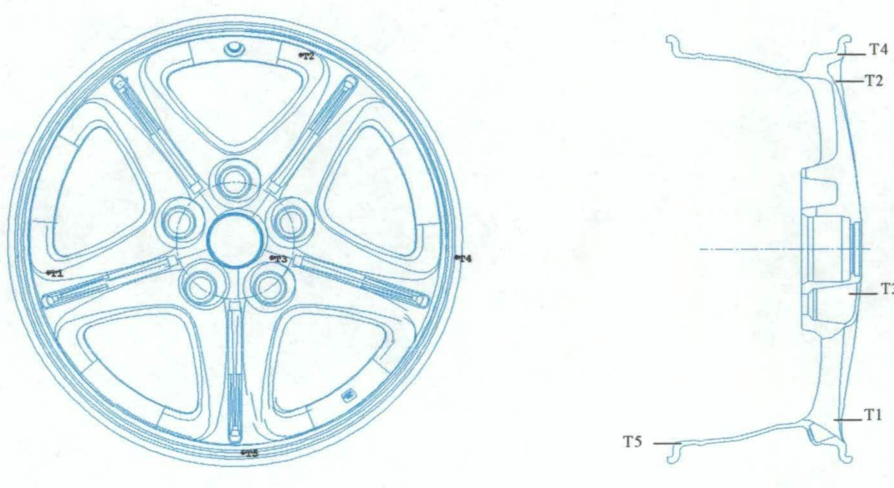
The data acquisition used for this part of the investigation consisted of k-type thermocouples, for temperature measurement, and an Anritsu AM-7002 data collector, for temperature recording, both detailed previously in Chapter Two. Temperature measurements were taken by inserting five thermocouples into various sections of the wheels. A sixth thermocouple was used to measure air temperature inside the oven heating chamber during solution treatment. The difficulties involved with inserting thermocouples into the wheel whilst on the transfer trolley has been mentioned in the previous investigation. Also due to the high temperature of the casting and the minimal time between casting and solution treatment, established as being sixty seconds in the previous investigation, it was not possible to insert the thermocouples into the wheels during the 'real' process. For this reason insertion of the thermocouples into the wheels took place whilst the wheels were at room temperature and a simulation temperature profile was obtained. The simulation was carried out by reheating the wheel to the predetermined initial temperature found from the previous investigation, followed by solution treatment with the oven set at the maximum solution treatment temperature of 540°C. For example, the heat-up curve for the MX5 wheel type was obtained by heating the wheel to an initial temperature of 390°C followed by solution treatment at a maximum temperature of 540°C. Temperature measuring and recording commenced only after the initial temperature of 390°C had been achieved. Similarly for the A32 wheel type, temperature recording commenced once an initial temperature of 455°C had been achieved using a maximum solution treatment temperature of 540°C. Temperature measurement and recording continued for a period sufficient enough to allow a satisfactory heat-up curve to be obtained. This simulation acted as a close representation of the 'real' process.

Thermocouple placement in either of the wheel types tested is shown in Figures 3.6 and 3.7 for the MX5 and A32 wheel types respectively. Positioning of the five thermocouples in each wheel type is represented by the abbreviations T1 to T5. Thermocouples one to four were inserted into the front face of the wheel, in the positions shown, whilst thermocouple five was inserted into the bottom of the wheel rim. The sixth thermocouple used for measuring the oven chamber air temperature was placed just above the front face of the wheel. Insertion of the thermocouples into the wheels was a relatively simple process. Firstly, holes were drilled in the wheels at the appropriate positions and depths using a drill size slightly larger than the thermocouple sheath diameter. Thermocouples were then inserted into the various holes and held in place by peening the surrounding area around the thermocouple. The purpose of measuring the wheel temperature in different locations was to investigate the variation in heat-up rate for thin and thick sections of the wheel and hence, investigate temperature uniformity throughout the wheel during heating.



Front Face View Cross-Sectional View

Figure 3.6: Thermocouple Placement in the MX5 Wheel Type



Front Face View Cross-Sectional View

Figure 3.7: Thermocouple Placement in the A32 Wheel Type

Two temperature profiles were obtained for both of the wheel types tested. Figures 3.8 and 3.9 show the temperature profiles obtained for the MX5 wheel type. It can be seen that the heat-up period for the MX5 wheel type is similar in either case. The temperature of this wheel immediately prior to solution treatment has been shown in the first part of this investigation to be approximately 390°C. From the temperature profiles obtained it is shown that this temperature increases to 540°C after approximately seven hundred and twenty seconds (720s), or alternatively, twelve minutes (12mins) of solution treatment. This indicates that the heat-up time for the MX5 wheel type during solution treatment is approximately twelve minutes when a solution treatment temperature of 540°C is used.

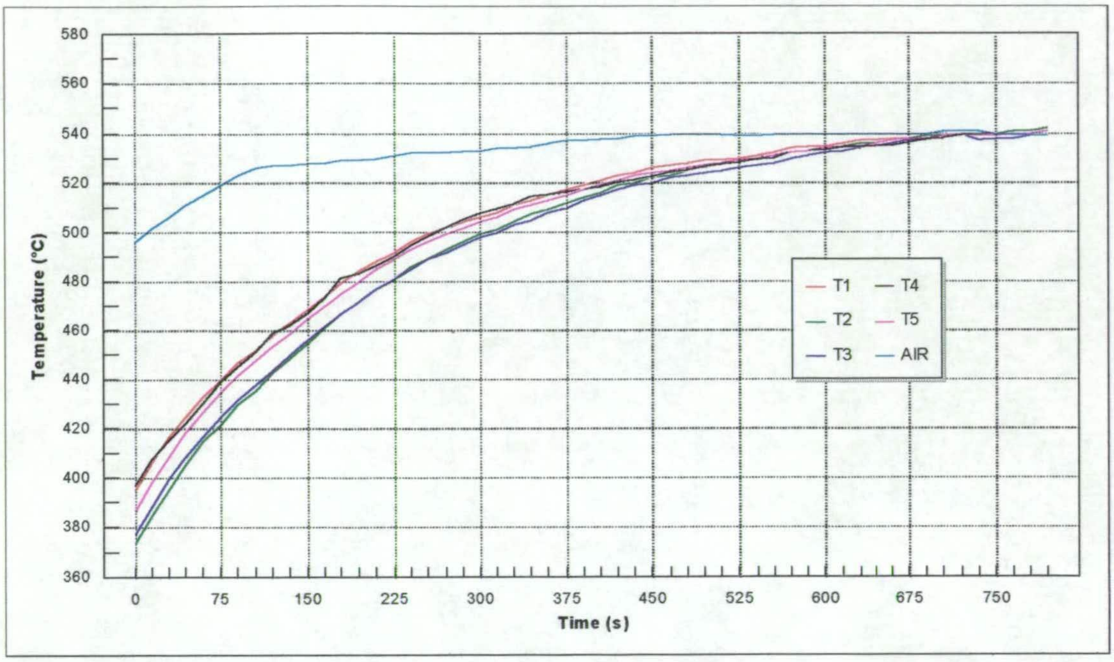


Figure 3.8: MX5 Wheel Type Temperature Profile During Solution Treatment (1)

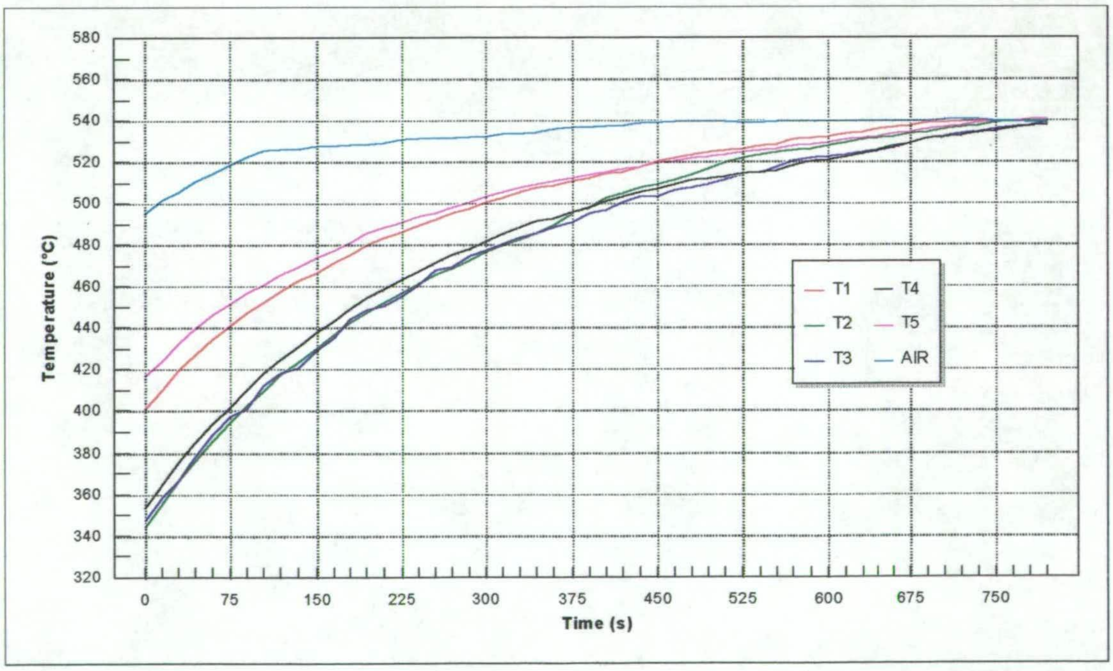


Figure 3.9: MX5 Wheel Type Temperature Profile During Solution Treatment (2)

Figures 3.10 and 3.11 show the temperature profiles that were obtained for the A32 wheel type. Again, the temperature profiles obtained were similar in either case. The wheel temperature immediately prior to solution treatment has been shown in the first part of this investigation to be approximately 455°C. From the temperature profiles obtained it can be seen that this temperature increases to 540°C after approximately seven hundred and fifty seconds (750s), or alternatively, twelve and a half minutes (12mins30s) of solution treatment. This indicates that the heat-up time for the A32 wheel type during solution treatment is approximately twelve and a half minutes when a solution treatment temperature of 540°C is used.

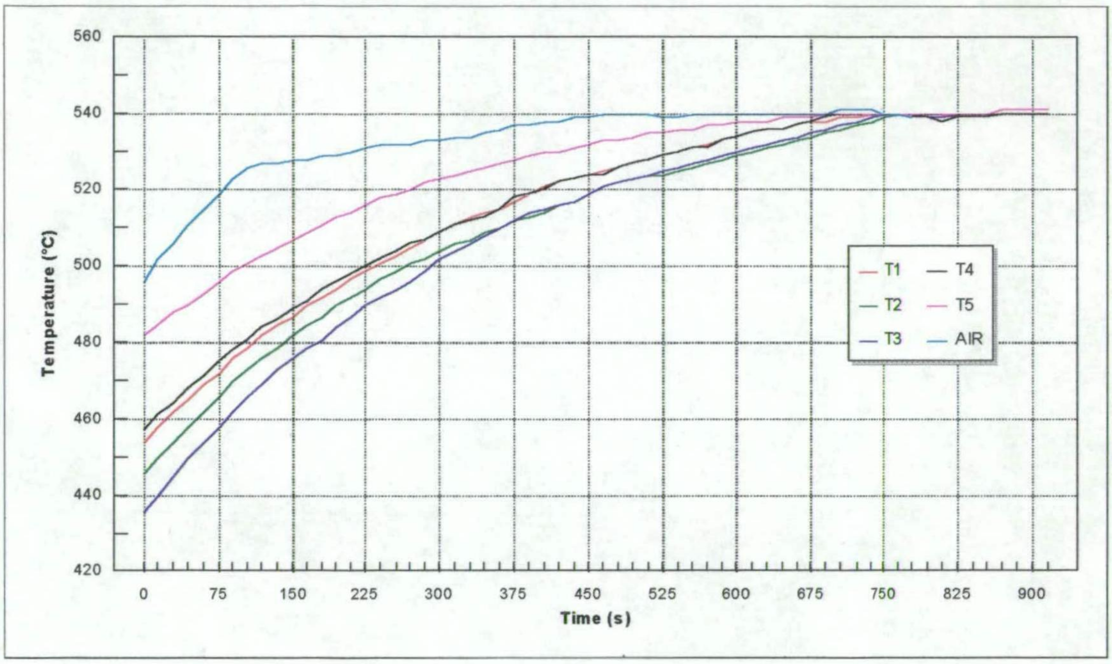


Figure 3.10: A32 Wheel Type Temperature Profile During Solution Treatment (1)

The findings from this part of the investigation are significant as they provide the necessary information to establish a total solution treatment time to be used in the optimised solution treatment process. For example, the MX5 wheel type, which is to be used as the test specimen for the initial stage of the major investigation, will have a total solution treatment time of twenty two minutes. This is a combination of the twelve minute heat-up time and the ten minute isothermal holding period. That is, the MX5 wheel type will be placed and left in the solution treatment oven for a period of twenty two minutes with the oven temperature set at 540°C. Similarly, total solution treatment time for the A32 wheel type would be twenty two and a half minutes.

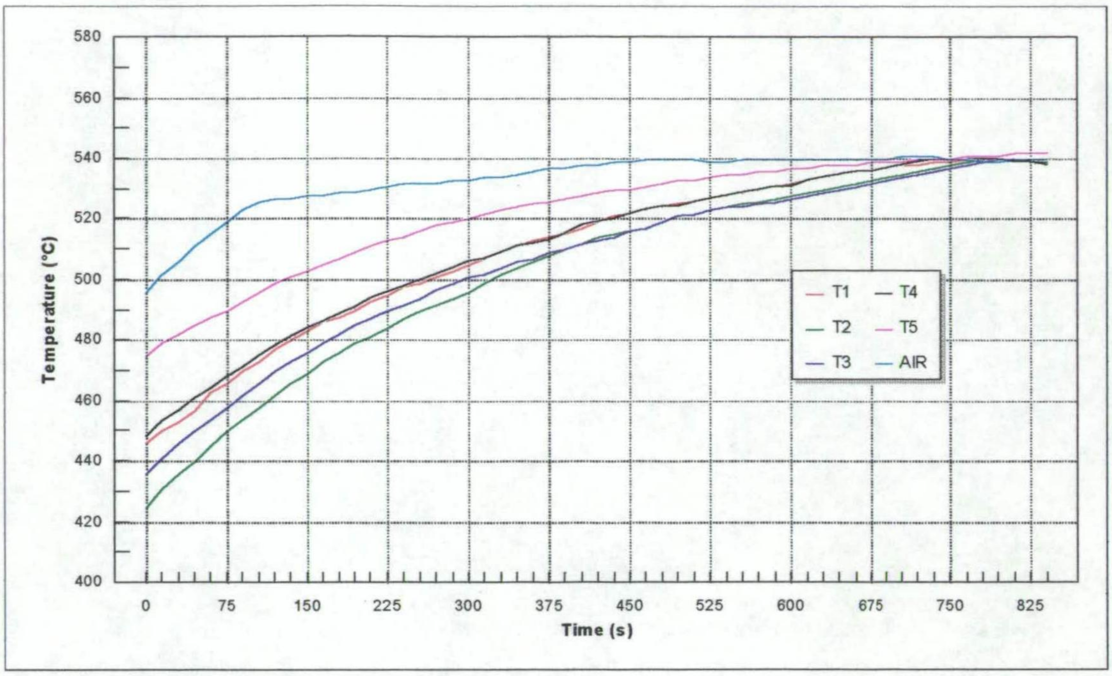


Figure 3.11: A32 Wheel Type Temperature Profile During Solution Treatment (2)

It is worthwhile mentioning at this point that although a faster heat-up rate could have been achieved through use of a higher oven temperature during the heating period of the alloy wheel, it was decided that a uniform temperature of 540°C be used to minimise the complexity of the investigation and also to avoid problems associated with operating the oven at changing temperatures. Furthermore, it will become apparent in later chapters that there are significant problems associated with subjecting the alloy to temperatures above its eutectic point.

However, the temperature profiles obtained can be used to investigate the relationship between wheel mass and wheel heat-up rate. To do this analysis accurately it is important that the heat-up curves obtained for the two wheel types be studied over the same temperature range only. That is, the difference in initial temperature between the two wheels is significant enough to affect the mechanisms of heat transfer during solution treatment. It is a basic tenet of heat transfer that the greater the temperature between two parties in contact then the higher is the rate of heat transfer from one party to the other. Consider the process of solution treatment in which a wheel of surface temperature, T_{surf}, is placed inside an oven chamber with circulating air at a temperature, T_{fluid}, where T_{surf} is less than T_{fluid} at the commencement of solution treatment. Convection heat transfer will be the main mode of heat transfer from T_{fluid}

to T_{surf}. The basic two dimensional equation for convection heat transfer is of the form shown in Eqn. 3.1[45].

$$q_x = hA(T_{surf} - T_{fluid}) \qquad \text{(Eqn. 3.1)}$$

where, q_x = rate of heat transfer (W),
h = heat transfer coefficient (W/m^2K), and
A = wheel surface area exposed to the circulating air (m^2)

It can be seen from Eqn. 3.1 that the greater the difference in temperature between T_{surf} and T_{fluid} then the greater is the rate of heat transfer, q_x. This theory plays a significant role when comparing the heat-up rates of the two wheel types studied. At the commencement of solution treatment the temperature difference between the MX5 wheel type and the oven chamber is greater than the temperature difference between the A32 wheel type and the oven chamber. Consideration of Eqn. 3.1 suggests then that the initial rate of heat transfer will be greater between the MX5 wheel type and the oven chamber compared to the A32 wheel type and the oven chamber. It can be seen then that for the purpose of comparing the heat-up rate of the two wheel types mentioned it is important that the temperature curves be compared over the same temperature range. To do this, consider only the heat-up curve for the MX5 and the A32 wheel types over the temperature range of 455 to 540°C. It can be seen from Figures 3.8 and 3.9 that the average time taken for the MX5 wheel type to heat from 455 to 540°C is approximately six hundred and fifteen seconds (615s). An average heat-up rate, or rate of change of temperature, for the MX5 wheel type can be determined by approximating the heat-up curve to a linear relationship. This yields the following:

Temperature Change = (Final Temp. - Initial Temp.) = (540 - 455) °C = 85°C
Average Heating Time = 615s
Rate of Change of Temperature = Temperature Change / Average Heating Time
$\Rightarrow$ Rate of Change of Temperature = 150°C / 615s = 0.24°C / s (or 14.6°C/min)

The same information can be obtained by considering the temperature profile of the A32 wheel type, Figures 3.10 and 3.11, during heating. This yields:

Temperature Change = (540 - 455) °C = 85°C

Average Heating Time = 750s

Rate of Change of Temperature = Temperature Change / Average Heating Time

⇒ Rate of Change of Temperature = 85°C / 750s = 0.11°C / s (or 6.8°C/min)

It is evident from the completed calculations that the higher mass wheel, the Nissan A32, has a lower heat-up rate compared to the lower mass wheel, the Mazda MX5. The heat-up rate for the MX5 wheel type (8.57kg) is 14.6°C/min whilst the heat-up rate for the A32 wheel type (12.12kg) is only 6.8°C/min. This finding suggests that the relationship between wheel mass and wheel heat-up rate is that the higher the mass of the wheel then the lower is its heat-up rate, and vice versa. This relationship is found to be consistent with the basic laws of heat transfer. Consider two bodies of the same temperature but different mass individually placed in a surrounding where the temperature of the surrounding is significantly higher than the temperature of the two bodies. The rate of heat transfer to the heavier body will be lower than the rate of heat transfer to the lighter body. If the bodies are of significant difference in mass then the rate of heat transfer to each body will be significantly different. The same theory can also be applied to a body of varying cross-section, such as the wheels used for this investigation. It can be seen in Figures 3.8 to 3.11 that the temperature profiles are slightly different in thin and thick sections of the wheel, ie. non-uniformity of temperature. Consider firstly the MX5 wheel type heat-up curve shown in Figures 3.8 and 3.9. Initially, there is a large variation in temperature between thin and thick sections of the wheel. This can be seen by comparing the measured temperatures from thermocouples three and five, T3 and T5 in Figures 3.6, 3.8 and 3.9. Thermocouple 3 was inserted into a thick section of the wheel and consequently showed a lower heat-up rate than thermocouple five which was in a significantly thinner section of the wheel. A comparison of these same two thermocouples, T3 and T5 in Figures 3.7, 3.10 and 3.11 shows similar results for the A32 wheel type. However, during the initial heat-up stage of the solution treatment process both wheel types have shown that by the time the maximum solution treatment temperature of 540°C is reached the temperature is uniformly 540°C throughout the entire wheel. In other words, all sections of the wheel converge towards a common temperature of 540°C at the end of the heat-up period. The rationale used to explain the difference in heat-up rate for bodies of different mass can also be applied in this instance to explain the difference in heat-up rate for sections of the wheel of varying size and mass. The laws of heat transfer suggest that thin sections of the wheel will allow heat transfer more readily than thick sections of the wheel. The fact that there is only a slight temperature difference noticed between thin and thick sections of the wheel is most likely due to the fact that aluminium is an excellent conductor of heat.

It is especially interesting to note from this part of the investigation that despite the large difference in wheel heat-up rate, the MX5 and the A32 wheel types exhibited essentially the same heat-up time. The heat-up time for the MX5 wheel type has been shown to be approximately twelve minutes compared to a heat-up time of approximately twelve and a half minutes for the A32 wheel type. The small difference in heat-up time for the two wheel types, regardless of their significantly different heat-up rates, can be explained by consideration of the initial temperature of each wheel. The MX5 wheel type with its initial temperature of 390°C heated to 540°C in twelve minutes and had a heat-up rate of 14.6°C/min. The A32 wheel type, even though it had a significantly lower heat-up rate, 6.8°C/min, also heated to 540°C in approximately the same time as the MX5 wheel type. This is due to the higher initial temperature of the A32 wheel type at the commencement of solution treatment. This behaviour has significant implications on the project as it introduces the possibility of heating two wheel types, of different mass, to the maximum solution treatment temperature in the same amount of time, assuming that the higher mass wheel has a sufficiently higher initial temperature.

In summary, this part of the investigation has proved useful for determining wheel heat-up time as part of the total solution treatment process. The findings of this investigation have shown that a heat-up time of approximately twelve minutes is required for the MX5 wheel type and twelve and a half minutes for the A32 wheel type during solution treatment. This investigation has also shown that although the wheels are of different mass the heat-up time required is essentially the same due to the higher initial temperature of the heavier wheel. These experimental findings will be directly incorporated into the major investigation for solution treatment of aluminium alloy wheels using an optimised process. It has been mentioned earlier that the MX5 wheel type will be used as the test specimen for the major investigation. It can be seen then that the optimum solution treatment process to be used in the initial stage of the major investigation will consist of a twenty two minute solution treatment time using a solution treatment temperature of 540°C.

3.3: UNIFORMITY OF HEAT DISTRIBUTION IN THE SOLUTION TREATMENT OVEN

As a further inspection of the experimental apparatus, an investigation carried out on the solution treatment oven has shown that the uniformity of heat distribution within the oven enclosure conforms with the requirements of Australian Standard 2853 - 1986, “Enclosures - Temperature Controlled - Performance Testing and Grading”. The test results are highlighted in Table 3.1 in which the values shown have been rounded to the nearest 0.5°C.

TABLE 3.1: Test Results for Solution Treatment Oven Heat Distribution Uniformity

Steady State Parameters	**Temperature (°C)**
Control Index Setting	540.0
Indicated Enclosure Temperature	540.0
Measured Enclosure Temperature	535.5
Measured Spatial Variation	6.5
Measured Temporal Variation	2.0
Maximum Measured Temperature	539.0
Minimum Measured Temperature	532.0
Overall Variation	7.0

It is useful here to define the terminology used to aid in the understanding of the results obtained. The definitions are as follows:

Indicated Enclosure Temperature: The enclosure temperature computed from indicated temperatures. It is equal to half the sum of the maximum and minimum indicated temperatures.

Measured Enclosure Temperature: The enclosure temperature computed from measured temperatures. It is equal to half the sum of the maximum and minimum measured temperatures.

Measured Spatial Variation: The difference between the mid-range value of all temperatures obtained at one site and that at another site for those sites which give the greatest difference.

Measured Temporal Variation: The maximum value of the measured temperature range obtained for each of the relevant sites throughout the test interval.

Maximum Measured Temperature: The highest measured temperature obtained during the test interval.

Minimum Measured Temperature: The lowest measured temperature obtained during the test interval.

Overall Variation: The difference between the maximum and the minimum measured temperatures.

This compliance was obtained for a test interval of sixty minutes and a test space as defined in Figure 3.12. Temperature measurements within the oven chamber were taken using nine k-type thermocouples with a 0 to 600°C temperature range. The numbered spaces represent the placing of thermocouples within the oven

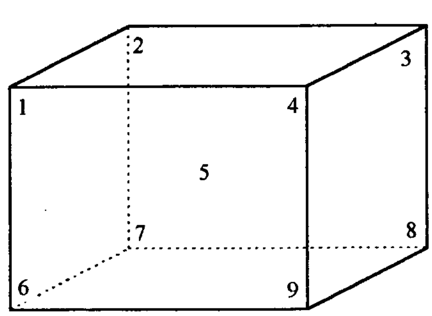


Figure 3.12: Temperature Measurement Sites

chamber. The internal dimensions of the solution treatment oven are 465mm (H) X 605mm (W) X 620mm (D). The oven chamber was in the unloaded condition during testing except for the test thermocouples. The oven was set to a temperature of 540°C using the Eurotherm controller on the oven control panel. A stabilisation period of one hour was used prior to the test to allow the oven chamber to be sufficiently heated. The recorded average temperatures over the sixty minute test period for the various thermocouple locations are shown in Table 3.2 in which the values shown have been rounded to the nearest 0.5°C.

TABLE 3.2: Measured Temperatures for Thermocouple Locations

Test Site	**Mean Temperature (°C)**
1	537.0
2	537.0
3	536.0
4	535.5
5	532.5
6	535.5
7	534.5
8	536.0
9	539.0

The fact that the solution treatment oven has been found to comply with the relevant Australian Standard indicates that the experimental apparatus is appropriate for use in the major investigation to study the effect that solution treatment has on the mechanical properties of aluminium alloy 601 and it reinforces the reliability of the results.

3.4 COMPARISON OF THE OPTIMISED AND THE EXISTING SOLUTION TREATMENT PROCESSES

It is now useful to compare the temperature profile of the optimised solution treatment process with that of the existing solution treatment process. This will provide a direct comparison between the degree of solution treatment in either case.

The optimised solution treatment temperature profiles for the MX5 and the A32 wheel types are both known at this stage of the project. A temperature profile for the existing solution treatment process was obtained by monitoring wheel temperature throughout the cycle of the existing solution treatment oven using temperature measuring techniques similar to those used for the previous preliminary investigations. The data acquisition used for this investigation consisted of the k-type thermocouples and Anritsu AM-7002 data collector detailed earlier. The MX5 and A32 wheel types were again used for this particular investigation such that a comparison could be made between the two solution treatment processes using the same wheel types. One thermocouple only was inserted into each of the two wheel types in a position corresponding to T3 in Figures 3.6 and 3.7 for the MX5 and A32 wheel types respectively. It can be seen that the positioning of the thermocouple is in a relatively thick section of the wheel. Previous work has shown that if the thick section of the wheel is at the maximum solution temperature then it can be assumed that the remainder of the wheel is also at the maximum solution temperature. The reason for using one thermocouple only in this instance was due to the fact that the aim of this particular investigation was not to study the uniformity of heat distribution within the existing oven or mass-temperature relationship but rather to obtain a 'general' temperature profile for the existing solution treatment process that would allow a suitable comparison with the optimised treatment that is to be trialed. One thermocouple was sufficient in this instance to provide this information.

The temperature profiles for both the optimised and the existing solution treatment processes are shown in Figure 3.13. The time, and consequently, energy savings that are available by using the optimised solution treatment process in preference to the existing standard T6 heat treatment process used at SAPL are evident through consideration of Figure 3.13. The advantage that the optimised process has over the existing process is not only the significantly reduced isothermal holding time but also the high temperature of the wheel immediately after casting is utilised to significantly reduce the heat-up period required.

It can be seen from Figure 3.13 that for the existing solution treatment process, wheels enter the solution treatment oven at room temperature and take approximately ninety minutes (90mins), or one and a half hours (1.5hrs), to heat to the maximum solution treatment temperature of 540°C. The wheels are then held at 540°C for a further one hundred and eighty minutes (180mins), or three hours (3hrs), before being quenched. Hence, the heat-up stage of the existing process occupies a significant portion of total solution treatment time. Figure 3.13 indicates that the optimised solution treatment process is complete in approximately one tenth of the time taken using the existing process. However, the question remains as to what are the implications of this revolutionary treatment on the physical properties of aluminium alloy wheels. This aspect together with technological, economic and ergonomic aspects will be discussed shortly.

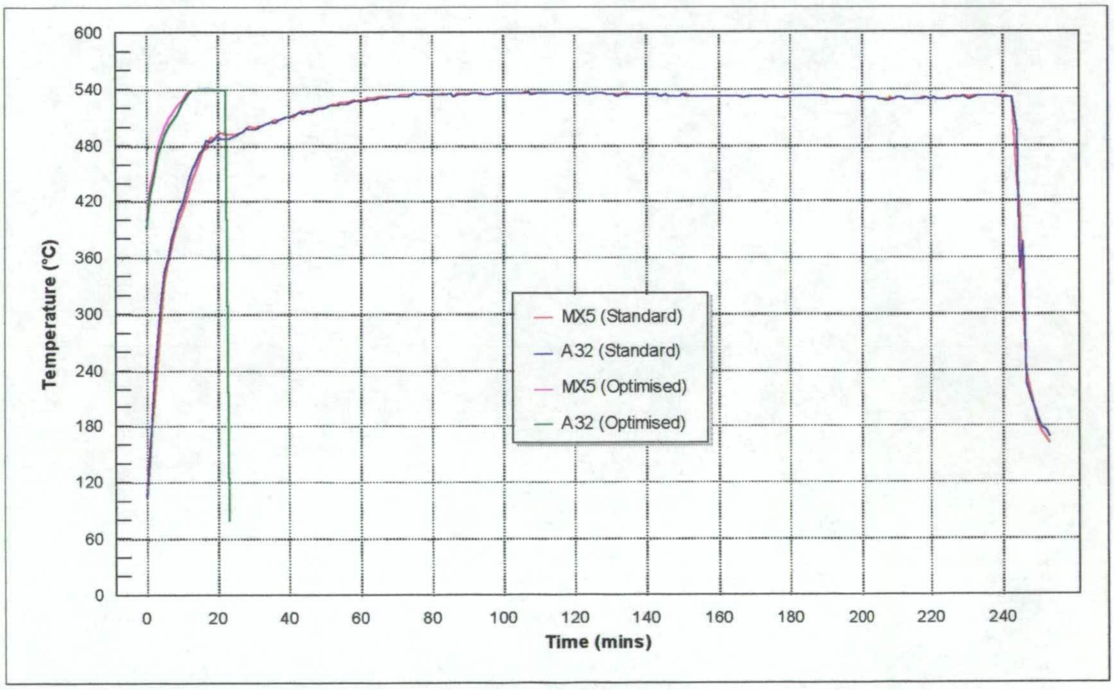


Figure 3.13: Comparison of the Standard and Optimised Solution Treatment Processes

3.5 DETERMINATION OF TEMPERATURE PROFILE THROUGH THE EXISTING AGING OVEN

It has been mentioned earlier that the criteria for using the particular solution treatment condition of ten minutes isothermal holding at a temperature of 540°C is that the existing aging treatment of four and a half hours at 140°C still be used as a subsequent process following solution treatment and quenching. For this reason it is useful to determine the temperature profile of the existing age oven such that the exact heat treatment conditions of the optimised process are displayed. The procedure detailed previously for obtaining temperature profiles throughout the existing solution treatment oven was followed for obtaining the age oven temperature profile. That is, the MX5 and A32 wheel types were used with one thermocouple only inserted into each of the two wheels in the positions shown previously. Temperature measurements were taken as the wheels moved in accordance with the normal production procedure through the length of the existing age oven. Figure 3.14 shows the temperature profiles that were obtained for both the MX5 and A32 wheel types.

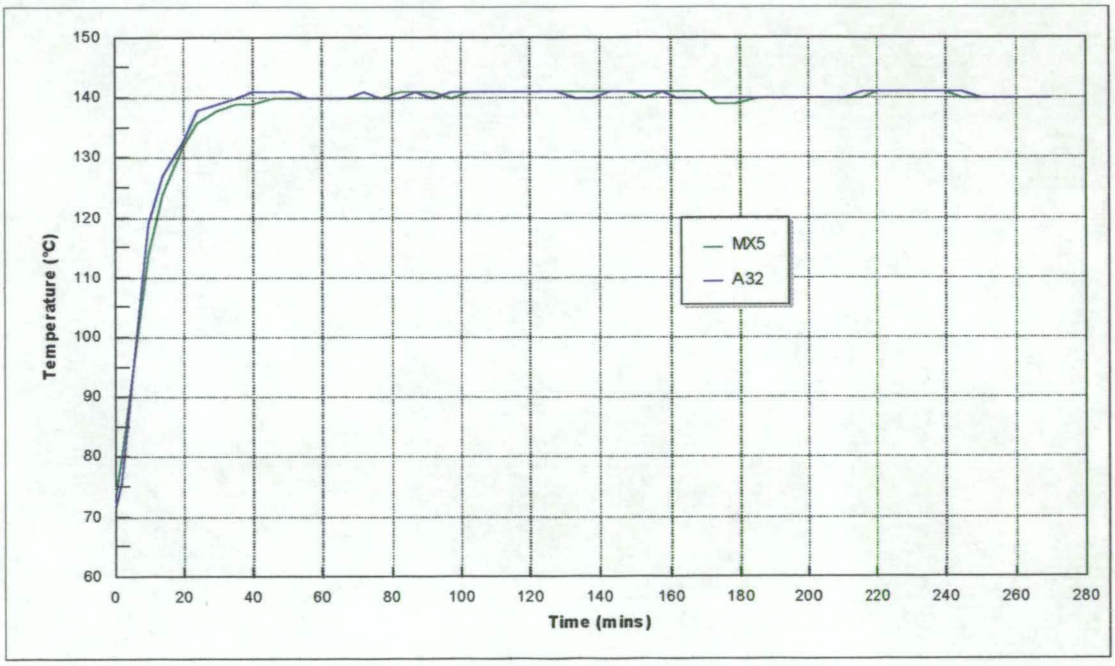


Figure 3.14: Temperature profile of the MX5 and A32 Wheel Types Through the Existing Aging Oven

It can be seen that the temperature profiles obtained for the two wheel types are very similar in either case even though the wheel types were of different mass. This indicates that these temperature profiles can be used as the general temperature profile for any wheel type through the existing age oven, regardless of wheel mass. The temperature profiles obtained show that the general heat-up time for a wheel to the maximum aging temperature of 140°C is approximately thirty five minutes followed by two hundred and thirty five minutes of constant holding at 140°C, making a total aging time of two hundred and seventy minutes (270mins), or four and a half hours (4.5hrs).

