

The Effect of Extrusion Conditions on Yield Strength of 6060 Aluminium Alloy

By

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Abstract

The objective of this investigation was to quantify whether T5 temper is equal to T6 temper in yield strength of 6060 extrusion alloys. Extrusion conditions achieving uniform yield strength along the whole length of extrudate were examined. The optimal ageing conditions relating to thicknesses of 1.1 mm and 1.5 mm were studied.

Firstly peak age hardening conditions were determined for thicknesses of 1.1 mm and 1.5 mm of both T5 temper and T6 temper at mid-length of extrudate. For T6 temper all samples were solution treated at 540°C for one hour in the furnace, followed by water quenching. Then all the specimens for T6 temper and T5 temper were artificially aged at 185°C or 205°C in the oven for varying times: 0.5, 1, 3, 5, 7, 9, 11, 13 and 15 hours, and then tensile tested to compare 0.2% proof strength values. Yield strength of extrudate along the whole length was investigated for thickness 1.1 mm. Samples were treated at 205°C for two and four hours, and at 185°C for six and twelve hours, for both T5 and T6 temper. The average cooling rate of thickness 1.1 mm extrudate was estimated. Chemical composition analysis using ICP-AES was performed. This was to determine Mg concentration distribution in pre-heated billet before extrusion, and in butt and extrudate after extrusion.

Results have shown that a cooling rate of greater than $5^{\circ}\text{C}/\text{s}$ in 6060 alloys is sufficient to prevent Mg_2Si forming during press quenching. Optimal yield strength for thickness 1.1 mm and 1.5 mm can be achieved above 180 MPa by press quenching, when homogenizing conditions were held at 575°C for two hours. Ageing at 205°C reached peak yield strength faster than ageing at 185°C for both T5 and T6 temper. When subjected to T5 temper at 205°C held for two hours, thickness 1.5 mm reached above 180 MPa but thickness 1.1 mm did not. It required ageing at 205°C for three hours, or at 185°C for five hours. Constant ram speed of 5 mm/s, when pre-heat temperature is $380\text{--}390^{\circ}\text{C}$, gives a nearly constant exit temperature of $530\text{--}545^{\circ}\text{C}$.

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Statement of Originality

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.”

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Chapter 1 Introduction

1.1 Yield strength of extrudate

Extrusion is a modern process which was only commercially available following its invention in 1886 [1]. It is mostly used to produce long, straight semi-finished products in the forms of solid and hollow sections with various complexities. Based on a report from the Europe Aluminium Association [2], the demand for aluminium products dramatically increased from 2000 to 2005. Figure 1-1 indicates that the construction industry has a great demand for aluminium products.

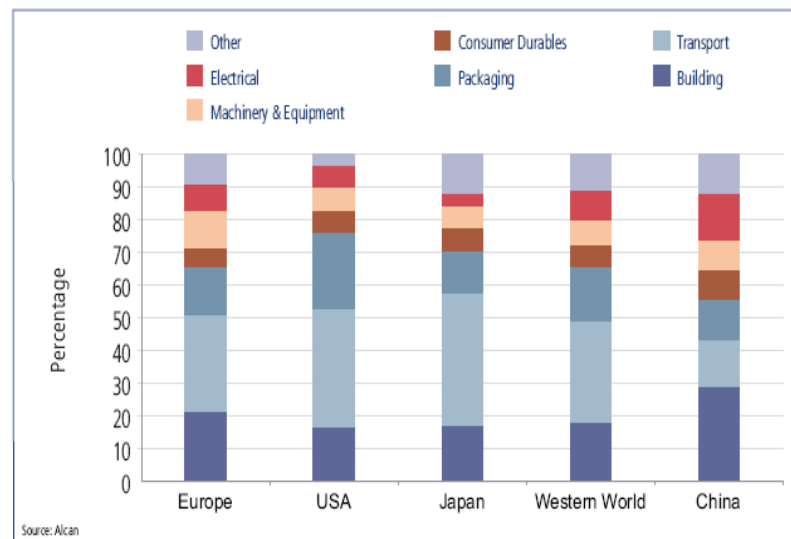


Figure 1-1 Total Aluminium Use by End-Use (2005) [2]

The extrusion fabrication process is usually the most economical way to make parts that have a constant cross-section, because the extrusion process puts the metal where it is needed, resulting in a very strong part with relatively low weight. AA6xxx (Al-Mg-Si series) have the biggest share of the aluminium extrusion market. More than 80 percent of the aluminium alloys employed worldwide in the manufacturing of extruded sections belong to the 6xxx series [3]. The reason is that this group of alloys has an attractive combination of properties, for both manufacturing and application. They have medium strength, are heat treatable, and have good formability, machinability, and weldability.

It is important to know that strength variations within a given composition are due to two causes. Some result from compositional differences and others result from Mg_2Si transformation conditions [1]. Therefore, intrinsic strength, extrusion processing and age hardening of the aluminium determine the overall strength of extrudate. It can be shown below [4]:

$$\sigma_{0.2} = \sigma_i + \sigma_{ss} + \sigma_{ppt}$$

Where: $\sigma_{0.2}$: overall yield strength of extrudate

σ_i : intrinsic strength of aluminium.

σ_{ss} : a function of the concentration of the solute atoms in the matrix.

σ_{ppt} : related to the relevant age hardening conditions.

There are two processes to attain σ_{ss} and σ_{ppt} of extrudate. Depending on alloys, sometimes extrudate may be heat-treated at the extrusion press, called T5 temper or press quenched. This is cooled from an elevated temperature shaping process, and then artificially aged. Sometimes it is heat treated in a separate furnace, called T6 temper. That is solution heat-treated, then artificially aged.

It had been advised by aluminium production engineers that some lower wall thicknesses of 6060 alloy extrudate did not achieve the mechanical properties for T6 temper by doing a T5 temper/press quenching process. The yield strength was non-uniform over the whole length of some profiles. The factor deciding whether T5 temper could be used instead of T6 temper is whether the Mg_2Si in pre-heated billet is sufficiently dissolved at the exit temperature, to be retained in solution during the cooling. It was reported in the literature that some factors can aid successful press quenching in the overall extrusion process. These are: chemistry, ingot casting practice, homogenizing treatment, billet preheat and extrusion temperature, press quenching conditions and precipitation heat treatment [5]. An overview of the extrusion process is shown in Figure 1-2.

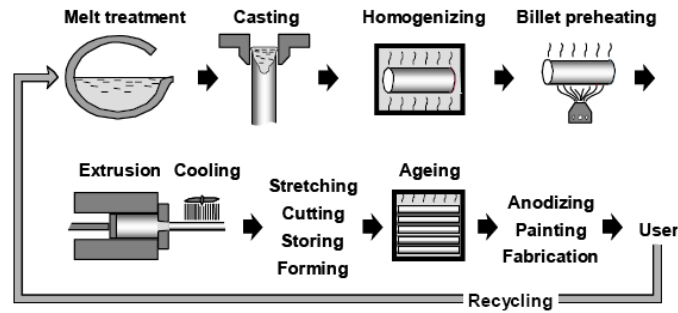


Figure 1-2 Aluminium production process steps [6]

Homogenized ingot is normally provided by a smelter. Therefore, investigations will focus on billet pre-heating conditions, extrusion exit temperature, press quenching conditions and precipitation heat treatment.

1.2 Extrusion process

Figure 1-2 shows the extrusion process begins with melt treatment, DC-casting and homogenizing. Ingot is formed in DC-casting. The homogenizing cycle typically consists of a soaking treatment, followed by cooling at a predetermined rate, to achieve the required structure. This may affect the extrudability and quench sensitivity during the extrusion process.

The ingots are then taken to the aluminium extrusion plant. Figure 1-3 shows an 8 MN hydraulic horizontal press. Horizontal extrusion presses, (the ram travels in a horizontal direction), are used for most commercial extrusion of bars and shapes. Figure 1-4 is a diagram of the extrusion press.



Figure 1-3 Extrusion press equipment

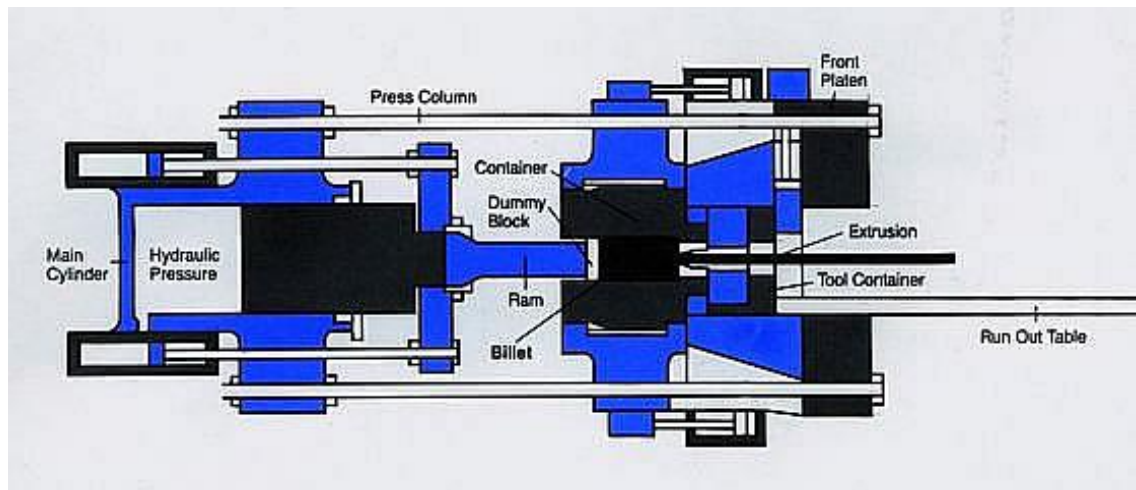


Figure 1-4 Direct extrusion press [7]

The features of extrusion process in industry practice can be described as follows: before extrusion, ingot is preheated in a three-stage heating system which raises the temperature in a controlled way until a certain temperature is reached. The desired preheating temperature and time for obtaining a suitable particle size to fit the extrusion press varies with the alloy composition, based on the extrusion exit temperature required. In general, the preheating temperature of 6060 alloys is set to $380-480^{\circ}\text{C}$, (when the solute starts to dissolve into the solution), and held for 40 – 45 minutes depending on the profile to be extruded. Then ingot is cut to a billet of required length. Billet diameter is slightly smaller than container diameter so that billet will slip into the container easily. When the first pressure is applied the billet will be crushed against the die and will expand in diameter to fill the container. The container and die must be heated to a similar temperature to prevent cooling of the inserted billet. The temperature of the billet inside the container during processing is controlled by the ram speed. Usually the exit temperature is maintained between $520-560^{\circ}\text{C}$ (where the solute has almost completely dissolved into the solution) for 6060 alloys. Figure 1-4 shows pressure being applied to a ram at one end of the billet. The deformed metal flows through the steel die at the other end of the container to produce the required shape. The maximum extruded length of the section depends on the volume of the billet (cross-section $\times$ length) and on the extrusion ratio (Extrusion Ratio = cross-area of billet/ cross-area of profile section).

For a given alloy, the interaction between the homogenized billet and extrusion conditions, such as exit temperature, extrusion ratio and extrusion speed, affects metal flow. The pattern of metal flow then influences the resulting properties and microstructure of the section and its surface finish. Die configuration, profile complex, temperature of die and container are several factors affecting the metal flow and extrusion exit temperature. Figure 1-5 shows the final shapes of product coming out from the die.



Figure 1-5 Final product leaving die

The extrusion press in Figure 1-3 has all the extrusion parameters during extrusion processing controlled by OMAV equipment. Pre-heating temperature and exit temperature are measured by using thermocouples/infrared cameras. The control panel in Figure 1-6 indicates variance of conditions during extrusion.



Figure 1-6 Control panel indicating dynamic extrusion parameters in extrusion

Depending on the alloy, the extrusion is cooled after leaving the die, either naturally, or through air or water quenches. This is a critical step to ensure sufficient metallurgical properties after ageing. In general, 6060 alloys of 1 mm to 3 mm thickness are extruded between $510 - 560^{\circ}\text{C}$, and then cooled by air. The extrudates are then transferred to a cooling table shown in Figure 1-7.



Figure 1-7 Cooling table

A stretcher then straightens the extrudates and corrects any twisting that may have occurred after extrusion. Yield strength is slightly improved by means of cold work. Conveyors feed the work to the saw. A finish cut saw is used to cut the profile to the specified commercial length.

Age hardening follows to improve the extrudate strength. The ageing temperature usually ranges from $175 - 210^{\circ}\text{C}$, holding for certain time periods depending on the type of alloy. Figure 1-8 shows the extrudates waiting for ageing.



Figure 1-8 Batched extrudate in front of ageing furnace

For yield strength of aluminium extrudate log pre-heating, extrusion process, cooling, and ageing are the most important stages.

1.3 Age hardening of 6xxx alloys

Figure 1-9 shows the principal elements of wrought alloys.

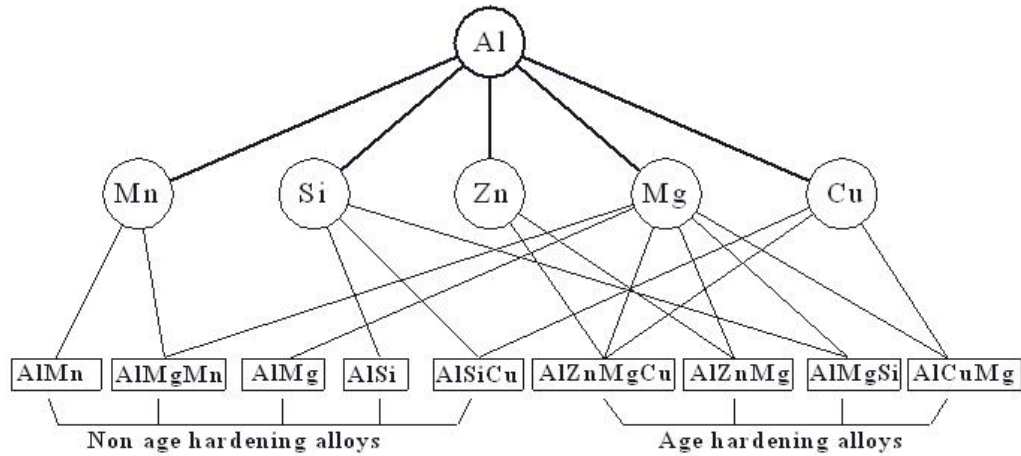


Figure 1-9 Wrought alloy classification [8]

Wrought alloy designations under the ISO alpha-numeric system are listed in Table 1-1. Heat treatable alloys include 2xxx, 6xxx, and 7xxx series, which have the highest strength of all aluminium alloys. They attain their maximum strength through controlled heat treatment.

Wrought alloys	Alloy number
Aluminum, 99.00% minimum and greater	1XXX
Alloys grouped by major alloying elements:	
● Copper	2XXX
● Manganese	3XXX
● Silicon	4XXX
● Magnesium	5XXX
● Magnesium and Silicon	6XXX
● Zinc	7XXX
● Other element	8XXX
● Unused series	9XXX

Table 1-1 Designation of wrought alloys [8]

Figure 1-10 shows the classification of most commonly used Al-Mg-Si alloys for extrusion purposes as a function of the composition in %Mg and %Si.

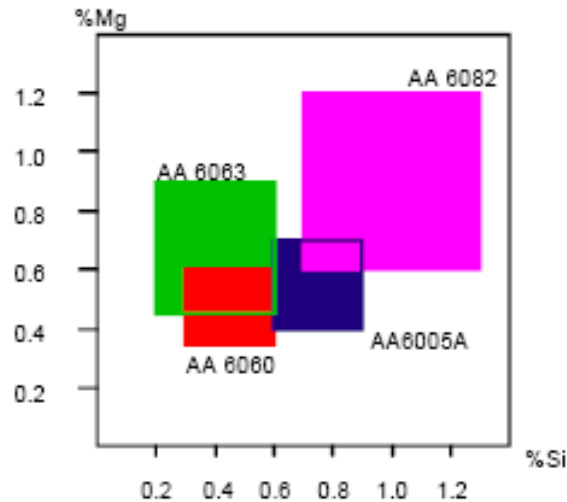


Figure 1-10 Composition in %Mg and %Si of some AlMgSi alloys [9]

The stronger 6082 type alloys are used for applications where tensile strength and impact resistance, as well as stiffness and fatigue resistance are important. AA6063 alloy extrudes at high speeds with good surface finish and maximum complexity of section shape - mainly for architectural applications. Since the early 1990's 6063 alloys have been replaced in most countries by 6060 alloy. The suppliers advise that 6060 alloy, a type of AA6063 derivative, is slightly more ductile and easier to extrude. 6060 alloy contains lower levels of magnesium and silicon - increased Si and Mg content significantly reduces ductility and maximum extrusion speed [10]. Hence, using 6060 alloy gives a significant reduction in manufacturing cost. Although a complete set of physical properties of 6060 are not available, they are substantially the same as for 6063 [11]. The other major alloys of the series include AA6351, AA6005A and AA6061. Table 1-2 shows the specifications of 6060 and 6063 alloy. The difference of composition between these two alloys is slight.