3.6 CONCLUDING REMARKS

The preliminary experimental investigations completed have proved useful for determining the total solution treatment time that will be required for the optimised process to be trialed in this instance. The significant findings of this work are that the optimised solution treatment process to be trialed in the first instance, using the MX5 wheel type as the test specimen, will essentially consist of a twelve minute heat-up period and a ten minute isothermal holding period, thus making a total solution treatment time of twenty two minutes. This information is based on a solution treatment temperature of 540°C being used. The preliminary work has also shown a significant relationship between wheel mass and heat-up time. It was shown that it is possible for wheels of different mass to have very similar heat-up times even though their heat-up rates are significantly different. It was shown that this is possible due to the higher initial temperature of the higher mass wheel. It is useful to summarise here the important findings of the preliminary experimental investigations completed, Table 3.3.

TABLE 3.3: Summary of Results from Preliminary Experimental Investigations

Property	**MX5**	**A32**
Mass (kg)	8.57	12.12
Initial Temperature (°C)	390	455
Heat-Up Rate (°C/min)	14.6	6.8
Heat-Up Time (mins)	12	12.5
Total Solution Time (mins)	22	22.5

The general qualitative trends exhibited during the preliminary investigations match well with the expected thermodynamic behaviour. The function and behaviour of the experimental apparatus has been shown to be of good order, in particular, the compliance of the solution treatment oven with the appropriate Australian Standard. In addition, the repeatability of the results is evident through consideration of the temperature profiles obtained. This reinforces the functioning of the experimental equipment. Hence, the necessary preliminary information has been obtained and the experimental equipment has been shown to be satisfactory for use in the major investigation. The next stage of the project now is to commence the major investigation. However, prior to this, it is necessary to detail the mechanical tests that will be used in the major investigation for the determination of the mechanical properties developed in the alloy during heat treatment.

CHAPTER FOUR

TEST PROCEDURE AND MECHANICAL TESTS USED

The preceding chapters have given an introduction to the project being completed and have been used to define and debate why it is desirable and beneficial to optimise the heat treatment process at SAPL. Information has also been provided on the material to be tested and the method by which the optimised heat treatment process will occur. It has been stated that evaluation of the optimised heat treatment process being trialed will be through analysis of the resulting mechanical properties developed in the alloy. Mechanical properties are the characteristics of a material that are displayed when a force is applied to the material. They usually relate to the elastic and plastic behaviour of the material[46]. It is now necessary, and is the aim of this chapter, to define the method by which these particular mechanical properties will be measured and highlight the testing equipment that is to be used. The mechanical tests described here will be used to substantiate any noticeable change in the mechanical properties of the material that occur whilst undergoing heat treatment. The mechanical properties of aluminium alloy 601 can be improved from the 'as-cast' condition without changing the chemical composition of the alloy since heat treatment affects its molecular structure rather than its chemical composition. Hence, it is useful to use mechanical testing as an investigative measure. The mechanical properties that are to be evaluated for the alloy in this instance are hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance. It was decided that a quantitative estimate on the developemnt of mechanical properties using the optimised heat treatment process could be made based on the measurement of these five properties. If any one of these five properties are found not to be developed to the desired level after heat treatment then it is evident that the optimised heat treatment process used is insufficient. That is, all five properties must be shown to be developed significantly to allow the optimised treatment to be classed as sufficient. Three separate mechanical tests were necessary and used in this instance to determine the five mentioned properties. They are commonly categorised as; i) hardness test, ii) tensile test, and iii) impact test and will be discussed in detail shortly. Prior to this it is interesting to discuss why the three mentioned mechanical tests were chosen and detail briefly the number of test specimens required for each test and the method of their preparation.

As an integral part of the quality system adopted at SAPL there is extensive mechanical testing completed on all wheel types periodically. The three mechanical tests that were used in this instance are commonly used at the plant as part of the quality system and are common throughout the wheel manufacturing industry. Furthermore, these three tests, as used at SAPL, will prove valuable and sufficient for evaluating the performance of the optimised solution treatment process in terms of its ability to develop the desired level of mechanical properties in the alloy by providing qualitative and quantitative results. Hence, these three tests were chosen as they were convenient to use and they have been shown to provide reliable results at SAPL. For each of the mechanical tests completed on site at SAPL there is a standard procedure that must be adhered to in order to minimise variation between testing methods and also to allow qualitative and quantitative results to be obtained. Hence, the relevant standard procedures were followed during testing.

It was established from the respective standard procedures that the following sample numbers were required for each of the three tests; i) hardness test: 12 samples (whole wheel), ii) tensile test: 12 samples (small samples cut and machined from a section of the wheel), and iii) impact test: 30 samples (whole wheel). To allow this sample size to be obtained a batch of thirty three wheels were prepared using the optimised solution treatment process. These thirty three wheels were divided into three wheels for tensile testing and thirty wheels for impact testing. Four tensile samples were cut and machined from each of the three wheels used for tensile testing, making a total of twelve tensile samples. Non-destructive hardness tests were completed on twelve of the specimens before impact tests were completed. Hence, the twelve samples used for hardness tests were also used for impact tests.

Whilst it is a requirement that the mechanical properties developed in the alloy during the optimised heat treatment process are in excess of the customer specifications, it is also necessary to compare the developed mechanical properties with those produced using the existing heat treatment system. To allow this comparison to be made a batch of only thirty wheels were collected from the existing heat treatment process. Quantitative data was already available on the tensile behaviour of the alloy during the standard T6 treatment therefore making it unnecessary to repeat tensile testing for this particular process. Tensile testing requires preparation of tensile samples which is a costly exercise in terms of labour and material. For this reason it was decided that the qualitative and quantitative information available would be sufficient. Therefore, twelve samples were collected from the existing heat treatment system and used for non-destructive hardness testing and then sent with a further eighteen wheels for impact testing, making a total of thirty wheels. Information on the hardness of the alloy following the standard T6 treatment was also available but the test was repeated in this instance as the test is non-labour intensive and the wheels were required to be used for impact testing anyway, for which quantitative results were not available.

The method by which heat treatment of alloy wheels at SAPL takes place has been shown for both the optimised and the existing processes in preceding chapters and furthermore, the method by which samples are processed after undergoing heat treatment has also been discussed. It is necessary to note here that specimen preparation in this instance for samples from either heat treatment process occurred using the same preparation as for normal production wheels and also that the batch of samples collected from the existing heat treatment process were identical to the batch of samples collected from the optimised heat treatment process other than the amount of heat treatment that either batch of samples had been exposed to. In addition, to minimise variation between the two batches, all samples were taken consecutively from the same casting machine, separated into the respective batch sizes for either heat treatment process, then united to complete further manufacturing. Hence, after heat treatment all wheels were processed as a single batch. This meant that process variation was limited to only the amount of heat treatment that each batch had undergone. Furthermore, as the same aging treatment was used for either heat treatment method then the only real difference between either batch of samples was the amount of solution treatment used. It was necessary to maintain a similarity between the two batches in order to accurately investigate the role that solution treatment plays in the development of mechanical properties in the alloy.

4.1 DESCRIPTION OF MECHANICAL TESTING

It is now convenient to document specific detail regarding each of the three individual mechanical tests used in this investigation to highlight the method by which the mechanical properties of the alloy were determined.

Hardness Test

One of the most simple and useful properties of metals is that of hardness. The hardness of a material is defined as the ability of the material to resist indentation or scratching[46]. The hardness test adopted was the Brinell hardness indentation test using an applied force (P) of 500kg and a steel indent ball of 10mm diameter (D). A standard procedure was adhered to for sample testing which outlined the correct operation when performing a hardness test using the 'Maekawa' hardness test machine, shown in Figure 4.1 where (1) represents the machine table and (2) represents the indent ball. To allow qualitative testing it was necessary that the test sample was flat, clean, smooth, horizontal and mechanically stable on the machine table. The sample test area used was the flange of the wheel. This area is easily prepared to meet the above requirements and is shown in Figure 4.2 on a sketch of an alloy wheel. The method of testing is a relatively simple process best described by highlighting the following steps. Firstly, the test piece (wheel) is placed on the machine table with the top flange of the wheel directly in line with the indent ball. The machine table is easily adjusted to accommodate wheels of varying width. The indent ball is then forced into the wheel flange for a minimum period of thirty seconds. This is then completed a second time so that two separate indents are placed on the wheel flange.

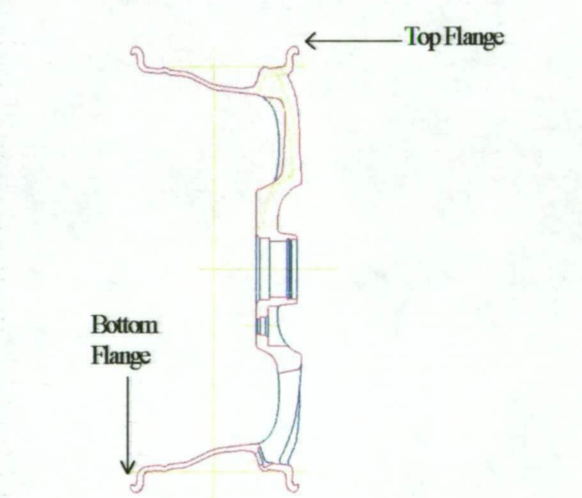


Figure 4.2: Cross-Sectional View Showing Wheel Flange

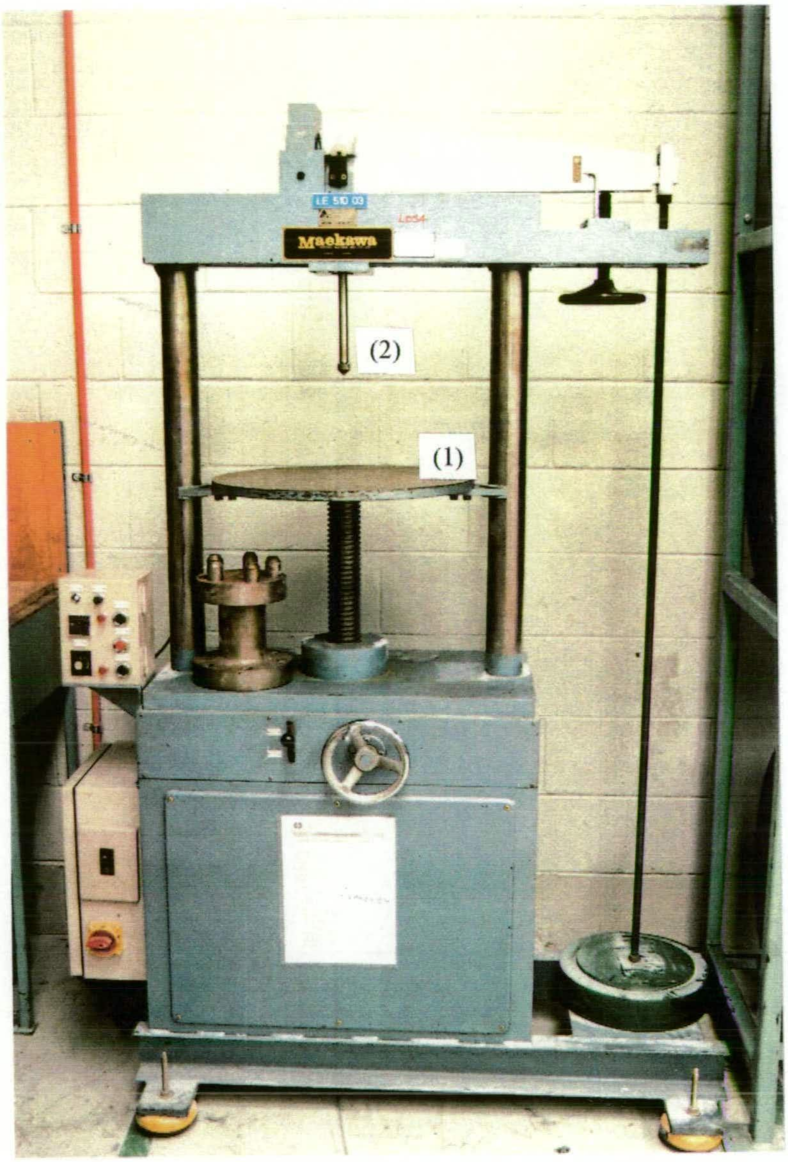


Figure 4.1: 'Maekawa' Hardness Test Machine

The diameter (d) of the indents are then measured using a microscope with an eye-piece scale. The two measurements are then averaged to obtain a Brinell hardness number (HB). HB is obtained by dividing the size of the applied force by the spherical surface area of the indentation, Eqn. 4.1[47].

HB = applied force / spherical surface area of indentation (Eqn. 4.1)

where, applied force (P) is in kg, and

surface area = $0.5*\Pi*D[D-\sqrt{(D^2 - d^2)}]$ (units of mm^2)

Alternatively, tables are available which give hardness values for different diameter indentations relating to the particular applied force and indent ball diameter used. The principles of the Brinell hardness test are shown schematically in Figure 4.3. The variables (P, D and d) used in Eqn. 4.1 are highlighted in this sketch.

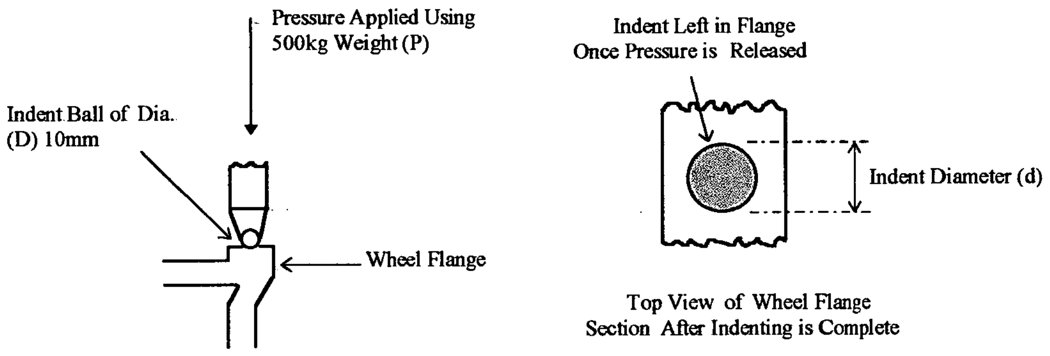


Figure 4.3: Principles of the Brinell Hardness Test

By using this relatively simple test it is possible to determine the hardness of the alloy. When completed on both batches of wheels this test will provide an immediate comparison between the ability of either heat treatment process to produce the desired level of hardness in the alloy. The desired level of hardness being that shown in the customer specifications given previously. The property of hardness is essential in aluminium alloy road wheels and thus must be developed sufficiently using the optimised heat treatment process if it is to be successful. However, the measure of hardness is necessary but not sufficient to fully evaluate the success of the optimised treatment. Thus, it is necessary that further mechanical tests be used for a full evaluation.

Tensile Test

This test involves measurements of the force required to extend a standard size test piece, or tensile sample, at a constant rate with the elongation of a specified gauge length of the tensile sample being measured by an extensometer. An 'Instron' tensile testing machine was used for testing samples that had been cut and machined from aluminium alloy wheels. A standard procedure was adhered to for this test to minimise variation between testing of the individual tensile samples. In order to eliminate any variation in tensile data due to differences in the geometry and dimensions of the individual test pieces, a standard shape was adopted and is shown in Figure 4.4.

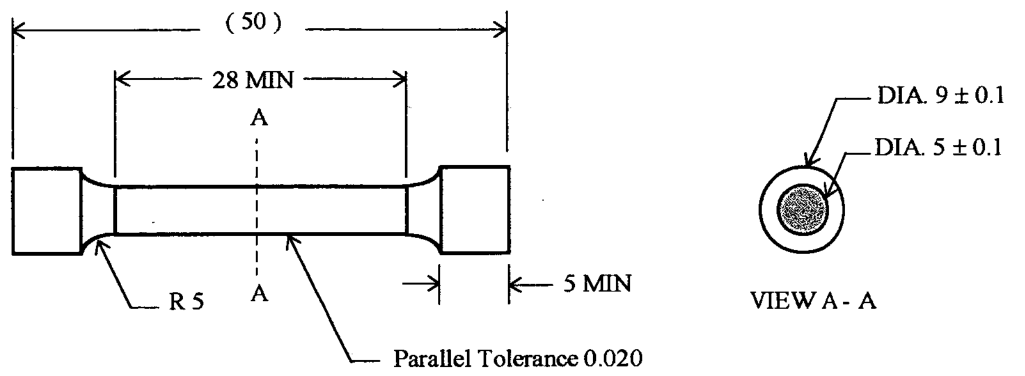


Figure 4.4: Round Tensile Test Piece (Note: All dimensions are in mm)

The thickness of the centre gauge was measured on each sample using a digital micrometer and the appropriate value included in the tensile property analysis. The gauge length is specified as (5 ± 0.1)mm on the sample geometry specification and thus can vary, and still remain in tolerance, from 4.9mm to 5.1mm, which is a significant variation when calculating the tensile properties of the sample. Thus, it was necessary to accurately measure the gauge diameter of each individual sample and include the measurement in the tensile property analysis.

Tensile testing was used in this instance to obtain specific information on the alloy yield strength, ultimate tensile strength and percentage elongation. The tensile testing machine used was equipped with an extensometer which was connected to an amplifier for recording the tensile properties of the alloy. The extensometer was attached to the 5mm cylindrical section of the tensile sample prior to the commencement of each tensile test. This is shown in Figure 4.5. It can be seen from this that the extensometer (1) is clamped to the centre section of the tensile sample (2) which is mounted between the two jaws (3) of the Instron test machine. Once the extensometer had been applied in this manner the measurement of tensile properties commenced by initiating movement of the jaws. As this particular test is a tensile test, the jaws move vertically away from each other in order to induce tension in the test specimen, ie. the test specimen is stretched, or elongated. As the jaws move the extensometer measures the change of strain in the sample. Movement of the jaws and tensile measurements continue until such a time as the tension on the sample becomes to excessive and the sample consequently fractures. The strain measurements recorded during testing are sufficient to evaluate the mechanical properties of the material such as yield strength, ultimate tensile strength and percentage elongation.

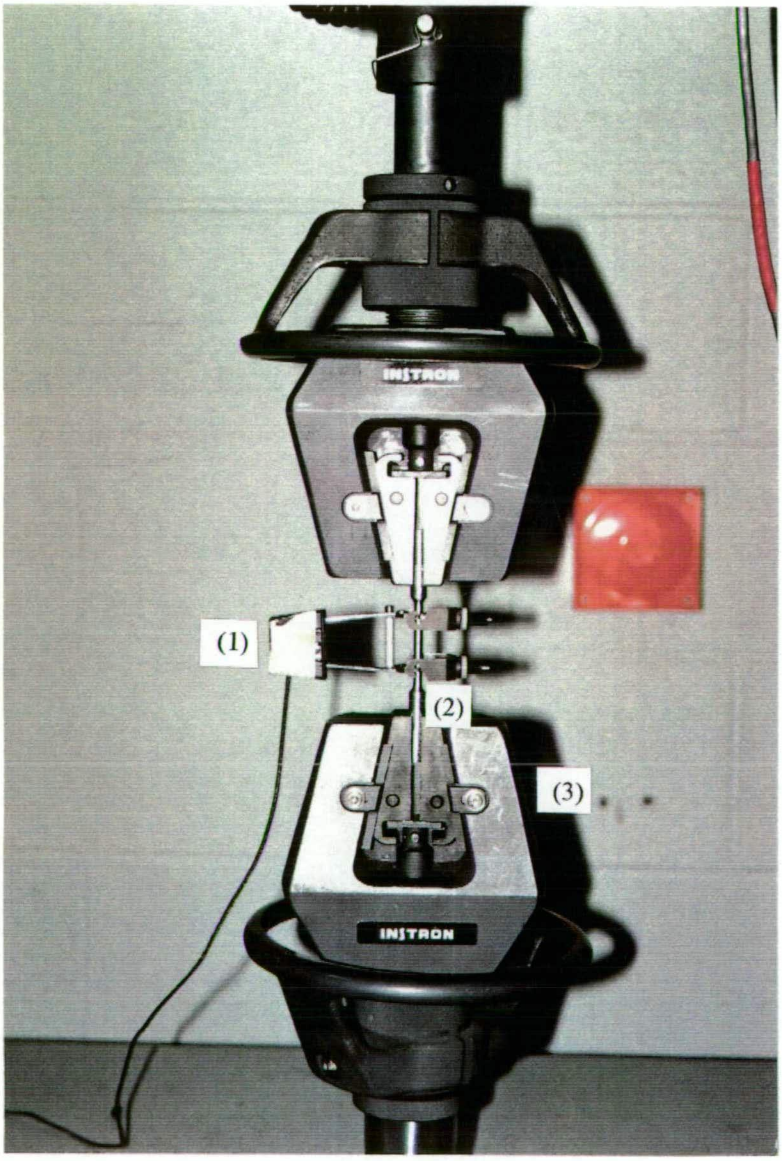


Figure 4.5: Instron Tensile Test Machine

A data acquisition system was used together with a 486 IBM compatible computer for recording the properties. The Series IX and Instron Model 1011 tensile testing machine and data acquisition set-up is shown in Figure 4.6 to aid in the understanding of the method by which the tensile results were obtained.

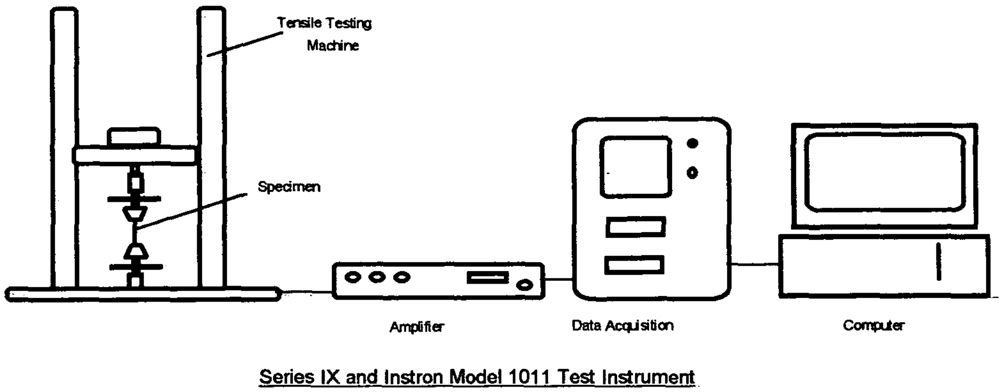


Figure 4.6: Instron Tensile Testing Machine and Data Acquisition Set-Up

It can be seen from Figure 4.6 that the tensile testing machine is connected to the data acquisition system through the amplifier to the computer. An analog signal indicates the real-time, instantaneous behaviour of the workpiece which can be monitored on the computer screen in the form of a stress-strain curve. The behaviour of materials subject to tensile and compressive forces can be described in terms of their stress-strain behaviour, stress being the applied force per unit area and strain the extension or contraction per unit original length of the material[47]. The stress-strain curve summarises a lot of useful information on the tensile properties of a material. A typical stress-strain curve for aluminium is shown in Figure 4.7.

The initial linear portion of the curve OA is the elastic region within which Hooke's law is obeyed[46]. Hooke's law states that within the elastic limits the strain produced is proportional to the stress producing it[48]. Point A is the elastic limit, defined as the greatest stress that the metal can withstand without experiencing a permanent strain when the load is removed[46]. The elastic limit is often replaced by the proportional limit, point A', as it is difficult to measure[46]. The proportional limit is the stress at which the stress-strain curve deviates from linearity[46]. The slope of the stress-strain curve in this region is called the modulus of elasticity, or Young's modulus. The modulus of elasticity of a material is a significant property as it represents the stiffness of the material. Hence, Young's modulus indicates the resistance of the material to elastic strain.

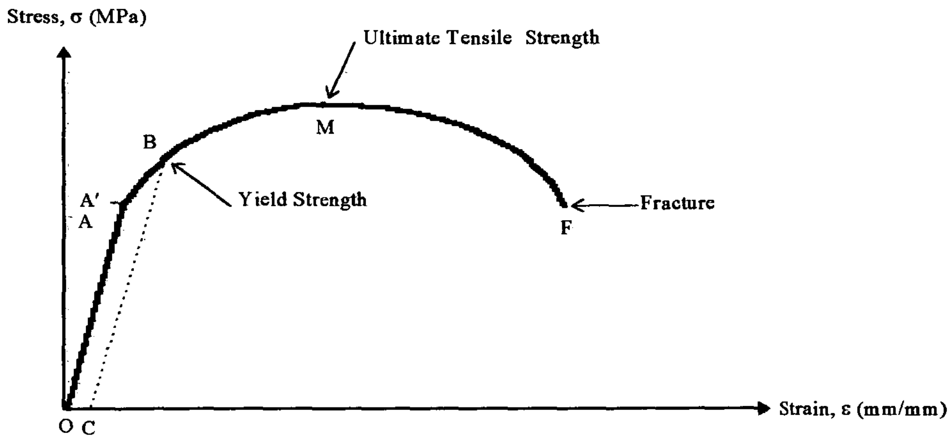


Figure 4.7: Typical Stress-Strain Curve for Aluminium[46]

The limit of useable elastic behaviour is described by the yield strength, point B[46]. The yield strength is defined as the stress which will produce a small amount of permanent deformation, generally a strain, equal to 0.01 or 0.2% of the gauge length of the tensile specimen[46]. In Figure 4.7 this permanent strain, or offset, is denoted by OC. To locate point B, firstly locate 0.2% elongation on the x-axis, point C, then from this point draw a line parallel to the elastic portion of the stress-strain curve until the newly constructed line intersects the stress-strain curve. The point where the intersection takes place is denoted as point B and represents the yield strength of the material. Yield strength has major practical significance as it shows the resistance of the material to permanent deformation and indicates the ease with which the material can be formed by rolling and drawing operations[4]. Plastic deformation begins when the elastic limit is exceeded. As the plastic deformation of the specimen increases, the metal becomes stronger (due to strain hardening)[46]. Higher and higher load is required as the strain increases until the load reaches a maximum value, as given by point M[46]. The maximum load, or ultimate load, divided by the original cross-sectional area of the specimen is called the ultimate tensile strength[46]. Ultimate tensile strength is a practical measure of the overall strength of a material[1]. For a ductile metal such as aluminium the diameter of the specimen begins to decrease rapidly beyond the maximum load, so that the load required to continue deformation drops off until the specimen fractures at point F[46]. As the load drops off after the ultimate tensile strength is reached then the stress required to fracture the material is less than the ultimate tensile stress. The final stress level at the point of fracture of the material is known as the breaking stress, or fracture stress[1]. The strain at the point of fracture is a measure of the ductility of the material. It gives an indication of the amount of strain the material can withstand before failure[1]. A common quantity used to define ductility in a tensile test is percentage elongation. It will be shown that this useful property is measured by considering the gauge length of the test specimen before and after testing.

Each of the mechanical properties shown on the stress-strain curve can be determined using some simple equations. Firstly, the yield strength of the alloy is determined using Eqn. 4.2[46]. It is the load corresponding to a small specified plastic strain divided by the original cross-sectional area of the specimen.

$$YS = P_e / A_0 \qquad \text{(Eqn. 4.2)}$$

where, YS = Yield strength (kg/ mm^2)

P_e = Load obtained at a plastic strain of 0.01 or 0.2 % (kg), and

A_0 = Original cross-sectional area (mm^2)

The ultimate tensile strength of the alloy is the maximum load obtained in a tensile test divided by the original cross-sectional area of the specimen, Eqn. 4.3[46].

$$UTS = P_{max} / A_0 \qquad \text{(Eqn. 4.3)}$$

where, UTS = Ultimate tensile strength (kg/mm^2)

P_{max} = Maximum load obtained in a tensile test (kg), and

A_0 = Original cross-sectional area (mm^2)

The percentage elongation of the alloy is the ratio of the increase in length of the gauge section of the specimen to its original length, expressed in percent, Eqn. 4.4[46].

$$\varepsilon = [(L - L_0)/ L_0] \times 100 \qquad \text{(Eqn. 4.4)}$$

where, ε = Percentage elongation (%)

L = Gauge length at fracture (mm), and

L_0 = Original gauge length (mm)

Hence, the properties of yield strength, ultimate tensile strength and percentage elongation can be determined using this tensile testing technique in which the tensile samples taken from the alloy wheels are placed under tension and examined. This particular test and the hardness test detailed previously will allow four major properties of the alloy to be determined and as a result the optimised heat treatment process can be evaluated. However, determination of these four properties, although necessary, is not sufficient for fully analysing and evaluating the trialed treatment. The hardness and tensile tests used are useful for analysing the static characteristics of the alloy but they are not useful for predicting the behaviour of the alloy when subject to rapidly changing stresses or sudden stresses and shock. During the hardness and tensile tests the loads were applied slowly so that the test piece was in equilibrium with the load at all times. Furthermore, the static tensile test does not always indicate the susceptibility of the alloy to sudden brittle fracture[46]. This important factor is determined by the impact test.

Impact Test

To evaluate the behaviour of the alloy subject to a sudden intense shock the 'Modified Staircase Method' impact test was used. This particular test is used frequently at SAPL during development of new wheels or assessment of modified processes on existing wheels. It is based on well established ASTM (American Society for Testing and Materials) methods and the results yield quantitative information suitable for statistical comparison. The modified staircase method is a sequential test used to determine mean impact height at the weakest impact angle of the wheel. The weakest impact angle is determined during wheel development and is the angle relative to the valve hole at which the percentage of failures is highest. The result of a test determines whether the height for the next sample is increased, due to a pass, or decreased, due to a fail. An impact pass is a wheel which has acceptable characteristics following an impact test. The definition of a pass is defined in the customer specifications for the impact test. The pass criteria used for comparison of the heat treatment methods in this instance was visual cracking. This involved thoroughly examining each wheel after impact to check for physical cracking of the wheel. A cracked wheel was a fail wheel whilst a wheel with no visible cracks was a pass wheel. This was the pass-fail criteria used in this instance.

A minimum of thirty fully machined, dimensionally correct, paint cured, but not painted wheels were required for each 'Modified Staircase Method' test. Figure 4.8 shows in detail the machine that was used for impact testing. From this the placement of the test specimen and the basic operating principles of the machine are evident. There are four parameters on the impact testing machine that can be varied to suit the particular wheel type being tested. These are; i) impact weight, ii) impact height, iii) impact angle, and iv) angle to valve hole. The impact weight and impact angle are specified by the customer of the wheel being tested whilst it has been stated earlier that the angle to valve hole, or weakest impact angle, is determined during the developmental stages of the wheel. The impact height is usually specified by the customer and is a specific height above the wheel that the impact weight must be dropped from. A batch of wheels are usually subject to this procedure and then examined on a pass-fail basis. However, the 'Modified Staircase Method' was used in this instance to determine the mean impact height above the wheel from which the impact weight could be dropped without causing the wheel to fail. Through obtaining this information not only could the optimised treatment samples be analysed against the relevant customer specifications but also these samples could be compared with those from the standard T6 treatment. A standard procedure was adhered to during impact testing in order to minimise any variation between testing of the individual samples. The standard procedure outlined the sequence of steps that must be followed during testing. An explanation of this test is aided by the use of the illustration shown in Figure 4.9. A brief description of the apparatus is also useful. Firstly, the impact weight shown in the diagram provides an impact force when released from a height above the wheel and can be varied easily to suit various testing conditions. Impact force is proportional to both the impact weight and the impact height. The mounting plate featured in the diagram is adjustable to suit all wheels types and particular impact angles.

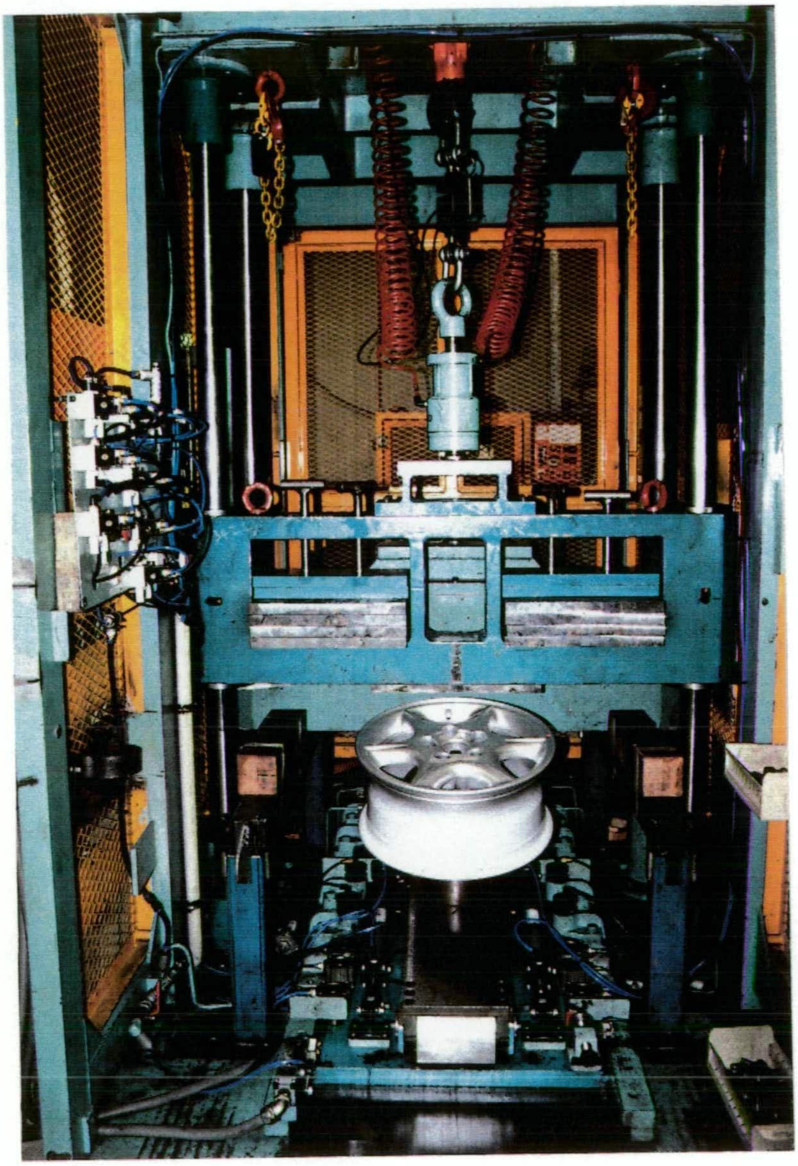


Figure 4.8: Impact Test Machine

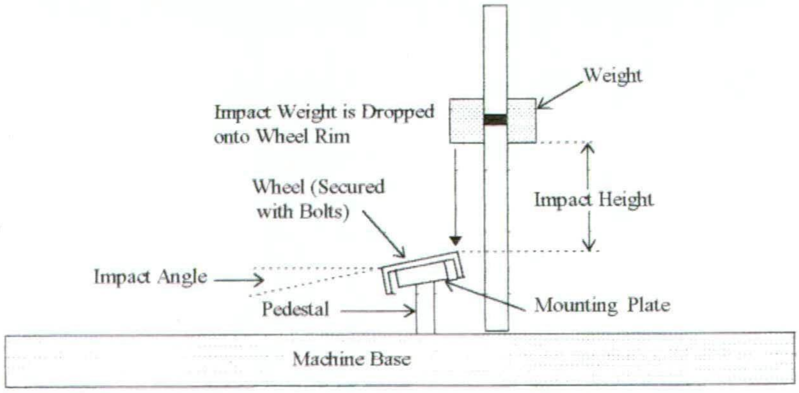


Figure 4.9: Basic Schematic of Impact Test Machine

It can be seen from Figure 4.9 that the impact angle is measured from the horizontal and is the particular angle that the wheel is placed on for impact testing. The impact angle is specified by the customer of the particular wheel type being tested and is usually either 13 or 90°. These two impact angles are common in the wheel manufacturing industry for impact testing.

The first step in the testing process is to determine the impact weight, impact angle and angle to valve hole that are to be used for the test from the customer testing specifications. The next step is to fit the test sample (wheel) to the mounting plate. The pedestal and mounting plate are then locked in position such that the edge of the weight is in direct vertical line with the top flange of the wheel. The top flange of the wheel is shown in Figure 4.2. The weight is then lowered until the edge of the weight just contacts the edge of the wheel rim. The weight height scale is then set to zero. The weight is then raised to the required height ready to be dropped using the quick release switch. The first test is carried out at the customer specified impact height and checked for a pass or fail. If previous tests are available then the previous height of the first failure is used. If the wheel passes then the impact height is increased by a predetermined amount, usually in 10mm increments. This continues until the first failure occurs. After a failure occurs the impact height is decreased by the same predetermined increment as used initially. The impact height continues to be increased or decreased dependant on the pass or fail of a wheel until all thirty wheels have been tested. The impact weight, impact angle and angle to valve hole, once initially set, remain the same for the testing duration of each sample batch. The result of each test is recorded on a worksheet during testing by marking 'O' for a pass wheel and 'X' for a fail wheel in columns next to a height scale. It is useful to show a sample section of a worksheet here, Figure 4.10, and give an example of the result recording process. If the first wheel is tested at an impact height of 330mm and it passes then 'O' is marked in a box corresponding to the 'wheel 1' column and the '330mm' row. If the increment height is chosen to be 10mm then the next test is

Impact Height	Wheel Number			
	1	2	3	4
350			X	
340		O		
330	O			

Figure 4.10: Worksheet Sample

completed at a height of 340mm. If the second wheel passes also then 'O' is marked in a box corresponding to the 'wheel 2' column and the '340mm' row. The third wheel is then tested at an impact height of 350mm. If the wheel fails at this height then an 'X' is marked in the 'wheel 3, 350mm' box and the impact height is reduced back to 340mm. This result recording process continues until all wheels have been tested.

On completion of the testing process the recorded data is analysed. The sample average is determined by using only the failures or only the passes, depending on which has the smaller total. The wheels tested up to the first opposites, ie. pass then fail, are discarded. The mean impact height is then calculated using Eqn. 4.5.

$$\text{Mean Impact Height} = So + d\,([A/N] \pm 0.5) \qquad \text{(Eqn. 4.5)}$$

where, +0.5 is used if passes are less frequent

-0.5 is used if failures are less frequent

ni = number of failures

So = height at first failure (mm)

i = height index, starting at 0 at the first failure and incrementing by 1 for each height increment there after

d = height increment (mm)

$A = \Sigma\, i(ni)$

$B = \Sigma\, i^2 ni$, and

$N = \Sigma\, ni$

Furthermore, the standard deviation (SD) of the test batch can be calculated using Eqn. 4.6.

$$SD = 1.62(d)([NB - A^2] / N^2] + 0.029) \qquad \text{(Eqn. 4.6)}$$

This particular test is of significance as it provides valuable information on the impact resistance of the alloy. By comparing the results obtained from both the optimised and the standard T6 heat treatment processes some conclusions can be drawn as to the effect that heat treatment has on the development of impact strength in aluminium alloy 601, ie. the results obtained from the optimised treatment will show a mean impact height that is either lower, equal to, or higher than that obtained with the standard T6 treatment. The results from the optimised treatment will also show whether or not the mean impact height is greater or less than the minimum impact height that the wheels must pass, as specified by the customer.

4.2: CONCLUDING REMARKS

The three tests discussed; i) hardness test, ii) tensile test, and iii) impact test, are necessary for determining the five mentioned mechanical properties of the alloy, ie. hardness, yield strength, ultimate tensile strength, elongation and impact resistance. These five properties give a good indication of the strength and toughness of the alloy and will thus be sufficient for evaluating the optimised heat treatment process. The evaluation will be used to determine whether or not an optimised solution treatment process can be used as an alternative to the existing system without affecting the quality of the final product. A comparison in quality of the final product produced using both the optimised and the standard T6 treatments will be achieved by comparing the mechanical properties developed using either process. The next stage of the project now is to produce the required samples for mechanical testing and subject the produced samples to the three mechanical tests mentioned. The following chapter outlines this particular process and gives detail of the developed mechanical properties in the alloy as a result of using both the optimised and the standard T6 treatments.

CHAPTER FIVE

EXPERIMENTAL RESULTS AND DISCUSSION

This chapter highlights the results that were obtained by subjecting aluminium alloy 601 to an optimised heat treatment process followed by a series of experimental tests used to determine and compare specific mechanical properties of the alloy to those developed using the standard T6 heat treatment process. The criteria used for evaluation of the developed mechanical properties in the alloy after exposure to the optimised heat treatment process were; i) the properties of the alloy wheel had to meet with or exceed the relevant customer specifications for the wheel type tested, and ii) the properties had to be comparable with the mechanical properties developed in the alloy using the existing standard T6 heat treatment process. The first criteria listed is important as all wheels produced at SAPL must have, as a minimum, the mechanical properties specified by the automotive manufacturer, such as Nissan, Mazda and Ford. The second criteria listed is also important as it is necessary that the optimised heat treatment process does not affect the physical properties and quality of the final product. Hence, evaluation of an optimised heat treatment process will involve a comparison of the developed mechanical properties with the relevant customer specifications and secondly, a comparison of the developed mechanical properties with those produced using the standard T6 heat treatment process.

In order to thoroughly investigate the influence that varying heat treatment has on the development of mechanical properties in aluminium alloy 601, it was necessary to carry out a five stage investigation. Each of the five stages were completed using varying solution treatment times and temperatures in order to determine the particular solution treatment time and temperature that could be used to achieve the best mechanical properties and economical advantages. It is now useful to provide some detail on each of the individual stages used for testing and highlight their significance. Furthermore, a rationale for each of the stages used is described to show why a five stage investigation was required. Prior to this however, it is important to note that solution treatment is the only aspect of the heat treatment process that has been investigated in this instance. The age hardening treatment utilised for this particular investigation is the same as the age hardening treatment used for the standard T6 process at SAPL using a condition of four and a half hours at 140°C. It has been shown previously that the criteria used for optimising the solution treatment process was that the standard aging treatment still be used. Hence, the varying conditions used for the individual stages of the investigation were in relation to solution treatment time and temperature only.

5.1 DETAILS OF THE EXPERIMENTAL TESTING CONDITIONS AND RATIONALE FOR THEIR USE

The initial stage of the experimental investigation, or Stage One, was necessary to obtain a better understanding of the heat treatment process, and in particular, to investigate the role that heat treatment plays in the development of mechanical properties in aluminium alloy 601. The heat treatment conditions used in this particular stage of the investigation incorporate the conditions that have been determined through previous investigations[43] and some preliminary experimental work. It has been shown previously for the Mazda MX5 wheel type, used as the test specimen for Stage One, that solution treatment time is a combination of twelve minutes heating time and ten minutes isothermal holding time when a solution treatment temperature of 540°C is used, making a total of twenty two minutes. Hence, the solution treatment condition used in this instance involved exposure of the alloy to a temperature of 540°C for twenty two minutes. This stage of the investigation will prove valuable for matching and complimenting the results determined through research[43] which have suggested that the yield strength, ultimate tensile strength, and percentage elongation of the alloy will not be significantly affected by using this optimised treatment process. In addition, this stage of the investigation will prove valuable for determining the effect that an optimised solution treatment process has on the hardness and impact resistance of the alloy.

On completion of Stage One it was considered necessary to conduct a further four stages in order to complete a thorough investigation. The second stage, or Stage Two, incorporated a solution treatment condition of twenty two minutes at 570°C and was necessary to investigate the effect that an increase in solution treatment temperature has on the development of mechanical properties in the alloy when a solution treatment time of twenty two minutes is maintained. The results from this stage can be compared with the results obtained from Stage One in order to study this effect. This particular stage will prove valuable for determining the significance of solution treatment temperature in the heat treatment process. Conversely, the objective of the final three stages of the investigation, Stages Three to Five, incorporating solution treatment conditions of ten minutes at 595°C, fifteen minutes at 580°C and eighteen minutes at 570°C respectively, was to determine the effect that solution treatment time has on the development of mechanical properties in the alloy when a high solution treatment temperature was used. That is, the final three stages of the investigation set about determining whether or not a solution treatment time less than twenty two minutes would be sufficient if a solution treatment temperature greater than 540°C was used. The information gathered from each of the five stages listed will provide valuable information on the behaviour of aluminium alloy 601 when heat treated using a variety of conditions.

Before the results are documented and discussed it is necessary to briefly describe some further detail about the testing process used for each of the five stages. Firstly, to allow a comparison of the mechanical properties developed using the optimised heat treatment processes from each stage with the mechanical properties developed using the standard T6 process a batch of thirty wheels were collected from the existing heat treatment system each time a stage of the investigation was completed. It has been documented previously that only thirty wheels were required from the standard T6 treatment for use in hardness and impact tests as sufficient quantitative and qualitative data on tensile properties was readily available. Although previously completed, it is useful to reproduce the description of the division of wheels to the respective tests used. The division was essentially; i) twelve samples for hardness testing (whole wheels), ii) twelve samples for tensile testing (four samples cut and machined from three whole wheels), and iii) thirty wheels for impact testing. It has been mentioned previously that non-destructive hardness tests are to be completed on twelve of the test specimens prior to impact testing. Hence, thirty three wheels were required from the optimised heat treatment process for each of the five stages whilst only thirty wheels were required from the standard T6 heat treatment process. The specific wheel type collected from the standard T6 treatment for each stage of the investigation was the same as the wheel type being used for the corresponding optimised treatment. In addition, the batches of wheels collected from either process were essentially subjected to the same production processes, using the same production techniques, throughout the manufacturing cycle. This meant that the only variable between the two batches of wheels collected from either treatment was the degree of heat treatment that the wheels had sustained, or more specifically, the degree of solution treatment.

The process of selecting the particular solution treatment temperature and time for each stage following Stage One was governed by two dominating factors. Firstly, the maximum allowable solution treatment temperature that could be used with a particular solution treatment time was governed by the eutectic point of the alloy. For aluminium-silicon alloys with 8% silicon by weight the eutectic point is at approximately 850°K, or alternatively 577°C[9]. For aluminium alloy 601 in which more alloying elements are present than in the binary system of aluminium-silicon alone the eutectic point of the alloy is slightly decreased due to the presence of more alloying elements. It is common behaviour that the eutectic point of an alloy decreases as its number of alloying elements increase[9]. Hence, the eutectic point of aluminium alloy 601 having alloying elements of approximately 6.6%Si, 0.3%Mg, 0.12%Fe, 0.01%Ti and 0.005%Sr by weight will be slightly reduced from that of 577°C for an aluminium-silicon alloy. Eutectic is defined as being an isothermal reversible reaction in which a liquid solution is converted into two or more intimately mixed solids on cooling, the number of solids formed being the same as the number of components in the system[5]. The eutectic point of aluminium alloy 601 is critical in determining the maximum solution treatment temperature that can be used. If the eutectic point of the alloy is exceeded then the alloy begins to convert from a solid state to a solid and liquid combined state. Further increase in temperature causes the remaining solid state to convert also to a liquid state, leading to a total liquid solution. Hence, if aluminium alloy wheels are subject to temperatures greater than the eutectic point then the wheel begins to melt. Melting of the wheel is evident through visual inspection as small cavities appear in the surface of a wheel that has been subject to elevated temperatures above the eutectic. The small cavities that appear are termed as 'bleed-out' and refer to alloying elements that have literally bled out of the wheel during solution treatment due to the high temperatures used. Wheels with obvious bleed out are classed as rejects as they are either mechanically weakened or their visual appearance is less than acceptable by the customers specified standards. Hence, the selection of a temperature to use with a particular solution treatment time was simplified by selecting the maximum allowable temperature that could be used without causing bleed-out in the alloy wheels. Theory[37] suggests that the higher the temperature of the wheel immediately prior to quenching then the better is the development of mechanical properties in the alloy. It has been shown previously in Chapter One that a strength improving compound, magnesium silicide (Mg_2Si), forms as solid solution when present in aluminium alloy 601 during solution treatment and is maintained in a solid solution form through rapid quenching of the alloy. It has also been shown that the time lag between the alloy leaving the solution treatment oven and entering the quench tank is significant as the solid solution formed starts to diminish during this time. The higher the temperature of the alloy at the time of leaving the solution treatment oven then the better is the opportunity for retaining as much as possible of the solid solution formed during quenching. The higher the level of retained solid solution then consequently, the higher is the level of mechanical properties developed in the alloy. A higher temperature used for shorter solution treatment times also gives the magnesium and silicon particles a better opportunity to form molecules of Mg_2Si during solution treatment and consequently form a higher level of strength in the alloy. For a short solution treatment time where the maximum allowable temperature is used and the treatment is shown to be insufficient then it is most likely that the same solution time with a lower temperature will also be insufficient. Hence, it is better to firstly trial a particular solution treatment time using the highest possible solution treatment temperature. This was the rationale used for the selection of a solution treatment temperature in Stages Two to Five in which the maximum allowable solution temperature was used.

Solution treatment time for each stage was selected using a methodical process. For Stage One the rationale for using twenty two minutes has been given and furthermore, a rationale for the use of the same solution time for Stage Two has also been provided. For the remaining three stages it was decided to use a sequence of solution times from ten to eighteen minutes in order to investigate the effect that solution treatment time has on the development of mechanical properties in the alloy. Ten minutes was chosen as a minimum solution time as it was anticipated that any time less than ten minutes would be insufficient for the development of substantial mechanical properties in the alloy. Hence, Stage Three incorporated a solution treatment time of ten minutes. For Stage Four, solution time was increased to fifteen minutes and then further to eighteen minutes for Stage Five in order to provide a substantial range of solution times between ten and twenty two minutes. The objective of the final three stages was to investigate the change in mechanical properties of the alloy with increasing solution treatment time. Due to the nature of the solution times used it will give a better understanding of the influence that solution treatment time has on the mechanical properties of the alloy.

With a general overview given on the five stages used for the investigation it is now useful to provide a summary of the particular conditions used for each of the five mentioned stages of the investigation, Table 5.1. The solution treatment temperatures shown for each of the final four stages represent the maximum allowable temperatures that could be used for the particular solution treatment time given without causing 'bleed-out' in the wheel.

TABLE 5.1: Solution Treatment Conditions Used for Each Stage of the Investigation

	Solution Temperature (°C)	**Solution Time (mins)**
Stage One	540	22
Stage Two	570	22
Stage Three	595	10
Stage Four	580	15
Stage Five	570	18

The particular wheel type that was selected for each stage was based solely on the availability of the wheel type at the time of testing. Each stage was carried out as an independent study meaning that there was some time difference between the completion of each stage. As destructive mechanical testing was required on the batch of test wheels used for each stage and because the batch size needed to be quite large then the selection of the wheel type to be used for testing is critical. As SAPL operate under rigid guidelines to meet production targets and satisfy customer orders then there are strict limitations on the availability of a wheel type that can be used for testing. For this reason different wheel types were used for different stages of the investigation. However, the difference in wheel type between stages is insignificant as a common material, aluminium alloy 601, was used and it is a particular temperature profile for the alloy that is important rather than the particular wheel type used. That is, the form of the alloy is not of significance as the solution treatment condition can be altered to accommodate the variety of forms used. A range of temperature profiles for the alloy have been obtained as a result of the five stages completed thus enabling an investigation into the effect of varying solution temperature and time on the development of mechanical properties in the alloy.

It has been shown previously that the characteristics of a wheel type, such as mass and initial temperature prior to solution treatment, have a significant influence on the setting of the solution treatment conditions to be used. Hence, it is useful to detail the characteristics of each of the different wheel types used for the five stages, Table 5.2. It is important to note at this point that the temperature measuring technique used for the preliminary investigation detailed in Chapter Three involving the determination of the initial temperature of the MX5 wheel type immediately prior to solution treatment was again utilised for this particular investigation in order to determine the initial temperature of both the J15 and the XR wheel types, used in Stages Two to Five, immediately prior to solution treatment. Just to re-establish the detail of the process used, it involved inserting k-type thermocouples into various sections of each of the wheel types used, subjecting each wheel type to the required solution treatment process and sequentially recording the temperature changes using an AM-7002 data logger. As with the preliminary investigation, five k-type thermocouples were inserted into each wheel type in order to investigate further the relationship between cross-sectional area and heat-up rate and determine its significance.

TABLE 5.2: Characteristics of the Different Wheel Types Used

Stage One

Wheel Type: MX5

Weight (kg): 8.57

Initial Temperature (°C): 390

Stage Two

Wheel Type: J15

Weight (kg): 10.98

Initial Temperature (°C): 435

Stages Three, Four and Five

Wheel Type: XR

Weight (kg): 13.65

Initial Temperature (°C): 423

In order to adequately examine the degree of solution treatment that the alloy had been subjected to in each of the five stages it was necessary to obtain a temperature profile of each wheel type during solution treatment. Again, the temperature measuring technique used for the previously detailed preliminary experimental investigation in Chapter Three was adopted. The described simulation of the solution treatment process was possible for each stage as the initial temperature of each wheel type immediately prior to solution treatment has been established.

Thermocouple placement in the Mazda MX5 wheel type for Stage One was the same as the set-up used in the previously documented preliminary experimental investigation and is shown in Figure 3.6. The temperature profile determined for the MX5 wheel type using the solution treatment condition of twenty two minutes at 540°C is shown in Figure 5.1 from which it can be seen that the alloy has approximately a twelve minute heat-up period followed immediately by a ten minute period where it is held constant at the maximum solution treatment temperature of 540°C. The temperature profile shows that the alloy sustained a solution treatment condition that incorporated the minimum required isothermal holding time of ten minutes using a maximum solution temperature of 540°C, as determined by previous research[43]. A key feature of the temperature profile is that the cross-sectional area to heat-up rate relationship in this instance is the same as that determined previously where it was shown that the thinner sections of the wheel heated comparatively faster than the thicker sections. However, it is shown that a uniform temperature of approximately 540°C is achieved throughout the wheel structure at the completion of the twelve minute heating period.

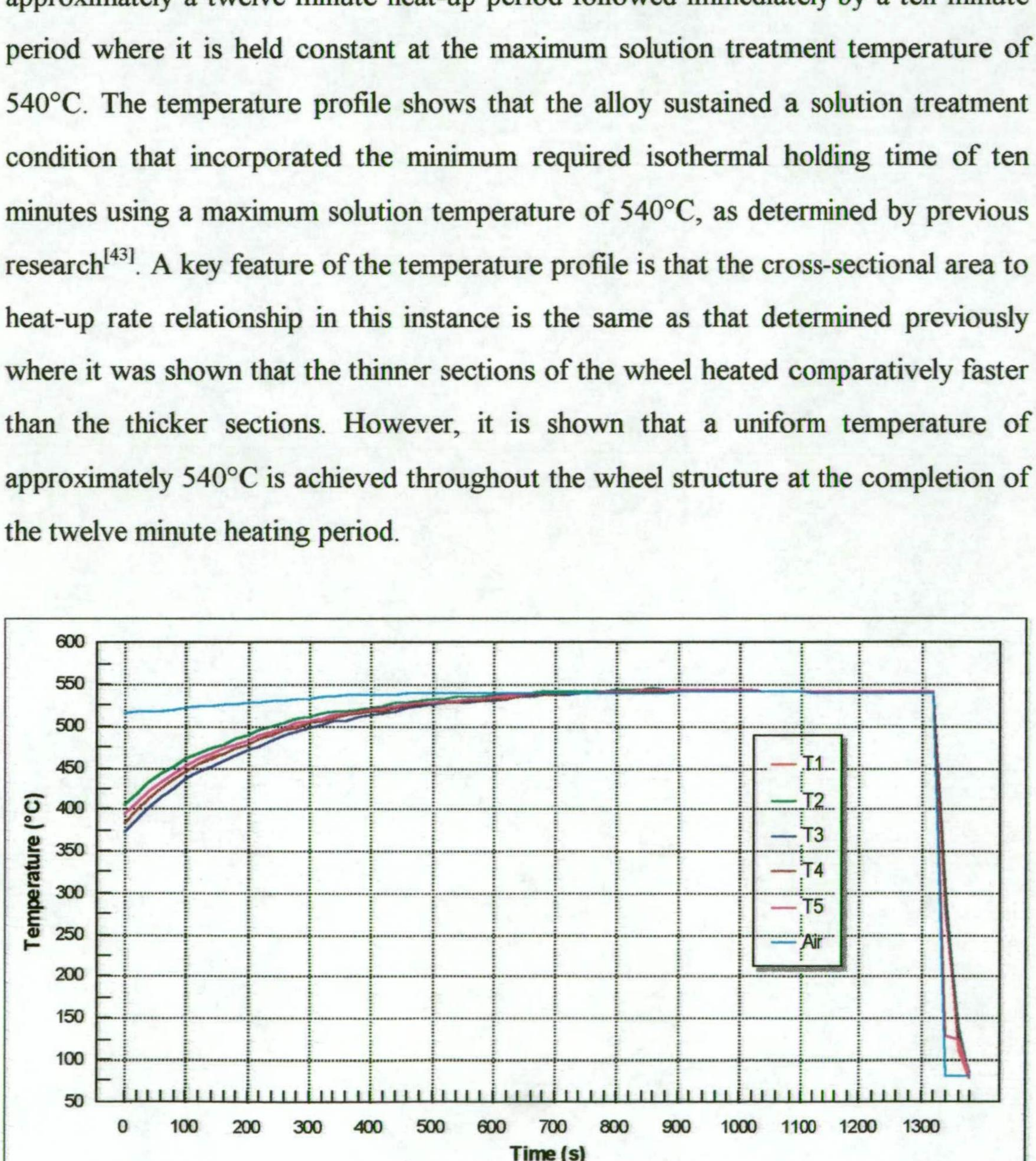
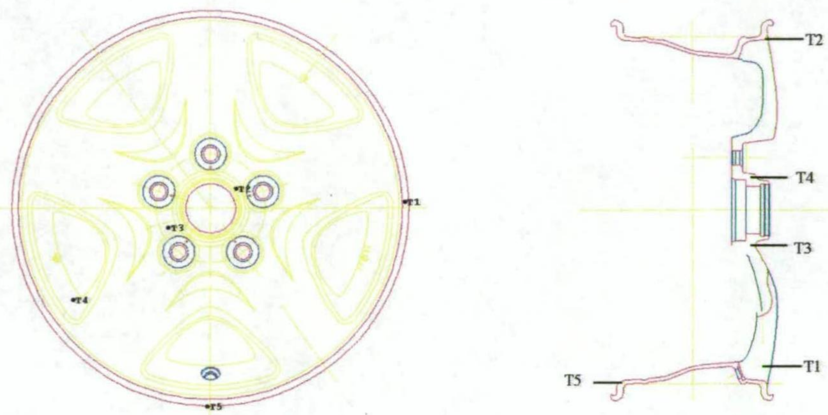


Figure 5.1: Aluminium Alloy 601 Temperature Profile During Solution Treatment (Stage One)

For Stage Two, it has been shown that the J15 wheel type was used as the test specimen and that the solution treatment condition used was twenty two minutes at 570°C. Thermocouple placement in the J15 wheel type for this stage is shown in Figure 5.2.



Front Face View Cross-Sectional View

Figure 5.2: Thermocouple Placement in the J15 Wheel Type

The temperature profile determined for the J15 wheel type during this particular solution treatment process is shown in Figure 5.3. It should be noted that the alloy was subjected to a significantly higher temperature treatment than for the previous stage. It can be seen that the alloy did not maintain a constant temperature throughout the solution treatment cycle but did achieve a maximum temperature of approximately 565°C after twenty two minutes of solution treatment. This is significantly higher than the maximum solution temperature of 540°C that was achieved in Stage One. Furthermore, it can be seen that the alloy sustained temperatures above 540°C for a period of at least twelve minutes. The heat-up rate to cross-sectional area relationship continued to follow the trend previously exhibited in the preliminary investigation and in Stage One by showing a faster heat-up rate in thinner sections of the wheel compared to the thicker sections. This can be seen from a comparison of thermocouples two (T2) and five (T5). T5, placed in a thin section of the wheel, showed a much steeper heat-up curve than T2 which was placed in a comparatively thick section of the wheel, as shown in Figure 5.2. Again, a uniform temperature was achieved throughout the wheel structure after approximately twelve minutes. The fact that the alloy achieved a maximum temperature of 565°C during solution treatment and also that bleed-out was evident in the samples subjected to temperatures higher than this suggests that the eutectic point of aluminium alloy 601 is possibly in the range of 565 to 570°C. This will be examined during further stages of the investigation.

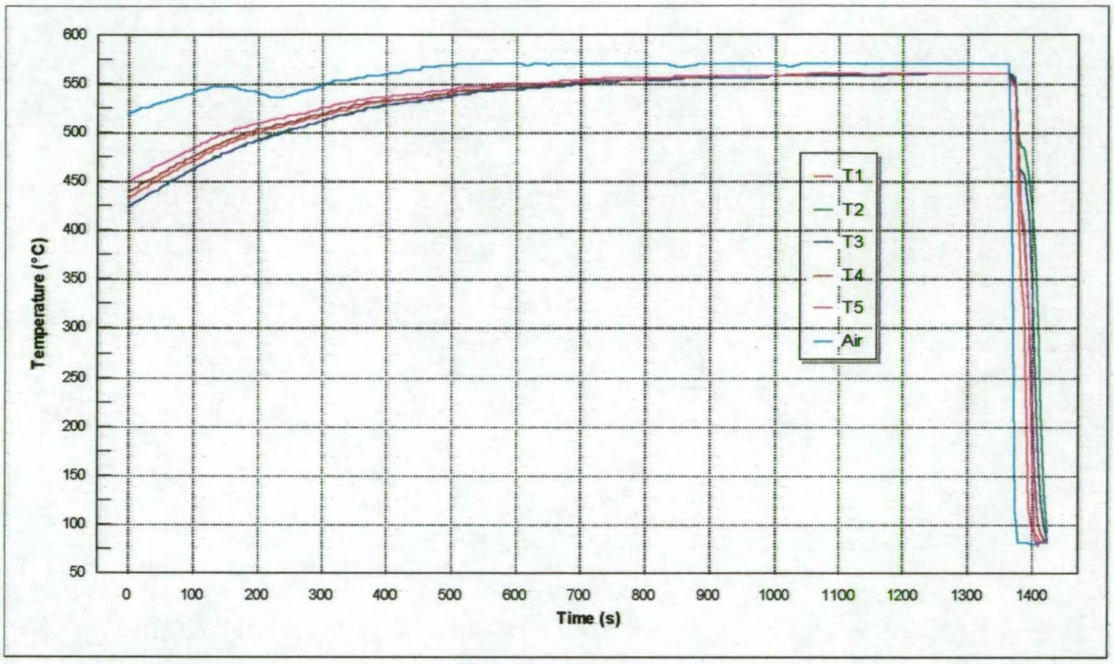


Figure 5.3: Aluminium Alloy 601 Temperature Profile During Solution Treatment (Stage Two)

For the third stage of the investigation, or Stage Three, it has been shown that the XR wheel type was used as the test specimen and also that the solution treatment condition used was ten minutes at 595°C. Thermocouple placement in the XR wheel type followed the technique used in the previous two stages and is shown in Figure 5.4.

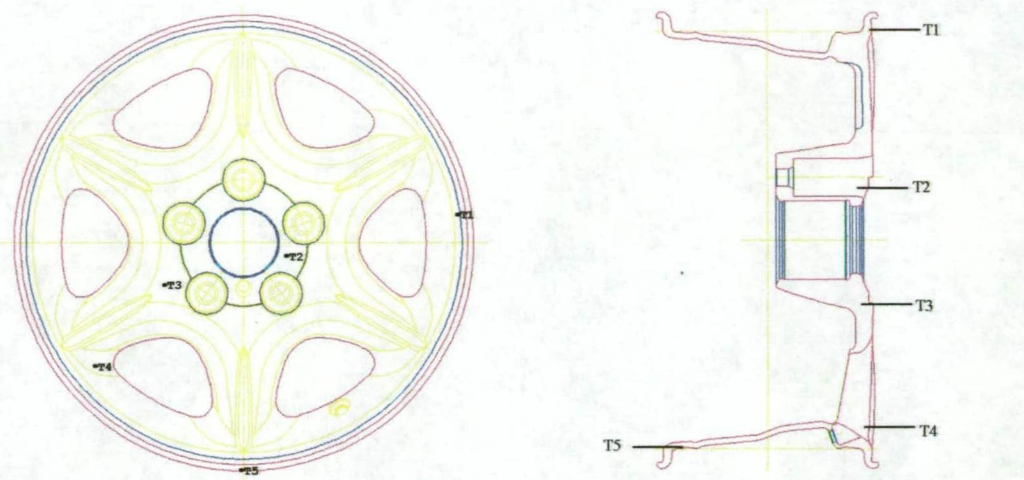


Figure 5.4: Thermocouple Placement in the XR Wheel Type

The temperature profile that was obtained for the XR wheel type for this particular optimised solution treatment process is shown in Figure 5.5, from which it can be seen can be seen that the alloy has a steady heat-up curve during the ten minute solution treatment time period and does not reach a constant temperature during that period. It is evident that the maximum temperature that the alloy achieves during solution treatment is approximately 565°C, which is the same as the maximum temperature achieved by the alloy in Stage Two. This reinforces the statement made earlier suggesting that the eutectic point of aluminium alloy 601 is in the range of 565 to 570°C as the alloy exhibited 'bleed-out' when subjected to temperatures above this. The difference in the degree of solution treatment between this stage and the previous stage is evident from this temperature profile which shows that the alloy was subjected to temperatures above 540°C for only a very short period of time. An average temperature of 540°C or greater was maintained in the wheel for a maximum of three minutes only. The heat-up rate is again shown to be affected by cross-sectional area. The previously witnessed relationship between heat-up rate and cross-sectional area, or mass, is shown to continue with the thinner sections of the wheel having a more rapid heat-up curve than the thicker sections. In this instance, the final temperature achieved by the alloy varied for different sections of the wheel although a trend of convergence of the entire wheel structure to a common wheel temperature is noted over the zero to ten minute heating period.

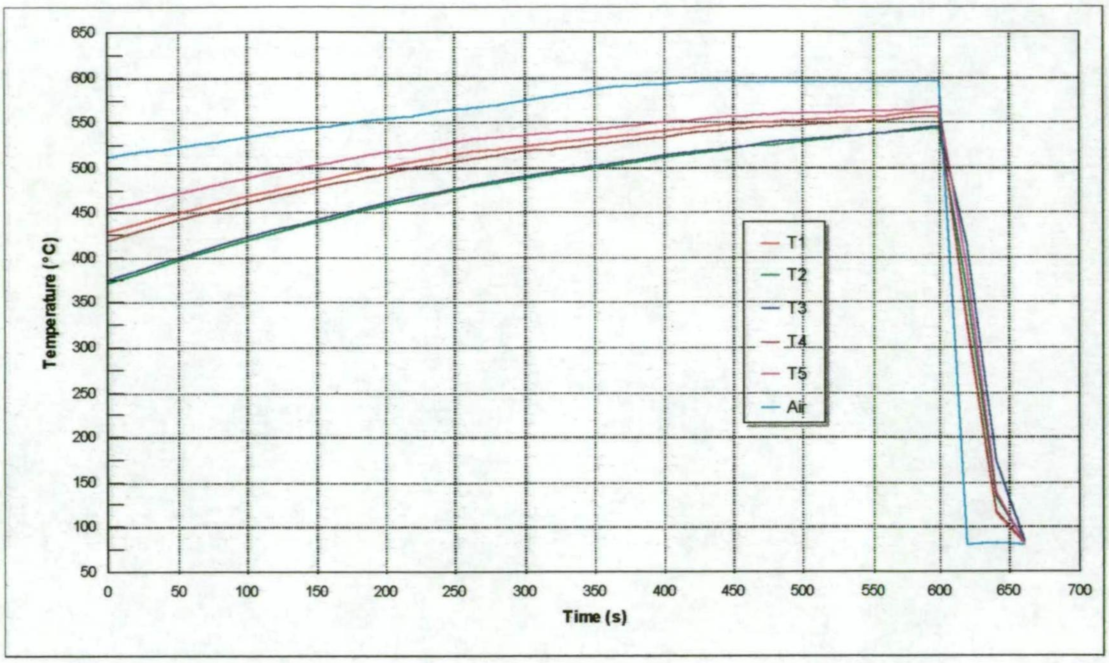


Figure 5.5: Aluminium Alloy 601 Temperature Profile During Solution Treatment (Stage Three)

The XR wheel type used in Stage Three was also used as the test specimen for Stage Four in which the solution treatment condition has been shown to be fifteen minutes at 580°C. Thermocouple placement in the wheel type remained the same as that shown in Figure 5.4. The temperature profile obtained for this particular solution treatment process is shown in Figure 5.6 from which it can be seen that the alloy increased in temperature during the fifteen minute solution period and did not maintain a constant temperature during that period. It can be seen that the maximum temperature the alloy was exposed to was approximately 565°C. Furthermore, the wheel was exposed to an average of 540°C or greater for a period of at least six minutes. It can be seen that this particular solution treatment process is more extreme than the conditions used in Stage Three but not as extreme as those used in Stage Two. Again, the eutectic point of the alloy is shown to be close to approximately 565°C. The previously witnessed trend of cross-sectional area and heat-up rate relationship was again exhibited in this temperature profile and again the entire wheel structure exhibited a strong trend of convergence to a uniform temperature over the fifteen minute heating period.