Chemical composition %										
Alloy	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
6060	Rem	0.30-0.6	0.10-0.30	0.10	0.10	0.35-0.6	0.05	0.15	0.10	0.05-0.15
6063		0.20-0.60	0.35	0.10	0.10	0.45-0.90	0.10	0.10	0.10	0.05-0.15

Table 1-2 Specifications of 6060 and 6063 alloy [9, 12]

The highest mechanical strength in aluminium alloys can be achieved with the age hardening alloys of 2xxx and 7xxx series. However, these alloys have

marked quench sensitivity and a severely limited solution range. In most cases they have to be solution heat treated and quenched in a separate operation - T6 temper [13]. AA6xxx series, Al-Mg-Si system, are considered to belong to the easily extruded alloys. Those alloys have lower flow stress which results in better workability. The temperature range of this series for the hot working process coincides with solution heat treatment. 6060 alloy extruded sections have low quench sensitivity. Air cooling is sufficient to retain Mg and Si in α - solid solution. Separate solution heat treatment of this alloy may not be required - T5 temper. A comparison between T6 and T5 temper process is shown in Figure 1-11.

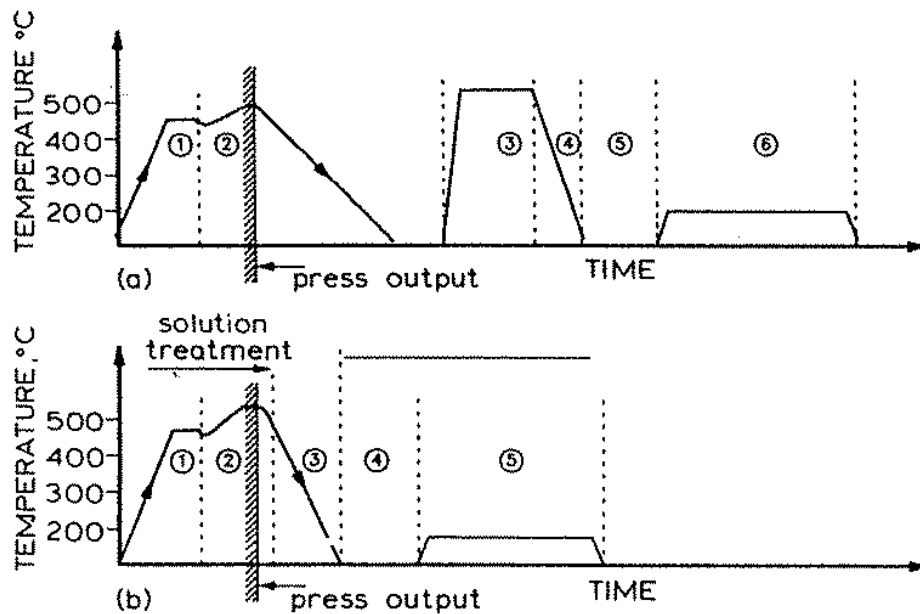


Figure 1-11 The difference in T6 and T5 temper process [1]

(a) Separate solution heat treatment-T6 temper

(1) pre-heating; (2) extrusion; (3) solution treatment;
(4) quenching; (5) waiting period; (6) ageing

(b) Simplified solution treatment – T5 temper or Press quenching

(1) reheating; (2) extrusion; (3) quenching;
(4) waiting period; (5) ageing

Small precipitates of the principal alloying elements are dissolved in the α -solid solution at the press exit temperature. They must remain as dissolved elements in a super-saturated solid solution state after cooling. For a given homogenized billet, the pre-heating conditions, extrusion temperature and quench rate are key factors to control in order that yield strength from T5 temper could be equal to that from T6.

Press quenching, therefore, is a method of combining solution treatment and extrusion which offers potential economic savings. The most important information about quench sensitivity is the nucleation rate $\dot{N}$ as a function of temperature T (without considering strain energy) that can be expressed as [1]:

$$\dot{N} = A_1 \exp\left[-\frac{\Delta H_m}{kT}\right] \exp\left[-\frac{\Delta H_n}{kT}\right]$$

Where A_1 : is a rate constant

ΔH_m : is the activation energy for diffusion

ΔH_n : is the energy barrier for formation of nuclei

k : is Boltzmann's constant

Thus, the driving force for precipitation is the degree of super-saturation, which increases as the temperature decreases. The process depends upon the diffusion of solute atoms to nucleation sites and the diffusion rate decrease with temperature increasing. A measure of the amount transformed during continuous cooling is given by the integral τ [1]:

$$\tau = \int_{t_0}^{t_f} \frac{dt}{C_1}$$

Where τ : is the amount transformed;

t : is the time from the cooling curve;

t_0 : is the time at the start of quench;

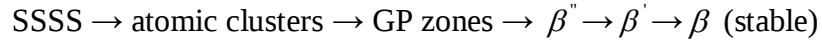
t_f : is the time at the finish of quench;

C_1 : is the critical time from the time-temperature-transformation curve.

The τ value varies considerably for each alloy since it is dependent upon the type of alloy. For a given alloy, exit temperature and cooling rate play significant roles in quench sensitivity. Due to the limitation of the literature, typical values for yield strength of 6060 which were affected by nucleation rate $\dot{N}$ and the integral τ have not been found.

The final stage of the extrusion process is age hardening. The strength of AA6xxx series alloys can be significantly improved by the precipitation of a finely dispersed second phase in the matrix. The behaviours of Al-Mg-Si alloy during age hardening have been studied intensively in the past [14]. Temperature and time have a marked effect upon the mechanical properties of these series alloys. The ageing process proceeds by growth of the nucleated G.P.

zones. The strengthening precipitate in Al-Mg-Si alloys is β'' precipitate. The precipitation sequence for Al-Mg-Si alloys that is generally accepted in the literature is [15]:

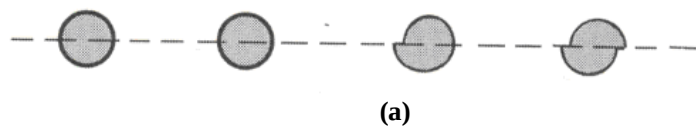


Where SSSS is the super-saturated solid solution. In general, the time and temperature needed to attain the β'' precipitate in terms of the maximum strength varies with alloys. The details of the precipitation process in Al-Mg-Si alloys systems are indicated in Table 1-3 [16].

Precipitate	Remarks
GP zones as needles alone $\langle 100 \rangle_\alpha$	GP zones solvus occurs at temperatures that are normally higher than the ageing temperatures
β'' Base-centered monoclinic	Needles of β'' precipitates
β' hexagonal Mg_2Si a = 0.705 nm c=0.405nm	Semi-coherent rods that probably form directly from GP zones. Lie along $\langle 100 \rangle_\alpha; (001)_\beta // (100)_\alpha; [100]_\beta // [011]_\alpha$
β face-centred cubic Mg_2Si a=0.639 nm	Platelets on $\{100\}_\alpha$ May transform directly from β' $(100)_\beta // (100)_\alpha; [110]_\beta // [100]_\alpha$

Table 1-3 Precipitation sequence for Al-Mg-Si alloys [16]

Ageing or precipitation of particles from a super-saturated solution is one way of producing dispersion hardening of a matrix by impeding the movement of dislocations [17]. Impairment of this movement increases the energy required for deformation and hence, increases the strength of the material. Figure 1-12 indicates two types of dislocation: cutting through closely spaced small particles for 'soft alloy', or forming on slip planes looping between large particles, leaving dislocation rings around particles for 'hard alloy'.



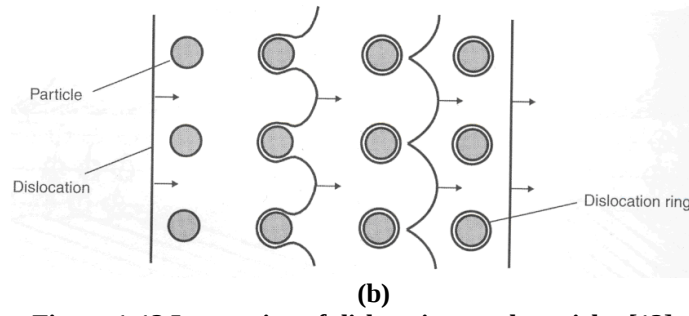


Figure 1-12 Interaction of dislocations and particles [13]
(a) Shearing of a particle by a dislocation
(b) Dislocation looping around a particle

Figure 1-13 shows the yield stress versus ageing time.

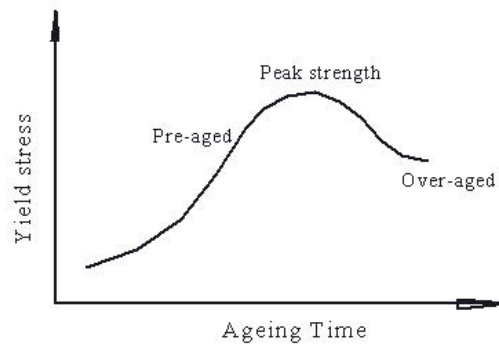


Figure 1-13 Yield stress versus ageing time

In the early stages of ageing, yield stress will increase rapidly through nucleation of many small precipitates that act as obstacles for dislocation motion. After reaching a specific size, the obstacles become too strong to be sheared by the dislocation (in Figure 1-12 a). The Orowan bypassing looping (in Figure 1-12 b) takes over and peak strength is reached. Further ageing the material softens it due to reducing numbers and increased size of nucleation precipitates.

For a given alloy, ageing time and temperature are significant factors influencing the ultimate strength of extrudate. Of two causes mentioned above - compositional differences and Mg_2Si transformation conditions- approximately 25% of the mechanical strength variation observed in extrudate is due to compositional variations existing within the alloy. The remainder is due to all the other variations in processing conditions [1]. In this study, σ_{ss} is mainly influenced by homogenizing conditions, extrusion exit temperature and quench sensitivity, while σ_{ppt} is affected by ageing temperature and time.

1.4 Current uncertainty

The usual requirement for yield strength in 6060 alloys in T6 temper is over 180 MPa. In general, profiles of 6060 alloys can achieve sufficient yield strength required for T6 temper by using the T5 temper process. However some aluminium production engineers have advised that the yield strength of some profiles is unstable. Two different profiles of 6060 alloy were both subjected to the usual age hardening under T5 temper conditions. This was at 205°C for two hours. Profile shape 2 with thickness 1.5 mm reached the yield strength requirement of above 180 MPa. Profile shape 1 with thickness 1.1 mm sometimes did not reach this requirement under those conditions. The yield strength was non-uniform over the whole length of profile shape 1. It required extra ageing time at a lower temperature, ageing at 185°C for six hours in total.

The reasons for these differences in strength and subsequent processing requirements are unclear. A reduction in processing time by removing the separate solution heat treatment stage, and by shortening ageing time, from six hours to two hours, would increase productivity and reduce costs.

1.5 Research Objective

The objective of this investigation was to quantify whether T5 temper was equal to T6 temper in yield strength. The investigation was to confirm the optimum temperature and time variables for age hardening 6060 alloy in thicknesses of 1.1 mm and 1.5 mm. It was to determine the Mg concentration and distribution in billet of 6060 alloy after pre-heating, in butt after extrusion, and in extrudate after air-cooling. This would confirm that the Mg had sufficiently dissolved, by the critical press quenching rate (faster cooling), to ensure maximum yield strength without compromising production speed.

Thus the research objectives of this study were:

- To quantify whether T5 temper was equal to T6 temper in yield strength of extrudate
- To relate the thickness in terms of yield strength, to the optimal ageing conditions
- To verify yield strength along the whole length of extrudate

Chapter 2 Literature Review

An overview of the factors affecting the strength of extrudate will be discussed in this chapter. The relationship of Processing-Structure-Properties is illustrated in Figure 2-1. The yield strength of extrudate can be significantly altered by the relationship between extrusion processing and age hardening. For a given ingot of 6060 alloy, development of the optimum conditions to attain peak strength of extrudate in T5 temper extrusions requires close control of all fabricating operations from pre-heating through artificial ageing, because of interrelated effects.

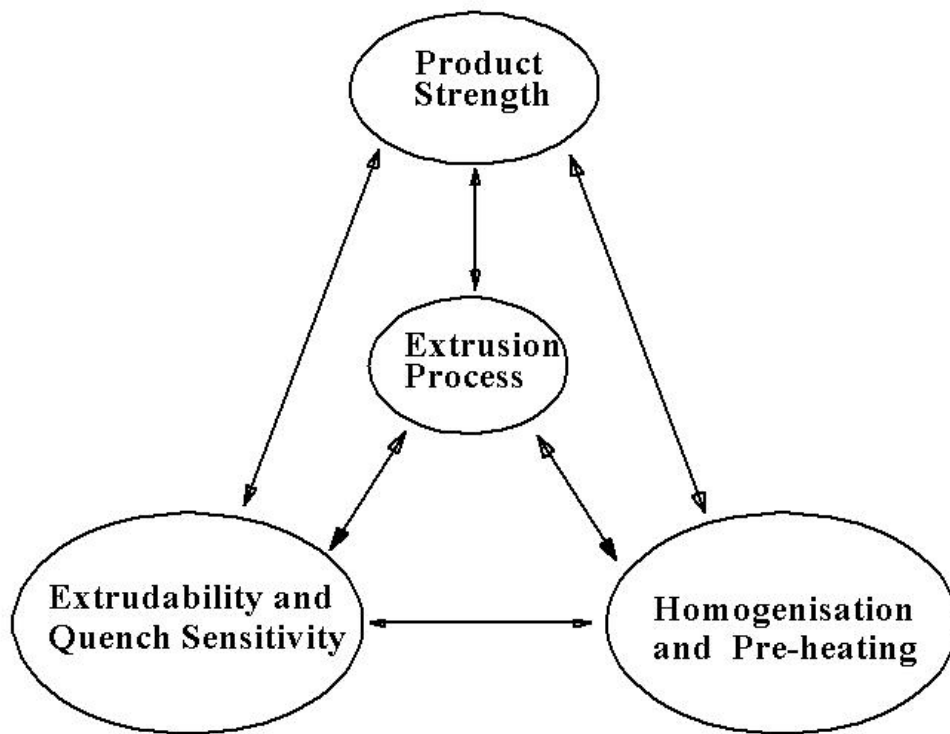


Figure 2-1 Relationship between productivity and product quality in aluminium extrusion

Heat-treatment of 6060 alloy extrudate typically consists of solutionising Mg and Si, which occurs right through extrusion exit temperature, press-quenching, and artificial ageing.

2.1 The strength of age hardened AA6060

Age hardening (or precipitation hardening) behaviour of Al-Mg-Si alloys has been widely studied since it was discovered in the 1920's [18]. AA6xxx series alloy can be strengthened by precipitation hardening heat treatment. Precipitation hardening consists of three main steps: solution heat treatment, quenching, and ageing.

2.1.1 T5 temper and T6 temper

T5 temper and T6 temper are two different tempering methods to increase the final mechanical properties of age hardening alloys. In general the yield strength of T6 temper is higher than T5 temper. Table 2-1 shows minimum 0.2% proof stress (PS) and ultimate strength stress of 6060 and 6063 alloy in both T5 and T6 temper [9, 12].

Alloy	Temper	Max Thickness (mm)	0.2% PS (MPa)	Ultimate Strength (MPa)	Elongation (%)
6060	T5	Up to 12	120	165	12
		12 – 25	115	155	10
	T6	----	180	200	----
6063	T5	25	160	200	8
	T6	25	190	230	8

Table 2-1 Some mechanical properties of 6060 and 6063 alloy [9, 12]

However, Rojest [19] reported that the T5 temper condition actually gives slightly higher strength than T6 temper in 6005 alloy shown in Figure 2-2.

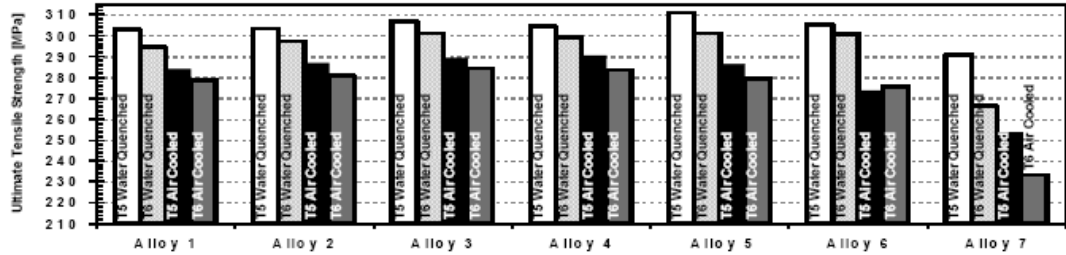


Figure 2-2 Ultimate tensile strength of extruded profiles of 6005 alloy in T5 and T6 temper [19]

An explanation is that some of the deformation substructure (subgrains, dislocations) still remains in the as-extruded profile, and gives a significant contribution to the strength of the age-hardened material. When solution heat treatment is applied to this profile, the substructure recovers and the strength of the subsequently age hardened material decreases accordingly [19].