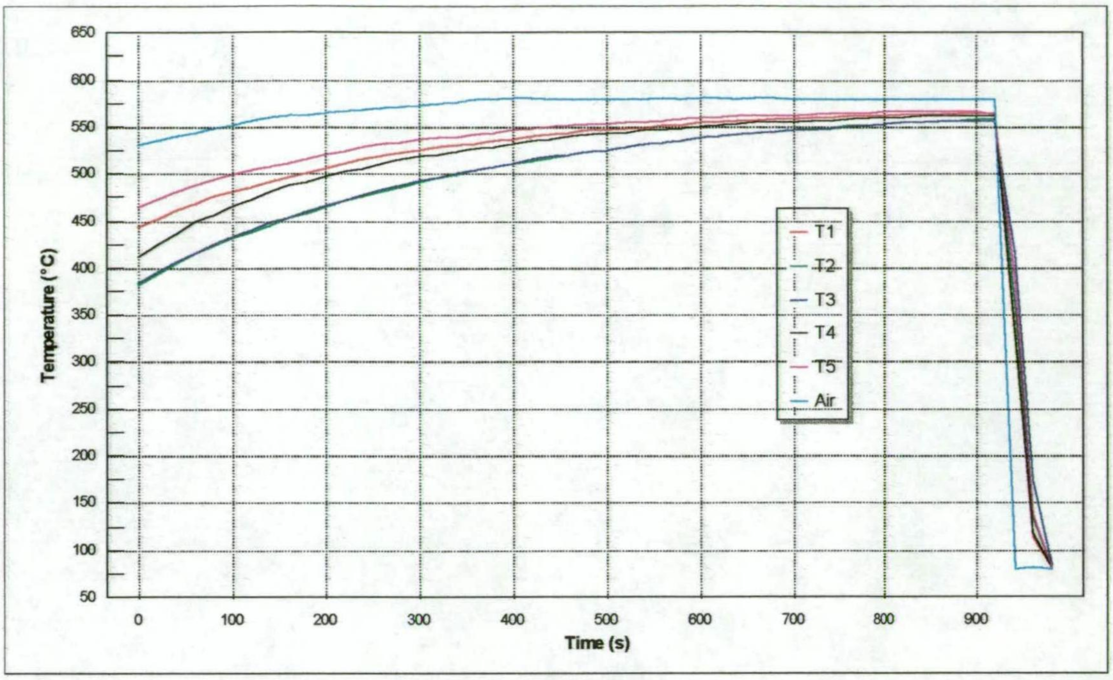


Figure 5.6: Aluminium Alloy 601 Temperature Profile During Solution Treatment (Stage Four)

Finally, for Stage Five, the XR wheel type was again used as the test specimen and it has been shown that the specific solution treatment condition used was eighteen minutes at 570°C. Again, thermocouple placement in the XR wheel type remained the same as that shown in Figure 5.4. The temperature profile determined for the alloy during this particular solution treatment process is shown in Figure 5.7 from which it can be seen that the alloy had a steady heating curve during the eighteen minute solution period and did not maintain a constant temperature during that period. It can be seen that the maximum temperature that the alloy was exposed to was again approximately 565°C which appears to be close to the eutectic point of the alloy. A closer inspection of the temperature profile also shows that the alloy was exposed to a temperature of 540°C or greater for a period of at least seven minutes. A trend of convergence of the entire wheel structure to a uniform temperature was again exhibited.

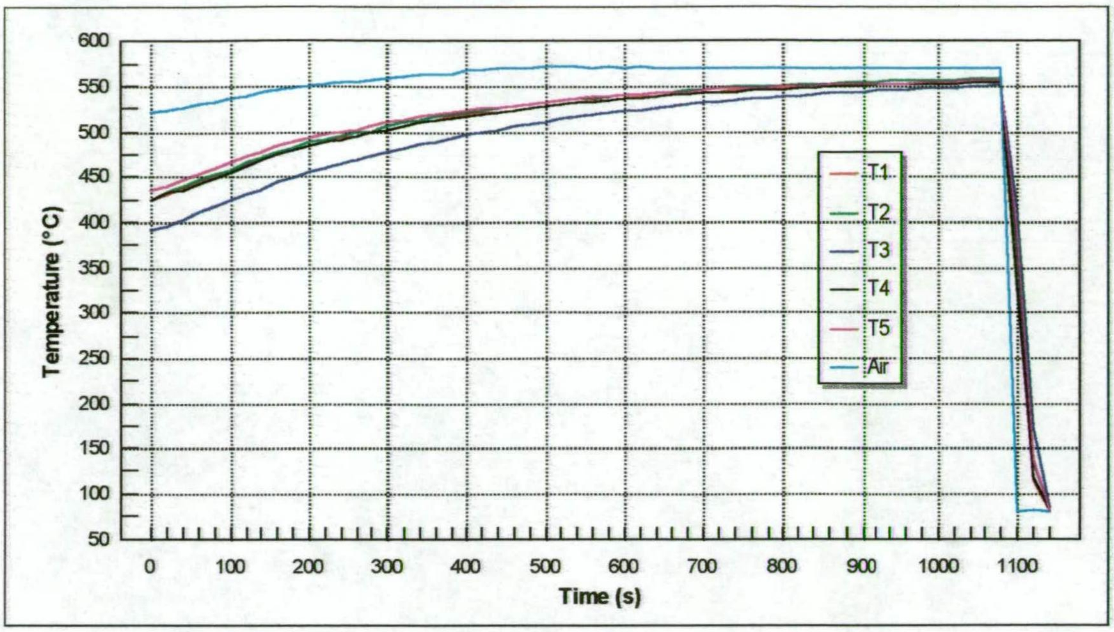


Figure 5.7: Aluminium Alloy 601 Temperature Profile During Solution Treatment (Stage Five)

The temperature profiles documented here for the alloy during each of the five different solution treatment conditions used are necessary and valuable for analysing the particular solution treatment process that the alloy was subjected to in either instance. The temperature profiles obtained will be useful later for comparing the mechanical properties developed in the alloy for each of the five stages.

With the details of the particular test specimens and conditions used for each of the five different stages of the investigation given it is now interesting to document and discuss the results obtained for each of the stages. It is important to note that a statistical analysis of the results was completed for each of the five stages of the investigation in order to thoroughly evaluate the solution treatment process being tested. A statistical analysis of the properties of hardness, yield strength, ultimate tensile strength and percentage elongation was possible as definite values for these properties were obtained for each of the individual samples tested. However, a statistical analysis was not possible for the impact test results as the particular test used does not allow definite values to be obtained for each sample tested, but rather an overall mean impact height for the test group. The statistical analysis is best documented after the experimental results.

5.2 EXPERIMENTAL RESULTS

It should be noted that particular values of hardness, yield strength, ultimate tensile strength and percentage elongation for each of the twelve samples used for each stage of the investigation are attached in Appendix C in tabulated form in Tables C.1 to C.5 for Stages One to Five respectively. The results from impact testing for each stage are also attached in Appendix C in Tables C.6 to C.15 for Stages One to Five respectively for both the standard treatment and the optimised treatment used in each stage.

Stage One: Firstly, consider a comparison of the hardness achieved in the alloy using either of the two mentioned heat treatment methods, Figure 5.8. It can be seen from this comparison that the level of hardness achieved using the standard heat treatment process is slightly higher than that achieved using the optimised heat treatment process. This will be confirmed later in the chapter in a statistical analysis of the results. The mean Brinell hardness number for the twelve samples taken from the standard T6 treatment was calculated to be 71.5 compared to only 67.4 for the optimised treatment. Furthermore, the materiel hardness was found to be constant for all the samples tested, confirming the homogeneity of the alloy. This is statistically confirmed as the correlation coefficient for each batch of samples was found to be statistically not significant.

The tensile properties of the alloy obtained using the optimised heat treatment process in this instance were also found to be lower than those obtained using the standard process, Figure 5.9. This will be confirmed later in a statistical analysis of the results. The mean yield strength and ultimate tensile strength obtained using the optimised heat treatment process were determined to be 141.2 and 239.6MPa respectively compared to the higher values of 184.5 and 266.5MPa respectively for the standard process. In addition, the yield strength and ultimate tensile strength of the material in either instance has been shown to be constant. The correlation coefficients for each batch of samples were found to statistically not significant, again confirming the homogeneity of the material.

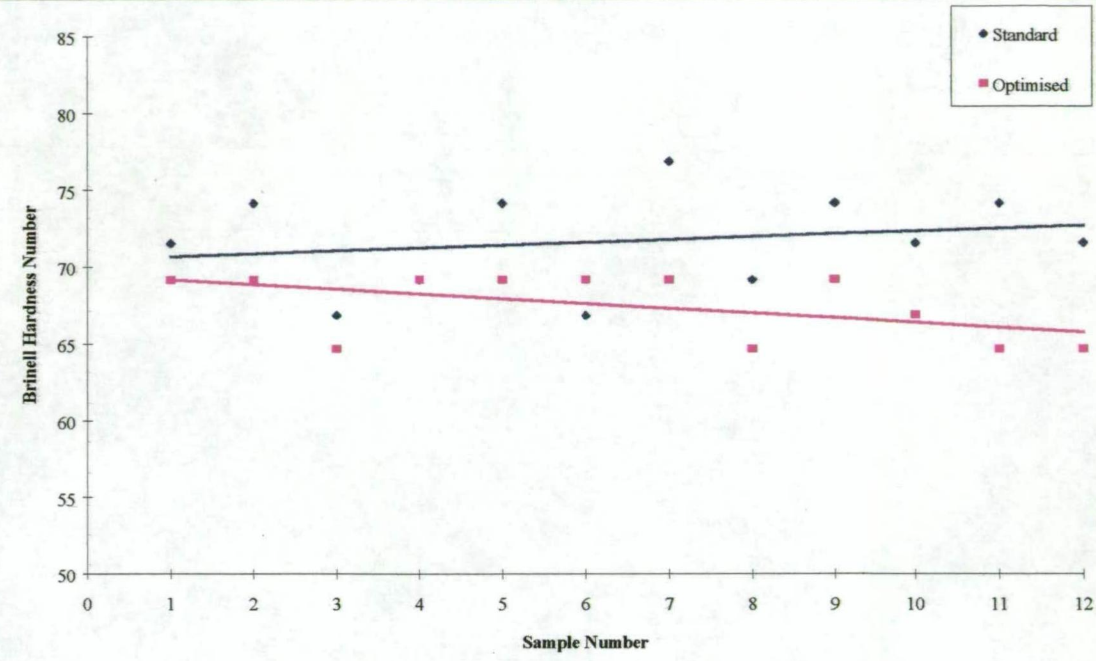


Figure 5.8: Brinell Hardness Number (Stage One)

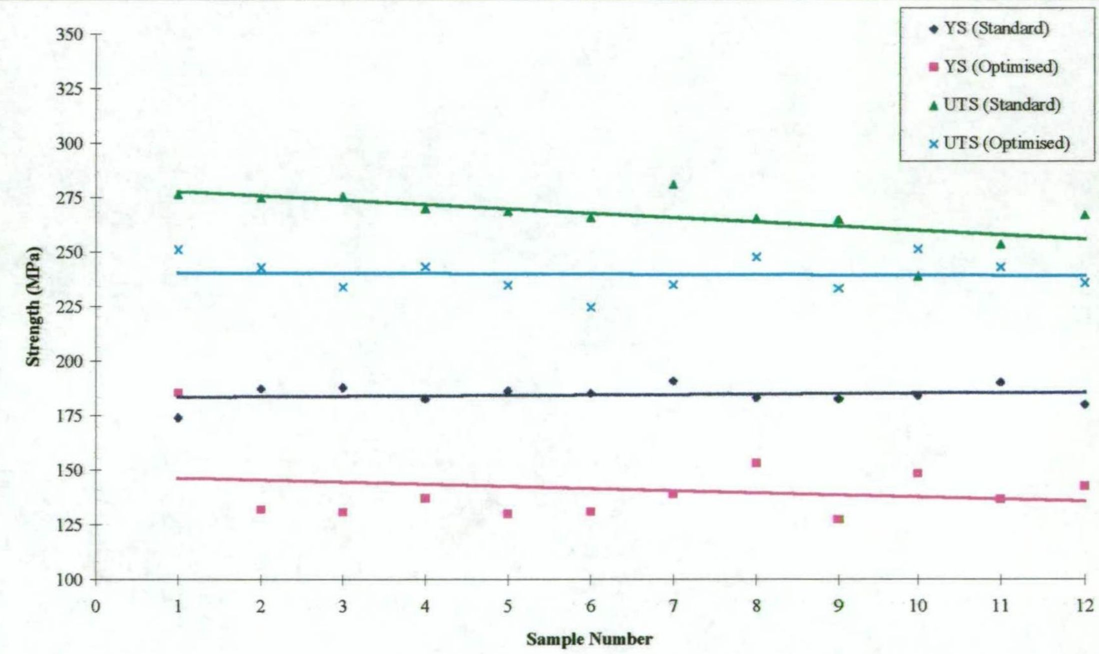


Figure 5.9: Tensile Strength (Stage One)

Elongation of the alloy obtained using either heat treatment method is shown in Figure 5.10. The mean elongation for the optimised heat treatment process has been calculated to be 10.2% which is similar to the mean elongation of 9.6% calculated for the standard treatment. A statistical analysis documented shortly will show the difference in means to be statistically not significant. The elongation of the material was found to be constant for all samples tested, again confirming the homogeneity of the alloy. The correlation coefficients for each batch of samples was found to be statistically not significant.

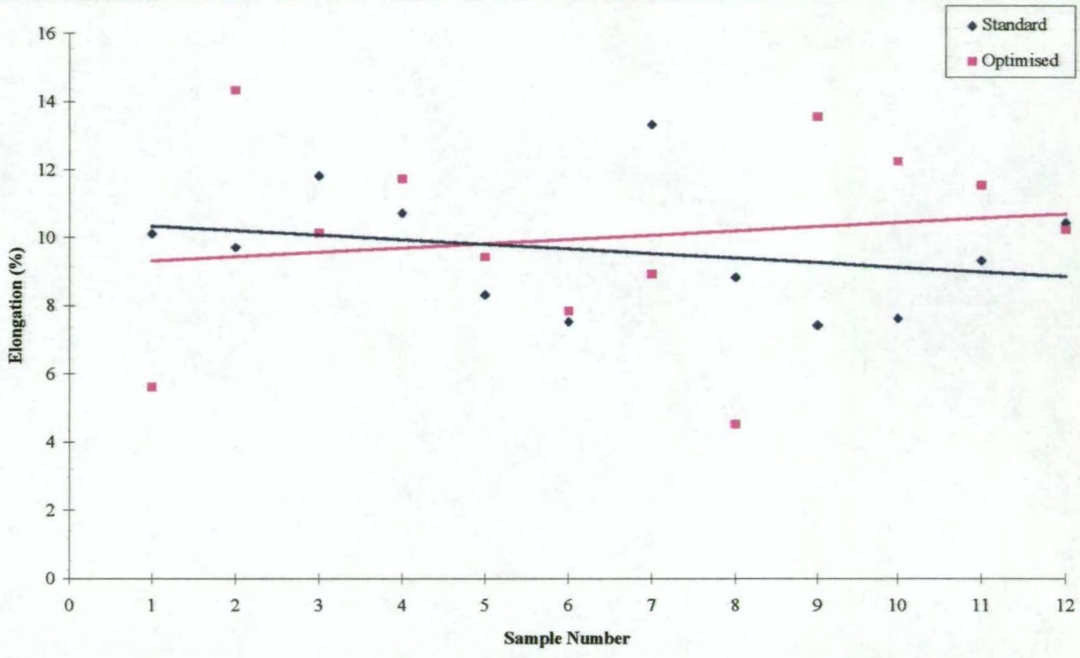


Figure 5.10: Percentage Elongation (Stage One)

The impact resistance of the alloy has been found to be significantly lower in specimens from the optimised treatment compared to those from the standard treatment. It has been found that the mean impact height for the samples is 275mm for the standard treatment whilst only 221mm for the optimised treatment using an impact weight of 465kg.

<u>Stage Two</u>: A comparison of hardness developed in the alloy using the optimised and the standard T6 heat treatment processes in Stage Two is shown in Figure 5.11. It can be seen that the level of hardness achieved is similar between either of the two processes. It will be shown later that a statistical analysis of the hardness results has shown that the difference in means is statistically not significant. The mean Brinell hardness number of the twelve samples taken from the standard process was calculated to be 71.3 compared to 70.1 for the optimised process. The hardness of the material was again found to be constant in each of the samples from either treatment

as the correlation coefficients for the two groups of samples were found to be statistically not significant.

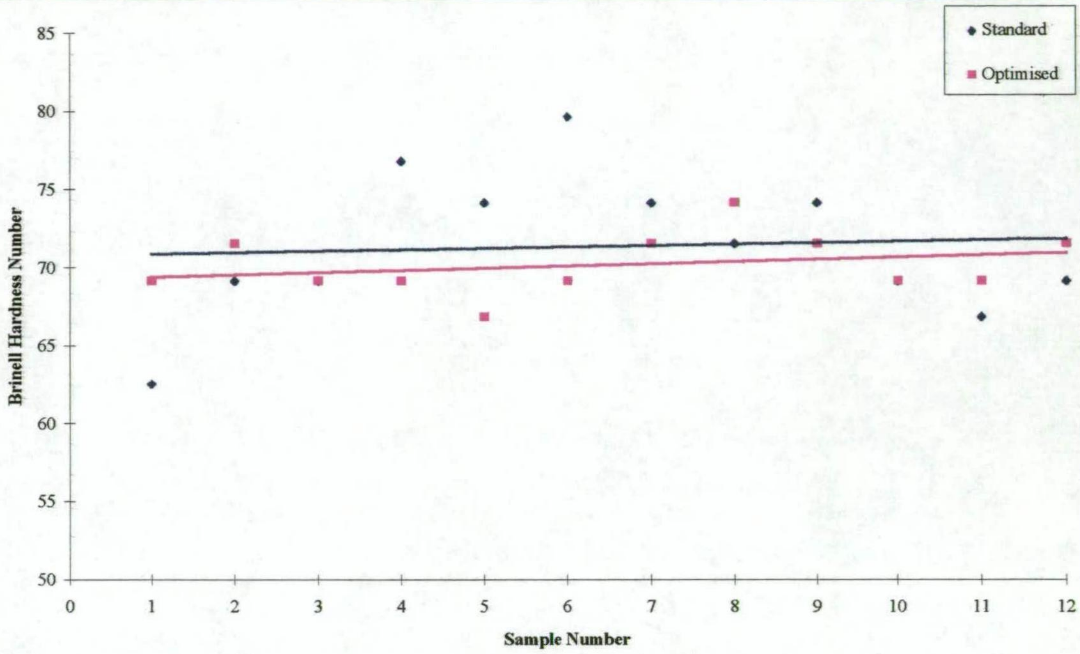


Figure 5.11: Brinell Hardness Number (Stage Two)

The tensile properties of the alloy were also found to be very similar between the two heat treatment methods used in this instance, Figure 5.12. A statistical analysis documented shortly will show the difference in means to be statistically not significant. The mean yield strength and ultimate tensile strength for the optimised heat treatment process were calculated to be 181.5 and 270.8MPa respectively compared to the yield strength and ultimate tensile strength for the standard process shown previously as being 184.5 and 266.5MPa respectively. Again, the yield strength and ultimate tensile strength of the material was shown to be constant, confirming the homogeneity of the alloy. The correlation coefficients for each group of samples were found to be statistically not significant.

Percentage elongation in the alloy, for both heat treatment methods is shown in Figure 5.13. The mean elongation for the optimised process has been calculated to be 11.7% compared to only 9.6% for the standard process. It will be shown shortly in a statistical analysis that the mean elongation of the optimised treatment samples is statistically significantly higher than the mean elongation of the standard treatment samples. The correlation coefficients for the two groups of samples from either treatment were found to be statistically not significant, again confirming the homogeneity of the alloy.

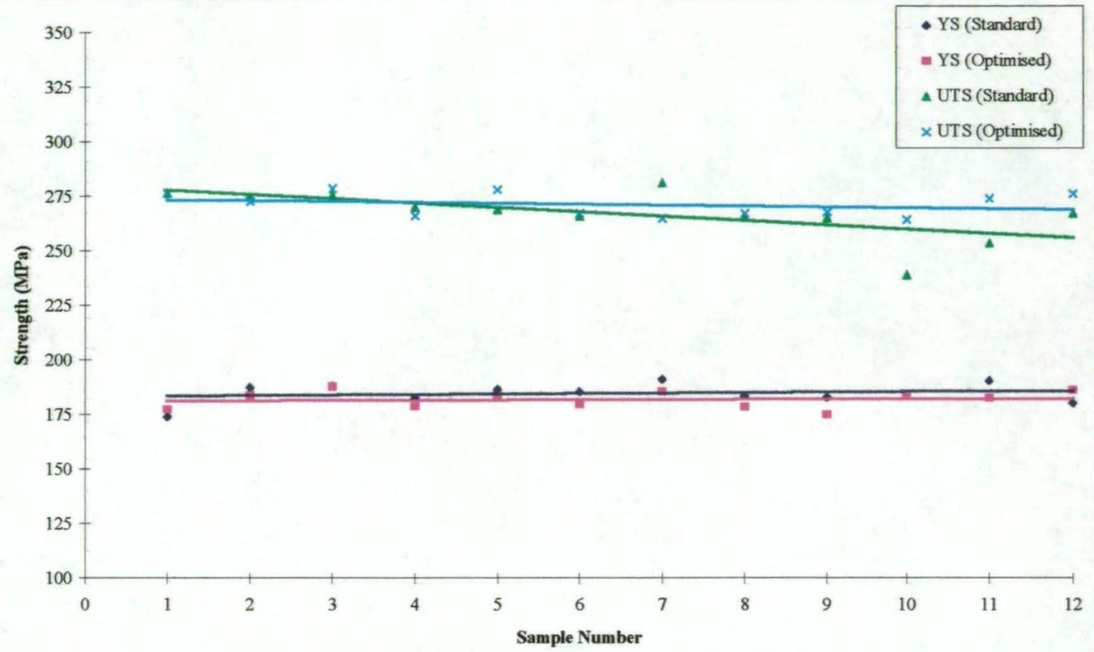


Figure 5.12: Tensile Strength (Stage Two)

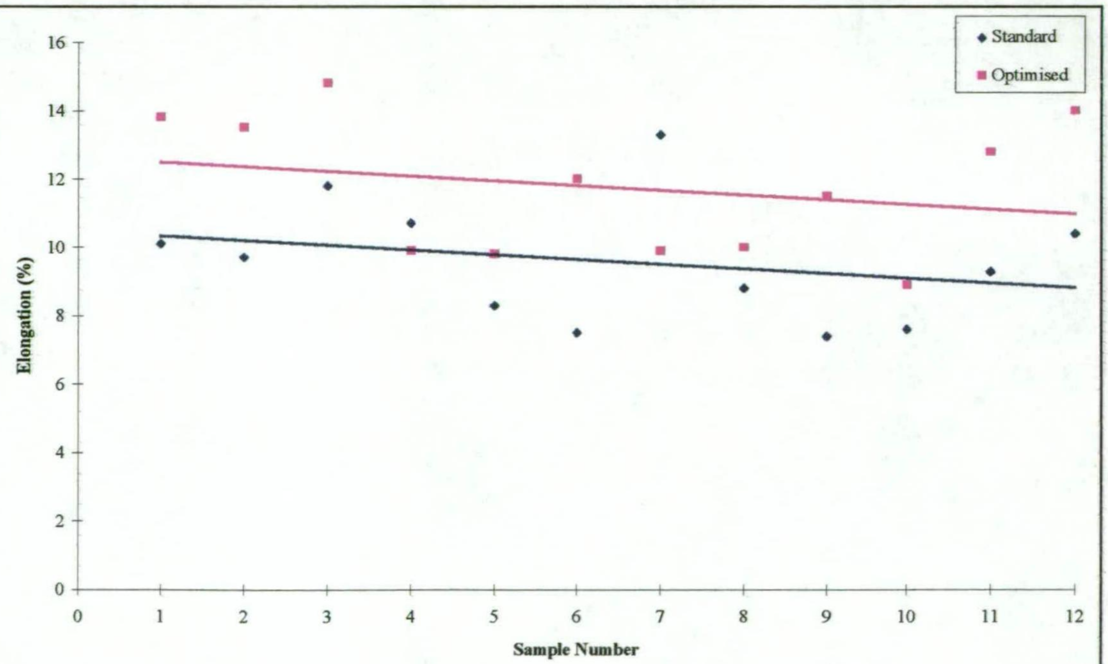


Figure 5.13: Percentage Elongation (Stage Two)

The mean impact height calculated for each batch of wheels from either heat treatment process has shown that the optimised heat treatment process produced better impact resistant wheels than the standard process. The mean impact height for the optimised heat treatment process has been calculated to be 421mm compared to only 392mm for the standard process using an impact weight of 630kg.

It can be seen from a comparison of the impact tests completed so far that the J15 wheel type has a much greater impact strength than the MX5 wheel type. Considering only the results obtained from impact testing completed on wheels produced using the standard T6 heat treatment process it can be seen that the mean impact height for the MX5 wheel type is 275mm compared to the higher value of 392mm for the J15 wheel type. It is useful to note at this point that the large difference between these values is due to the fact that the J15 wheel type is a 'tougher' wheel than the MX5 wheel type. The J15 wheel type, because of its design and structure, is superior in strength to the MX5 wheel type. The J15 wheel type customer specification for mean impact height is 230mm, the same as for the MX5 wheel type, but the specified impact weight for the J15 wheel type is 630kg compared to only 465kg for the MX5 wheel type. Hence, it is useful to note here that the large difference between the mean impact height for wheels produced using an identical process is due to wheel design and structure rather than any other reason.

For the remaining three stages of the investigation processing of the results has been carried out in a similar manner as for Stages One and Two. The qualitative trends of the effect of change in mechanical properties for Stages Three to Five are shown in Appendix C. Figures C.1 to C.9 in Appendix C highlight the hardness, tensile strength and percentage elongation of the alloy for each of the treatments used in the latter three stages of the investigation. A statistical analysis of the results obtained from the five stage investigation is shown in Table 5.3 and a summary of the results from each stage is shown in Table 5.4. For the remaining three stages the correlation coefficients have been found to be statistically not significant in all cases. This result highlights the homogeneity of the alloy and gives confidence in the reliability of the results.

5.3 STATISTICAL ANALYSIS OF EXPERIMENTAL RESULTS

A statistical analysis of the results was necessary to evaluate thoroughly the results obtained from each of the five stages completed. A t-statistic test, which is a special case of ANOVA (ANalysis Of Variance) used for two group univariate analysis, was adopted in this instance to statistically distinguish the difference between the results obtained for both the optimised and standard T6 heat treatment processes used. The t-statistic test assesses the statistical significance of the difference between two independent sample means[49]. The t-statistic is the ratio of the difference between sample means to its standard error - an estimate of the degree of fluctuation between means to be expected because of sampling error rather than real differences between means[49]. In this instance, the t-statistic test was adopted to assess the statistical difference between the mean values of hardness, yield strength, ultimate tensile strength and percentage elongation for each of the twelve samples from the optimised treatment and the twelve samples from the standard treatment for each stage of the investigation. The t-statistic test is completed by obtaining a value for the t-statistic from the two groups being considered and comparing the obtained value with a critical value ($t_{critical}$). If the value of the t-statistic exceeds $t_{critical}$ then the means of the two independent sample batches are shown to be statistically significantly different[49].

A critical value ($t_{critical}$) for the t-statistic is determined by;

I. Specifying an error rate (denoted as α or significance level and equal to the probability of incorrectly rejecting the null hypothesis that the means of the independent sample groups are equal), that is, concluding that the group means are different when in fact they are not, and
II. Referring to the t-distribution with ($N_1 + N_2 - 2$) degrees of freedom, denoted as ν, and a specified α, where N_1 is the degrees of freedom for group one and N_2 is the degrees of freedom for group two[3].

A table '*Percentage Points on the t-Distribution*[50]' was used to determine $t_{critical}$ for the t-distribution, where the level of confidence, α, was 0.05, which is the equivalent of a 95% confidence interval, and the degrees of freedom, ν, was 22, ($12 + 12 - 2 = 22$). The corresponding $t_{critical}$ value for this condition was found to be 1.717. A statistical program was used to determine the corresponding t-statistic value for each mechanical property for each stage of the investigation. The particular program used in attached in Appendix D, *Program Used for Statistical Analysis*, and a summary of results from the statistical analysis is shown in Table 5.3.

TABLE 5.3: Statistical Analysis of Results

		Mean Value		Standard Deviation		T - Value	
		Std	Opt.	Std	Opt.	Theor.	Calc.
Stage One	**HB**	71.5	67.4	3.2	2.2	1.717	3.801
	YS	184.5	141.2	4.6	16.0	1.717	9.602
	UTS	266.5	239.6	11.4	8.1	1.717	6.704
	ε	9.6	10.2	1.8	2.5	1.717	0.843
Stage Two	**HB**	71.3	70.1	4.7	1.9	1.717	0.829
	YS	184.5	181.5	4.6	3.9	1.717	1.711
	UTS	266.5	270.8	11.4	5.4	1.717	1.193
	ε	9.6	11.7	1.8	2.0	1.717	1.774
Stage Three	**HB**	71.6	73.1	2.9	3.2	1.717	1.198
	YS	184.5	164.7	4.6	11.5	1.717	5.536
	UTS	266.5	226.4	11.4	18.9	1.717	6.323
	ε	9.6	4.5	1.8	4.5	1.717	7.045
Stage Four	**HB**	71.6	69.9	2.9	1.5	1.717	1.797
	YS	184.5	167.1	4.6	6.2	1.717	7.828
	UTS	266.5	250.6	11.4	10.5	1.717	3.762
	ε	9.6	6.4	1.8	2.1	1.717	3.955
Stage Five	**HB**	71.6	71.4	2.9	2.0	1.717	0.254
	YS	184.5	173.9	4.6	6.4	1.717	4.625
	UTS	266.5	263.4	11.4	15.2	1.717	0.561
	ε	9.6	6.8	1.8	2.8	1.717	2.797

KEY: Std. = Standard T6 Treatment, Opt. = Optimised T6 Treatment, Theor. = Theoretical T-Value, Calc. = Calculated T-Value

The valuable information obtained from this statistical analysis will be incorporated into the following discussion of results in which an evaluation of each stage of the investigation will be completed.

5.4 DISCUSSION OF EXPERIMENTAL RESULTS

It is now interesting to compare the five optimised heat treatment processes trialed to investigate the effect that each process had on the development of mechanical properties in the alloy. This is particularly useful for the purpose of investigating the influence that both solution treatment time and temperature have on the development of mechanical properties in aluminium alloy 601. It is useful to discuss the results of each of the stages completed and evaluate the success of each optimised treatment using the two criteria given previously, ie. comparison of the optimised process with both the customer specifications and the standard treatment. A summary of the customer specifications for each of the various wheel types used and a summary of the mechanical properties developed using both the optimised and the standard treatments is given in Table 5.4 for each of the five stages completed.

TABLE 5.4: Summary of Mechanical Properties and Wheel Specifications

		HB (500/10)	**YS (MPa)**	**UTS (MPa)**	**ε (%)**	**Mean Impact Ht.**
Stage One	**MX5 Specs.**	64.6 - 85.7	N/A	≥ 245	≥ 5	230mm/465kg
	Standard	71.5	184.5	266.5	9.6	275mm/465kg
	Optimised	67.4	141.2	239.6	10.2	221mm/465kg
Stage Two	**J15 Specs.**	64.6 - 85.7	N/A	≥ 245	≥ 5	230mm/630kg
	Standard	71.3	184.5	266.5	9.6	392mm/630kg
	Optimised	70.1	181.5	270.8	11.7	421mm/630kg
Stage Three	**XR Specs.**	64.6 - 85.7	≥120	≥ 220	≥ 7	230mm/560kg
	Standard	71.6	184.5	266.5	9.6	382mm/560kg
	Optimised	73.1	164.7	226.4	4.5	264mm/560kg
Stage Four	**XR Specs.**	64.6 - 85.7	≥120	≥ 220	≥ 7	230mm/560kg
	Standard	71.6	184.5	266.5	9.6	382mm/560kg
	Optimised	69.9	167.1	250.6	6.4	294mm/560kg
Stage Five	**XR Specs.**	64.6 - 85.7	≥120	≥ 220	≥ 7	230mm/560kg
	Standard	71.6	184.5	266.5	9.6	382mm/560kg
	Optimised	71.4	181.2	263.4	6.8	308mm/560kg

Firstly, consider the mechanical properties developed in the alloy as a result of using the optimised heat treatment process in Stage One incorporating a solution treatment condition of twenty two minutes at 540°C. It can be seen from Table 5.4 that the although the hardness and elongation of the alloy meet with the relevant specifications, the ultimate tensile strength and impact resistance of the alloy are insufficient. Furthermore, the mechanical properties developed using the standard treatment, with the exception of elongation, are greater than those developed using the optimised treatment. This has been proven in a statistical analysis of the results in which it has been shown that for the standard treatment samples the mean hardness, yield strength, ultimate tensile strength were higher than those of the optimised treatment samples, Table 5.3. The statistical analysis has shown the means from either treatment to be statistically significantly different with the exception of percentage elongation which was shown to be statistically similar in either case.

The results obtained from Stage One are of particular interest as the tensile properties achieved in the alloy from this optimised process can be compared to the tensile properties that were expected after consideration of the findings from research[43]. The yield strength and ultimate tensile strength of the alloy developed using the optimised heat treatment process of twenty two minutes at 540°C were measured to be approximately 141.2 and 239.6MPa respectively. It was suggested[43] that these values should be slightly higher at 150 and 255MPa respectively. This slight discrepancy may be due to measurement error rather than a real difference in means. A statistical comparison is not possible in this instance due to only the availability of a mean value for yield strength and ultimate tensile strength from research[43] but may well have shown the two treatments to produce mechanical properties in the alloy which are not statistically significantly different. In addition, slight variation in alloy content between the samples used in research[43] and those used at SAPL is possible and may be partly responsible for the witnessed discrepancy. Nevertheless the elongation for this optimised process was measured to be 10.2% which is very similar to the suggested[43] value of 10.0%.