2.1.2 Solution temperature and time

Solution heat treatment of Al-Mg-Si, or solutionising, is the first step in the precipitation hardening process. The alloy is heated above the solvus temperature, and then soaked until all the solute has dissolved into the solution to minimize segregation. The maximum possible amount of hardening solutes such as magnesium and silicon enter into solid solution in the aluminium matrix. Table 2-2 expresses the invariant reactions at the Al end of the Al-Mg-Si Diagram.

Reaction	Temperature °C
(1) $L \rightarrow \text{Al dendritic network}$	655°C to 653°C
(2) $L \rightarrow \text{Al} + \text{Al}_8\text{Fe}_2\text{Si}$	618°C to 615°C
(3) $L + \text{Al}_8\text{Fe}_2\text{Si} \rightarrow \text{Al} + \text{Al}_5\text{FeSi}$	613°C
(4) $L + \text{Al}_8\text{Fe}_2\text{Si} \rightarrow \text{Al} + \text{Al}_5\text{FeSi} + \text{Mg}_2\text{Si}$	576°C

Table 2-2 Invariant reactions of the Al-Mg-Si system [20]

The reaction that produces Al, Al_5FeSi and Mg_2Si at 576°C is presented. Figure 2-3 shows the effects of soaking temperature and time on the volume fraction of particles of Mg_2Si phase in AA6063 alloy. The volume fraction varies with the precipitated particles melting or solidifying in the solution treated sample at three treating temperatures (520 , 550 and 580°C) for different soaking times (2, 3, 4, 5, and 6 hours).

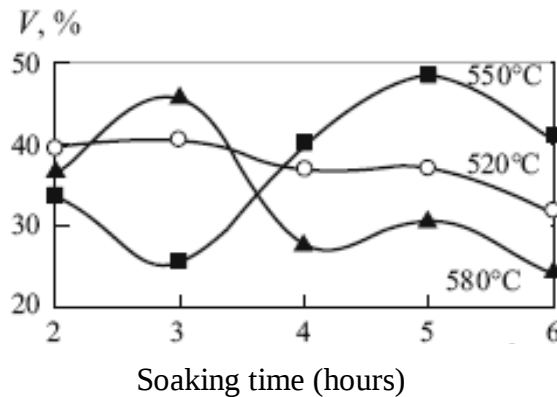


Figure 2-3 Effects of soaking time and temperature on volume fraction of Mg_2Si [21]

As the melting and solidification of the second phase particles are continuous, no clear trend can be drawn from the 550 and 580°C curves. The 520°C treatment showed a decreasing trend. It indicated that dissolution of the second phase was a little more effective, but still within a small range. The strength of material increases when the volume-fraction of Mg_2Si increases. Figure 2-3 shows the peak volume fraction was attained at 580°C , soaking for three hours. Figure 2-4 shows a nearly peak Vickers value achieved at 580°C with minimum soaking for two hours.

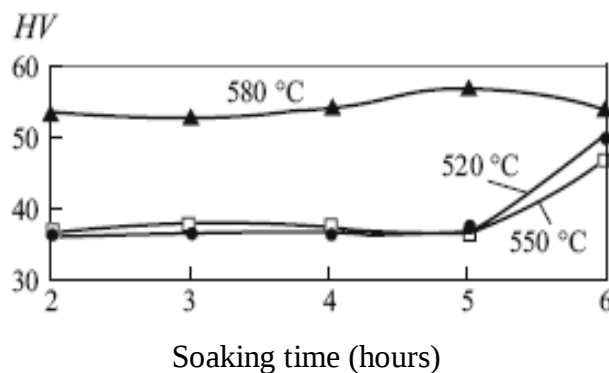


Figure 2-4 Vickers microhardness of aluminium alloy 6063 for the duration of homogenizing at 580 , 550 and 520°C [21]

In comparison with the extrusion process the solutionising time is extremely short. It requires the optimal homogenized billet to achieve the requirement of T6 temper by doing a T5 temper process. (Homogenized billet will be discussed in Chapter 2.4.1)

2.1.3 Ageing temperature and time

Table 1-3 (in Chapter 1) shows that in solid solution several types of atomic clusters are formed in Al-Mg-Si alloys. These clusters gradually transform into GP-zones related to the crystallography of the matrix and further into β'' -precipitates that are strengthening precipitates in Al-Mg-Si alloys.

Munitz [22] stated that ageing of Al-6063 caused internal microstructure changes. Needle-like precipitates inside the entire grains could be observed after a certain ageing state, except for the area adjacent to the grain boundary, where a precipitation free zone (PFZ) could be observed. The maximum strength is gained just before the rods of particles transform into platelets - T6 conditions [22]. Mg_2Si precipitates throughout the entire grain, while at the grain boundary a precipitation - free zone (PFZ) is formed during ageing. Mg diffusion into the grain boundary causes the formation of large Mg_2Si precipitates at the grain boundary, and the formation of a vacancy depleted zone near a grain boundary [22]. The peak-aged condition is best described as the correct 'balance' of Mg and Si available to form Mg_xSi precipitates, with x close to 1 during heat treatment [23].

The variation in tensile strength when exposed to different temperatures for different intervals of time in AA6063 alloy is shown in Figure 2-5 [14]. The solution heat treatment for all the specimens was carried out in a furnace by soaking the alloy for two hours at 520°C , followed by quenching in water at room temperature to preserve the super-saturated solid solution. Then samples were subject to ageing at different temperatures and times. At all the temperatures, the initial increased time caused tensile strength to increase from the pre-aged stage to peak at the aged stage. This is caused by the diffusion-

assisted mechanism of hindrance of dislocation. Further increase in the ageing time (over-aged stage) reduced the tensile strength. This causes the size of the individual particles to increase, but the number of particles to decrease. Obstacles to the movement of dislocations are less, resulting in a decrease in yield strength.

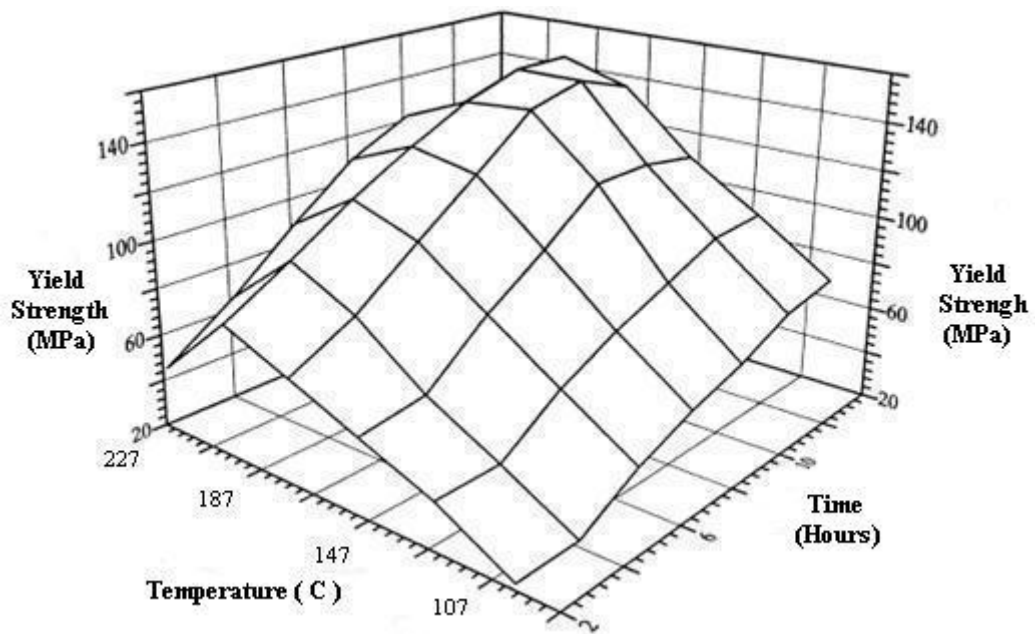


Figure 2-5 Effect of time and temperature on yield strength of 6063 Al-alloy [14]

Silva [24] studied the mechanical properties of the two 6060 alloys (composition is listed in Table 2-3). Both specimens were placed into a heat treatment solution at 560°C for one hour, then water quenched, followed by ageing at 180°C - up to a maximum ageing time of eight hours. It can be seen from Figure 2-6 that the yield strength of both 6060 alloys reached above 180 MPa when aged at 180°C for six and eight hours.

Alloy	Mg	Si	Fe	Cu	Mn	Cr	Zn	Ti	Al
6060	0.405	0.549	0.176	0.040	0.064	0.007	0.022	0.022	Bal. (a)
6060-A	0.400	0.405	0.239	0.067	0.062	0.015	0.046	0.030	Bal.

Table 2-3 Composition of 6060 alloys (wt.%) studied by Silva [24]

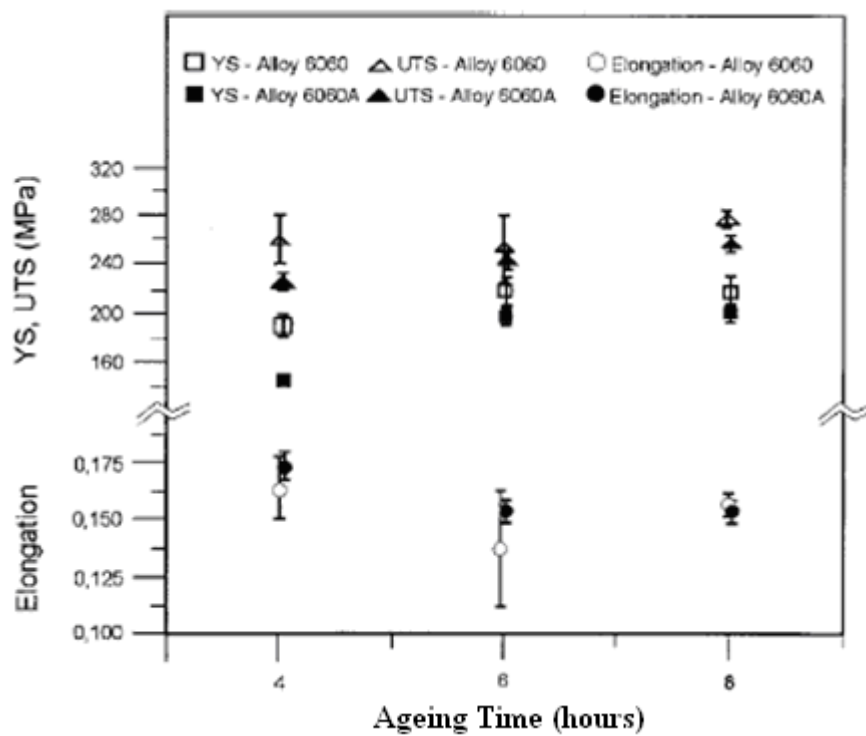


Figure 2-6 Evolution of 6060 mechanical properties ageing at 180°C [24]

2.2 Effects of variations in Mg and Si

Magnesium and silicon are two significant elements in Al-Mg-Si series alloy. In general, magnesium increases strength significantly while silicon lowers the melting point. Silicon in combination with magnesium form Al-Mg-Si heat-treatable alloys with good extrudability. It was reported by Brassard [25] that AA 6063 and AA6060 would give similar tensile strengths for industry values of 215 MPa in alloys with 0.30 - 0.35 wt% magnesium, by raising the silicon content to 0.50 - 0.55 wt%.

2.2.1 Mg content

Figure 2-7 [5] shows that tensile strength increases dramatically by increasing the percentage of magnesium in comparison with silicon.

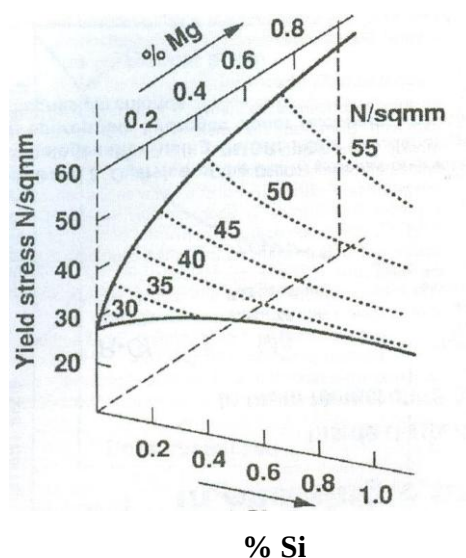


Figure 2-7 Variation of yield stress for Al-Si and Al-Mg and curves of constant yield stress in the Al-rich corner of the Al-Mg-Si system [5]

Caceres [26] also found that alloys with higher magnesium content have a stronger response to ageing. On the other hand, magnesium lowers extrudability by significantly increasing maximum extrusion pressure, regardless of silicon content. It increases quench sensitivity, increases strength and lowers both ductility and toughness [5].

2.2.2 Excess Si

6xxx series aluminum alloys contain an excess of Si above that required to form stoichiometric Mg_2Si . This is added to improve age hardening, due mostly to precipitation of metastable β'' precipitates [27]. The excess Si is not believed to alter the precipitation sequence, structure and lattice parameters of the different metastable precursors. The precipitation sequence in the balanced alloy is independent of the composition, and the strength increases with increasing Mg_2Si level. Excess Si reduces the time to initiate strengthening, and increases strength in artificially aged tempers. This is due primarily to both a higher volume fraction and a refined distribution of the β'' particles. Excess Si modifies the Mg/Si ratio in the clusters/zones and β'' precipitates and improves strength by altering their size, number, density and distribution.

Brassard reported [25] that tensile strength decreased as the magnesium content of the alloy was reduced, but could be recovered by raising silicon content (shown in Figure 2-8). Silicon is not as influential as magnesium in extrudability and it has a minor influence on quench sensitivity for strength. Silicon will decrease both ductility and toughness, most likely by precipitating elemental silicon on grain boundaries.

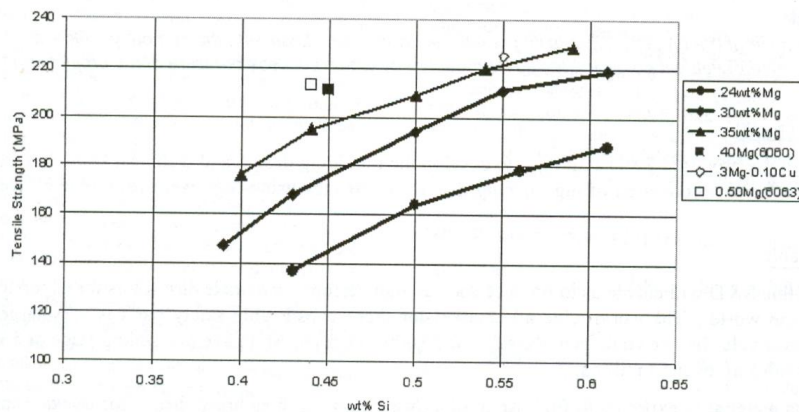


Figure 2-8 Effect of composition on tensile strength [25]

Figure 2-9 shows the ageing curves of a balanced alloy containing varying amount of excess Si. The higher excess Si, the higher yield strength is achieved.

This figure also includes an ageing curve of a binary Al-Si alloy for comparison purposes.

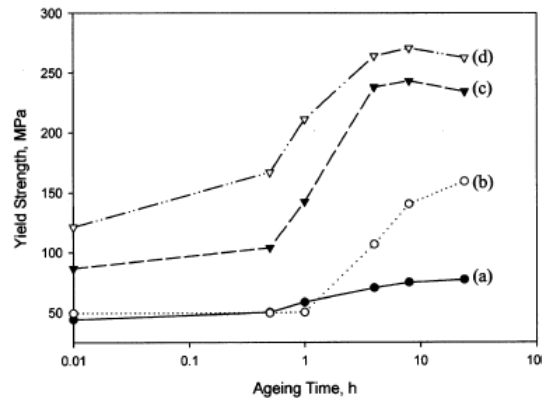


Figure 2-9 Effect of Si on ageing behaviour [27]
 (a) Binary Al-1.32wt. %Si (b) 0.28wt. %Si;
 (c) 0.72wt. %Si; (d) 1.32wt. %Si.

Magnesium content of 6060 alloy in this study is between 0.36% and 0.38% and silicon is in the range of 0.52-0.53%. In the correct proportion to fulfil the stoichiometric requirements for Mg_2Si , 0.36% - 0.38% Mg is required for 0.21% to 0.22% of Si.

2.3 Material flow

In general two factors greatly influence metal flow in extrusion. They are the friction conditions at the billet-container-die interfaces and thermal gradients in the billet [28]. Figure 2-10 shows that in direct extrusion billet goes forward in the standstill container. Shear friction generates at the outer billet surface. Metal flow in the centre of billet is faster than in the outer part of the billet. Therefore, a shear deformation zone appears between the dead metal zone and the flow zone.

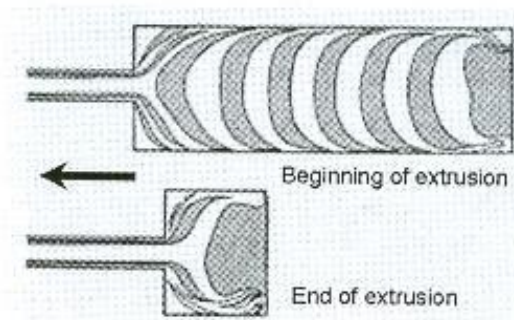


Figure 2-10 Metal flow of billet in direct extrusion [28]

Figure 2-11 (a) indicates the core of the material appears to be heavily deformed with material flowing into the die throat during the extrusion [1].