The results obtained from this stage are of significance as it was not known prior to this stage of the investigation the effect that a significant reduction in solution treatment time would have on the hardness and impact response of the alloy. The results obtained from this stage indicate that the decrease in solution time when a solution temperature of 540°C is used causes a slight decrease in the level of hardness and impact resistance achieved. This is evident from a comparison of the results for the standard and optimised treatments shown in Table 5.4. It can be seen that the mean Brinell hardness number of samples from the optimised treatment is 67.4 which is slightly lower than 71.5 for the standard treatment. The statistical analysis results documented in Table 5.3 have shown the difference in means to be statistically significant. Likewise, the mean impact height of samples from the optimised treatment was found to be lower at 221mm than that of 275mm from the standard treatment.

The results obtained from Stage Two in which a solution treatment condition of twenty two minutes at 570°C was used have shown that the mechanical properties developed in the alloy with this particular optimised heat treatment process are the same as, or better, than those produced using the existing standard process and that the mechanical properties developed in the alloy meet with all the relevant customer specifications. This is evident in the summary of results provided in Table 5.4 from which it can be seen that the level of hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance developed in the alloy using this optimised heat treatment process meet with the relevant specifications and are comparable to those developed using the standard heat treatment process. A statistical analysis of the results, Table 5.3, has shown the mean hardness, yield strength and ultimate tensile strength to be similar using either treatment but the mean elongation from either treatment to be significantly different. The optimised treatment samples had a higher mean elongation which indicates the optimised treatment used in this instance was preferable to the standard treatment for developing a high level of elongation in the alloy. In addition, it is shown that the impact resistance is also significantly higher in samples from the optimised treatment. It can be seen from Table 5.4 that a mean impact height of 421mm was achieved using the optimised treatment whilst only 392mm was achieved using the standard treatment.

A chief outcome of Stage Two that is especially valuable is the finding that solution treatment temperature has a significant influence on the development of mechanical properties in the alloy. It has been shown that an increase in solution temperature of only 30°C, ie. an increase from 540°C in Stage One to 570°C in Stage Two, can influence greatly the development of mechanical properties in the alloy. It can be seen from Table 5.4 that for a fixed solution treatment time of twenty two minutes an increase in solution temperature from 540 to 570°C is significant enough to cause an increase in hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance in the alloy. The cause for the witnessed increase in mechanical properties with an increase in temperature will be discussed later in this section.

For Stage Three in which a solution treatment condition of ten minutes at 595°C was used, it can be seen from a comparison of the results in Table 5.4 that a solution treatment time of ten minutes, using the maximum allowable solution treatment temperature without causing bleed-out in the wheel, is not sufficient for achieving the desired level of mechanical properties in the alloy. Although the majority of the measured mechanical properties, ie. hardness, yield strength, ultimate tensile strength and impact resistance, meet with the relevant specifications it can be seen that percentage elongation is significantly lower than required. Percentage elongation of greater than 7% is specified but a mean elongation of only 4.5% was achieved. In addition, a statistical analysis of the results from this stage, Table 5.3, has shown that although the mean hardness is not statistically different between samples from either treatment the mean yield strength, ultimate tensile strength and percentage elongation are. The mean impact height of samples from the optimised treatment was also found to be much lower than those from the standard treatment. These findings suggest that this particular optimised heat treatment process is not sufficient for achieving the desired level of mechanical properties in the alloy. That is, the degree of solution treatment used in this instance was not sufficient enough to cause the development of adequate mechanical properties in the alloy.

Similar behaviour was exhibited by the alloy for the optimised heat treatment process used in Stage Four which incorporated a solution treatment condition of fifteen minutes at 580°C. A comparison of the mechanical properties developed in the alloy using the particular optimised treatment trialed in this instance and the respective specifications for the particular wheel type used show that although hardness, yield strength, ultimate tensile strength and impact resistance in the alloy were sufficiently developed, percentage elongation in the alloy was significantly less than that specified. Again an elongation of 7% was specified but a mean elongation of only 6.4% was achieved using the optimised treatment. A statistical analysis of the results from this stage, Table 5.3, has shown that the mean hardness, yield strength, ultimate tensile strength and percentage elongation are statistically significantly different in either instance and that the means of the standard treatment samples are higher for each of the mechanical properties measured. The mean impact height of the optimised treatment samples was also found to be significantly lower than that of the standard treatment samples. Hence, using the two mentioned criteria for the evaluation it is evident that this particular solution treatment process is not sufficient for achieving the desired level of mechanical properties in the alloy. However, it is interesting to note that the developed mechanical properties in this instance are improved from those developed in Stage Three. This suggests that the increase in solution treatment time from ten to fifteen minutes is necessary to improve the condition of the alloy. This will be expanded in more detail later in the discussion.

Finally, for Stage Five, in which a solution treatment condition of eighteen minutes at 570°C was used it can be seen from Table 5.4 that the hardness, yield strength, ultimate tensile strength and impact resistance of the alloy meet with the relevant specifications but again the level of elongation is insufficient. A mean elongation of 6.8% was achieved which is slightly lower than that of 7% specified. A statistical analysis of the results from this stage, Table 5.3, has shown that the mean hardness and ultimate tensile strength were statistically similar between samples from both the optimised and the standard treatments but the mean yield strength and percentage elongation of the samples were statistically significantly different. In addition, the mean impact height of samples from the optimised treatment was found to be much lower than that of the standard treatment samples. The results from this stage have shown that this particular optimised heat treatment process trialed here is similar to the standard process in some aspects and significantly different in others. For example, the hardness and ultimate tensile strength developed in the alloy using this optimised process were very similar to those developed using the standard process but the yield strength, elongation and impact resistance of the alloy were found to be much lower in the optimised treatment specimens compared to the standard treatment specimens. This factor combined with the fact that elongation is lower than the customer specification indicates that this particular optimised heat treatment process is insufficient for producing the required level of mechanical properties in the alloy.

With the results of each of the five stages of the investigation available it is now interesting to study the particular treatment that the alloy was subjected to in each stage and study the resulting mechanical properties that were developed. It has been shown in the results that the developed mechanical properties in the alloy after heat treatment varied significantly for each of the five optimised treatments used. A study of the degree of solution treatment that the alloy was subjected to in each stage is useful to determine a relationship between the degree of solution treatment used and the development of mechanical properties. Information on the degree of solution treatment that was sustained by the alloy in either of the five stages of the investigation is available from the temperature profiles documented previously for each of the individual treatments used. It is interesting to plot the determined temperature profiles for each of the five stages on a common graph in order to highlight the difference in solution treatment conditions between either stage, Figure 5.14. It should be noted that although the temperature profiles documented previously have shown the heating curve for five different sections of the test specimen for each stage, only the average wheel temperature for each stage has been shown here to simplify the graphical comparison.

It is evident from the temperature profile comparison that the maximum solution treatment temperatures achieved by the alloy in either of the five stages is shown to be approximately 540°C in Stage One and approximately 565°C in the remaining four stages. It has been suggested that as 565°C was the maximum temperature that the alloy could achieve before a liquidus state was observed then the eutectic point of the alloy is probably close to 565°C. A comparison of the individual temperature profiles with the corresponding resulting mechanical properties is useful to analyse the effect that the degree of solution treatment has on the development of mechanical properties in the alloy. Starting with Stage One, it has been shown that a solution treatment time of twenty two minutes using a condition such that the maximum solution temperature achieved by the alloy is 540°C is not sufficient for achieving the desired level of mechanical properties in the alloy.

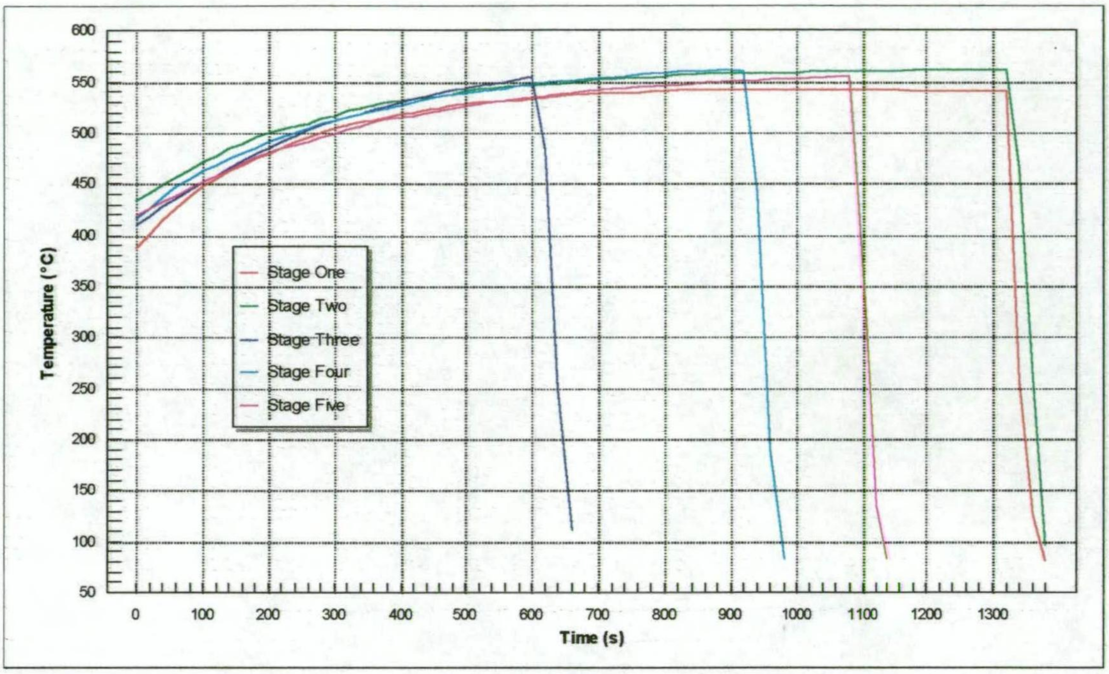


Figure 5.14: Temperature Profile Comparison for the Five Stage Investigation

It has been shown that this particular condition in which the alloy was held at a temperature of 540°C for a period of ten minutes following a twelve minute heating time causes the alloy to have mechanical properties that are lower than required by the customer specifications and also that the resulting mechanical properties are lower than those developed using the standard heat treatment process. However, when the same solution time of twenty two minutes was used in conjunction with a higher solution temperature of 570°C, ie. Stage Two, the development of mechanical properties in the alloy increased significantly. As a result of the Stage Two solution treatment conditions used a maximum temperature of 565°C was achieved by the alloy, which is significantly higher than that of 540°C achieved in the preceding stage. As a result of the increase in solution treatment temperature the mechanical properties developed in the alloy were of a significantly higher level than those developed in Stage Two and consequently the hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance met with the relevant customer specifications and were similar to the mechanical properties developed using the standard treatment. The same maximum temperature was achieved by the alloy in

Stage Three after only a ten minute period as a higher solution treatment temperature was used. Even though the same maximum temperature was achieved in both Stages Two and Three the results have shown that the treatment with the shorter solution time, Stage Three, gave rise to a lower level of mechanical properties being developed in the alloy. This suggests that the exposure of the alloy to a high solution temperate is significant rather than the maximum temperature achieved. This was also shown to be the case in Stage Four for which a maximum temperature of 565°C was achieved after only a fifteen minute period. Once again, the results have shown that the lower solution treatment time gave rise to a lower level of mechanical properties being developed in the alloy. However, a comparison of the mechanical properties developed using both Stages Three and Four has shown that the properties developed in Stage Four, using the longer solution time, are of a higher level than those developed using Stage Three. This further reinforces the statement that exposure time of the alloy to the solution treatment temperature is critical. Finally, the results of Stage Five have shown that an increase in solution time to eighteen minutes using the maximum solution temperature possible is still not sufficient for achieving the desired level of mechanical properties in the alloy after consideration of the two criteria used for the evaluation, but the mechanical properties developed in the alloy are improved from those developed using the solution treatment conditions used in both Stages Three and Four. Hence, the results have shown that an increase in solution time over the ten to twenty two minute time period investigated gives a proportional increase in mechanical properties.

An analysis of each of the mechanical properties measured, ie. hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance, is now useful to investigate the effect that the various solution treatment conditions used had on the development of mechanical properties in the alloy. A graphical comparison of each of the developed mechanical properties is beneficial in order to highlight the difference in properties obtained using either treatment. In addition, it is useful to include the 'as-cast' condition of the alloy in the comparison in order to show the improvement in the level of mechanical properties obtained using the optimised heat treatment processes trialed in this instance. Firstly, Figure 5.15 shows the mean Brinell hardness number developed in the alloy for the 'as-cast' condition and for each of the five stages of the investigation. It can be seen from this plot that the mean level of hardness developed is similar for either of the five stages. That is, allowing for normal measurement errors, the measured level of hardness is not significantly different in samples from either treatment.

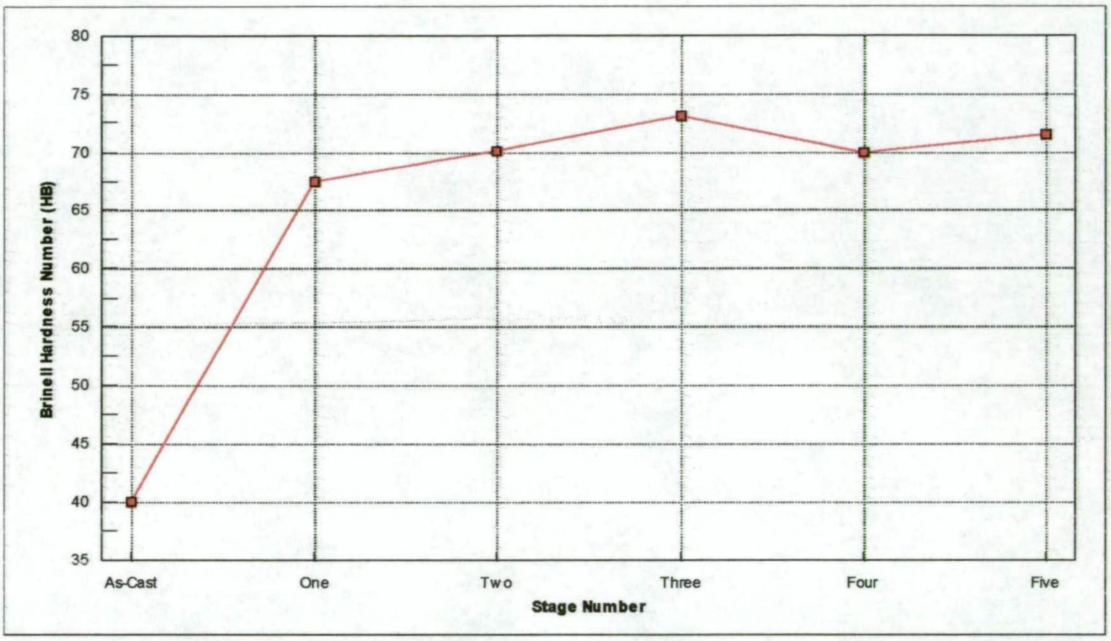


Figure 5.15: Mean Brinell Hardness Number for the Five Stage Investigation

Secondly, consider the tensile strength of the alloy for either of the five heat treatment processes used in the investigation, Figure 5.16. It can be seen that both yield strength and ultimate tensile strength increase from the 'as-cast' condition with the initial solution treatment condition of twenty two minutes where the alloy achieves a maximum temperature of 540°C and further increases in Stage Two when a solution treatment time of twenty minutes is used and the alloy achieves a maximum temperature of 565°C. The increase in yield strength and ultimate tensile strength using the higher temperature treatment has been shown to be 141.2 and 239.6MPa respectively in Stage One to 181.5 and 270.8MPa respectively in Stage Two. As a common maximum temperature of 565°C was achieved by the alloy in the final three stages of the investigation using treatment times of ten, fifteen and eighteen minutes and also in Stage Two using a treatment time of twenty two minutes it is interesting to analyse the effect that the different exposure times had on the development of tensile strength in the alloy. In Stage Three where a solution treatment time of ten minutes was used it has been shown that the yield strength and ultimate tensile strength of the alloy decrease significantly from that of Stage Two even though a maximum temperature of 565°C was achieved in either instance. It has also been shown that an increase in solution treatment time to fifteen minutes in Stage Four gave an increase in yield strength and ultimate tensile strength and then a further increase in these properties was witnessed for a further increase in treatment time to eighteen minutes in Stage Five. The behaviour exhibited by the alloy for the varying solution treatment times used where the alloy achieved a temperature close to its eutectic in either instance has shown that increasing solution treatment time from ten to twenty two minutes yields an increase in the tensile strength of the alloy. Furthermore, as the tensile strength of the alloy after the twenty two minute treatment was close to the values obtained using the standard treatment then an increase in treatment time beyond twenty two minutes is not necessary or beneficial. This relationship between solution treatment time and the development of tensile strength can be explained by considering the change in microstructure of the alloy during solution treatment. It has been shown previously that three major changes in the microstructure of aluminium alloy 601 occur during solution treatment. These three changes have been shown to be; i) dissolution of magnesium silicide particles which form during solidification and subsequent slow cooling, ii) homogenisation of solutes in the aluminium matrix, and iii) spheroidisation and coarsening of the eutectic silicon particles[20]. The degree of completion of these three changes influences significantly the development of tensile strength in the alloy. The increase in yield strength and ultimate tensile strength with an increase in solution temperature and time can be explained by considering the change in microstructure of the alloy. For the initial stage of the investigation, Stage One, it is evident from the results that some completion of magnesium silicide formation and also homogenisation and spheroidisation has occurred as the yield strength and ultimate tensile strength of the alloy are improved from the 'as-cast' condition. For an increase in solution temperature, Stage Two, the resulting yield strength and ultimate tensile strength indicate that a higher degree of magnesium silicide formation and also homogenisation and spheroidisation has occurred as the tensile strength is significantly higher. For the final three stages where the maximum solution temperature possible was used and solution time was increased from ten to eighteen minutes respectively, both yield strength and ultimate tensile strength have been shown to increase with increasing time. This suggests that the degree of homogenisation and spheroidisation increases with increasing solution treatment time. As the yield strength and ultimate tensile strength developed in the alloy using the optimised treatment in Stage Two is similar to those developed using the standard treatment then it is evident that a high degree of completion of magnesium silicide particle formation, homogenisation of solutes in the matrix and also spheroidisation of the eutectic silicon particles has occurred.

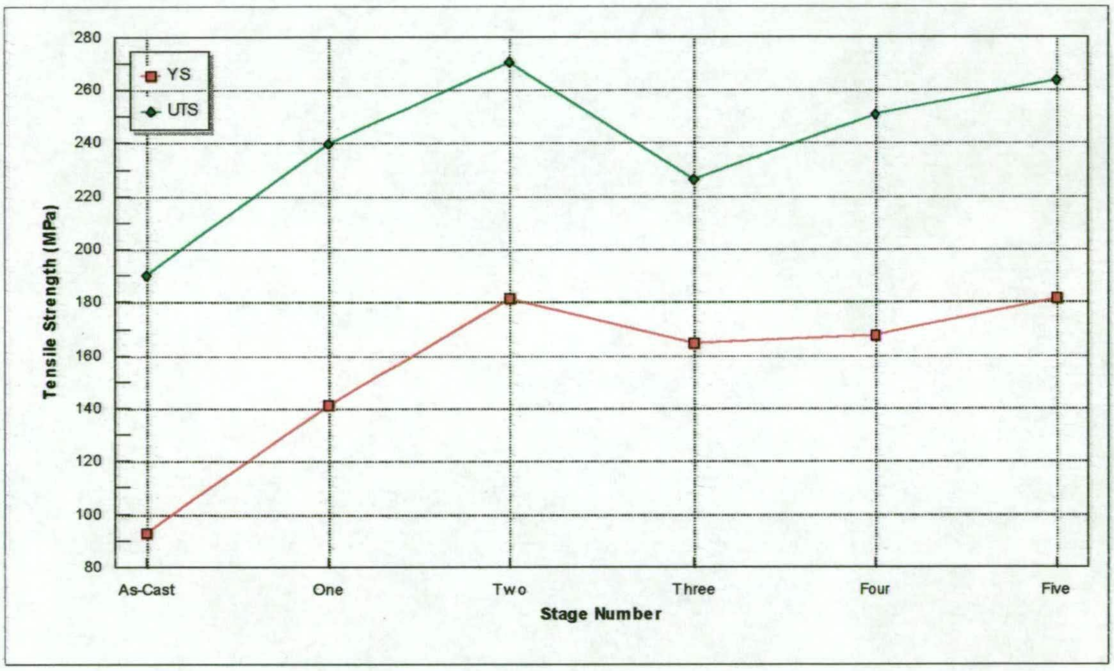


Figure 5.16: Mean Tensile Strength for the Five Stage Investigation

Similar behaviour was exhibited by the elongation of the alloy for each of the five stages, Figure 5.17. An increase in elongation was witnessed from Stage One to Stage Two with an increase in solution temperature for a common solution time of twenty two minutes. Elongation then decreased in Stage Three when solution time decreased to ten minutes. As solution time increased to fifteen and eighteen minutes in Stages Four and Five respectively the elongation of the alloy also increased respectively. The mean elongation of the alloy has been shown to increase in the sequence of 4.5, 6.4, 6.8 and 11.7% for solution times of ten, fifteen, eighteen and twenty two minutes respectively. Even though a maximum temperature of 565°C was achieved by the alloy in Stages Two to Five the exposure time has been shown to be significant. Again, an increase in solution time beyond twenty two minutes is not beneficial as a high level of elongation, higher than that achieved using the standard treatment, is achieved after only twenty two minutes when the maximum allowable solution treatment temperature is used. As with tensile strength, the change in elongation with increasing solution temperature and time gives a good indication of the change in microstructure of the alloy during solution treatment. It has been shown in previous research[43] that the change in elongation is closely related to the change in morphology and size of eutectic silicon particles. The witnessed increase in elongation with increasing solution time suggests that after only ten minutes of solution treatment only a slight degree of spheroidisation of silicon particles has occurred and increases sequentially to twenty two minutes where it is evident that a high degree of spheroidisation of the eutectic silicon particles has occurred.

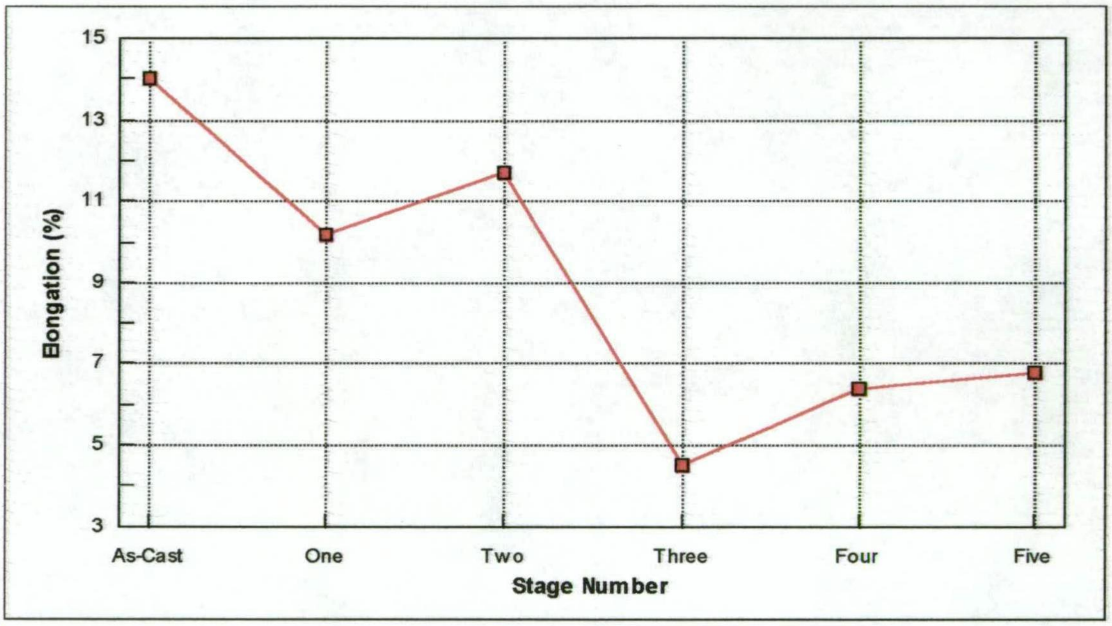


Figure 5.17: Mean Percentage Elongation for the Five Stage Investigation

Impact strength has also been shown to vary for the particular solution treatment conditions used and is best considered in conjunction with the following discussion. Through the mechanical tests completed it has been possible to establish a relationship between the tensile properties and the impact strength of the alloy. A correlation of the mechanical properties measured indicates that the impact strength and tensile strength of the alloy are closely related. It has been shown that the lower the tensile properties of the alloy then the lower is the impact strength of the alloy. It has been mentioned before that a high degree of tensile strength without sufficient ductility will lead to a low fracture toughness in the alloy[33]. A review of the mechanical properties summarised in Table 5.4 highlights the relationship between tensile properties and impact strength. It can be seen from the summary of results that the mean impact height determined from Stage One is lower in the case of the optimised treatment samples. Although similar elongation was observed in the alloy from either heat treatment process, ie. 9.6 and 10.2% for the standard and optimised treatments respectively, the optimised treatment samples were found to have significantly lower yield strength and ultimate tensile strength, ie. 141.2 and 239.6MPa respectively compared to the higher values of 184.5 and 266.5MPa respectively for the standard treatment. The lower impact resistance of the alloy from the optimised treatment may be attributed to this difference in tensile strength. Alternatively for Stage Two, in which the optimised treatment samples were found to have similar tensile strength and higher elongation compared to the standard treatment samples, it was found that the optimised treatment samples exhibited a higher value of mean impact height. The higher elongation of the alloy shows that the optimised samples were of a higher ductility and hence, higher impact resistance. It is interesting to evaluate the results obtained from the last three stages of the investigation in which the XR wheel type was used as the test specimen. The fact that the same wheel type was used makes it is possible to examine the increase in impact resistance of the alloy as a result of increasing solution time and consequently, increasing tensile properties. The yield strength, ultimate tensile strength and percentage elongation of the optimised treatment samples from Stage Three have been shown to be 164.7 and 226.4MPa and 4.5% respectively compared to the higher values of 184.5 and 266.5MPa and 9.6% respectively for the standard treatment samples. It has been shown that these lower tensile values result in a lower impact resistance in the alloy for the optimised treatment, ie. 264mm for the optimised treatment compared to 321mm for the standard treatment. In the results obtained from Stage Four it has been shown that the tensile properties of the optimised treatment samples increase significantly to a yield strength and ultimate tensile strength of 167.1 and 250.6MPa respectively and an elongation of 6.4%. It is also shown that the impact resistance of the alloy increased giving a mean impact height of 294mm for the optimised treatment samples which is an improvement on the previous impact height of 264mm from Stage Three. This increase in impact resistance is most likely attributed to the increase in the tensile properties of the alloy. Although the mean impact height increased from Stage Three to Stage Four the impact resistance of the optimised treatment samples was still lower than that of the standard treatment samples. Again, this is most likely due to the fact that the tensile properties of the optimised treatment samples were still lower than those of the standard treatment samples. Finally, for Stage Five the tensile properties of the optimised treatment samples and consequently, impact resistance, increased from the values obtained in Stage Four. The yield strength and ultimate tensile strength were found to increase to 173.9 and 263.4MPa respectively and elongation increased to 6.8%. As a result of this increase the mean impact height of the alloy also increased to 308mm. Once again, the increase in tensile properties gave an increase in impact resistance but the mean impact height of the optimised treatment samples was still lower than that of the standard treatment samples. This again can be attributed to the fact that the tensile properties of the optimised treatment samples were still lower than those of the standard treatment samples thus giving a lower impact resistance in the alloy.

In summary, it can be seen from the temperature profile comparison given in Figure 5.14 that the solution treatment condition used in Stage Two gave the most extreme solution treatment process. This particular treatment subjected the alloy to the highest temperature for the longest period of time. The effect that this particular solution treatment process had on the development of mechanical properties in the alloy is evident from the results given. It can be seen from Table 5.4 that the solution treatment process used in Stage Two gave the best overall mechanical properties in the alloy out of the five stages completed, ie. a good level of hardness and the maximum yield strength, ultimate tensile strength, percentage elongation and impact resistance were all achieved using this particular optimised heat treatment process. The results indicate that a solution treatment condition of twenty two minutes where the alloy is heated to a temperature close to its eutectic is sufficient to achieve the desired level of mechanical properties in the alloy. On the other hand, the results have also shown that the other trialed solution treatment conditions were not sufficient to achieve the desired level of mechanical properties in the alloy.

5.5 CONCLUDING REMARKS

It is evident from the results obtained from this investigation that an optimised heat treatment process can be used successfully at SAPL for the production of aluminium alloy wheels with the desired mechanical properties still being achieved. The optimised process shown to be sufficient in this instance occupies a significantly lower portion of total manufacturing time than the existing heat treatment process yet it is comparable to the existing heat treatment process in terms of the mechanical properties that are developed in the alloy. The objective of heat treatment is simply to improve the mechanical properties of the alloy from the 'as-cast' condition and develop a sufficient level of strength and toughness in the aluminium wheels. Since it has been shown that the existing four and a half hour solution treatment process can be modified to a twenty two minute process without affecting the quality of the product then it is desirable to replace the existing solution treatment process with this optimised process. As a consequence, this replacement will lead to a much sought after reduction in total processing time of aluminium wheels at SAPL. Furthermore, the results have shown that it is not possible to reduce solution treatment time below twenty two minutes using the maximum possible temperature and without modifying the alloy. The nearest trialed solution treatment time of eighteen minutes was not sufficient for achieving the desired level of mechanical properties in the alloy. Thus, it was considered that a solution treatment time of twenty two minutes is the optimum time that can be used.

As a result of the five stages completed it has been possible to investigate the effect that solution treatment time and temperature has on the development of mechanical properties in aluminium alloy 601. It was found that an increase in solution temperature from 540 to 570°C using a solution time of twenty two minutes caused a significant increase in the mechanical properties developed in the alloy. Likewise, it was also found that increasing solution treatment time from ten to twenty two minutes gave a significant increase in mechanical properties. A trend of increasing mechanical properties with increasing solution treatment time was witnessed for the four sequential solution treatment times used. A relationship between the change in tensile properties of the alloy and the change in microstructure was determined and found to be comparable with previously determined relationships[43]. The fact that the established relationship was the same as that previously determined gave confidence in the reliability of the results.

The results obtained so far have shown that the mechanical properties of the alloy are not affected by reducing the existing heat treatment time to that of the optimised process. This behaviour, although necessary, is not sufficient to fully analyse the optimised heat treatment process and immediately select it as a viable replacement for the existing process. In order to complete a full analysis it is necessary to investigate the effect of the optimised heat treatment process on the further manufacturing operations of the wheel. That is, it is necessary to investigate the effect that the optimised heat treatment process has on the machinability and painted finish of the wheel. The following chapter details work that has been completed to address this need.

CHAPTER SIX

QUANTITATIVE TESTING OF OPTIMISED SOLUTION TREATMENT PROCESS

As stated in the concluding remarks of the preceding chapter it is necessary to evaluate the effect that the optimised heat treatment process has on the machinability and painted finish of the wheel in addition to examining mechanical properties. In this part of the investigation, the evaluation of the optimised heat treatment process is carried out on the machinability and painted finish of the alloy wheel to further substantiate the optimised treatment. The assessment of machinability and painted finish of the wheel is carried out by examining samples taken from both the optimised and the standard treatments. A study of the machinability and the painted finish of the wheel together with the mechanical properties will fully evaluate the capability of the optimised process. Comprehensive tests on machinability and paint finish were carried out and are detailed in the following documentation.

6.1 MACHINABILITY ANALYSIS

The machining test used in this instance is comparative rather than conclusive. The aim of this experimental investigation is to compare the particular machinability parameters between two alloys that differ only by the degree of heat treatment. The comparison of the particular machining characteristics will be conducted for a certain set of machining conditions. The machining conditions used will be the same for the alloy in both the optimised and standard solution treated form and will be used to evaluate the effect that variation in solution treatment has on the machinability of the alloy.

Machinability in the Context: It has been stated in Chapter One that machinability is the measure of the machining characteristics of a material. Machinability is used to describe the ease or difficulty with which a material can be machined. Measurable parameters of machinability include tool wear, or tool life, material removal rate, cutting forces, power, surface finish or roughness and chip formation, or chip shape. However, depending on the type of investigation the performance parameters to be analysed can vary. The definition of machinability has remained as a collection of criteria from which the machinability of a material, for a specific situation, can be assessed[51]. Influences on machinability can be categorised as either; i) machining process parameters, ie. tool material, tool geometry and cutting fluid, or ii) properties of the work piece material, ie. hardness, abrasiveness and surface condition. It was the latter of these influences that was being studied as part of this particular investigation. Two performance parameters were measured and considered sufficient in this situation for a comparison of the machinability of aluminium alloy 601 heat treated using two significantly different conditions. The two performance parameters selected were *surface roughness* and *frequency of cutting tool vibration*. It is useful to briefly define these two parameters before going any further.

Surface finish metrology is concerned with the specification and measurement of the topographical features of surfaces[52]. These topographical features comprise minute hills and valleys which, recurring at regular intervals, tend to form a kind of pattern or texture[52]. The resulting pattern or texture of the machined surface is measured in terms of surface roughness. Two measures of surface roughness are i) Centre Line Average Value (Ra), and ii) Peak-to-Valley Height (Rt), both of which are recognised by the International Standards Organisation (ISO) as an effective means of measuring surface quality. Both Ra and Rt are shown diagrammatically in Figure 6.1. Ra is the arithmetical average value of the departure of the profile both above and below its centre line over the prescribed sampling length[8]. Rt is the distance between the highest peak and the lowest valley over the sampling length[8].

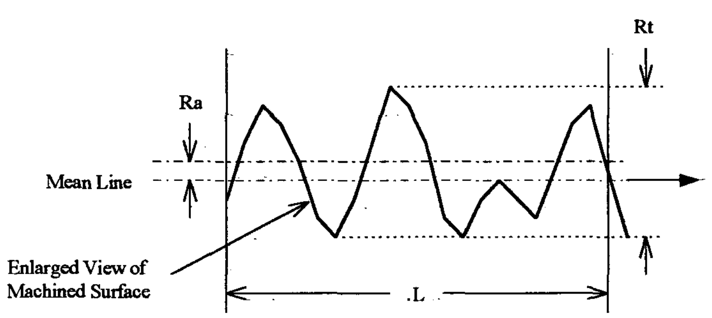


Figure 6.1: Measurement of Surface Roughness[8]

The frequency of the cutting tool vibration when interacting with the workpiece is an important measure of machinability. As the cutting tool is subjected to external forces during cutting it exhibits vibrational motion. The cutting tool is subject to displacement from its equilibrium point due to the forces acting on it. The to-and-fro motion of the tool from some initial point back to that same point is referred to as a cycle. Frequency, which is a measure of the cutting tool vibration is the number of completed cycles per second and is specified in hertz (Hz), where one Hz = one cycle per second. In turning operations it is measured in a plane parallel to the resultant velocity.

It has been shown by Jocumsen[44] that the surface roughness of aluminium alloy 601 after machining is affected by the hardness of the alloy. It was shown in Figure 1.13 that surface roughness (Ra) of the alloy improved with increasing hardness. In addition, it has been shown by Trent[36] that the surface roughness of the alloy after machining is also affected by microstructure. It was shown that the shape and size of the silicon particles present in the alloy had a notable influence on the quality of the machined surface. Trent showed that alloys with fully spheroidised silicon particles dispersed throughout the alloy structure achieve much better surface finish after machining than alloys with non-spheroidised, large silicon particles. The principles of both Jocumsens' and Trents' work have been discussed in detail in Chapter One.

Test specimens were prepared for machining using the following process:

- A mold was manufactured to allow a length of aluminium billet with a particular length and diameter to be cast. The length and diameter of the billet was selected to suit the chuck of the lathe in which the turning operations were completed. The dimensions and weight of the cast billet are shown in Figure 6.2.

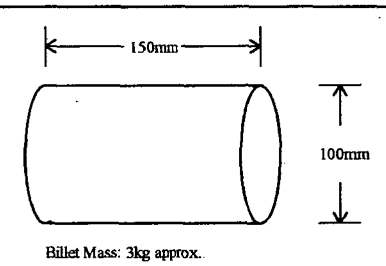


Figure 6.2: Details of Aluminium Alloy Billet

- The billet was cast using prepared molten aluminium alloy 601. The molten aluminium was taken from a transfer immediately before the remaining molten metal was transferred to a casting crucible. Hence, the particular alloy composition and preparation used in this instance was the same as that used for normal wheel production. Casting of the billet was conducted by filling a ladle with molten aluminium from the transfer crucible and pouring the molten aluminium into the prepared mold. The molten metal was left sufficiently long enough to solidify in the mold and then removed.

- Two billets were cast using this method. One billet was heat treated using the optimised heat treatment process and the other was heat treated using the standard heat treatment process.

- Machining of the billet was completed using an experimental set-up arranged especially for the determination of both surface finish and cutting tool vibrations.

The machining operation used in this instance was turning, which means the workpiece was rotating as it was being machined. Figure 6.3 shows the experimental set-up diagrammatically. A Harrison VS330 TR lathe and four jaw chuck were used to rotate the workpiece. The material was machined using a carbide cutting tool (CCMT 09T308) which had a Bruel and Kjaer accelerometer connected to it. The accelerometer then relayed a signal to the four channel amplifier which relayed a signal to the IBM 486 computer. Through use of the data acquisition system used the real-time instantaneous behaviour of the workpiece was plotted to the computer screen and also recorded and stored on the computer hard disk. Surface roughness of the workpiece was measured using a Mitutoyo Surftest MST-301. The properties recorded were Ra and Rt. The measurement of surface roughness was completed after each cut using the process shown diagrammatically in Figure 6.4. It can be seen that a stylus is dragged over the machined surface in order to ascertain the values of Ra and Rt. The stylus is used to

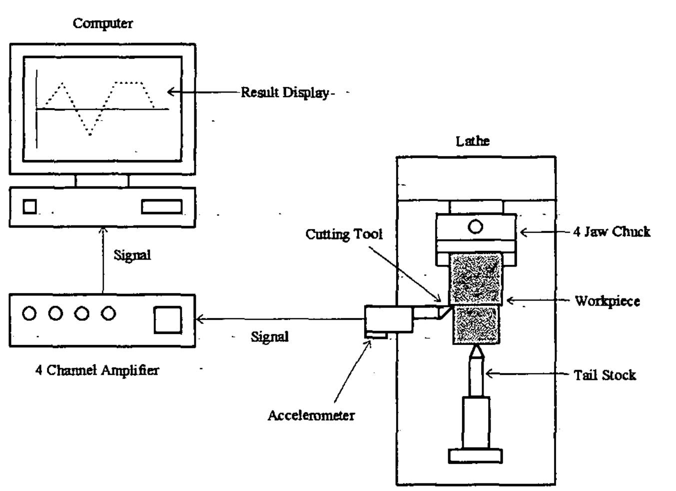


Figure 6.3: Experimental Set-Up for Machining Investigation

sense variations in the actual surface contour of the machined workpiece. The frequency of the cutting tool vibration was measured using the accelerometer and associated software including Spectrum to Frequency Converter and Spectrum Analyser. A Hewlett Packard Vectra 286/12, Data Translation DT2801 Series Data Acquisition Board and Bruel and Kjaer conditioning amplifier were also required for vibration recording.

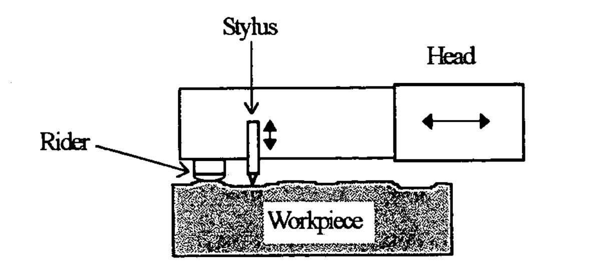


Figure 6.4: Measuring Surface Roughness with a Stylus

With the conventional cylindrical turning operation used there are three main machining parameters that need to be either set or varied. They are commonly recognised as i) spindle speed, ii) depth of cut, and iii) feed rate, and are shown in Figure 6.5. For this particular investigation the spindle speed and depth of cut remained constant and the feed rate was varied. The spindle speed and depth of cut were set at 1020 rpm and 0.5mm respectively. The feed rate was varied from 0.03 to 0.20 mm/rev.

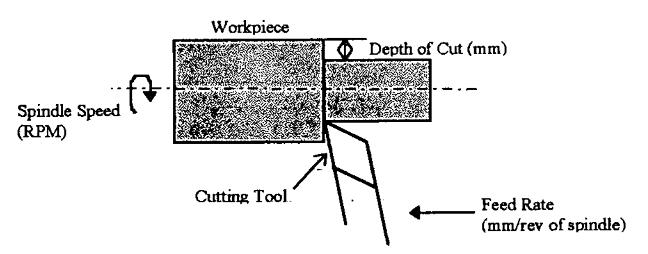


Figure 6.5: Parameters Involved with a Basic Turning Operation

It should be noted that the values of peak to valley ratio (Rt), average surface roughness (Ra) and frequency of cutting tool vibration for increasing feed rate in ten sequential steps from 0.03 to 0.20mm/rev are shown in Tables E.1 and E.2, attached in Appendix E, for the optimised and the standard treatment samples respectively. The measured parameters of average surface roughness and frequency of cutting tool vibration, can be plotted graphically against feed rate to indicate the machinability of the samples from both the optimised and the standard heat treatment processes used. Firstly, consider Ra for both the standard and the optimised treatment samples plotted against increasing feed rate, Figure 6.6. It can be seen that the surface roughness of the alloy increases with increasing feed rate for both the optimised and the standard treatments. This has been confirmed through a statistical analysis of the results. The correlation coefficients of the two samples from either treatment indicated that the surface roughness is dependant on feed rate. Furthermore, the statistical analysis has shown that the mean values of surface roughness are statistically significantly different for either treatment. It was found that the mean surface roughness of 1.07μm determined for the alloy using the optimised treatment was statistically significantly higher than the mean surface roughness of 0.79μm for the alloy using the standard treatment.

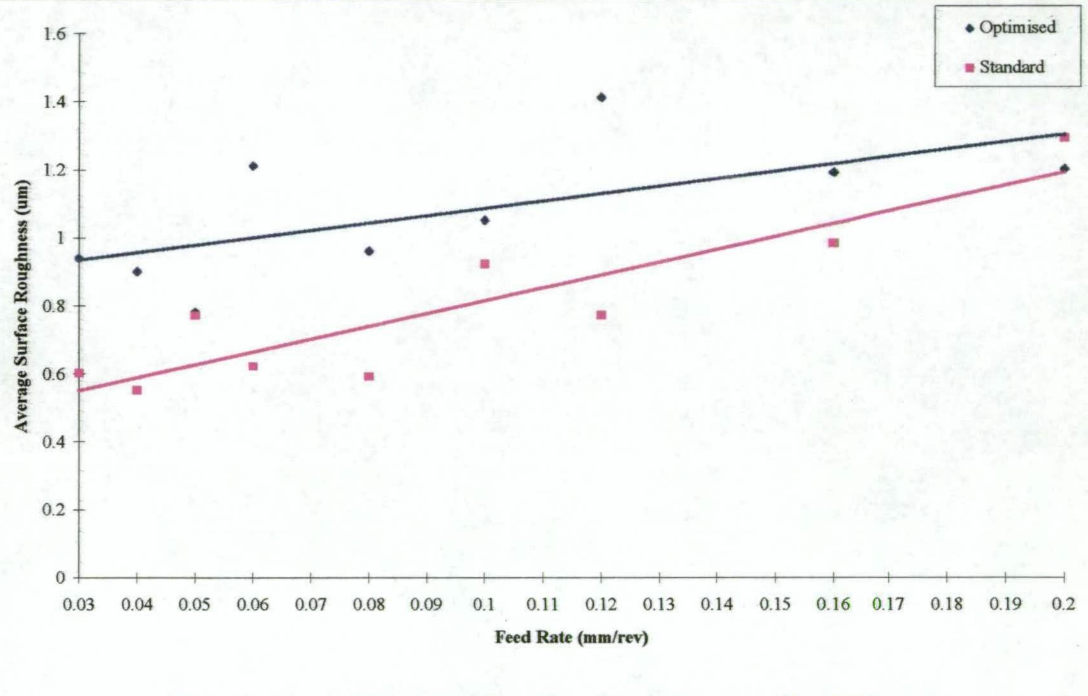


Figure 6.6: Average Surface Roughness versus Feed Rate

A plot of frequency of cutting tool vibration versus feed rate is shown in Figure 6.7. The general qualitative trend is that cutting tool vibration increases with increasing feed rate for both of the samples from either treatment. Again this has been confirmed with a statistical analysis of the results. The correlation coefficients of the two samples from either treatment indicated that cutting tool vibration is dependant on feed rate. The statistical analysis has also shown that the mean frequency of cutting tool vibration of 2.22kHz using the optimised treatment is statistically significantly lower than the mean frequency of cutting tool vibration of 2.38kHz using the standard treatment.

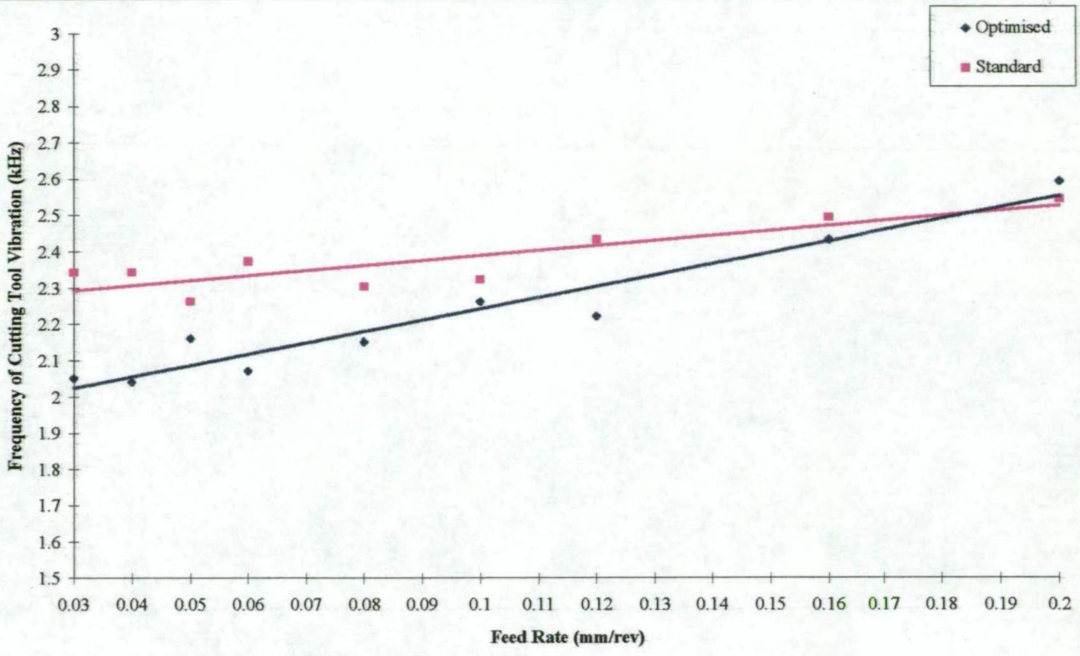


Figure 6.7: Frequency of Cutting Tool Vibration versus Feed Rate

It is interesting to relate the witnessed behaviour of the surface roughness and frequency of cutting tool vibration to the microstructural changes of the alloy that occur during heat treatment. It has been discussed earlier that the shape and size of silicon particles present in the alloy has a significant influence on the quality of surface roughness achieved after machining. The degree of spheroidisation of the eutectic silicon particles for the optimised treatment samples has been mentioned previously as being possibly slightly lower than for the standard treatment. Hence, the slightly poorer surface finish of the optimised treatment sample matches well with the microstructural features of the alloy. In addition, it has been shown by Jocumsen[44] that surface roughness is significantly influenced by hardness. Jocumsen[44] has shown that surface roughness improves with increasing hardness in the alloy. It has been shown previously that the hardness of the alloy using the optimised treatment is slightly lower than the hardness of the alloy using the standard treatment. This relates well with the surface roughness behaviour of the alloy as it is shown that the optimised treatment sample had a slightly poorer surface finish and lower hardness than the standard treatment sample. Furthermore, it has been shown that hardness is directly related to frequency of cutting tool vibration, with a higher level of hardness leading to a higher level of frequency of cutting tool vibration. Hence, the lower hardness in the optimised treatment sample gave rise to a lower frequency of cutting tool vibration.

The results obtained from this machinability analysis have shown that the surface roughness of the alloy is slightly poorer in the optimised treatment sample but the frequency of cutting tool vibration is improved. The results from this investigation are encouraging as it is shown that the desired benefit of lower cutting tool vibrations is achievable using the optimised treatment and there is only a slightly poorer surface finish after machining. However, this poorer surface finish is not significant as it is still well within an acceptable level for a machined aluminium surface.

6.2 PAINT FINISH ANALYSIS

The particular test used in this instance was a measure of paint adhesion to the alloy. A two part test was used that involved immersing the test specimen in hot water at a particular temperature for a predetermined period of time followed by an assessment of paint adhesion. The particular test used in this instance is a standard testing procedure at SAPL. Details of the Hot Water Immersion and Paint Adhesion tests will follow shortly. It is first useful to describe briefly the method by which test specimens were prepared.

Five test specimens were used in total from both the optimised and the standard treatments for analysing the effect the optimised heat treatment process has on the painted finish of aluminium wheels. Five specimens only were needed from each treatment to provide qualitative and quantitative results. Specimens were cut from wheels that had been subjected to the following production processes:

- Each of the five wheels from either treatment were cast using the low pressure die casting techniques at SAPL described previously.

- Five wheels were prepared using the optimised heat treatment process detailed previously and five wheels were prepared using the standard heat treatment process detailed previously.

- Each of the five wheels from either treatment were shot blast, machined and painted using the standard techniques used at SAPL for the preparation of normal production wheels.

- One test specimen was cut from each of the five wheels from either treatment making a total of five test specimens for the optimised treatment and five test specimens for the standard treatment.

It can be seen from the production process followed for the preparation of the test specimens that the batch of test specimens from either treatment differed only by the amount of solution treatment that either batch of specimens had been subjected to. This was necessary to maintain consistency throughout the testing procedure in comparing the quality of the final product between both the optimised and the standard heat treatment processes.

Hot Water Immersion Test

Before evaluation of paint adhesion between the alloy surface and the paint film could commence it was necessary to subject the test specimens to the Hot Water Immersion Test. This particular test is not sufficient alone for analysing paint adhesion but is necessary as a preparation test that allows paint adhesion to be subsequently evaluated. A procedure was adhered to that outlined the conditions for successfully completing the Hot Water Immersion Test. The experimental set-up used is shown in Figure 6.8. The test involved placing the test specimen in a bath containing demineralised water maintained at a temperature of 60°C. The test piece was submerged in the water for a period of seventy two hours without interruption. After this time had elapsed the test piece was removed from the water and left to sit at room temperature for a period of twenty four hours. The test piece was then assessed for

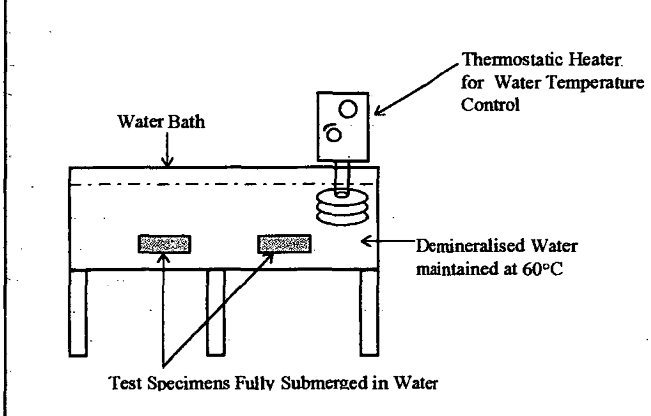


Figure 6.8: Experimental Set-Up for Hot Water Immersion Test

blistering, change in colour and gloss. The adhesion performance was assessed using the paint adhesion test detailed below.

Cross-Cut Adhesion Test

This test was used in conjunction with the Hot Water Immersion Test for measuring adhesion between the alloy surface and the paint film. Again, a standard procedure that outlined the testing method was adhered to. The first step of the analysis was to cut, using a specified cutter, a square check area on the test sample consisting of eleven horizontal and eleven vertical lines, spaced at two millimetres and reaching the substrate. An example of the cut area on the test specimen is shown in Figure 6.9. Once this area had been cut the next step was to press firmly a sheet of cellophane tape over the pattern, using a rubber eraser to ensure good contact and to expel any air bubbles that may be present. The test was then completed by pulling the tape up quickly and away from the painted surface. The test specimen was then examined to determine the type and extent of the damage and was assessed by comparing the specimen with the relevant customer specifications.

Figure 6.9: Test Specimen Showing Cut Tessellated Area

An example of a tested area is shown in Figure 6.10 to give an indication of the types of failures that may occur in any one given square section of the cut area. There is one hundred squares in total inside the cut area. The example given in Figure 6.10 shows the varying degrees of paint removal that may occur on any of the one hundred squares as the cellophane tape is pulled quickly away from the specimen. The grading of the specimen as a pass or failure is completed by examining each of the squares within the tested area and giving the specimen a rank from 10 to 0 depending on the result. The method of ranking is shown in Figure 6.11 with an explanation of the particular

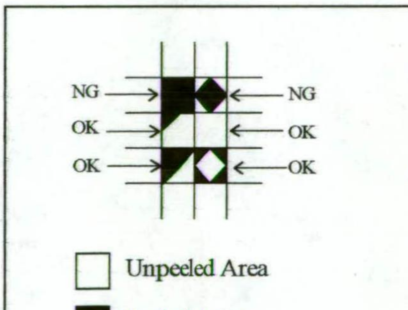


Figure 6.10: Example of Tested Area

ranking given in Table 6.1. It can be seen that the most desirable ranking for paint adhesion is 10 whilst a ranking of 0 is undesirable.

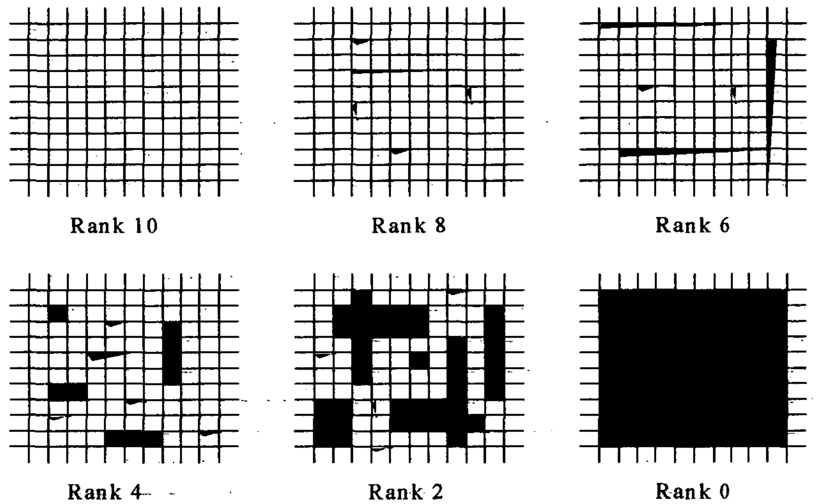


Figure 6.11: Examples of the Ranking Procedure for the Cross-Cut Adhesion Test

TABLE 6.1: Ranking in Cross-Cut Adhesion Test

Rank	Degree of Damage
10	Both sides of each cut are thin and smooth with no peeling at the point of intersection or in each of the squares
8	Slight peeling is found at the point of intersection but not in each of the squares, with the damaged area accounting for 5% or less of the total area of the squares
6	Peeling is found on either side of a cut and at the point of intersection, with a damaged area accounting for 5 to 15% of the total area of all squares
4	Peeling caused by a cut is wide, with a damaged area accounting for 15 to 35% of the total of all the squares
2	Peeling caused by a cut is broader than Rank 4, with a damaged area accounting for 35 to 65% of the total area of all the squares
0	The area of peeling is 65% or more of the total area of all the squares

The results of the Hot Water Immersion and the Cross-Cut Adhesion tests are recorded on a worksheet. This worksheet is reproduced in Table 6.2 with the results shown for the five specimens tested from both the optimised and the standard heat treatment processes. The colour, gloss, adhesion and overall result of the test specimens are noted in the table.

TABLE 6.2: Paint Test Results for Optimised and Standard Treatment Specimens

	Sample Number	Colour	Gloss	Adhesion	Overall Result
Optimised	1	Pass	Pass	Pass	Pass (Rank 10)
	2	Pass	Pass	Pass	Pass (Rank 10)
	3	Pass	Pass	Pass	Pass (Rank 9)
	4	Pass	Pass	Pass	Pass (Rank 9)
	5	Pass	Pass	Pass	Pass (Rank 10)
Standard	1	Pass	Pass	Pass	Pass (Rank 9)
	2	Pass	Pass	Pass	Pass (Rank 9)
	3	Pass	Pass	Pass	Pass (Rank 8)
	4	Pass	Pass	Pass	Pass (Rank 8)
	5	Pass	Pass	Pass	Pass (Rank 9)

It can be seen that each of the specimens had a pass as an overall result from both the optimised and the standard treatments. Furthermore, the results were similar in either instance. This finding is significant as it indicates the optimised heat treatment process has no detrimental effect on the painted finish of the wheel. The outcome of this paint finish analysis is significant as it has been shown through quantitative and qualitative results that the optimised heat treatment process has a non-detrimental effect on the painted finish of the alloy wheels. There was no underlying factor that suggested the optimised heat treatment process may have a detrimental affect on the painted finish of the wheel but nevertheless it is useful to conduct an experimental investigation to study the effect and consequently have experimental evidence as proof.

6.3 CONCLUDING REMARKS

The findings from this investigation have major implications in regard to optimising the heat treatment process at SAPL. Firstly, the machinability analysis has shown that the optimised heat treatment process has no real affect on the machinability of the alloy. A comparison of the optimised treatment and the standard treatment has shown surface roughness after machining to be slightly poorer in the optimised treatment sample but frequency of cutting tool vibration to be lower. It was shown that the poorer surface roughness was not significant as the achieved level was well within the acceptable limits. Furthermore, a paint finish analysis has shown the optimised treatment to have no real affect on the painted finish of the alloy wheel. A comparison of the optimised treatment and the standard treatment has shown that the painted finish of the wheel is similar in either instance. The measure of machinability and painted finish along with the mechanical properties is necessary and sufficient to evaluate fully the optimised treatment as a viable process. The measure of these three parameters together with the evaluation criteria used for the optimised treatment allows some conclusions to be drawn in regard to using the optimised treatment at SAPL. These conclusions are highlighted in the following chapter.

CHAPTER SEVEN

FINAL CONCLUDING REMARKS AND RECOMMENDATIONS FOR FUTURE WORK

The importance of productivity improvements in manufacturing organisations has been highlighted in this work. It was shown that productivity improvements have a substantial influence on the economic health of a manufacturing organisation. Productivity improvements were identified as being obtainable through implementing manufacturing techniques to achieve optimum product flow and reduce processing time. An investigation of a modern manufacturing plant, Southern Aluminium Pty Ltd, or SAPL, revealed that productivity improvements for the plant were possible through a substantial reduction in processing time of a major manufacturing operation. Heat treatment was identified as being the greatest contributor to total wheel manufacturing processing time and thus seen as being the operation that would result in significant productivity improvements if its processing time was substantially reduced. Heat treatment has been shown to be a necessary operation in the production of aluminium wheels to improve their mechanical properties from the 'as-cast' condition and consequently prepare them for use on passenger vehicles. It has been shown that the principal reason for optimising heat treatment is to obtain a significant decrease in wheel processing time whilst an increase in defect detection time, lower plant power costs and floor space savings due to the lower capacity requirements of the optimised treatment associated equipment have been highlighted as secondary benefits. It is also recognised that product flow through the plant is improved as a result of optimising the process of heat treatment.

A literature survey conducted to investigate the process of heat treatment and its effect on the mechanical properties of aluminium alloy 601, the working material used at SAPL for the production of aluminium wheels, gave insight into optimisation of the heat treatment process. The literature survey has shown that varying alloy content and heat treatment time and temperature significantly influence the mechanical properties of aluminium alloy 601. Furthermore, preliminary experimental work carried out at the major research laboratories of Comalco Aluminium Ltd gave encouraging results for optimising the heat treatment process with the majority of mechanical strength still retained in the final product. It has been shown that a solution treatment condition incorporating an isothermal holding period of ten minutes at 540°C is sufficient to achieve a level of tensile strength and percentage elongation in the alloy close to that achieved using the standard heat treatment process.

A small scale experimental heat treatment cell was developed at SAPL in order to establish an optimised heat treatment process. The experimental heat treatment cell developed allowed for heat treatment of the alloy using an optimised heat treatment cycle in a combined casting and heat treatment process. It has been shown through some experimental investigations that the functioning and behaviour of the heat treatment cell is of good order. Although an isothermal holding period of ten minutes at 540°C is sufficient to achieve the desired level of mechanical properties, it has been shown that it is necessary also to subject the alloy to a heating period in order to heat the wheel to 540°C. It has been shown through some preliminary experimental investigations that a heat-up period of twelve minutes was required to heat the wheel from its initial temperature immediately prior to solution treatment up to the maximum solution treatment temperature. This heat-up time was determined for the Mazda MX5 wheel type that was used as the test specimen for the initial stage of the major experimental investigation. Furthermore, it was found that two wheels of significantly different mass and initial temperature can both be heated in a common time of approximately twelve minutes due to the higher initial temperature of the heavier mass wheel. It has been shown that the determined heat-up time of twelve minutes for the test specimen combined with an isothermal holding time of ten minutes led to the determination of a total solution treatment time of twenty two minutes. It is noted that the standard aging treatment of four and a half hours at 140°C was necessary for using this particular optimised solution treatment process.

Alloy wheels heat treated using this particular heat treatment process were tested to determine specific mechanical properties including hardness, yield strength, ultimate tensile strength, percentage elongation and impact resistance. It has been shown that these five properties allowed a quantitative and qualitative analysis of the optimised treatment. Evaluation of the optimised treatment as being sufficient for achieving the desired level of mechanical properties in the alloy has been completed using two criteria. It has been shown that these criteria were; i) comparison of the developed mechanical properties with the customer specifications, and ii) comparison of the developed mechanical properties in the alloy using both the optimised and the standard treatments.

A five stage experimental investigation was designed and carried out to examine the behaviour of the alloy for varying heat treatment temperatures and times. It is shown that the initial stage of the investigation was used to compliment and match the mechanical properties obtained in previous work at the research laboratories of Comalco Aluminium Ltd whilst the further four stages of the investigation were needed to investigate the effect of varying solution treatment temperature and time on the mechanical properties of the alloy. The results of the five stages completed have shown that both solution treatment temperature and time have a significant influence on the development of mechanical properties in aluminium alloy 601. The chief outcome of the five stage experimental investigation is that an optimised solution treatment process of twenty two minutes at 570°C is necessary and sufficient to achieve a level of mechanical properties that meet with the relevant customer specifications and are comparable to those developed using the standard treatment. In addition, a machinability analysis of the alloy heat treated using the optimised and the standard treatments has shown that the machinability of the alloy is not significantly affected. It has been shown that the optimised heat treatment process caused a slightly poorer machined surface finish of the alloy but produced a decrease in the frequency of the cutting tool vibration. Furthermore, it has been shown that the painted finish of the alloy wheel is also not affected by the implementation of the optimised heat treatment process. It has been shown that adhesion of paint to the alloy surface is similar for both the optimised and the standard treatments.

A relationship between the change in tensile properties of the alloy and the change in microstructure was determined and found to be comparable with previously determined relationships in research[34]. It was found that the change in microstructural features of the alloy matched well with the change in mechanical properties. This witnessed relationship gave confidence in the reliability of the results.

As a result of using the optimised treatment processing time is substantially reduced, leading to significant productivity improvements at the plant. Furthermore, implementation of the optimised treatment gives rise to a substantial improvement in product flow.

RECOMMENDATIONS FOR FUTURE WORK

The following are recommendations for future work that can be incorporated into the heat treatment techniques used at SAPL to achieve further productivity improvements.

- There is an opportunity to optimise the existing aging treatment used at SAPL. It has been documented that only the solution treatment part of the heat treatment process has been optimised as a result of the work completed to date. There is an opportunity to optimise the heat treatment process further if the existing aging treatment can be used in conjunction with the optimised solution treatment process without affecting the mechanical properties or quality of the final product.

- It may be possible to achieve further reductions in heat treatment time whilst retaining the current level of mechanical properties in the alloy if the alloy content is modified to include strength improving elements. Some work has been documented to suggest that an increase in strontium for example leads to an increase in the strength and elongation of the alloy. It may be possible to further optimise heat treatment time using modification of the alloy.