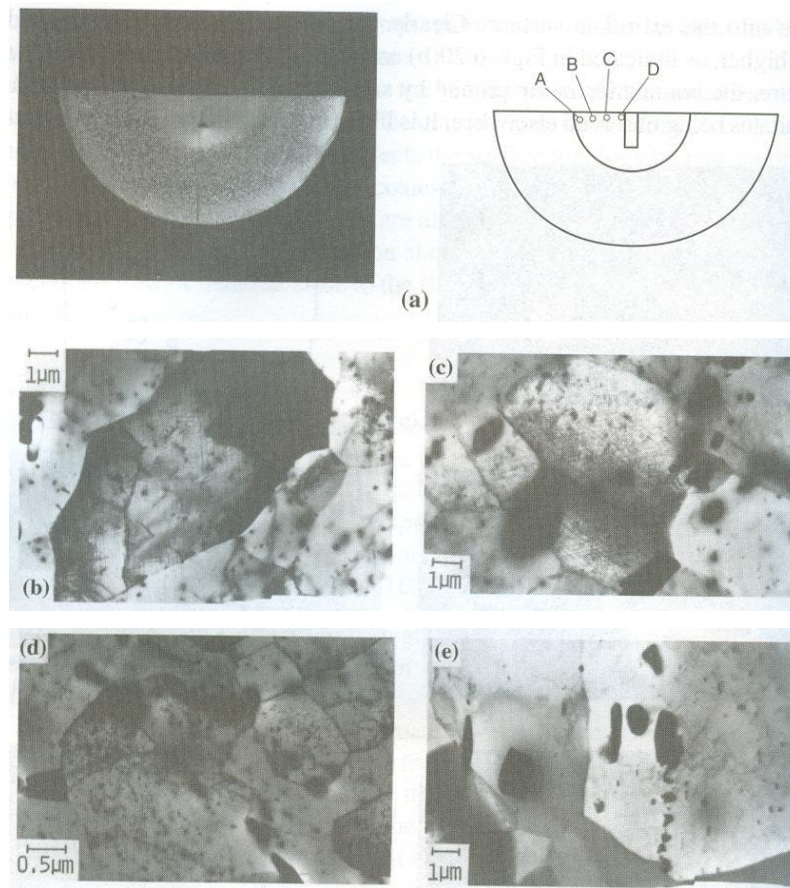


Figure 2-11 Deformed material flowing into the die throat during extrusion [1]
(a) Macrograph of front billet face and locations of specimens;
(b) High volume fraction of precipitates at 'A';
(c) Increase in coarse precipitation at 'B'
(d) Alignment and fracturing of AlFeSi and coarse Mg₂Si precipitates;
(e) Initial stages of precipitate disintegration and spheroidization

In (b) and (c), they indicate that the volume fraction of dispersoid is much higher at 'A' and there is an increase in coarse precipitation at 'B'. At this stage, the precipitates are not aligned into the flow direction. The micrograph shows most of the particles in cross-section. When the material moves from location B to location C in (c) and (d), the fragments are clearly deposited by the intense shear zone moving along the dead metal zone boundary. In (e) at location D, the fragmentation of the residual large particles just before entry to the die is clearly illustrated. The surface of the extrudate is mainly contributed by the deformation zone of intense shear, dividing it from the dead metal zone [1].

2.3.1 Billet skin and back end effect

It is common knowledge that the billet skin contains oxides that can flow into the extrudate, resulting in lower strength. General acceptance in the industry is that billet surface, in direct extrusion, will be retained by container friction and accumulate in the butt - as long as the butt exceeds a critical length [29]. It is illustrated in Figure 2-12 where billet skin begins to flow from the back end of the billet to the extrudate.

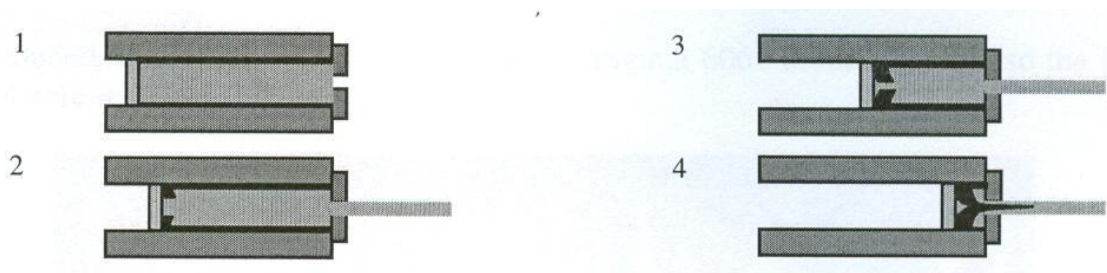


Figure 2-12 Flow of billet skin via the back end of billet [30]

More recently, the two-layer clad billet consisting of skin material and core material was used for an experiment to study the material flow behaviour by Ishikawa [31]. AA6063 was selected as the core material and AA3003 was selected as the skin material. Results indicated that temperature distribution does not affect the skin material flow but the friction coefficient between billet and ram does. Strain rate distribution can be associated with recrystallization. Strain distribution can be associated with recrystallised grain size.

Jowett [32] states that skin flow in billet surface entering the extrudate occurs approximately when 80 to 90% of the billet has been extruded. It was confirmed by Sano [28] that the surface material did not flow to the die exit, but flew to the back end of the billet. When billet skin runs into the extrudate defects may result in lower strength. The billet surface typically consists of oxide in an enriched segregation region and an associative denuded zone. This results in different grain and cell size. Figure 2-13 shows the segregation of coarse AlFeSi and Mg_2Si particles in the liquated zone of a billet. Large clusters of $\alpha\text{-AlFeSi}$

adversely affect extrudability and surface finish. The Mg_2Si particles will not completely redissolve during normal billet reheating or extruding [33].

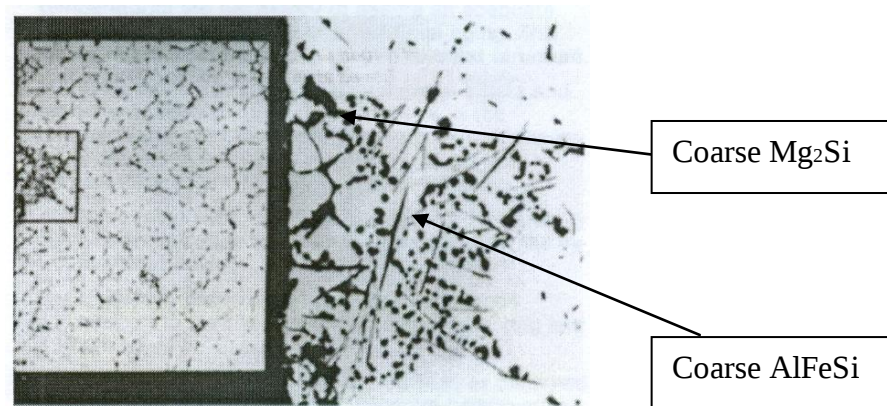


Figure 2-13 Coarse AlFeSi and Mg_2Si near the surface of a billet [33]

The yield strength is non-uniform over the whole length of profiles. One of the reasons could be that billet skin begins to flow from the back end of the billet to the extrudate.

2.3.2 Pocket die geometry

Pocket die geometry is one of the factors influencing material flow behaviour during extrusion of profiles with varying thicknesses. This has consequences on their geometrical stability and surface quality [34]. Figure 2-14 presents the shapes of die geometry. Figure 2-15 shows different flows caused by those die geometries. A flat die and different pocket dies were used at the thin profile part: 1mm (pocket A), 3 mm (pocket B) and 7 mm (pocket C).

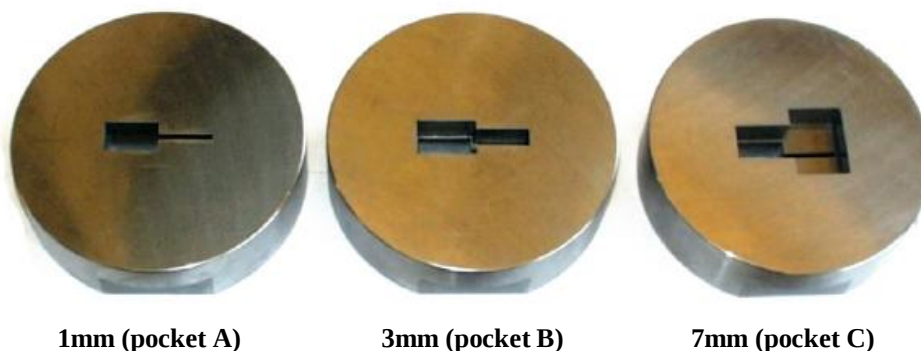


Figure 2-14 Pocket die geometry [34]

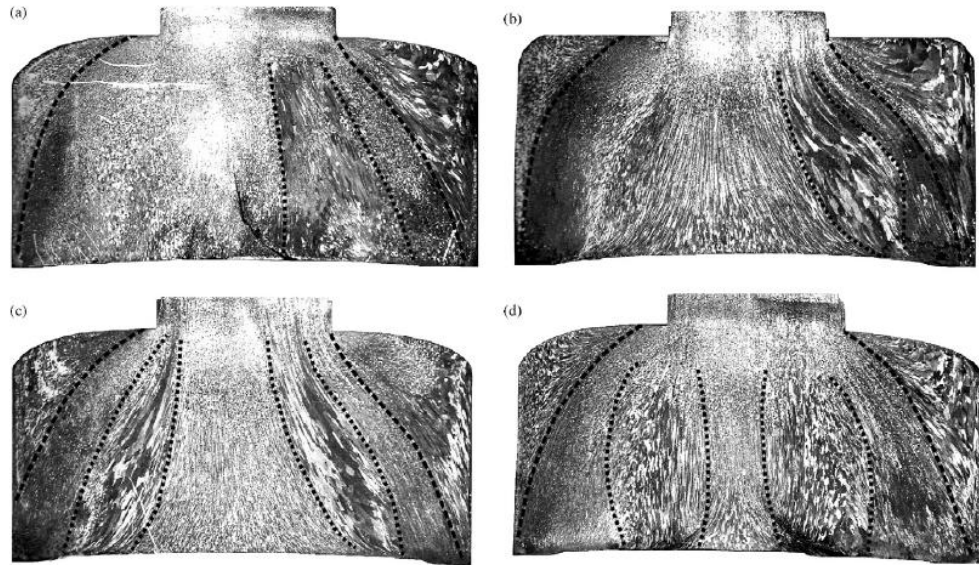


Figure 2-15 Macrostructures of material in the billet rest using different die configurations [34]:
(a) Flat die; (b) Pocket die 1 mm; (c) Pocket die 3 mm; (d) Pocket die 7 mm

Figure 2-15 (a), (b), and (c) show a large-grained zone inside the deformation zone (bounded with dotted lines). This unexpected phenomenon results from the non-uniform metal deformation. In the case of the largest pocket C, there is an almost ideal symmetry of the shape of deformation zone in Figure 2-15 (d) resulting from the uniform material flow [34].

The deformation flow pattern influences the dispersion of the AlFeSi , Mg_2Si particles significantly in extrudate, resulting in the final yield strength.

2.4 Effect of the extrusion process

Zhang [30] mentioned that, assuming peak ageing conditions, low strength is always caused by not enough Mg and Si being retained in the solid solution prior to artificial ageing. The reasons include:

- 1) Excessive precipitation of Mg-Si precipitates in the homogenised billet by slow post-homogenisation cooling
- 2) Prolonged billet preheating
- 3) Insufficient dissolution of coarse Mg-Si precipitates by the exit temperature being below 520°C
- 4) Inadequate quenching rate

Therefore, for a given as-cast billet, three stages are important to control for preventing coarsening of Mg_2Si . They are homogenization, preheating, and extrusion.

2.4.1 Billet homogenization

The purpose of homogenizing at a high temperature is, firstly, to reduce microsegregation by diffusion of magnesium and silicon throughout the structure. Secondly, to transform the insoluble eutectic phases to the equilibrium phase α -AlFeSi. This produces billets with uniform structures that are more amenable to reheating and extruding than as-cast billets.

AlFeSi constituents are important in the extrusion process as the characteristics of the AlFeSi in DC cast affect extrudability [23]. Spheroidization is necessary for good extrudability. Therefore transformation of the β -AlFeSi phase to the α -AlFeSi form is required for improving extrudability [5]. During the homogenizing process, the β -AlFeSi phase (angular needles) transforms to the α -AlFeSi phase (grey rounded particles). Poor ductility and surface defects are primarily attributed to the presence of the β -AlFeSi phase. This is due to poor cohesion with the surrounding aluminium matrix. α -AlFeSi particles are smaller in size than the pre-existing β -AlFeSi. They have a more diffuse interface with the aluminium matrix, with higher thermal stability [35]. A relative α fraction of at least 85% is required to obtain optimal extrudability. Birol [36] stated that the β -AlFeSi phase completely transformed after six hours soaking at 580°C - which is shown in Table 2-4.

The insoluble constituents in soaked billets

Temperature ($^\circ\text{C}$)	Time (h)		
	2	4	6
540	β -AlFeSi, α -AlFeSi	β -AlFeSi, α -AlFeSi	β -AlFeSi, α -AlFeSi
560	α -AlFeSi (β -AlFeSi)	α -AlFeSi (β -AlFeSi)	α -AlFeSi (β -AlFeSi)
580	α -AlFeSi (β -AlFeSi)	α -AlFeSi (β -AlFeSi)	α -AlFeSi

Table 2-4 Insoluble constituents in soaked billets [36]

Figure 2-16 [36] shows the optical micrographs of the distribution of Mg_2Si precipitates at different cooling rates. The population of the Mg_2Si precipitates was reduced dramatically. A very fine and dense dispersion was replaced by relatively coarse, stable precipitates when the cooling rate dropped below 100°C/h .

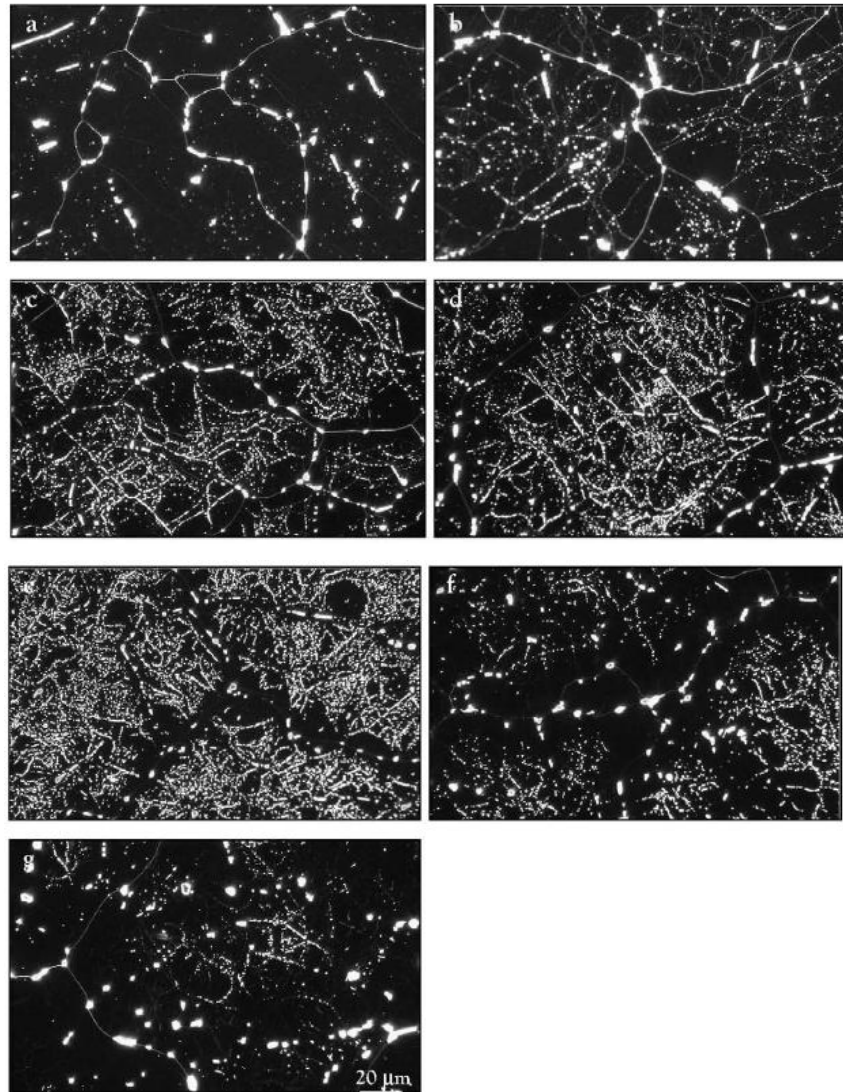


Figure 2-16 Optical micrographs showing the distribution of Mg_2Si precipitates in samples soaked at 580°C for six hours and subsequently cooled to 200°C at cooling rates of: [36]
 (a) 2000°C/h ; (b) 800°C/h ; (c) 400°C/h ; (d) 200°C/h ;
 (e) 100°C/h ; (f) 30°C/h ; (g) 12°C/h

2.4.2 Billet pre-heating

The aim of pre-heating is to lessen flow stress of the alloy. This allows extrusion at the maximum speed, maintaining excellent surface finish and mechanical properties. The pre-heating rate depends on how long it takes for the post-homogenized microstructure of the billets to change. It was shown that extrudability, as well as mechanical properties and surface quality, might be significantly improved by using billet-preheating practices different from accepted normal production practices. During the heat-up cycle, any Mg_2Si phase present in the homogenized structure has enough time to go into solid solution again [5]. The pre-heating rate influences the amount of Mg_2Si dissolved. Gas-fired re-heating can cause more Mg_2Si to go back into solution [5].