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APPENDIX A: SCHEMATICS OF EXPERIMENTAL APPARATUS

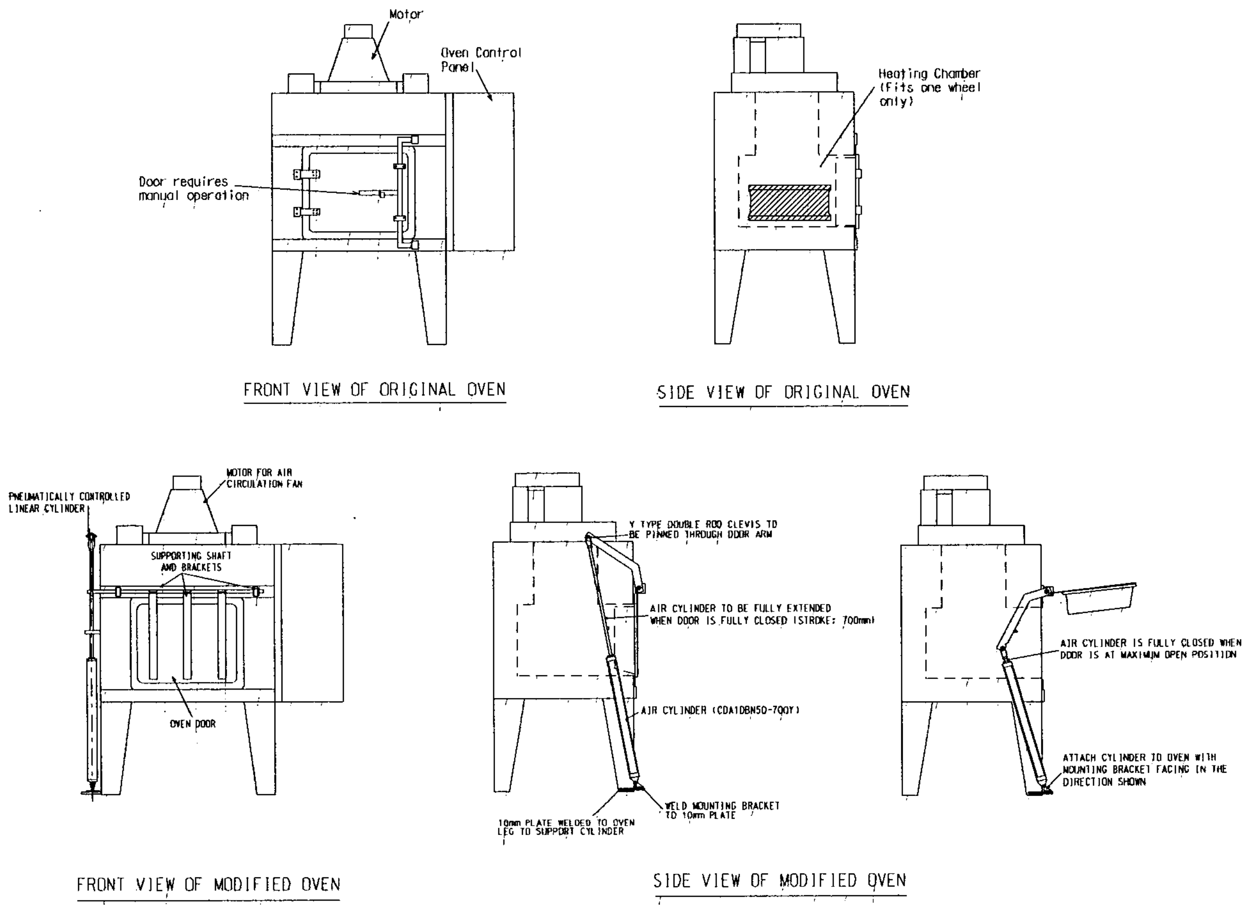

Figure A.1 : Solution Treatment Oven Details and Oven Door Modifications

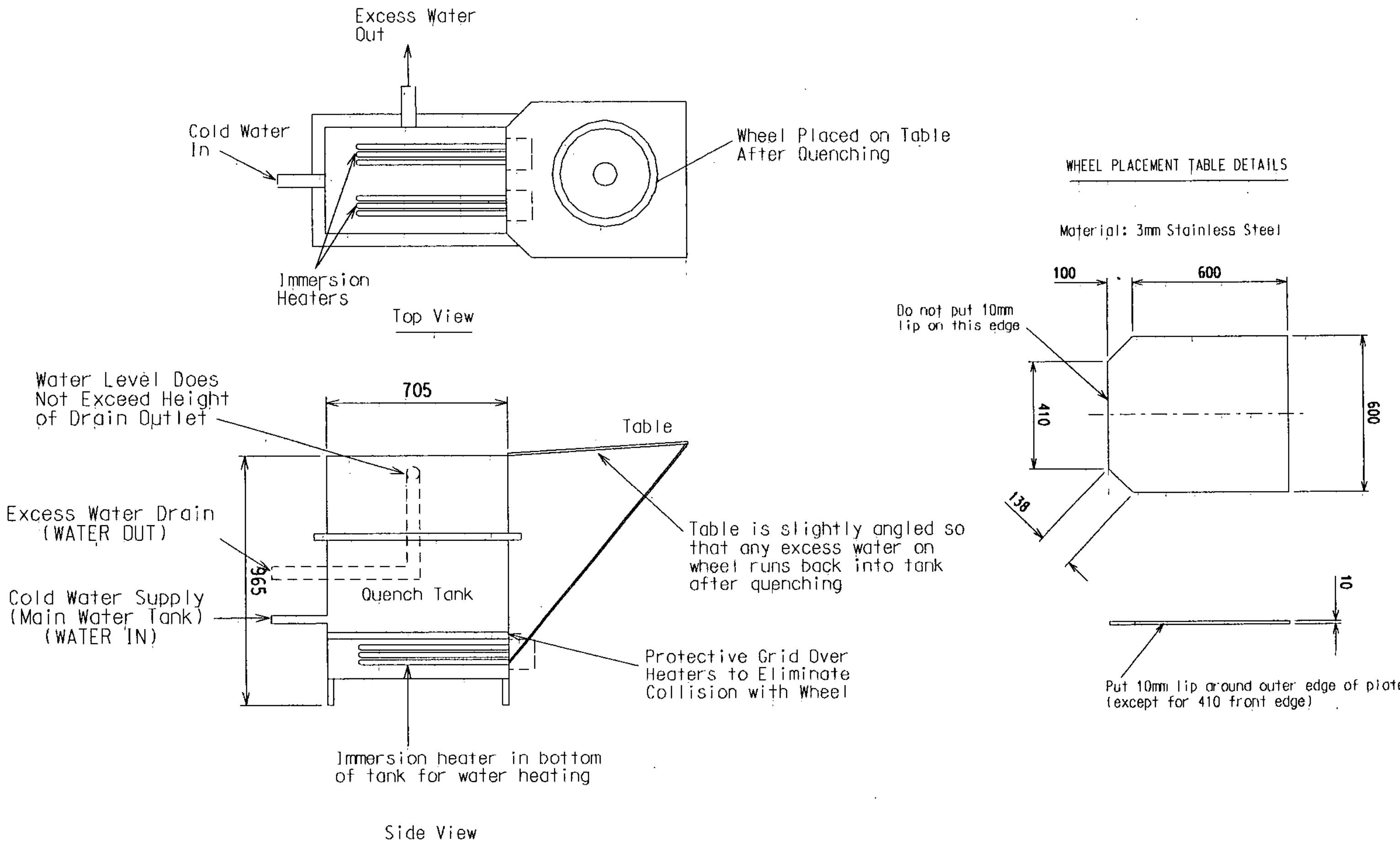

Figure A.2 : Quench Tank and Wheel Placement Table Details

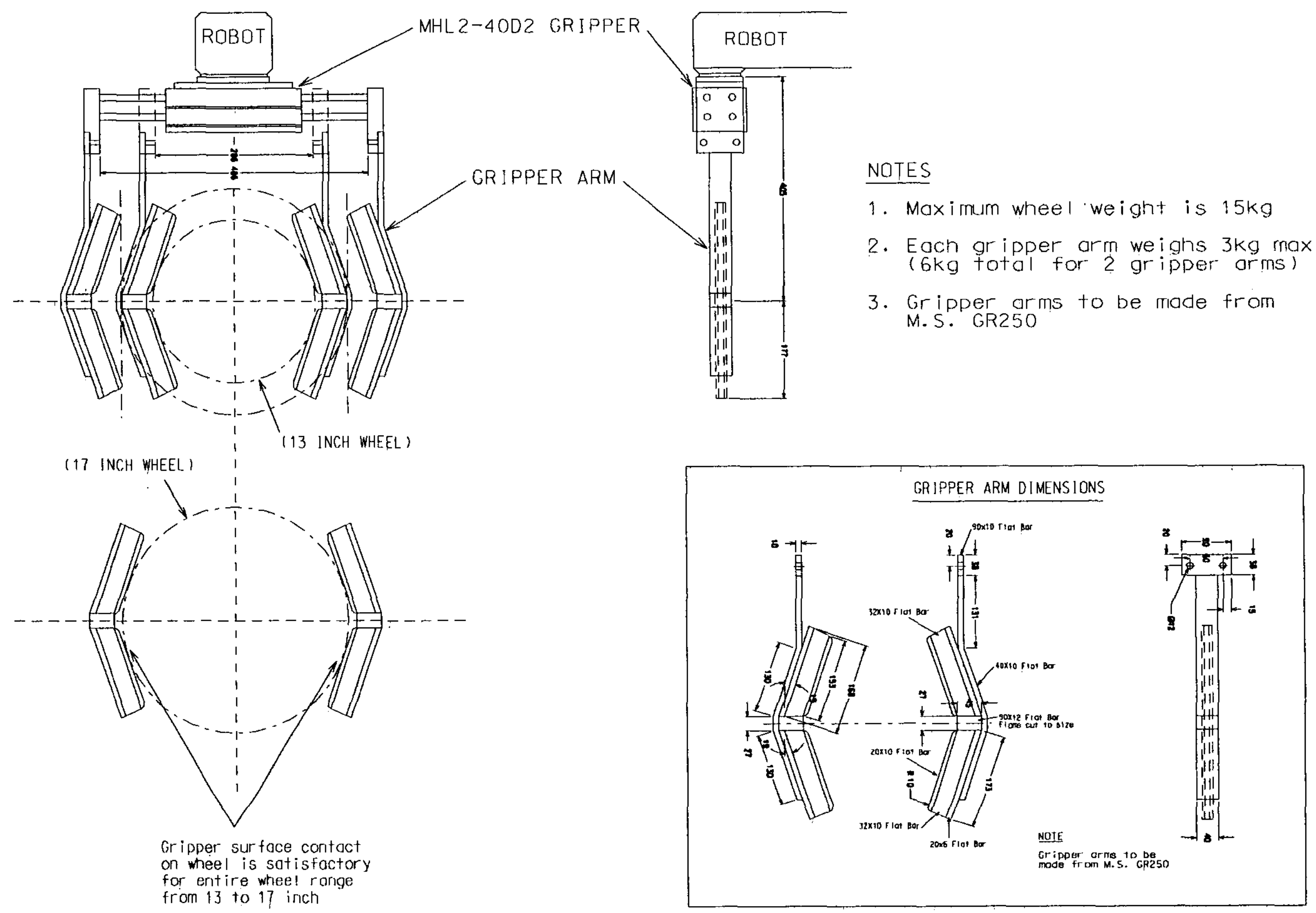

Figure A.3 : Robot Gripper and Arm Details

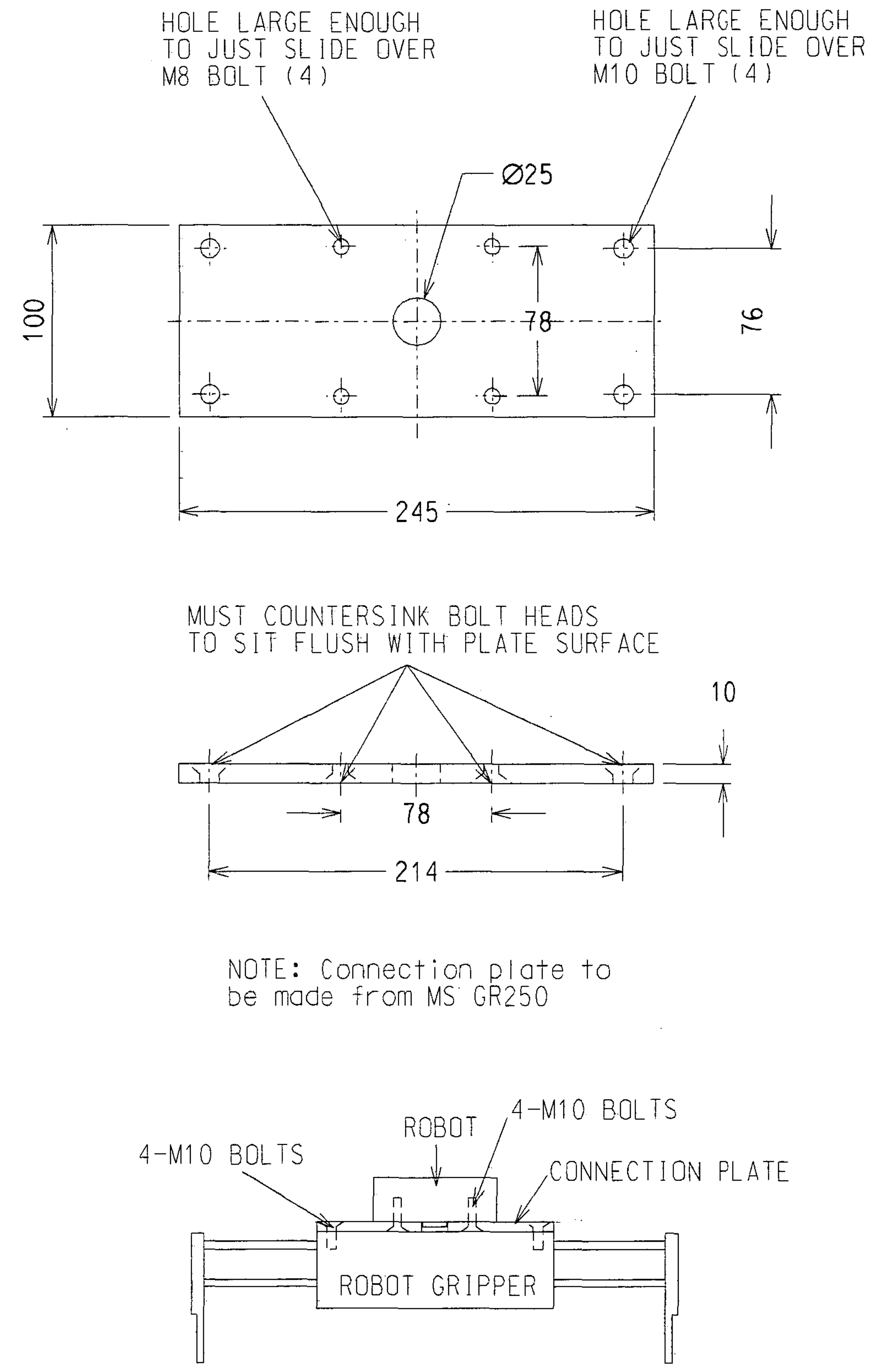

Figure A.4: Robot to Gripper Connection Plate

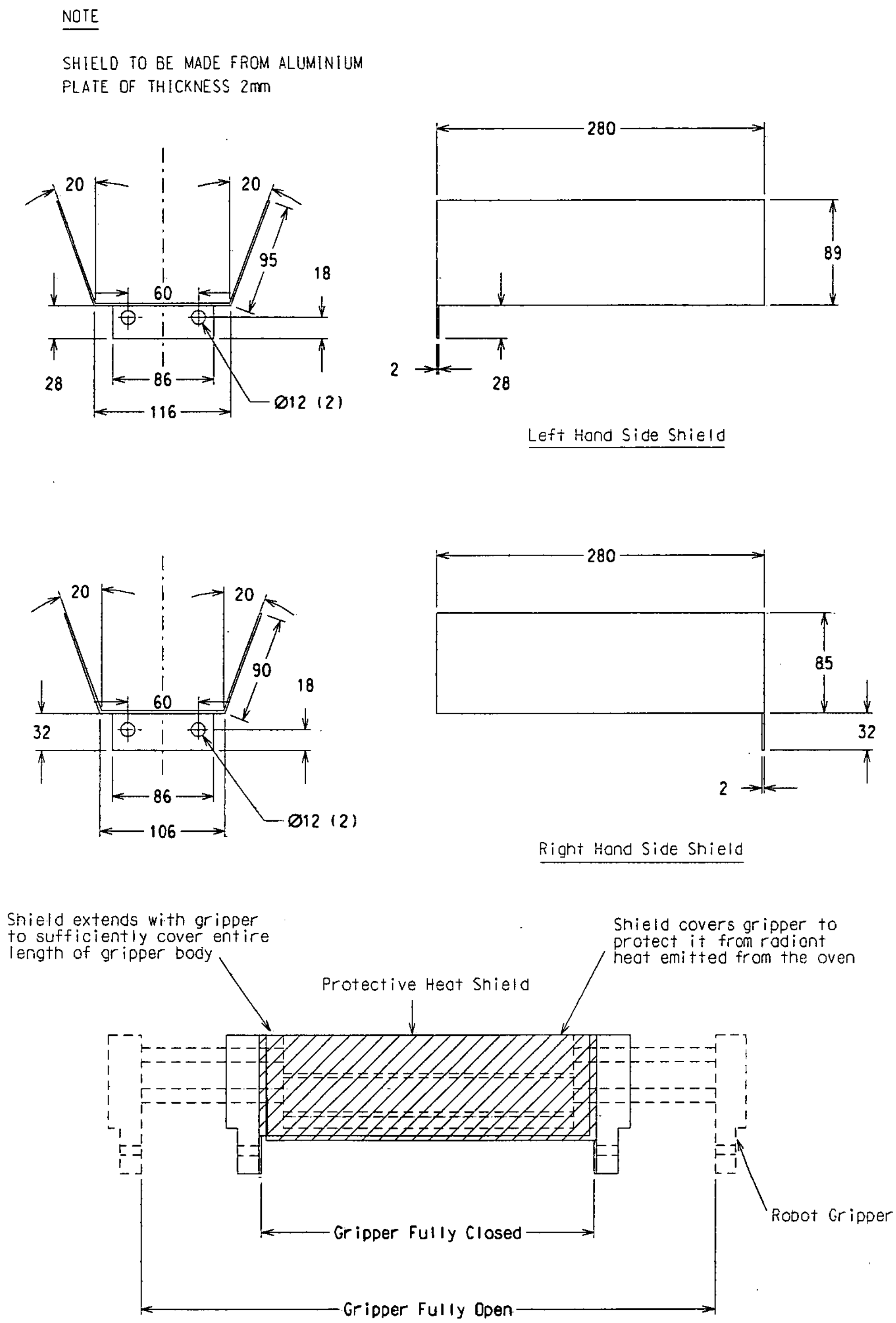

Figure A.5: Robot Gripper Protective Heat Shield

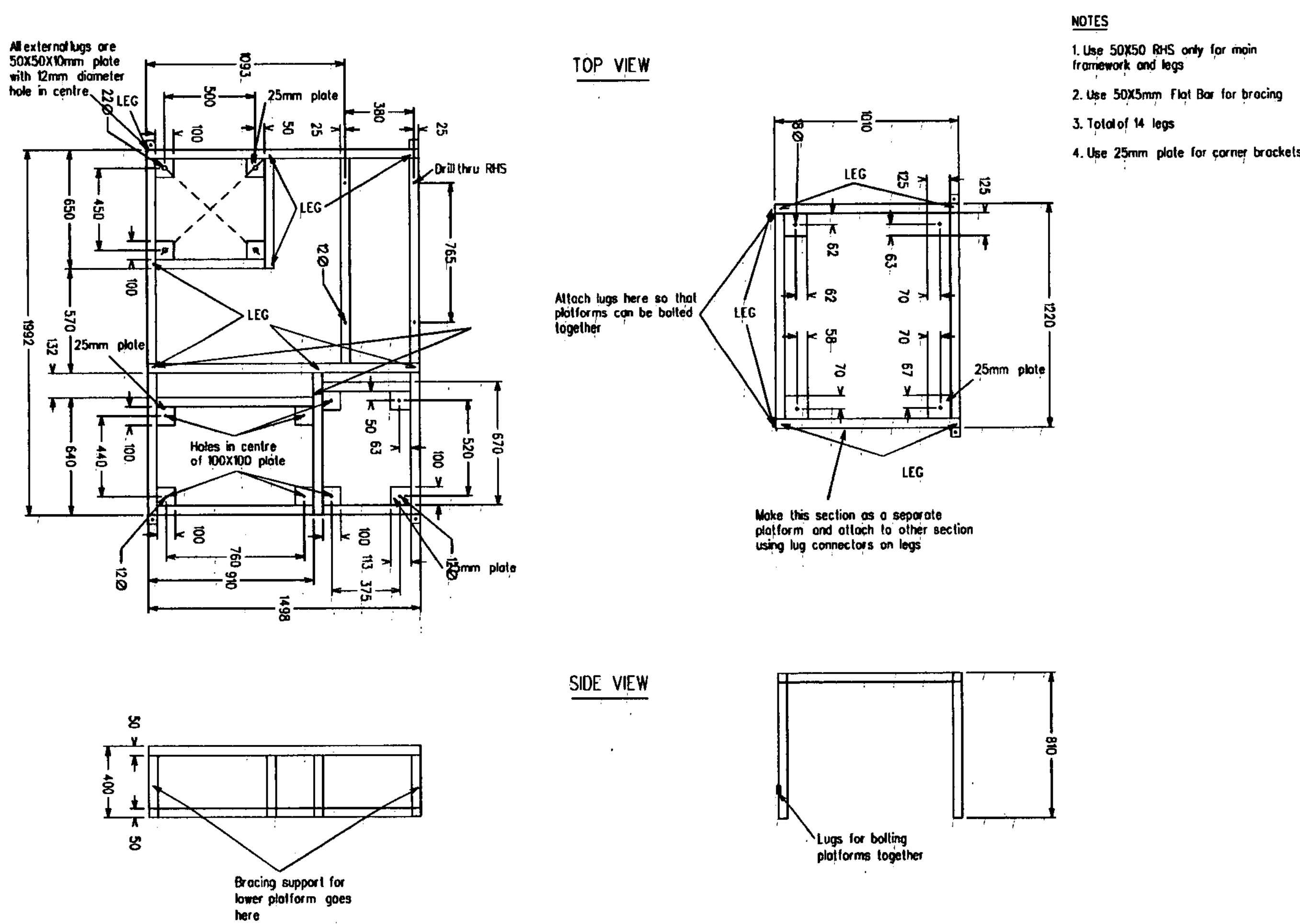

Figure A.6: Details of Base used for Heat Treatment Cell

APPENDIX B: ROBOT PROGRAM USED FOR SOLUTION TREATMENT PROCESS

JOB NAME: HEATREAT

JOB DESCRIPTION: Master Job for Program Execution

Line	Step	Instruction	Function
0000	000	NOP	Start of Program
0001		DOUT OT#10 = 1	Sends output signal from robot to casting machine to signal that the robot is ready to remove a wheel
0002		WAIT IN#01 = 1	Sends input signal to robot from casting machine to signal that that the casting machine is ready for the robot to remove a wheel
0003		HAND1 OFF T=0.5	Ensures that the robot gripper is open before program starts
0004		CALL JOB: JOB1	Lines 0004 to 0007 are used to call individual jobs to be used in the main program (Note: Individual jobs are detailed on the following pages)
0005		CALL JOB: JOB2	
0006		CALL JOB: JOB3	
0007		CALL JOB: JOB4	
0008		DOUT OT#10 = 0	Sends output signal from robot to casting machine to signal that the robot has removed a wheel and is clear of the casting machine
0009		WAIT IN#08 = 1 T=1320	Wheel stays in the solution treatment oven for twenty-two minutes (1320s) for shortened solution treatment
0010		CALL JOB: JOB5	Lines 0010 to 0013 are used to call individual jobs to be used in the main program
0011		CALL JOB: JOB6	
0012		CALL JOB: JOB7	
0013		CALL JOB: JOB8	
0014		END	End of Program

JOB NAME: JOB1

JOB DESCRIPTION: Remove a Wheel from the Transfer Trolley

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=15.00	Lines 0001 to 0016 are a series of move commands that are used to move the robot from its home position to the transfer trolley, ready to remove a wheel. (VJ=15.00 indicates that the robot speed is fifteen percent of its maximum allowable speed)
0002	002	MOVJ VJ=15.00	
0003	003	MOVJ VJ=15.00	
0004	004	MOVJ VJ=15.00	
0005	005	MOVJ VJ=15.00	
0006	006	MOVJ VJ=15.00	
0007	007	MOVJ VJ=15.00	
0008	008	MOVJ VJ=15.00	
0009	009	MOVJ VJ=15.00	
0010	010	MOVJ VJ=15.00	
0011	011	MOVJ VJ=15.00	
0012	012	MOVJ VJ=15.00	
0013	013	MOVJ VJ=15.00	
0014	014	MOVJ VJ=15.00	

0015	015	MOVJ VJ=15.00	
0016	016	MOVJ VJ=15.00	
0017		HAND1 ON T=3.50	The robot gripper closes on the wheel and remains there for 3.5s to ensure a sufficient grip of the wheel
0018	017	MOVJ VJ=15.00	Lines 0018 to 0029 are a series of move commands used to move the robot gripper and wheel away from the casting machine and towards the solution treatment oven
0019	018	MOVJ VJ=15.00	
0020	019	MOVJ VJ=15.00	
0021	020	MOVJ VJ=15.00	
0022	021	MOVJ VJ=15.00	
0023	022	MOVJ VJ=15.00	
0024	023	MOVJ VJ=15.00	
0025	024	MOVJ VJ=15.00	
0026	025	MOVJ VJ=15.00	
0027	026	MOVJ VJ=15.00	
0028	027	MOVJ VJ=15.00	
0029	028	MOVJ VJ=15.00	
0030		END	

JOB NAME: JOB2

JOB DESCRIPTION: Place a Wheel in the Solution Treatment Oven for Shortened Solution Treatment

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=25.00	This command ensures that the robot is in a position that is clear of the oven door
0002		HAND2 OFF T=1.00	The oven door opens and one second passes before the robot can move again. This ensures that the robot does not move as the oven door is opening
0003	002	MOVJ VJ=25.00	Lines 0003 to 0009 are a series of move commands used to place a wheel in the oven
0004	003	MOVJ VJ=25.00	
0005	004	MOVJ VJ=25.00	
0006	005	MOVJ VJ=25.00	
0007	006	MOVJ VJ=25.00	
0008	007	MOVJ VJ=25.00	
0009	008	MOVJ VJ=25.00	
0010		HAND1 OFF T=1.50	The robot releases the wheel and remains stationary for 1.5s to ensure that the gripper is free of the wheel
0011	009	MOVJ VJ=25.00	Lines 0011 to 0015 are a series of move commands used to remove the robot gripper from the oven and clear of the oven door
0012	010	MOVJ VJ=25.00	
0013	011	MOVJ VJ=25.00	
0014	012	MOVJ VJ=25.00	
0015	013	MOVJ VJ=25.00	
0016		HAND2 ON T=1.00	The oven door closes and one second must pass before the robot can move again. This ensures

Line	Step	Instruction	Function
			that the robot does not collide with the oven door as it is closing
0017		END	

JOB NAME: JOB3

JOB DESCRIPTION: Pick-Up a Solution Treated Wheel from the Wheel Placement Table

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=5.00	Lines 0001 to 0003 are a series of move commands used to position the robot near the wheel ready to pick it up
0002	002	MOVJ VJ=5.00	
0003	003	MOVJ VJ=5.00	
0004		HAND1 ON T=1.50	The robot gripper closes on the wheel and holds for 1.5s to ensure that the robot has a sufficient grip of the wheel
0005	004	MOVJ VJ=25.00	Lines 0001 to 0012 are a series of move commands used to pick-up a solution treated wheel from the table and move to the robot home position
0006	005	MOVJ VJ=25.00	
0007	006	MOVJ VJ=25.00	
0008	007	MOVJ VJ=25.00	
0009	008	MOVJ VJ=25.00	
0010	009	MOVJ VJ=25.00	
0011	010	MOVJ VJ=25.00	
0012	011	MOVJ VJ=25.00	
0013		END	

JOB NAME: JOB4

JOB DESCRIPTION: Place a Solution Treated Wheel on the Transfer Trolley

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=25.00	Lines 0001 to 0016 are a series of move commands used to move the solution treated wheel to the transfer trolley, ready for the robot to release it
0002	002	MOVJ VJ=25.00	
0003	003	MOVJ VJ=25.00	
0004	004	MOVJ VJ=25.00	
0005	005	MOVJ VJ=25.00	
0006	006	MOVJ VJ=10.00	
0007	007	MOVJ VJ=10.00	
0008	008	MOVJ VJ=10.00	
0009	009	MOVJ VJ=10.00	
0010	010	MOVJ VJ=10.00	
0011	011	MOVJ VJ=10.00	
0012	012	MOVJ VJ=10.00	
0013	013	MOVJ VJ=10.00	
0014	014	MOVJ VJ=10.00	
0015	015	MOVJ VJ=10.00	
0016	016	MOVJ VJ=10.00	
0017		HAND1 OFF T=1.50	The robot gripper releases the wheel and remains stationary for 1.5s to ensure that the gripper is free of the wheel

0018	017	MOVJ VJ=10.00	Lines 0018 to 0031 are a series of move commands used to move the robot clear of the transfer trolley and casting machine
0019	018	MOVJ VJ=10.00	
0020	019	MOVJ VJ=10.00	
0021	020	MOVJ VJ=10.00	
0022	021	MOVJ VJ=10.00	
0023	022	MOVJ VJ=10.00	
0024	023	MOVJ VJ=10.00	
0025	024	MOVJ VJ=10.00	
0026	025	MOVJ VJ=10.00	
0027	026	MOVJ VJ=10.00	
0028	027	MOVJ VJ=10.00	
0029	028	MOVJ VJ=10.00	
0030	029	MOVJ VJ=10.00	
0031	030	MOVJ VJ=10.00	
0032		END	

JOB NAME: JOB5

JOB DESCRIPTION: Remove a Solution Treated Wheel from the Oven

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=25.00	This command ensures that the robot is in a position clear of the oven door
0002		HAND2 OFF T=1.00	The oven door opens and one second passes before the robot can move again. This ensures that the robot does not move as the oven door is opening
0003	002	MOVJ VJ=25.00	Lines 0003 to 0007 are a series of move commands used to position the robot inside the oven ready to pick-up a wheel
0004	003	MOVJ VJ=25.00	
0005	004	MOVJ VJ=25.00	
0006	005	MOVJ VJ=25.00	
0007	006	MOVJ VJ=25.00	
0008		HAND1 OFF T=1.50	The robot gripper releases the wheel and remains stationary for 1.5s to ensure that the gripper is free of the wheel
0009	007	MOVJ VJ=25.00	Lines 0009 to 0015 are a series of move commands used to remove the robot from the oven and clear of the oven door. The robot speed is increased for the final steps to minimise heat loss from the oven and shorten the time before quenching
0010	008	MOVJ VJ=25.00	
0011	009	MOVJ VJ=50.00	
0012	010	MOVJ VJ=50.00	
0013	011	MOVJ VJ=50.00	
0014	012	MOVJ VJ=50.00	
0015	013	MOVJ VJ=50.00	
0016		HAND2 ON T=1.00	The oven door closes and one second must pass before the robot can move again. This ensures that the robot does not collide with the oven door as it is closing
0017		END	

JOB NAME: JOB6

JOB DESCRIPTION: Quench a Solution Treated Wheel

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=50.00	Lines 0001 to 0005 are a series of move commands used to submerge the wheel into the quenchant. The speeds here are the maximum safe working speeds that can be used for this particular task
0002	002	MOVJ VJ=50.00	
0003	003	MOVJ VJ=50.00	
0004	004	MOVJ VJ=20.00	
0005	005	MOVJ VJ=20.00	
0006		WAIT IN#08=1 T=50.00	The wheel is held in the quenchant for 50s to allow sufficient cooling
0007	006	MOVJ VJ=15.00	Lines 0001 to 0005 are a series of move commands used to remove the wheel from the quenchant
0008	007	MOVJ VJ=15.00	
0009	008	MOVJ VJ=15.00	
0010	009	MOVJ VJ=15.00	
0011	010	MOVJ VJ=25.00	
0012		WAIT IN#08 = 1 T=5.00	The wheel is held above the quench tank for 5s to allow excess water to run from the wheel back into the quench tank
0013	011	MOVJ VJ=25.00	This move command is used to lift the wheel clear of the quench tank ready for the next operation
0014		END	

JOB NAME: JOB7

JOB DESCRIPTION: Place Heat Treated Wheel on Table

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=50.00	Lines 0001 and 0002 are move commands used to place a quenched wheel on the wheel placement table
0002	002	MOVJ VJ=25.00	
0003		HAND1 OFF T=2.50	The robot releases the wheel and remains stationary for 2.5s to ensure that the wheel is free from the gripper
0004		END	

JOB NAME: JOB8

JOB DESCRIPTION: Move the Robot from the Wheel Placement Table Back to its Home Position, Ready to Start Another Cycle

Line	Step	Instruction	Function
0000	000	NOP	
0001	001	MOVJ VJ=50.00	Lines 0001 to 0001 are a series of move commands used to move the robot gripper from
0002	002	MOVJ VJ=50.00	

0003	003	MOVJ VJ=50.00	the wheel back to the robot home position, ready for the robot to start another cycle
0004	004	MOVJ VJ=50.00	
0005	005	MOVJ VJ=50.00	
0006	006	MOVJ VJ=50.00	
0007	007	MOVJ VJ=50.00	
0008		END	The robot is in its home position at this point and is ready to commence another cycle, ie. start JOB1

NOTE: The robot is programmable to complete a desired number of program cycles, including a continuous option that allows the robot to continue executing program cycles until it is powered off.