Langkruis [37] revealed that Mg solute content in pre-heating can be used to predict the peak hardness after artificial ageing. The dissolution diagrams are constructed in Figure 2-17.

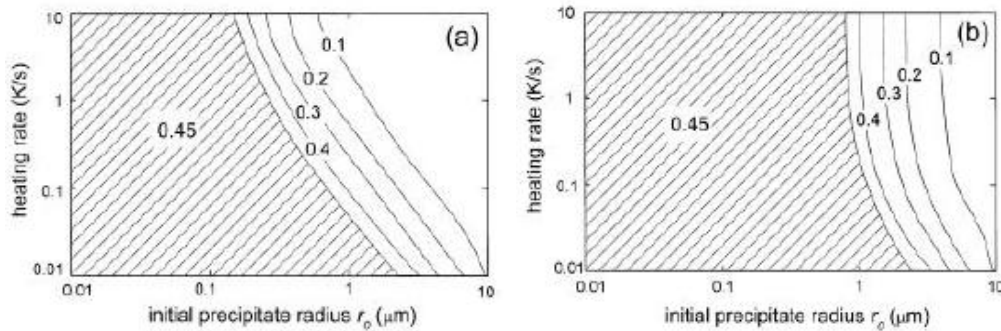


Figure 2-17 Mg solute content after pre-heating, as a function of heating rate and initial particle radius
(a) holding time 4 seconds; (b) holding time 5 minutes [37]

This dissolution diagrams show the iso-solute Mg contours. The numbers in the Figure indicate Mg solute content (wt %). It can be observed that the final solute Mg content is significantly influenced by the holding time.

2.4.3 Extrusion speed and temperature

During extrusion, the operating conditions should allow the Mg_2Si phase to dissolve completely, within the speed and temperature limitations, resulting in the correct microstructure for press quenching and ageing treatment [38].

The exit temperature varies during extrusion. Its variation depends on the billet pre-heating temperature and extrusion speed due to heat transfer from billet to container, and heat developed by deformation and friction. Figure 2-18 [13] is a limit diagram of the relationship between exit speed and billet temperature. Limit curve 1 indicates that the surface temperature cannot exceed a maximum value at any point or it results in excessive scoring or transverse cracks. Limit curve 2 shows that the average section temperature has to be high enough to ensure adequate solution heat treatment with Al-Mg-Si alloys. Limit curve 3 shows that the press and its power source determine the maximum extrusion load and ram speed. When billet temperature reaches between 380 - 400°C, the extrusion speed is limited to around 40 – 50 m/min.

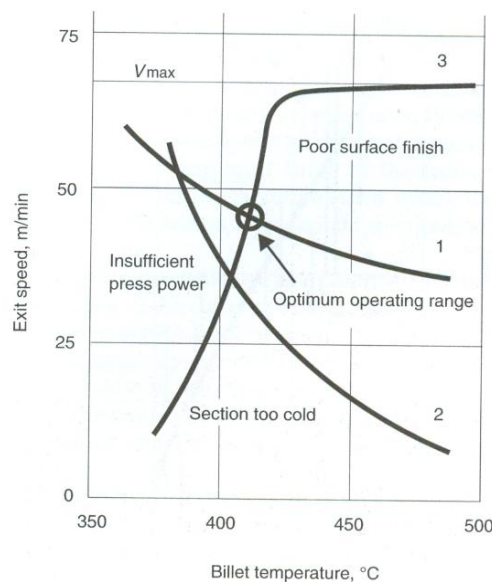


Figure 2-18 Limitation diagram of exit speed and billet temperature [13]

For 6063 and its derivative 6060, to allow Mg_2Si particles to dissolve completely, the deformation temperature should lie between a solution temperature of 500–600°C in terms of the 1% of Mg_2Si (by weight) as shown

in Figure 2-19. Therefore, if the amount of Mg_2Si in 6060 alloy is less than 1%, its deformation temperature must be within the above range.

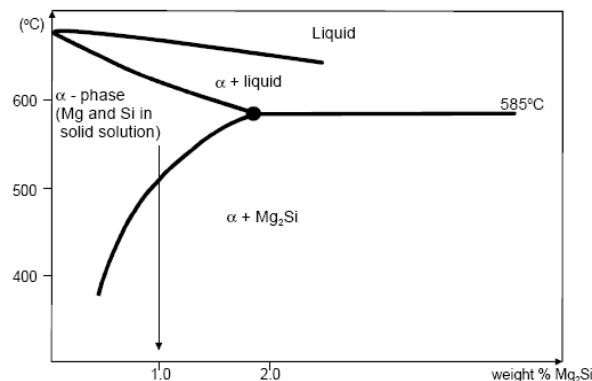


Figure 2-19 Phase diagram of Al-Mg- Si system [39]

When aluminium is deformed at high temperatures, gradual formation and appearance of a microscopically resolvable grain structure occurs [5]. However many hot worked alloy products, especially those from the higher strength alloys, may resist recrystallization even when subjected to solution heat treating temperatures [5]. Large recrystallised grains may be found just below the periphery of the extrusion. Deformation during extrusion is more severe at the outer surface than toward the centre. For lower strength alloys such as AA6063 [40] or possibly for medium strength alloys, the use of higher than normal extrusion speeds and minimum billet temperature can give a fully recrystallised structure with a fine uniform grain size [40].

The effect of ram speed and billet temperature on microstructure in AA6005 was studied by Parson [40]. Three types of grain structure were found and shown in Figure 2-20. It indicates that above the dotted line in Figure 2-20 at actual exit temperature of 510°C, Mg_2Si particles were dissolved sufficiently to meet the T6 property requirements. Any conditions on or to the right of this dotted line will give T6 its yield strength.

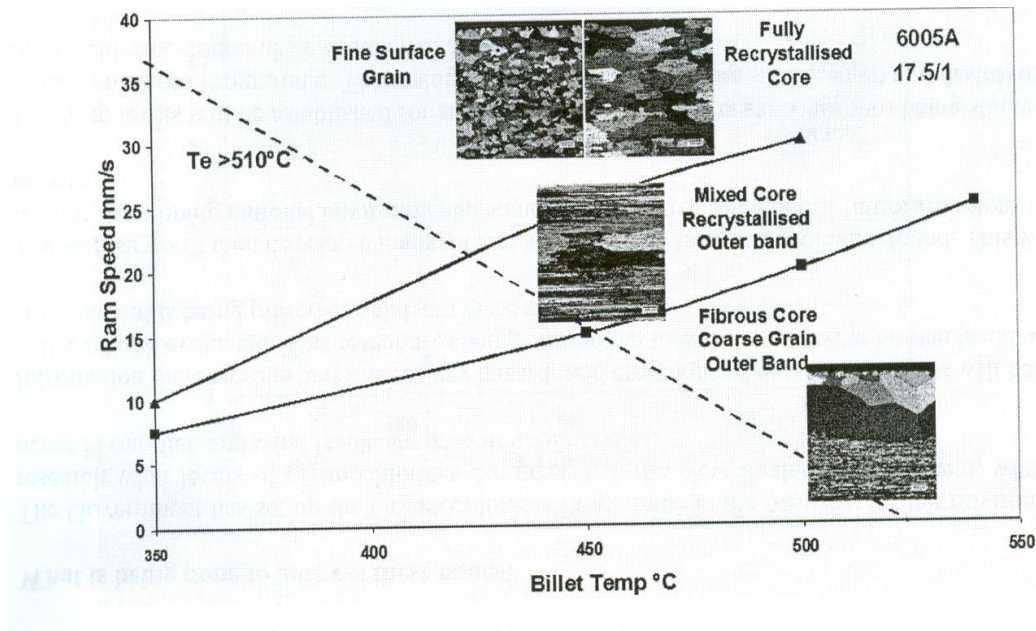


Figure 2-20 Effect of ram speed and billet temperature on grain structure for a 25 mm bar in AA6005A [40]

Low billet temperatures and high ram speeds promote this condition along with a finer grain size. In contrast, high billet temperature and low ram speeds promote stability of the unrecrystallised structure, but when recrystallisation occurs the grain size is generally coarser.

To achieve uniform product quality, a constant exit temperature is required in an extrusion cycle [1, 13]. The exit temperature of an extrudate varies from one point to another on its cross-section and along its length, relative to the ram position during extrusion processing. Initial billet temperature, container temperature, and ram speed must be assigned appropriately to equalize the heat flow from billet to container and heat generation due to shearing deformation. Figure 2-21 shows the constant exit temperature attained based on experimental extrusion of AA6060 (dark line) by Tibbetts [41] under ram velocity of 2.0 cm/s, with extrusion ratio 10:1. This shows that a constant exit temperature can be achieved if the extrusion parameters are chosen appropriately and extrusion speed adjusted as required.

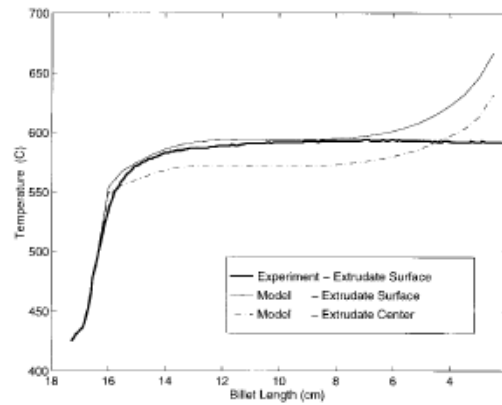


Figure 2-21 Extrudate exit temperature [41]

The pre-heating temperature varies with different type of alloys. This determines the exit temperature. An unstable extrusion exit temperature could be another reason for yield strength being non-uniform over the whole length. The exit temperature is adjusted by the extrusion speed.

2.4.4 Press quenching rate

To retain a solid solution of Mg and Si in the aluminium matrix, the extrudate must be rapidly cooled as it emerges from the die. Rapid quenching, (usually achieved with water), will approximate the ideal, but is not necessary with 6063. This alloy is much less quench-sensitive than any other heat treatable alloy.

Traenkner [42] pointed out that cooling 6063 extrusion by 149°C per minute or faster substantially eliminates Mg_2Si and excess silicon precipitates. It produces an acceptable microstructure and yields an extrudate with good tensile properties and finishing characteristics.

Anderson [5] stated that quenching is also a function of the thickness of extrusion. Very thick-walled extrusions may not be cooled rapidly enough. This results in some uncontrolled precipitation of Mg_2Si occurring at favourable sites such as grain and subgrain boundaries and dislocations. This may lower the peak strength attainable in the finished extrusion.

2.5 Summary

Extrusion proceeding is very complex and the interaction of parameters is still not fully understood. Factors affecting final extrusion strength were presented in this chapter based on current knowledge. For a given composition alloy, casting structure, homogenizing and pre-heating conditions influence the transformation of β -AlFeSi to α -AlFeSi. They also should prevent coarsening of the Mg_2Si phase, resulting in good extrudability. During extrusion, remaining Mg_2Si particles are further dissolved. Press quenching aims to retain as much Mg and Si as possible in solution prior to age hardening. The peak-aged condition in heat treatment is gained by correcting the 'balance' of Mg and Si available to form Mg_xSi precipitates.

To achieve optimum yield strength in peak-aged T5 temper which are as least as good as T6 temper, (without compromising productivity of the alloys), experimental tests in this study will investigate Mg content before and after extrusion in 6060 alloy, and yield strength with peak ageing hours at 205°C and 185°C , for thicknesses of 1.1 mm and 1.5 mm.

Chapter 3 Experimental Procedures

Factors that may affect the final strength and the aim of this research have been discussed in the previous chapters. This chapter introduces the extrusion conditions, profiles used, sampling method, and age hardening experiments, tensile testing and chemical composition analysis in this study.

3.1 Materials, sampling and extrusion conditions

3.1.1 Materials

6060 alloy direct chill cast ingot was used in this experimental work. For this research, the alloy was supplied by a smelter. Homogenizing of the ingot was performed by the supplier by soaking for two hours at 575°C .

The profiles of 6060 alloy employed in this study had thicknesses of 1.1 mm and 1.5 mm. The chemical composition range of the investigated alloy is given in Table 3-1.

Component	Wt %
Si	0.52 - 0.53
Fe	0.17 - 0.19
Cu	<0.02
Mg	0.36 - 0.38
Mn	0.04
Cr	<0.01
Ti	<0.02
Zn	<0.01
Aluminium (Al)	Balance

Table 3-1 Chemical composition ranges of alloy used in this study

For a given alloy in this study, the range of the principal element Mg was between 0.36 - 0.38 wt% while Si was between 0.52 - 0.53 wt%.

3.1.2 Profile shapes and specimen locations

The geometry of two extruded profile shapes in this study is presented in Figure 3-1 (a) and (b). Those geometries were chosen because of similarity in shape but different thicknesses.

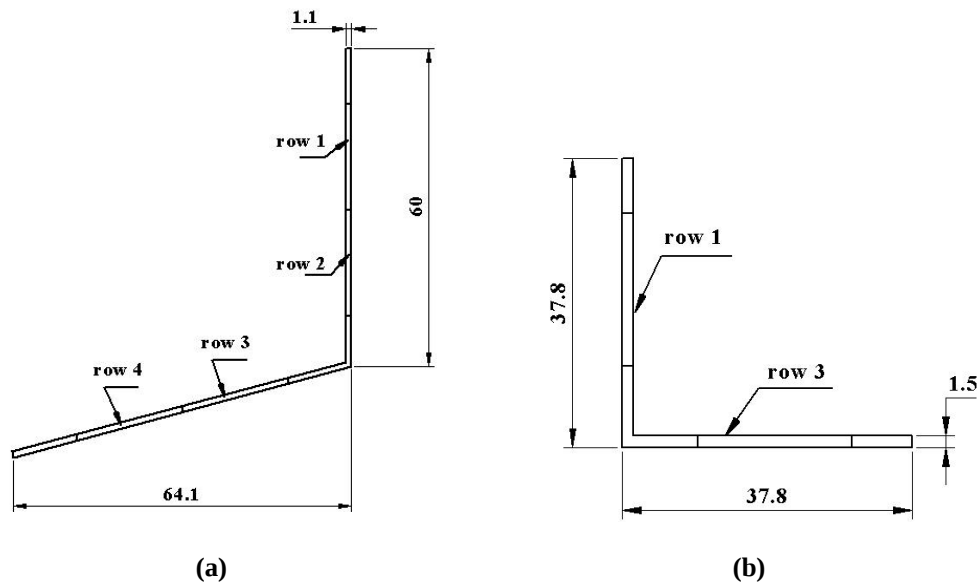


Figure 3-1 Profile shapes of extrusion used in this study
(a) Shape 1 – thickness 1.1 mm (b) Shape 2 – thickness 1.5 mm

Figure 3-2 indicates the die configurations of profile shape 1 and shape 2. There are two cavities in die shape 1 and four cavities in die shape 2.

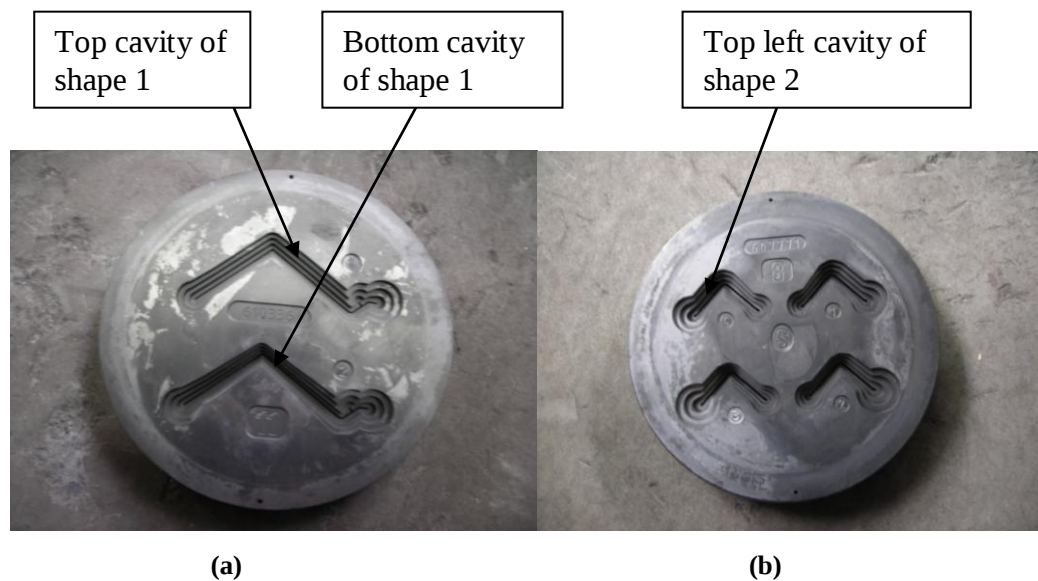


Figure 3-2 Extrusion dies used for producing extrudate in this study
(a) Die for shape 1
(b) Die for shape 2

The location of samples in different experimental tests is indicated in Figure 3-3. There were five experimental tests conducted in this study. The middle length of four metres long was cut for specimens for experimental tests 1, 3, 4, 5 (see Table 3-2) and shown in Figure 3-3 (a). The whole length of extrudate was used for experimental test 2. The position of the specimens is indicated in Figure 3-3 (b).

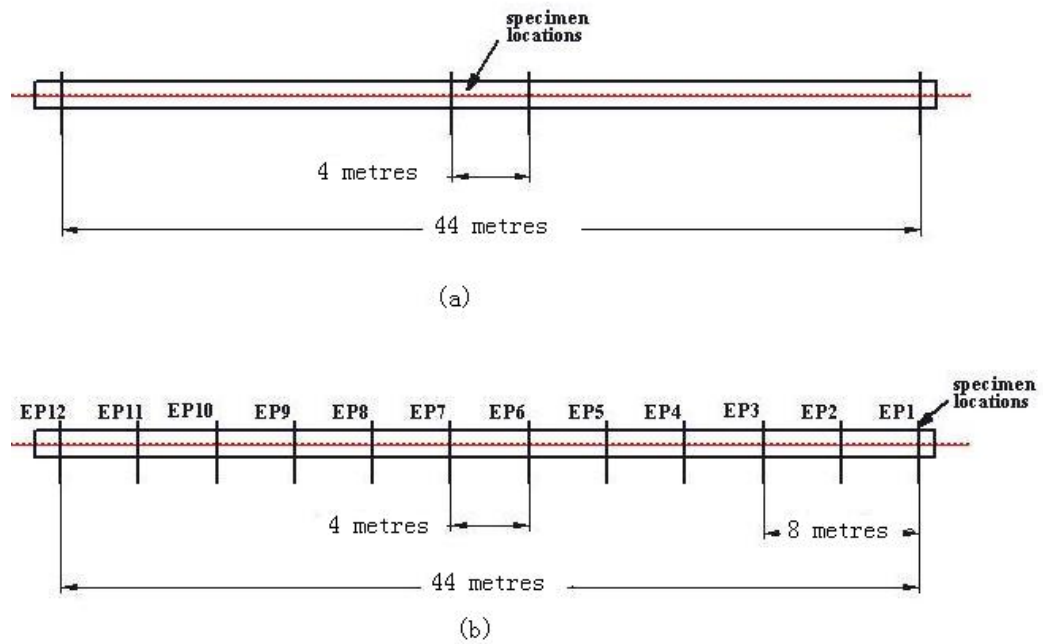


Figure 3-3 Locations of samples over whole length of extrudate
(a) For experimental test 1, 3, 4, 5
(b) For experimental test 2

3.1.3 Extrusion speed and exit temperature

Extrusion processing for trials was performed in an 8 MN hydraulic horizontal extrusion press shown in Figure 1-4 (Chapter 1). All the extrusion parameters during extrusion processing were controlled by OMAV equipment. Temperatures were measured by means of thermocouples /or infra- red cameras. Some data from a trial are shown in Figure 3-4. The OMAV equipment is checked regularly by the operator.

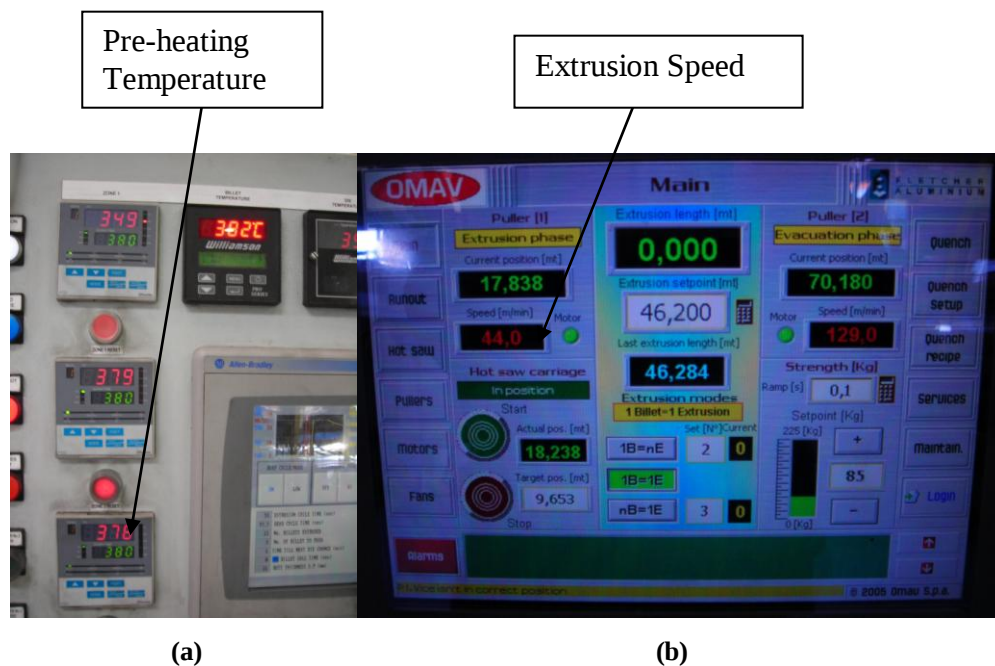


Figure 3-4 Examples of extrusion parameters shown on screen of OMAV equipment

Extrusion processing was conducted for investigating the yield strength at mid-length and along the whole length. Extrusion conditions used in this study are summarised in Table 3-2.

Extrusion conditions	Test 1	Test 2	Test 3	Test 4		Test 5	
* Profile	Shape 1	Shape 1	Shape 2	Shape 1 (test 1)	Shape 2 (test 2)	Shape 1 (test 1)	
** Cavity	Top cavity	Top cavity	Left top cavity	Top cavity	Left top cavity	Top cavity	Bottom cavity
*** Sample Location	Mid-length	Whole-length	Mid-length	Mid-length	Mid-length	Mid-length	Mid-length
Extrusion speed (m/min)	45	44	40	45	40	45	45
Billet pre-heat Temperature	387°C	380°C	384°C	387°C	384°C	387°C	387°C
Billet pre-heat Time (min)	40 – 45	40 – 45	40 – 45	40 - 45	40 - 45	40 - 45	40 - 45
Billet exit Temperature	536 °C	541 °C	546 °C	536 °C	546 °C	536 °C	536 °C

Table 3-2 Extrusion parameters used in this study

* Shape 1 – see Figure 3-1 (a)

* Shape 2 – see Figure 3-1 (b)

** Top cavity / Bottom cavity – see Figure 3-2 (a) * Left top cavity - see Figure 3-2 (b)

*** Sample location - see Figure 3-3

The temperature of the container was maintained at around 350°C during the process. Table 3-2 shows that for shape 1 the pre-heating temperature was between 380 - 400°C and held for 40-45 minutes. The exit temperature of the extrudates as they left the die varied between 535 - 545°C. The extrusion speed was between 40 – 45 m/min. For shape 2, billet pre-heating temperature was 384°C and exit temperature was 546°C, while the extrusion speed was 40 m/min.

The aim of tests 1 and 3 were to determine the peak age hardening conditions at 205°C and 185°C for different thicknesses of 1.1 mm and 1.5 mm. Variations in strength over the length were investigated in test 2. The purpose of test 4 was to compare the yield strength of samples after ageing at the aluminium manufacturer and at AUT under the same ageing conditions. Test 5 contrasts yield strength between the top and bottom cavities.

3.1.4 Average cooling rate

For examining the average cooling rate, ten trials of air cooled extrudates were conducted on shape 1. Figure 3-5 indicates the ram pressure and ram speed curve for trial 5. The maximum pressure was 3600 Psi (24.8 MPa) and constant ram speed was achieved at 5 mm/s after about one third of the extrusion cycle was done.

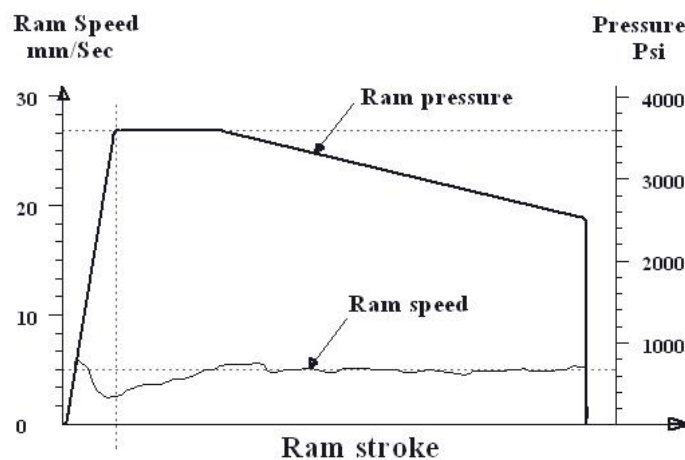
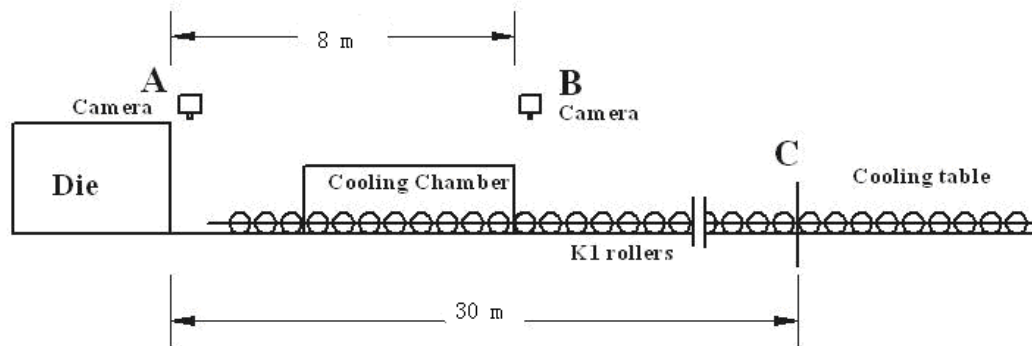


Figure 3-5 Example of extrusion ram pressure and ram speed curve for trial 5

Table 3-3 presents some of the extrusion parameters of ten trials obtained from the OMAV equipment. The extrusion exit temperature and quench exit temperature was the temperature when the ram speed reached a constant 5 mm/s in Figure 3-5. Figure 3-6 shows a schematic diagram of the production line at the aluminium manufacturer where the cooling process is performed. Two infra-red cameras are located at positions A and B. Infra-red camera A records the die exit temperature and B records the quench exit temperature. The distance between extrusion exit temperature and quench exit temperature was eight metres.



**Figure 3-6 Schematic diagram showing extrusion cooling system
(Air cooling condition: Cooling chamber is open)**

The average cooling rate of shape 1 in these trials can be calculated as follows:
Example: the extrusion speed in trial 5 was 44 m/min, extrusion exit temperature was 541°C and quench temperature was 468°C . Therefore:

$$\begin{aligned}
 \text{Average cooling rate} &= \frac{\text{Exit temperature} - \text{Quench temperature}}{\text{Time}} \\
 &= \frac{\text{Exit temperature} - \text{Quench temperature}}{\frac{\text{Distance}}{\text{Speed}}} \\
 &= \frac{541^{\circ}\text{C} - 468^{\circ}\text{C}}{\frac{8\text{ m}}{44\text{ m/min}}} = \frac{73 \times 44}{8 \times 60} \approx 6.69^{\circ}\text{C} / \text{second}
 \end{aligned}$$

From the results for average cooling rates for ten trails in Table 3-3, the cooling rate of shape 1 is greater than $5^{\circ}\text{C} / \text{s}$.

Trial No.	Average-extrusion Speed (m/min)	Billet-preheat Temperature (°C)	Extrusion exit Temperature (°C)	Quench exit Temperature (°C)	*Average cooling rate (°C /s)
Trial 1	45	384	535	478	5.34
Trial 2	45	389	537	474	5.91
Trial 3	45	388	539	471	6.36
Trial 4	44	389	538	480	5.44
Trial 5	44	380	541	468	6.69
Trial 6	43	392	538	476	5.55
Trial 7	43	390	534	471	5.64
Trial 8	42	396	533	467	5.78
Trial 9	44	388	540	474	6.05
Trial 10	43	390	536	473	5.64

Table 3-3 Experimental data for exit temperature over ten trials

3.2 Age hardening

3.2.1 Equipment

All the solution treatment (T6 temper) was done in the furnace at AUT University shown in Figure 3-7 (a). The oven at the aluminium manufacturer in Figure 3-7 (b) was used for the age hardening experimental tests. All the temperatures in tests were monitored with a thermocouple.



(a)



(b)

Figure 3-7 Age hardening equipment

(a) Furnace at AUT

(b) Oven at the aluminium manufacturer

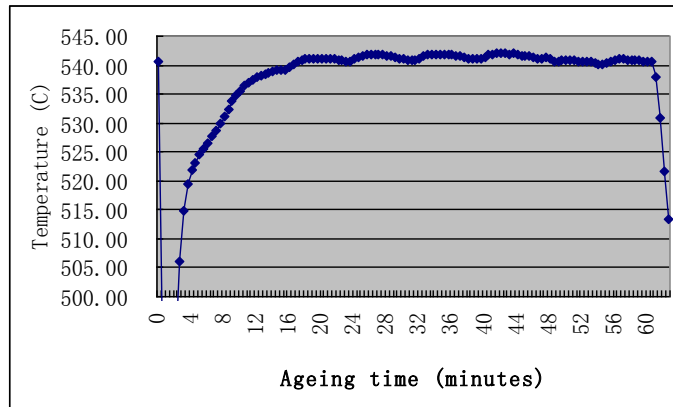
3.2.2 Procedure and conditions

The ageing hardening conditions for five experimental tests are given in Table 3-4. In this study, all the specimens were solution treated at 540°C for one hour in the furnace, followed by water quenching. The holding time at this temperature was sufficient for dissolution to be complete. Afterwards all the solution treated specimens (for T6 temper) and the as-extruded specimens (for T5 temper) were artificially aged at 185°C and/or at 205°C in the oven for different periods of time as shown in Table 3-4.

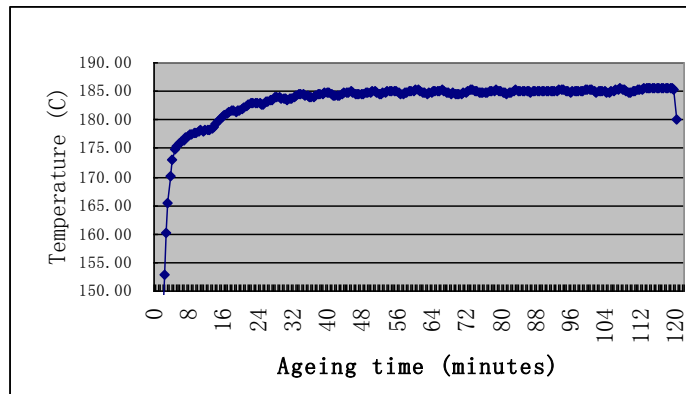
The temperatures of all the specimens were measured at the centre of the furnace/oven by monitoring thermocouple. Three temperature histories for different heat treatment conditions are presented in Figure 3-8. The fluctuations of temperature were $\pm 3^{\circ}\text{C}$.