APPENDIX C: EXPERIMENTAL RESULTS

TABLE C.1: Mechanical Properties Measured in Test Specimens (Stage One)

Sample Number	Hardness (500kg/10mm)		Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (%)	
	Std.	Opt.	Std.	Opt.	Std.	Opt.	Std.	Opt.
1	71.5	69.1	173.9	185.3	275.9	250.9	10.1	5.6
2	74.1	69.1	187.3	131.7	274.7	242.7	9.7	14.3
3	66.8	64.6	187.7	130.6	275.3	233.8	11.8	10.1
4	69.1	69.1	182.5	136.8	269.5	243.1	10.7	11.7
5	74.1	69.1	186.3	129.8	268.4	234.6	8.3	9.4
6	66.8	69.1	185.1	130.7	265.4	224.6	7.5	7.8
7	76.8	69.1	190.8	138.8	280.8	234.8	13.3	8.9
8	69.1	64.6	183.3	153.0	265.2	247.4	8.8	4.5
9	74.1	69.1	182.6	127.3	264.6	233.1	7.4	13.5
10	71.5	66.8	184.1	148.1	238.5	251.1	7.6	12.2
11	74.1	64.6	190.2	136.5	253.1	242.8	9.3	11.5
12	71.5	64.6	180.0	142.4	266.6	235.6	10.4	10.2
Mean	71.5	67.4	184.5	141.2	266.5	239.6	9.6	10.2

TABLE C.2: Mechanical Properties Measured in Test Specimens (Stage Two)

Sample Number	Hardness (500kg/10mm)		Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (%)	
	Std.	Opt.	Std.	Opt.	Std.	Opt.	Std.	Opt.
1	62.5	69.1	173.9	176.9	275.9	276.5	10.1	13.8
2	69.1	71.5	187.3	183.3	274.7	272.4	9.7	13.5
3	69.1	69.1	187.7	187.4	275.3	278.2	11.8	14.8
4	76.8	69.1	182.5	178.3	269.5	265.9	10.7	9.9
5	74.1	66.8	186.3	183.1	268.4	277.8	8.3	9.8
6	79.6	69.1	185.1	179.5	265.4	266.9	7.5	12.0
7	74.1	71.5	190.8	185.2	280.8	264.5	13.3	9.9
8	71.5	74.1	183.3	178.1	265.2	266.9	8.8	10.0
9	74.1	71.5	182.6	174.7	264.6	267.6	7.4	11.5
10	69.1	69.1	184.1	183.1	238.5	264.1	7.6	8.9
11	66.8	69.1	190.2	182.3	253.1	273.6	9.3	12.8
12	69.1	71.5	180.0	185.7	266.6	275.7	10.4	14.0
Mean	71.3	70.1	184.5	181.5	266.5	270.8	9.6	11.7

TABLE C.3: Mechanical Properties Measured in Test Specimens (Stage Three)

Sample Number	Hardness (500kg/10mm)		Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (%)	
	Std.	Opt.	Std.	Opt.	Std.	Opt.	Std.	Opt.
1	69.1	69.1	173.9	185.9	275.9	197.0	10.1	2.7
2	71.5	71.5	187.3	163.5	274.7	228.3	9.7	3.4
3	74.1	69.1	187.7	159.6	275.3	191.7	11.8	3.5
4	71.5	74.1	182.5	168.1	269.5	251.0	10.7	6.5
5	64.6	74.1	186.3	162.2	268.4	229.6	8.3	4.2
6	71.5	76.8	185.1	154.0	265.4	246.2	7.5	8.2
7	74.1	79.6	190.8	155.2	280.8	226.9	13.3	4.2
8	74.1	69.1	183.3	156.2	265.2	220.6	8.8	3.8
9	69.1	74.1	182.6	164.4	264.6	251.2	7.4	6.1
10	74.1	74.1	184.1	161.8	238.5	215.4	7.6	2.8
11	71.5	71.5	190.2	157.3	253.1	233.9	9.3	5.2
12	74.1	74.1	180.0	189.2	266.6	224.5	10.4	3.7
Mean	71.6	73.1	184.5	164.7	266.5	226.4	9.6	4.5

TABLE C.4: Mechanical Properties Measured in Test Specimens (Stage Four)

Sample Number	Hardness (500kg/10mm)		Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (%)	
	Std.	Opt.	Std.	Opt.	Std.	Opt.	Std.	Opt.
1	69.1	71.5	173.9	168.4	275.9	239.2	10.1	4.6
2	71.5	66.8	187.3	168.1	274.7	239.5	9.7	4.6
3	74.1	69.1	187.7	169.2	275.3	256.8	11.8	6.7
4	71.5	69.1	182.5	166.2	269.5	262.2	10.7	8.8
5	64.6	69.1	186.3	171.0	268.4	237.4	8.3	3.7
6	71.5	71.5	185.1	161.2	265.4	257.9	7.5	5.9
7	74.1	71.5	190.8	183.9	280.8	239.7	13.3	3.1
8	74.1	71.5	183.3	163.4	265.2	266.1	8.8	8.5
9	69.1	69.1	182.6	164.8	264.6	241.1	7.4	5.9
10	74.1	69.1	184.1	164.1	238.5	251.1	7.6	7.2
11	71.5	71.5	190.2	163.2	253.1	257.8	9.3	9.4
12	74.1	69.1	180.0	161.1	266.6	258.1	10.4	8.3
Mean	71.6	69.9	184.5	167.1	266.5	250.6	9.6	6.4

TABLE C.5: Mechanical Properties Measured in Test Specimens (Stage Five)

Sample Number	Hardness (500kg/10mm)		Yield Strength (MPa)		Tensile Strength (MPa)		Elongation (%)	
	Std.	Opt.	Std.	Opt.	Std.	Opt.	Std.	Opt.
1	69.1	74.1	173.9	172.3	275.9	262.6	10.1	5.6
2	71.5	71.5	187.3	178.9	274.7	260.9	9.7	4.7
3	74.1	69.1	187.7	168.2	275.3	273.5	11.8	8.0
4	71.5	74.1	182.5	182.3	269.5	281.9	10.7	8.4
5	64.6	71.5	186.3	175.0	268.4	247.3	8.3	4.2
6	71.5	69.1	185.1	179.0	265.4	251.9	7.5	4.5
7	74.1	69.1	190.8	165.3	280.8	276.5	13.3	12.0
8	74.1	71.5	183.3	178.9	265.2	279.2	8.8	8.1
9	69.1	74.1	182.6	167.7	264.6	235.6	7.4	4.3
10	74.1	71.5	184.1	175.3	238.5	246.0	7.6	3.8
11	71.5	71.5	190.2	180.8	253.1	271.2	9.3	7.1
12	74.1	69.1	180.0	163.5	266.6	274.7	10.4	11.5
Mean	71.6	71.4	184.5	173.9	266.5	263.4	9.6	6.8

WHEEL: MX5 **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 0° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Standard T6 Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.6: Impact Test Results (Stage One)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
310												X						X												
300											O		X				O		X											
290										O				X		O				X										
280							X		O						O						X									
270						O		O														X		X				X		
260			X		O																		O		X		O		X	
250		O		O																						O				O
240	O																													
230																														
220																														
210																														

AVERAGE DROP HEIGHT (mm): 275

WHEEL: MX5 **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 0° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Optimised Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.7: Impact Test Results (Stage One)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
290																														
280																														
270																														
260		X																												
250	O		X																											
240				X		X																								
230					O		X				X																			
220								X		O		X				X														
210									O				X		O		X				X									
200														O				X		O		X		X						
190																			O				O		X					
180																										X				O
170																											X		O	
160																												O		
150																														

AVERAGE DROP HEIGHT (mm): 221

WHEEL: J15 **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 0° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Standard T6 Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.8: Impact Test Results (Stage Two)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
460																													X	
450																												O		O
440																			X						X		O			
430																		O		X				O		O				
420																	O				X		O							
410																O						O								
400													X		O															
390												O		O																
380											O																			
370		X								O																				
360			X		X				O																					
350	O			O		X		O																						
340							O																							
330																														
320																														
310																														

AVERAGE DROP HEIGHT (mm): 392

WHEEL: J15 **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 0° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Optimised Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.9: Impact Test Results (Stage Two)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
460																														
450																														
440																														
430		X						X																		X				
420	O		X				O		X								X		X						O		X			
410				X		O				X				X		O		O		X		X		O				X		O
400					O						X		O		O						O		O						O	
390												O																		
380																														
370																														
360																														
350																														
340																														
330																														
320																														
310																														

AVERAGE DROP HEIGHT (mm): 421

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Standard T6 Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.10: Impact Test Results (Stage Three)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
410																														
400	X		X		X																									
390		O		O		X						X																		
380							X		X		O		X																	
370								O		O				X																X
360															X														O	
350																X										X		O		
340																	X								O		O			
330																		X		X				O						
320																			O		X		O							
310																						O								
300																														

AVERAGE DROP HEIGHT (mm): 382

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Optimised Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.11: Impact Test Results (Stage Three)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
320																														
310																														
300																														
290																														
280																														
270												X		X		X		X						O						
260	X		X								O		O		O		O		X				O		X					
250		O		X		X				O										X		O				X				O
240					O		X		O												O						X		O	
230								O																				O		
220																														
210																														
200																														

AVERAGE DROP HEIGHT (mm): 264

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Standard T6 Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.12: Impact Test Results (Stage Four)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
410																														
400	X		X		X																									
390		O		O		X						X																		
380							X		X		O		X																	
370								O		O				X																X
360															X														O	
350																X										X		O		
340																	X								O		O			
330																		X		X				O						
320																			O		X		O							
310																						O								
300																														

AVERAGE DROP HEIGHT (mm): 382

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Optimised Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.13: Impact Test Results (Stage Four)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
350																														
340																														
330																												X		
320																											O		X	
310				X																						O				X
300	X		O		X		X		X						X										O					
290		O				O		O		X		X		O		X						X		O						
280											O		O				X		X		O		O							
270																		O		O										
260																														
250																														
240																														

AVERAGE DROP HEIGHT (mm): 294

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Standard T6 Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.14: Impact Test Results (Stage Five)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
410																														
400	X		X		X																									
390		O		O		X						X																		
380							X		X		O		X																	
370								O		O				X																
360															X														X	
350																X										X		O		O
340																	X								O		O			
330																		X		X				O						
320																			O		X		O							
310																						O								
300																														

AVERAGE DROP HEIGHT (mm): 382

WHEEL: XR **IMPACT ANGLE:** 13° **ANGLE TO VALVE HOLE:** 210° **ASSESSMENT METHOD:** Visual Cracking

SAMPLE DESCRIPTION: Optimised Heat Treatment **DROP WEIGHT:** 560 kg

TABLE C.15: Impact Test Results (Stage Five)

DROP HEIGHT (mm)	A - SETUP												B						C						D					
WHEEL NO.	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
350																														
340																														
330		X																												
320	O		X																X											
310				X		X												O		X										
300					O		X		X		X				X		O				X		X							
290								O		O		X		O		O						O		X						O
280													O												X		X		O	
270																										O		O		
260																														
250																														
240																														

AVERAGE DROP HEIGHT (mm): 308

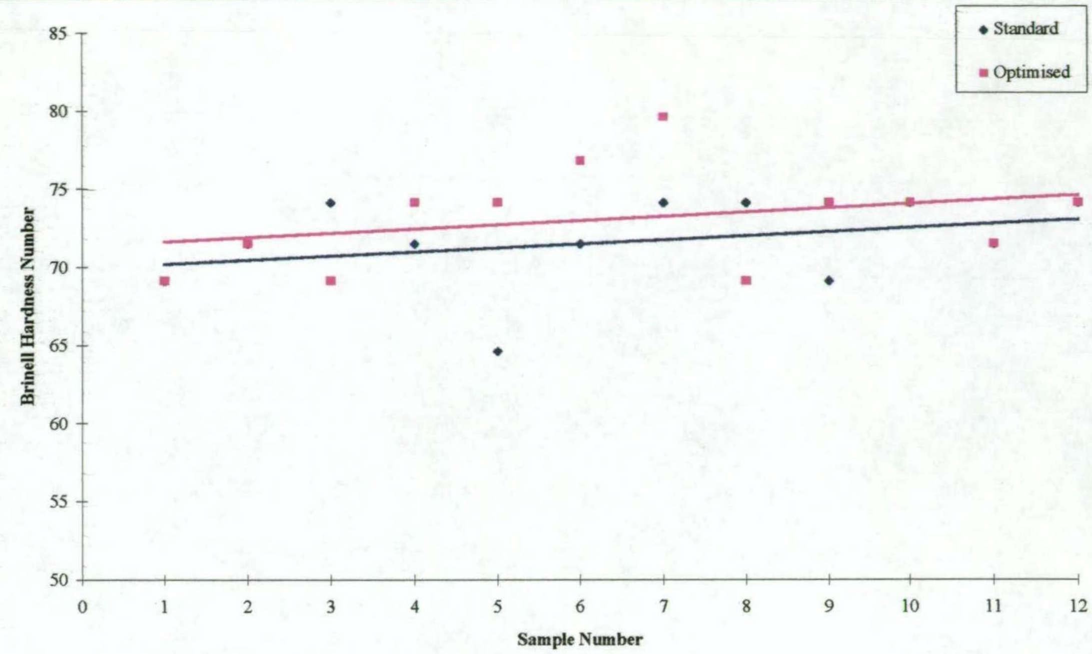

Figure C.1: Brinell Hardness Number (Stage Three)

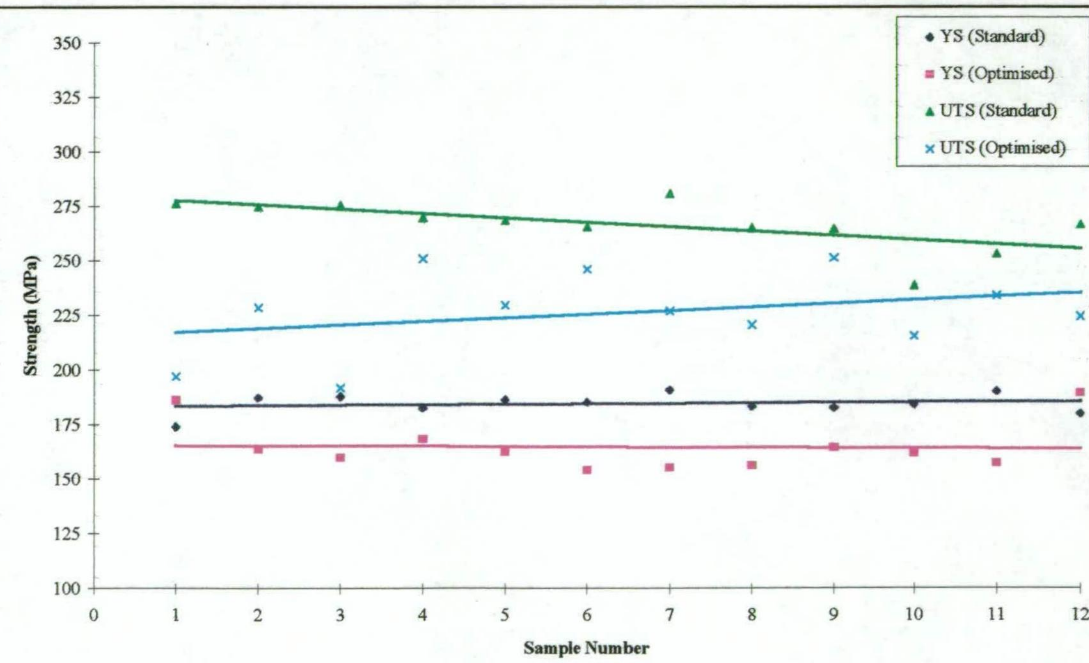

Figure C.2: Tensile Strength (Stage Three)

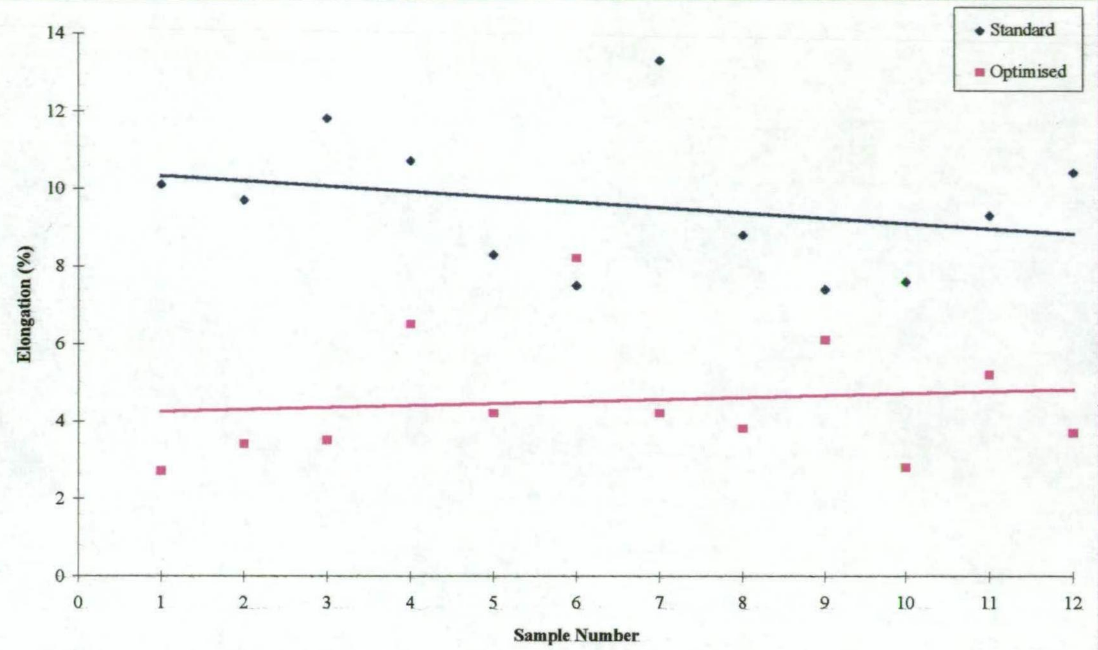

Figure C.3: Percentage Elongation (Stage Three)

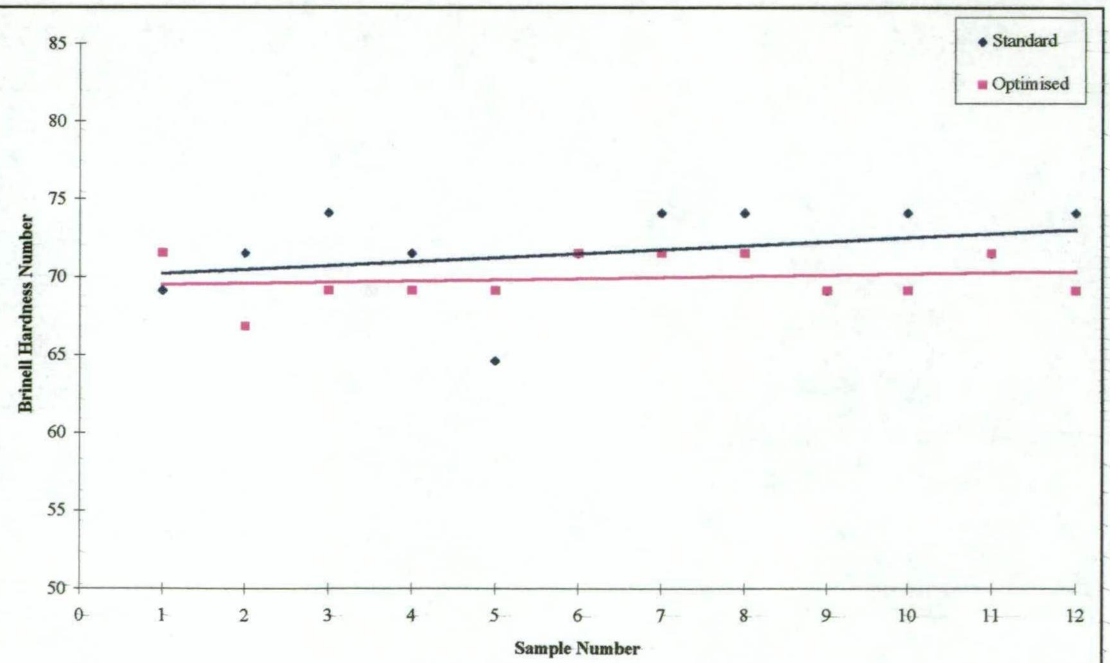

Figure C.4: Brinell Hardness Number (Stage Four)

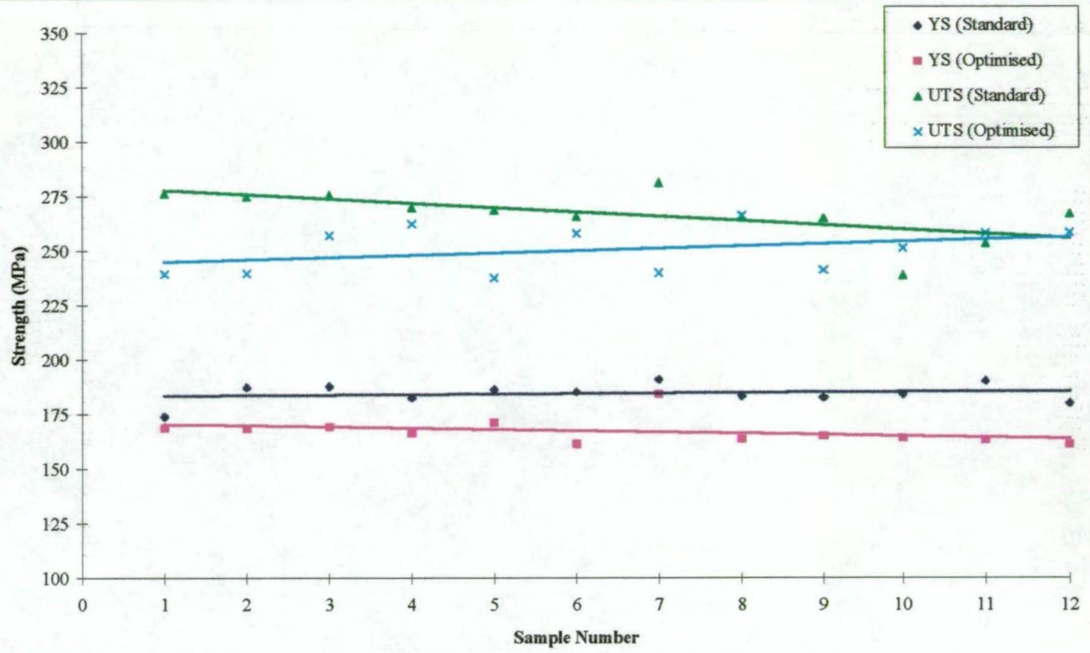

Figure C.5: Tensile Strength (Stage Four)

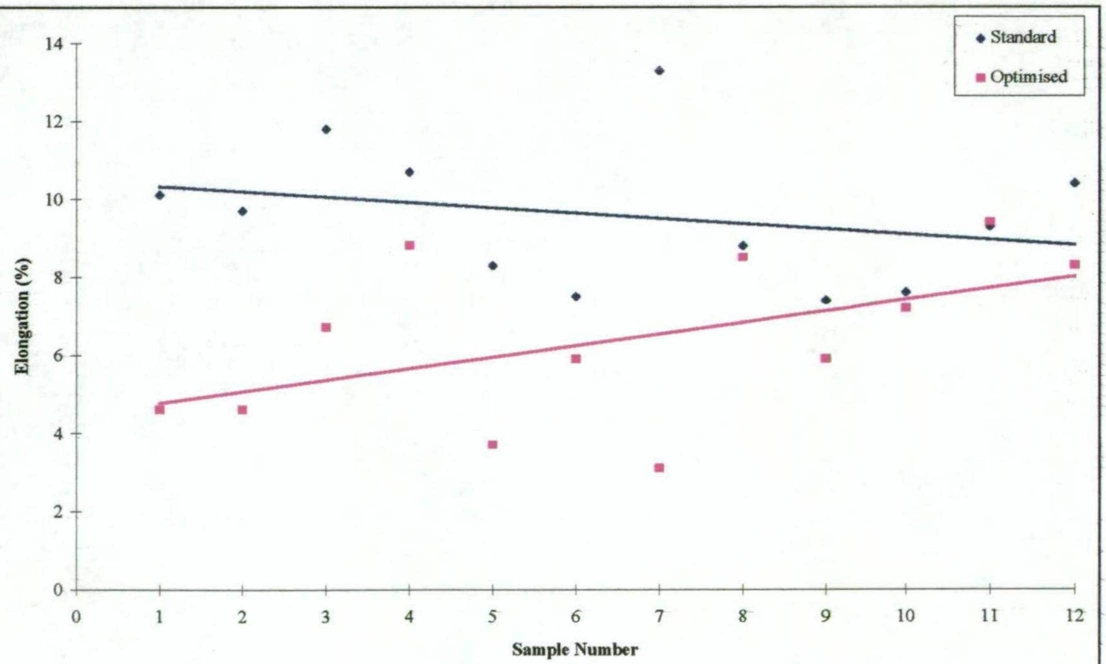

Figure C.6: Percentage Elongation (Stage Four)

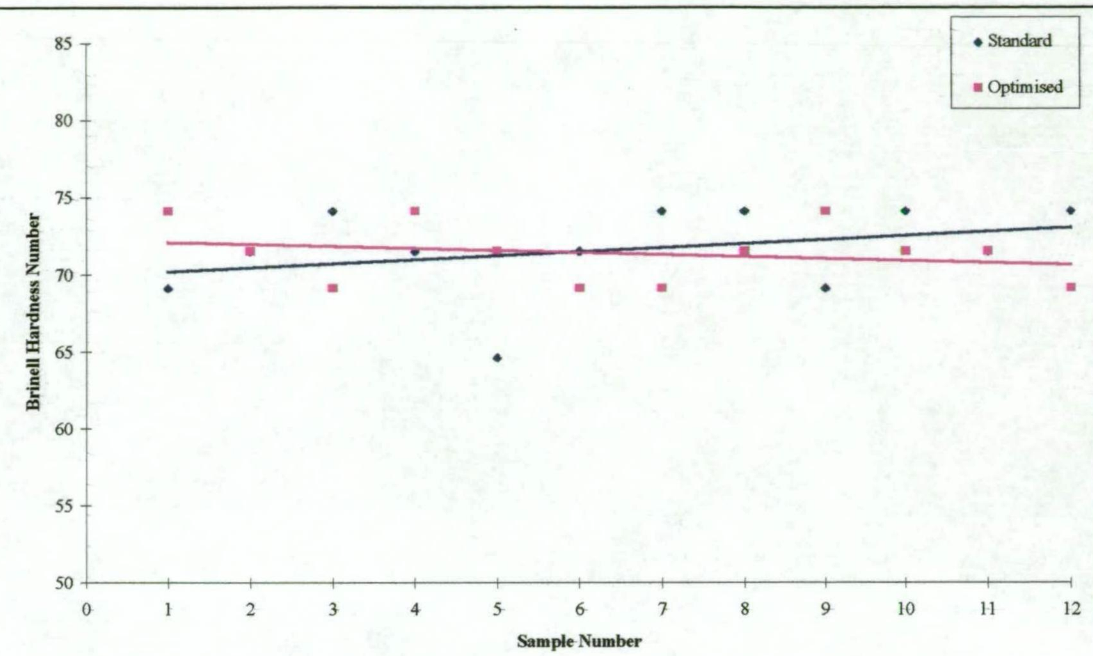

Figure C.7: Brinell Hardness Number (Stage Five)

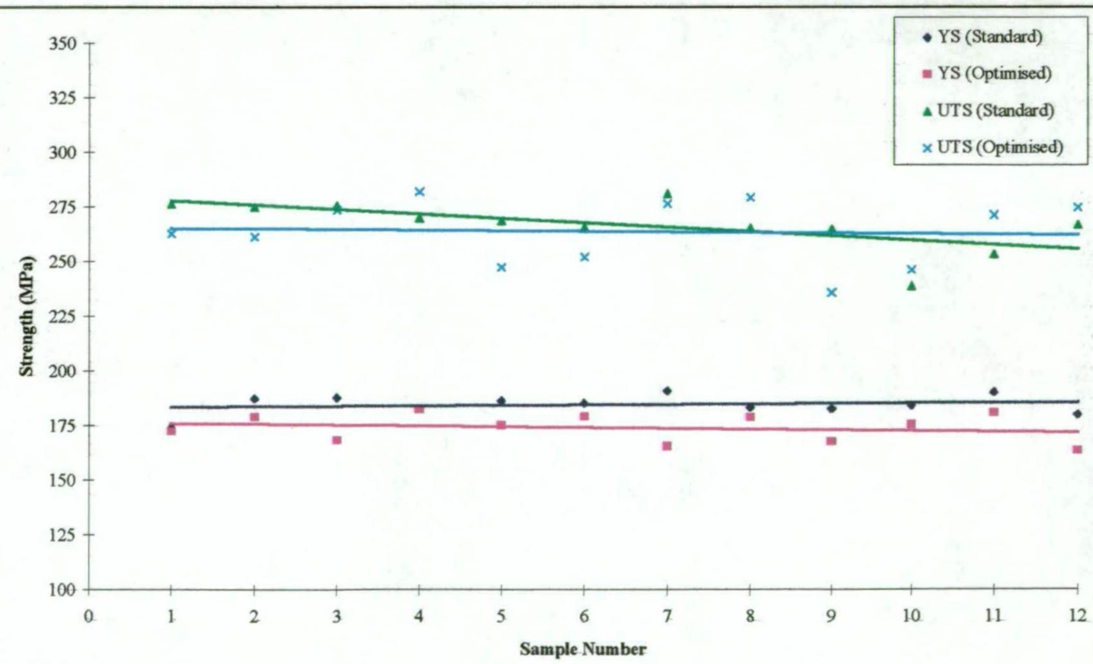

Figure C.8: Tensile Strength (Stage Five)

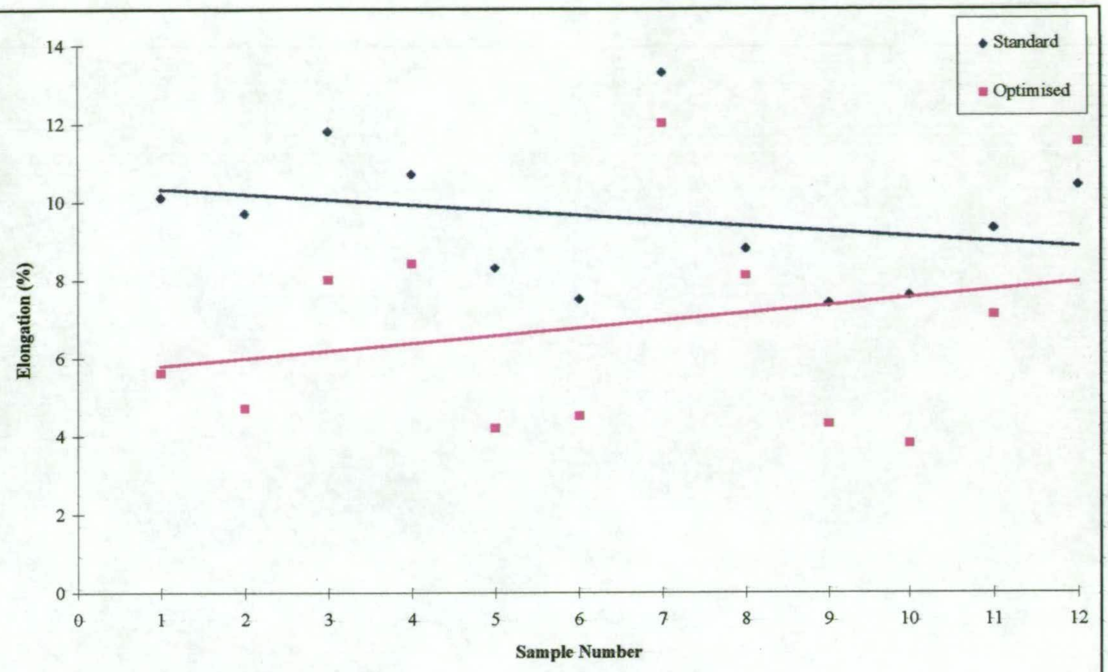

Figure C.9: Percentage Elongation (Stage Five)

APPENDIX D: PROGRAM USED FOR STATISTICAL ANALYSIS

PROGRAM T_F_TEST

VARIABLE DEFINITION

X	* First set of values to be tested
Y	* Second set of values to be tested
SumX	* Sum of all X values
SumY	* Sum of all Y values
SumSqX	* Sum of X**2 values
SumSq	* Sum of Y**2 values
SqsumX	* Square of the Sum of X values
SqsumY	* Square of the Sum of Y values
Xm	* Mean of the X-values
Ym	* Mean of the Y-values
Vx	* Variance of X-values
Vy	* Variance of Y-values
Sx	* Standard Deviation of the X-values
Sy	* Standard Deviation of the Y-values
Sp	* Standard Deviation of the pool
F	* Variance ratio
Dof1	* Degree of freedom for Large variance variable
Dof2	* Degree of freedom for Small variance variable
T	* Value of T-distribution
Spm	* Std. deviation of difference in means of two samples
Doft	* Degree of freedom for T-test
Srx	* Residual Standard Deviation of X-values
Sry	* Residual Standard Deviation of Y-values

MAIN PROGRAM

```
        CHARACTER*80 DISCVAR
        CHARACTER*20 INFL,RSFL
        DIMENSION X(40),Y(40)
        REAL NptsX,NptsY

WRITE(6,4001) ! Asking about the discription of test
READ(5,3001)DISCVAR

WRITE(6,4011)
READ(5,3011)INFL

WRITE(6,4021)
READ(5,3011)RSFL

OPEN(UNIT=2,FILE=INFL,STATUS='OLD')
OPEN(UNIT=3,FILE=RSFL,STATUS='NEW')

READ(2,*)NptsX,NptsY
READ(2,*)(X(i),Y(i),i=1,NptsX )
SumX=0.0
SumY=0.0
SumSqX=0.0
SumSqY=0.0
      I=1.0
```

```
      DO 999 I=1,NptsX
       SumX=SumX+X(i)
       SumY=SumY+Y(i)
       SumSqX=SumSqX+X(i)*X(i)
       SumSqY=SumSqY+Y(i)*Y(i)
999    CONTINUE


       SqSumX=SumX**2.0
       SqSumY=SumY**2.0


       Xm=SumX/NptsX
       Ym=SumY/NptsY


       Vx=(SumSqX-(SqSumX/NptsX))/(NptsX-1)
       Vy=(SumSqY-(SqSumY/NptsY))/(NptsY-1)


       Sx=SQRT(Vx)
       Sy=SQRT(Vy)

       Comparison of two variances by F-test

       IF(Vx-Vy.GT.0.0)THEN
              VX1=VX*1000.0
              VY1=VY*1000.0
              F=Vx1/Vy1
              Dof1=NptsX
              Dof2=Nptsy
       ELSE
              VX1=VX*1000.0
              VY1=VY*1000.0
              F=Vy1/Vx1
              Dof1=NptsY
              Dof2=NptsX
       END IF


       Vp=(SumSqX-SqSumX/NptsX+SumSqY-SqSumY/NptsY)/(NptsX+NptsY-2)
       Sp=SQRT(Vp)
       Value1=(SumSqX-SqSumX/NptsX)
       Value2=(SumSqY-SqSumY/NptsY)

       Comparison of two means by T-distribution

       T=(ABS(Xm-Ym)/Sp)*(SQRT(NptsX*NptsY/(NptsX+NptsY)))
       Doft=NptsX+NptsY-2.0
       Spm=Sp*SQRT((NptsX+NptsY)/(NptsX*NptsY))


       WRITE(3,2031)DISCVAR
       WRITE(3,1900)Xm,Ym
       WRITE(3,2001)Vx,Vy
       WRITE(3,2011)Sx,Sy
       WRITE(3,2021)Sp,F,Dof1,Dof2
       WRITE(3,2121)T,Doft,Spm
```

```
1900   FORMAT(T5,'Xm= ',F8.2,T20,'Ym= ',F8.2)
2001   FORMAT(T5,'X-Var=',F9.2,T30,'Y-Var=',F9.2)
2011   FORMAT(T5,'Std-x=',F7.2,T30,'Std-y=',F7.2)
2021   FORMAT(T5,'Pl Std=',F9.2,T30,'F-Ratio=',
       1      F5.2,/,T5,'Dof n1=',F6.2,T30,'Dof n2='F6.2)
2121   FORMAT(T5,'T-value=',F7.2,T30,'Dof t=',F6.2,/,T5,
       1  'Std dif means=',F9.2)
3001   FORMAT(A80)
3011   FORMAT(A20)
4001   FORMAT(T5,'Please write something about the Variable used
       1in the test')
4011   FORMAT(T5,'enter data file ')
4021   FORMAT(T5,'enter Result file')
2031   FORMAT(T5,A80)
       CLOSE(UNIT=2)
       CLOSE(UNIT=3)

       STOP 'YOUR-RESULTS-ARE-READY'
       END
```

APPENDIX E: MACHINABILITY RESULTS

TABLE E.1: Machinability Results (Optimised Heat Treatment Process)

Cut No.	Turning Speed (RPM)	Feed Rate (mm/rev)	Depth of Cut (mm)	Average Surface Roughness (µm)	Total Surface Roughness (µm)	Cutting Tool Vibration (kHz)
1	1020	0.03	0.5	0.94	9.80	2.05
2	1020	0.04	0.5	0.90	8.90	2.04
3	1020	0.05	0.5	0.78	6.10	2.16
4	1020	0.06	0.5	1.21	8.40	2.07
5	1020	0.08	0.5	0.96	7.70	2.15
6	1020	0.10	0.5	1.05	6.90	2.26
7	1020	0.12	0.5	1.41	10.80	2.22
8	1020	0.16	0.5	1.19	9.20	2.43
9	1020	0.20	0.5	1.20	12.20	2.59

TABLE E.2: Machinability Results (Standard Heat Treatment Process)

Cut No.	Turning Speed (RPM)	Feed Rate (mm/rev)	Depth of Cut (mm)	Average Surface Roughness (µm)	Total Surface Roughness (µm)	Cutting Tool Vibration (kHz)
1	1020	0.03	0.5	0.60	5.10	2.34
2	1020	0.04	0.5	0.55	3.40	2.34
3	1020	0.05	0.5	0.77	5.90	2.26
4	1020	0.06	0.5	0.62	4.60	2.37
5	1020	0.08	0.5	0.59	4.70	2.30
6	1020	0.10	0.5	0.92	6.50	2.32
7	1020	0.12	0.5	0.77	7.70	2.43
8	1020	0.16	0.5	0.98	5.60	2.49
9	1020	0.20	0.5	1.29	6.60	2.54