Test No.	* Profile Shape		Ageing Condition		
			Temper	Temperatures	Time (hours)
Test 1 (Lab)	Shape 1 Thickness 1.1 mm	Row 1, 3	T6	205°C, 185°C	0.5,1,3,5,7,9,11,13,15
		Row 2, 4	T5	205°C, 185°C	0.5,1,3,5,7,9,11,13,15
Test 2 (Lab)	Shape 1 Thickness 1.1 mm	Row 1	T6, T5	205°C	2
				185°C	6
		Row 2	T6, T5	205°C	4
				185°C	12
Test 3 (Lab)	Shape 2 Thickness 1.5 mm	Row 1	T6, T5	205°C, 185°C	0.5,1,3,5,7,9,11,13,15
		Row 3	T6, T5	205°C	0.5,1,3,5,7,9,11,13,15
Test 4 (Industry practice)	Shape 1	Row 1	T5	185°C	6
	Shape 2	Row 1	T5	205°C	2
Test 5 (Lab)	Shape 1	Row 1	T6	205°C	0.5,1,3,5,7,9
		Row 2	T5	205°C	0.5,1,3,5,7,9

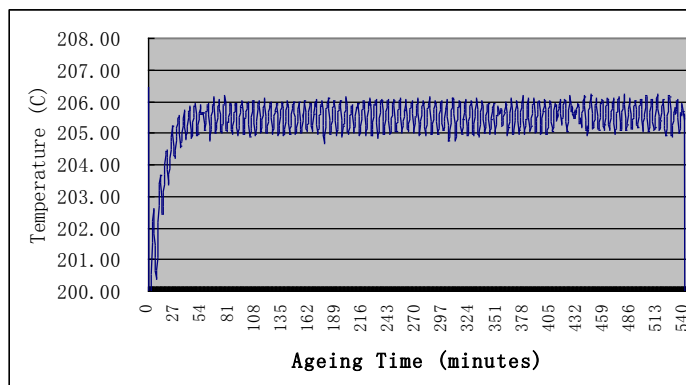
Table 3-4 Experimental age hardening conditions over five tests
*** Profile shape and row locations – see Figure 3-1 (a) and (b)**



(a) Curve of solution temperature at 540° C for one hour (at furnace)



(b) Curve of ageing temperature at 185° C for two hours (at oven)



(c) Curve of ageing temperature at 205° C for nine hours (at oven)

Figure 3-8 Temperature histories of specimens

3.3 Tensile testing

3.3.1 Testing machine

A Tinius Olsen tensile machine was used in this study (Figure 3-9). This testing machine is one of a range of compact machines for determining tension, compression shear, flexure and other mechanical and physical properties of materials. It has a capacity of up to 50 kN. The control display unit shows the force and displacement values and can also graphically display the test results, combined with Navigator software in the computer system. The precision encoder in the extension measuring system operates directly from the crosshead driving ballscrew for readout of the extension position.

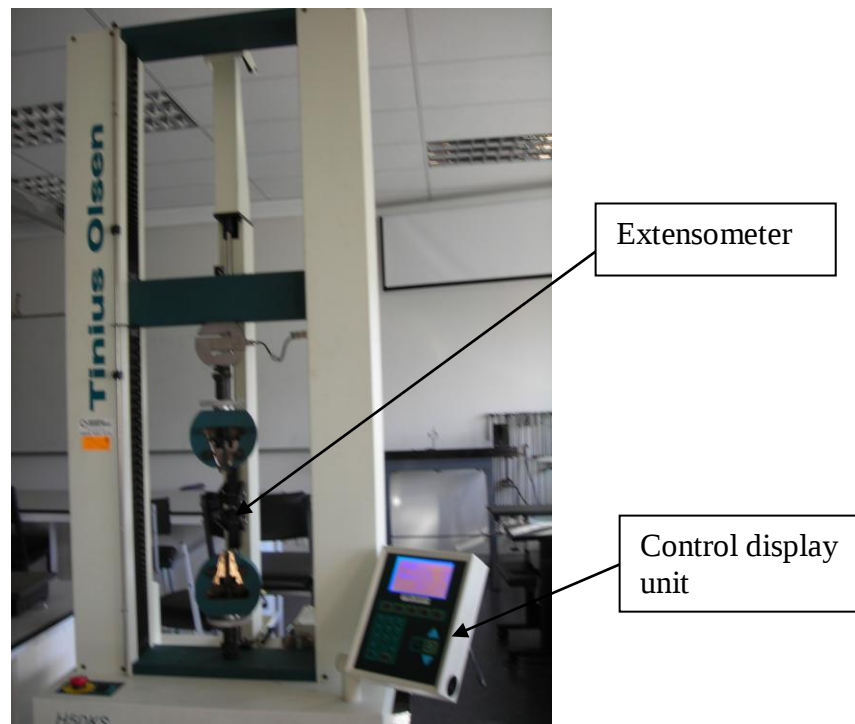


Figure 3-9 50kN tensile machine for determining tensile properties

3.3.2 Specimen preparation

Tensile test specimens were prepared according to the E-8 ASTM. The specimens had a 50 mm gauge length and 12.5 mm gauge width. Specimen shapes and dimensions are shown in Figure 3-10.

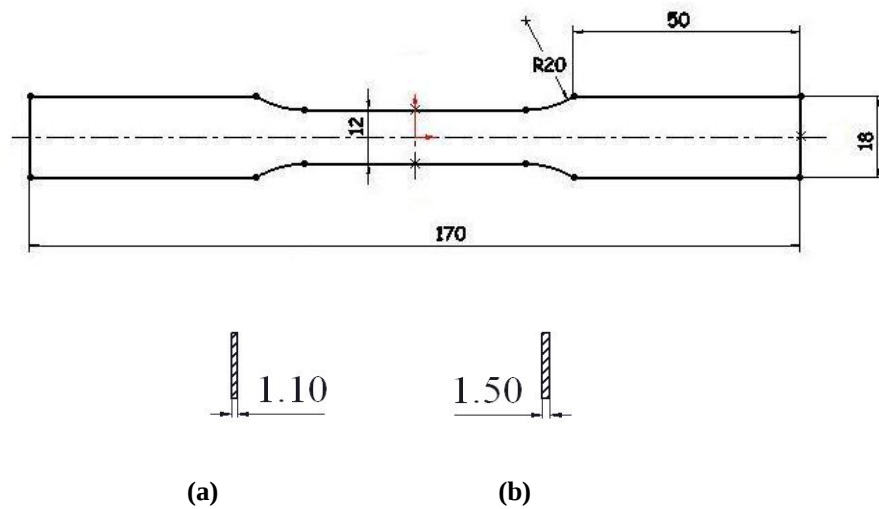


Figure 3-10 Tensile sample (all units in mm)
(a) Thickness 1.1 mm (shape 1)
(b) Thickness 1.5 mm (shape 2)

There were two ways the tensile specimens were prepared. In experimental test 1, 2, 3, and 5 in the laboratory, specimens were first cut, and then underwent age hardening and tensile testing. In experimental test 4 (industry practice), the samples were aged to peak strength in the aluminium manufacturer's oven then machined at AUT's workshop, before performing the tensile test.

3.3.3 Tensile testing procedure

Tensile tests were performed at room temperature using the Tinius Olsen tensile testing machine shown in Figure 3-8. The cross-head speed (test speed) was set at 3 mm/min. Strain was measured using an extensometer attached to the sample with gauge length of 50 mm. 0.2% proof stress was obtained from data files from the Navigator system saved in Microsoft Excel software.

3.4 Chemical analysis

3.4.1 Inductively coupled plasma-atomic emission spectrometry

For determining Mg concentration distribution in pre-heated billet before extrusion, and butt and extrudate after extrusion, inductively coupled plasma-atomic emission spectrometry (ICP-AES) was used. Figure 3-11 shows the ICP-AES machine.

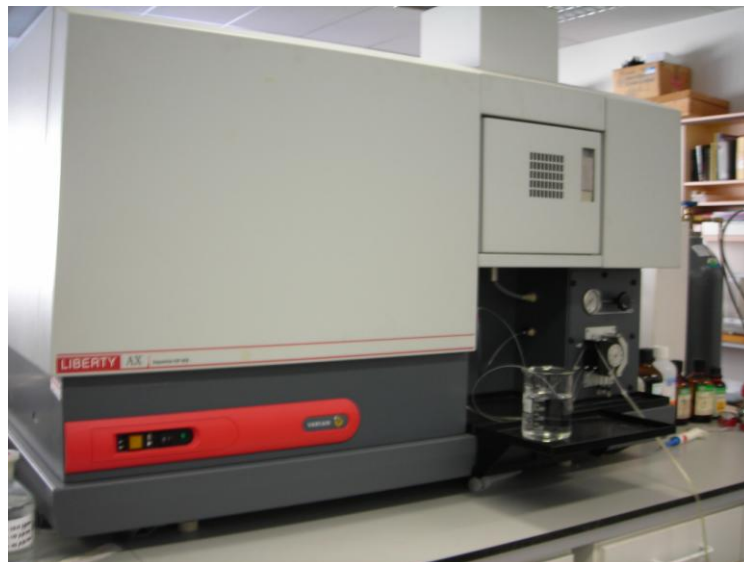


Figure 3-11 ICP-AES machine for determining Mg concentration

An ICP spectrometer is used in this machine to measure the upper and lower limits of analytic concentrations called linear dynamic range. A linear range verification check standard must be analysed and reported quarterly for each analyte. The concentration of the analytes in the LRA (linear range analytes) standard define the upper limit of the ICP linear range beyond which results cannot be reported without dilution. The analytes in the LRA standard must be recovered to within +5% of their true values [43].

3.4.2 Specimen preparation and locations

In order to avoid contamination, a blank new drill was used to drill chips in the specimens that were used as samples for composition analysis.

ICP specimen locations for the chemical tests are shown in Figure 3-12. The billet ($\Phi 202\text{mm}$) shown in Figure 3-12 (a) was subjected to a pre-heating temperature of 380°C held for 40 minutes. Figure 3-12 (b) was the original butt shape after cutting following the extrusion process.

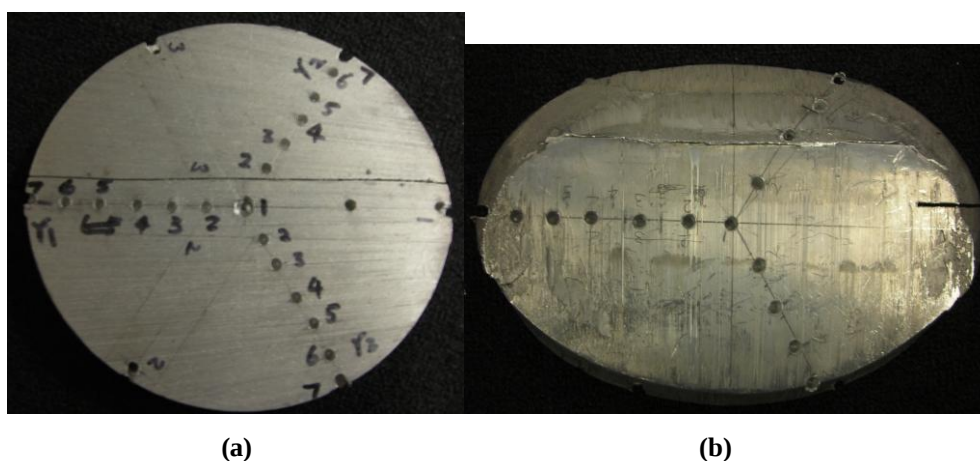


Figure 3-12 Location of specimens for chemical testing
(a) Specimen positions in pre-heated billet
(b) Original butt of shape 1

3.4.3 Test procedure

Before operating the ICP machine, three types of sample solutions should be prepared: standard solution preparation, blank solution, and sample solution.

Mg standard solutions were prepared using reagents of magnesium standard with 10,000 mg/ml. The solutions were then diluted to 1 ppm, 2 ppm, and 5 ppm and were transferred to separate 100 ml volumetric flasks.

The procedure used to make Mg sample solutions was: 0.05g of sample was weighed and transferred into a 250 ml conical flask covered with a filter funnel. 25 ml of HCl (1:1 v/v) was then added slowly into the flask. When the reaction subsided, the sample was heated on a hot plate until dissolved, and then 1 ml of

H₂O₂ was added. The sample was then boiled gently on a hot plate down to a volume of about 20 ml, and then cooled and the solution transferred to a 100 ml volumetric flask. Then made up to the 100 ml mark with distilled water. The reagent blank was prepared using the same procedure without the sample in it.

Once three types of Mg solution were prepared, the concentration of the magnesium content was determined by ICP-AES. The two diagonal lines in Figure 3-13 indicate that the calibration of the Mg concentration test passed. Since the reference standard of magnesium was not used during the test, the results of these composition experimental tests indicated the trends of Mg variation before and after extrusion.

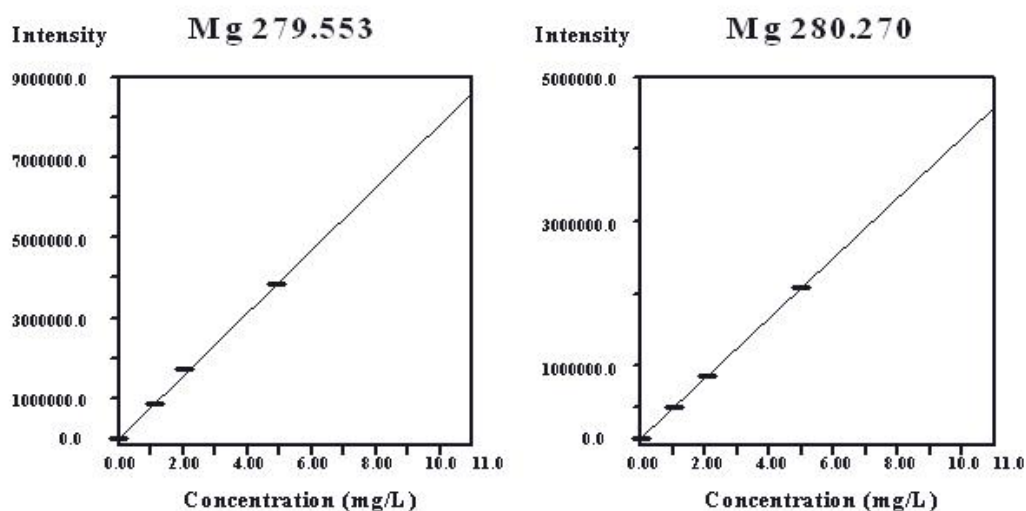


Figure 3-13 The passed calibration of Mg concentration in test

Silicon standard solutions were prepared using reagents of silicon standard with 10,000 mg/ml. The standard solution was then diluted to 1 ppm, 2 ppm, and 5 ppm respectively. The standard solutions were transferred to separate 100 ml polypropylene volumetric flasks.

The procedure to make Si sample solution was: weigh 0.05g of the Si sample into a 250 ml polypropylene beaker and add 25 ml of HNO₃ (1:1 v/v). The beaker was then put into a water bath until there was no further reaction. The beaker was removed from the water bath and 5 ml of HF (42% v/v) added, and

then stood for ten minutes until dissolution was complete. The solution was then transferred to a 100 ml polypropylene volumetric flask and made up to the 100 ml mark with distilled water.

The reagent blank solution was prepared using the same procedure as the sample solution, without the sample in it.

After three types of Si solution were prepared, the concentration of the silicon content was determined by ICP-AES. Unfortunately, the calibration of the Si concentration test failed repeatedly, as the intensity of the reagent blank solution was much higher than the Si standard solution shown in Figure 3-14. Therefore, the test for Si was terminated.

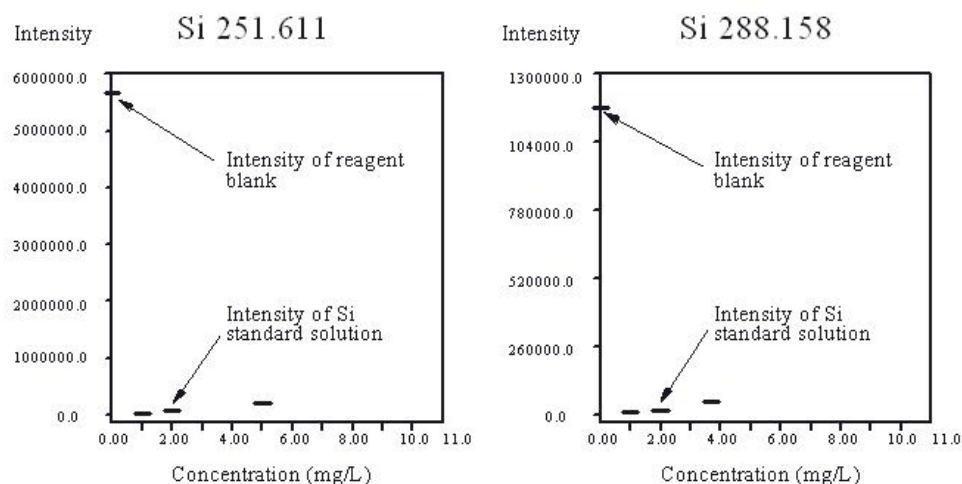


Figure 3-14 Failed calibration of Si concentration test

Chapter 4 Results

The previous chapter described how extrusion trials and samplings for age hardening and tensile testing was done to evaluate whether T5 and T6 tempers could give the same yield strength distributed along the whole length of the extrudate. Thus, yield strength data will be presented first in this chapter. These test data will also be compared to those obtained normally in industry. Then it is followed by detailing the results for Mg distribution. Explanation of the tensile test results obtained considering Mg distribution and thermal history will be given in Chapter 5.

4.1 Yield strength at mid-length

Two specimens were examined under each age condition (T5 and T6). Table 4-1 shows the data from tensile tests 1, 3, and 5 aged at 185°C and 205°C held for different time periods. Table 4-1 (a) is for T6 temper and (b) is for T5 temper. The data for yield strength shown in test 1 is shape 1 with thickness 1.1 mm. Test 3 presents the yield strength data for shape 2 with thickness 1.5 mm. The data for strength between top and bottom cavities are shown in test 5 for shape 1.

Tensile Data (0.2% proof strength MPa)										
Test No.		Test 1 (Shape 1 thickness 1.1 mm)				Test 3 (Shape 2 thickness 1.5 mm)			Test 5 (Shape 1)	
Temperature		205° C		185° C		205° C		185° C	205° C	
Temper	Time (h)	Row 1	Row 3	Row 1	Row 3	Row 1	Row 3	Row 1	Row 1 *(Top)	Row 1 *(Bottom)
T6	0.5	56	56	60	51	70	58	70	58	62
	1	110	112	70	69	130	124	78	130	135
	3	172	172	160	152	180	188	170	165	172
	5	176	183	190	191	192	190	200	163	161
	7	168	170	190	200	192	190	205	156	155
	9	165	178	195	205	190	182	215	168	160
	11	160	173	208	208	190	186	212		
	13	156	170	200	202	185	178	215		
	15	146	155	198	200	175	178	220		

(a) For T6 temper

Table 4-1 Tensile data for experimental tests 1, 3, and 5
* Shape and Row number – see Figure 3-1

Tensile Data (0.2% proof strength MPa)										
Test No.		Test 1 (Shape 1 thickness 1.1 mm)				Test 3 (Shape 2 thickness 1.5 mm)			Test 5 (Shape 1)	
Temperature		205° C		185° C		205° C		185° C	205° C	
Temper	Time (h)	Row 2	Row 4	Row 2	Row 4	Row 1	Row 3	Row 1	Row 1 *(Top)	Row 1 *(Bottom)
T5	0.5	63	62	66	66	70	84	78	65	61
	1	125	125	82	78	132	132	80	134	130
	3	185	180	160	168	195	185	170	170	172
	5	181	188	198	192	190	190	200	168	165
	7	175	176	200	200	190	182	208	160	158
	9	172	172	205	202	190	180	220	165	160
	11	170	165	200	201	190	178	218		
	13	168	160	202	200	182	178	220		
	15	168	160	202	200	180	176	222		

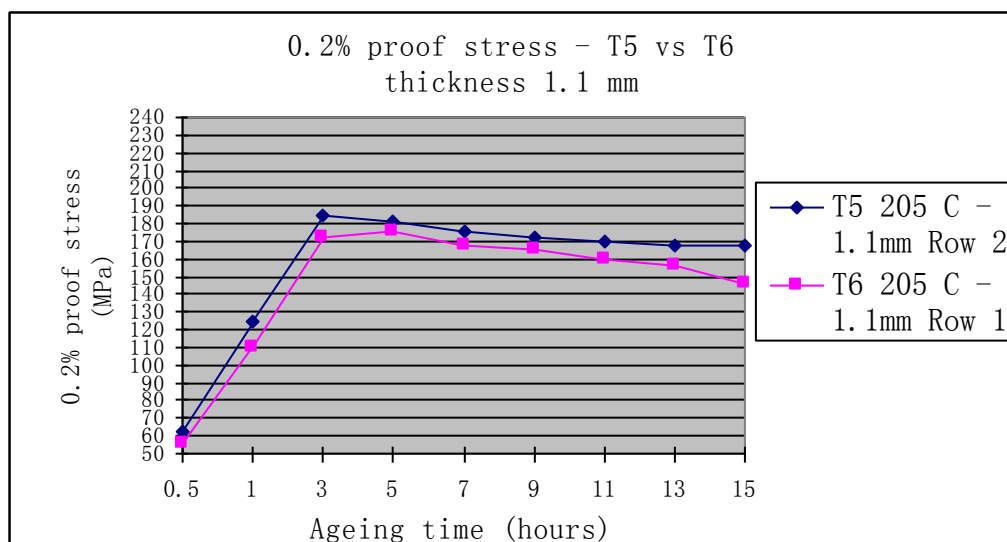
(b) For T5 temper

Table 4-1 Tensile data for experimental test 1, 3, and 5

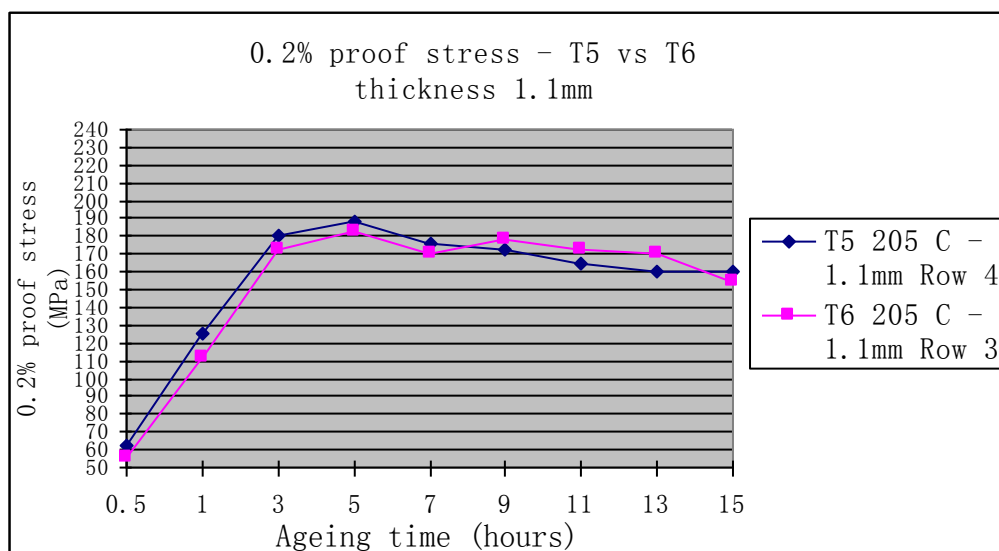
* Shape and Row number – see Figure 3-1

4.1.1 Thickness 1.1 mm

Results of strength at mid-length for T5 and T6 temper for shape 1 (thickness 1.1 mm) are presented in Figure 4-1. It shows the variation of strengths at 205°C holding for times of 0.5, 1, 3, 5, 7, 9, 11, 13, and 15 hours.



(a) In Row 1 and Row 2



(b) In Row 3 and Row 4

Figure 4-1 Strength of extrudate at mid-length for thickness 1.1 mm aged at 205°C for different times

* Location of Row number - See Figure 3-1 (a)

Maximum yield strength is obtained when the alloy was aged at 205°C for three hours in Figure 4-1 (a), or five hours in (b) for thickness 1.1 mm.

As shown in Figure 4-1 (a) T5 at Row 2 reached 185 MPa when held for three hours. At Row 4 peak strength of 188 MPa needed holding for five hours. Peak strength at Row 1 and Row 3 reached 176 MPa and 183 MPa respectively when aged for five hours. Peak strength in T5 is higher than T6 for Row 1 and Row 2 regardless of the ageing time. The difference between T5 and T6 in peak strength is 13 MPa when aged for three hours in (a). However when aged for nine, eleven, and thirteen hours did T6 strength at Row 3 was higher than T5 strength for Row 4 in (b). The fluctuation was around 10 MPa. In general, the difference for four rows was slight. Figure 4-2 shows T5 and T6 results plotted on the same graph.

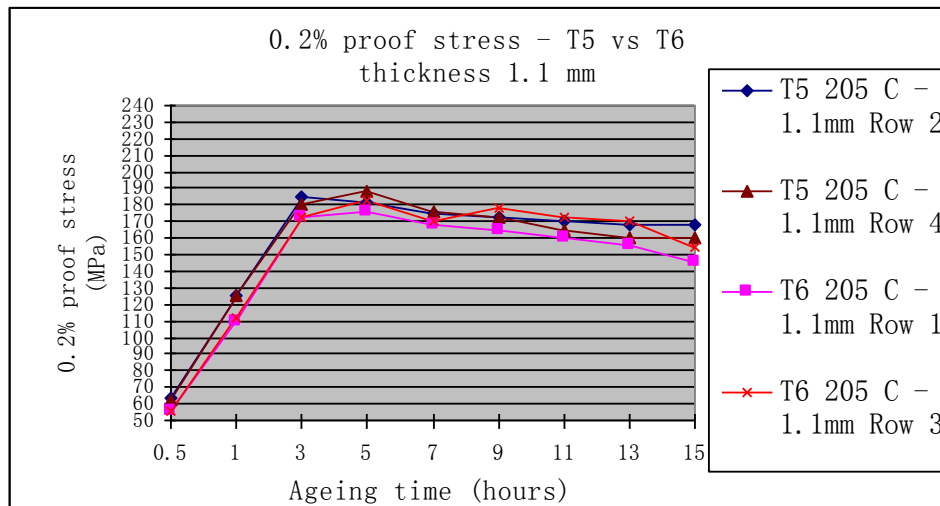
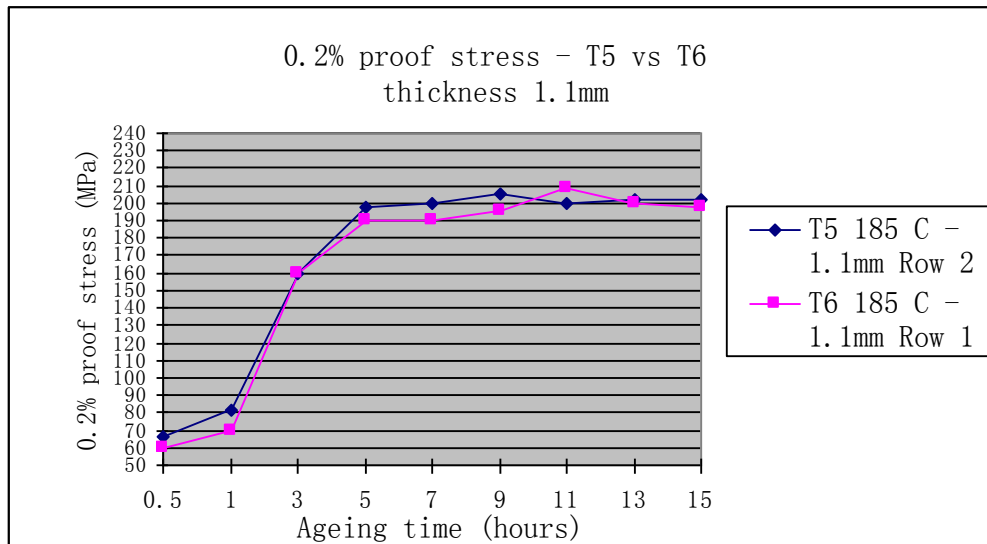


Figure 4-2 Strength of extrudate at mid-length for thickness 1.1 mm aged at 205° C for different times

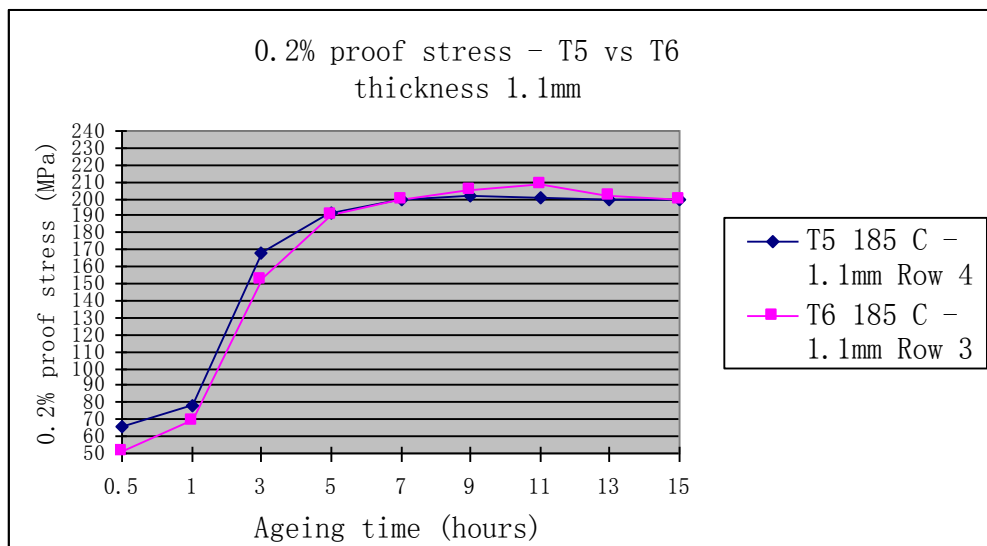
* Location of Row number - See Figure 3-1 (a)

To compare with two data under the same age condition, the yield strength difference between Row 2 and Row 4 in T5 is not greater than 8 MPa. Between Row 1 and Row 3 in T6, the difference is less than 15 MPa. It is interesting to discover that yield strength reached above 180 MPa at 205° C, when held for three to five hours, for T5 temper.

Figure 4-3 shows the variation of strengths at 185° C holding for times of 0.5, 1, 3, 5, 7, 9, 11, 13, 15 hours. Yield strength behaviour at 185° C is different from at 205° C. It needs more time to reach the peak when aged at 185° C than those at 205° C.



(a) In Row 1 and Row 2



(b) In Row 3 and Row 4

**Figure 4-3 Strength of extrudate at mid-length for thickness 1.1 mm
aged at 185°C for different times**

*** Location of Row number - See picture 3-1 (a)**

Curves in Figure 4-3 (a) and (b) show that yield strength reaches above 190 MPa, for both T5 and T6 temper, when the alloy is aged for five hours or more. The greatest difference in yield strength for T5 and T6 at 185°C is 12 MPa when aged for one hour in (a) and 16 MPa when aged three hours in (b). Results show that yield strength in T5 temper is at least equal to T6 temper. Ageing at 185°C makes the peak conditions last longer, compared to ageing at 205°C (Figure 4-1). Figure 4-4 shows the combination of graphs in Figure 4-3 (a)

and (b). It can be seen that yield strength is comparable for different rows under the same age conditions. This is similar to Figure 4-2.

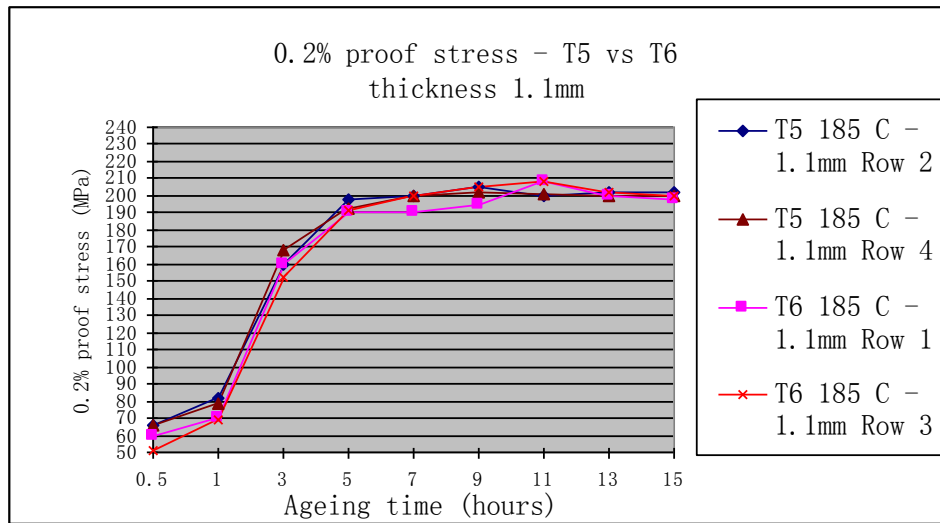


Figure 4-4 Strength of extrudate at mid-length for thickness 1.1 mm aged at 185° C for different times for T5 and T6 temper

* Location of Row number - See picture 3-1 (a)

Figure 4-5 shows the stress-strain curve when aged at 205° C for three hours and aged at 185° C for five hours for both T5 and T6 temper. It indicates that yield strengths for T5 temper are generally higher than for T6 temper regardless of the temperature and time. Ductility is also better for T5 than for T6. T5 temper gives a great substantial increase over T6 in the elongation to fracture. More stress-strain curves for different times at both temperatures are shown in the appendix.

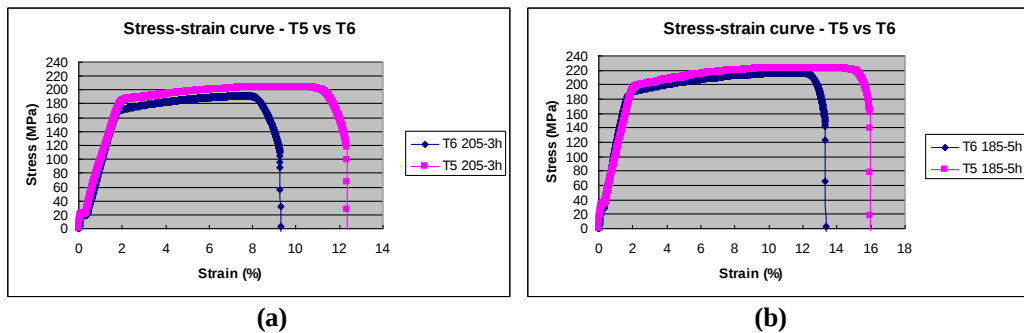


Figure 4-5 Engineering stress-strain curve (1.1 mm)

(a) ageing at 205° C for three hours

(b) ageing at 185° C for five hours

Furthermore, to compare strength of extrudate between the top and bottom cavities, mid-length extrudate from these two cavities from experimental test 5 were studied for both T6 and T5 temper at 205° C . Results are shown in Figure 4-6.

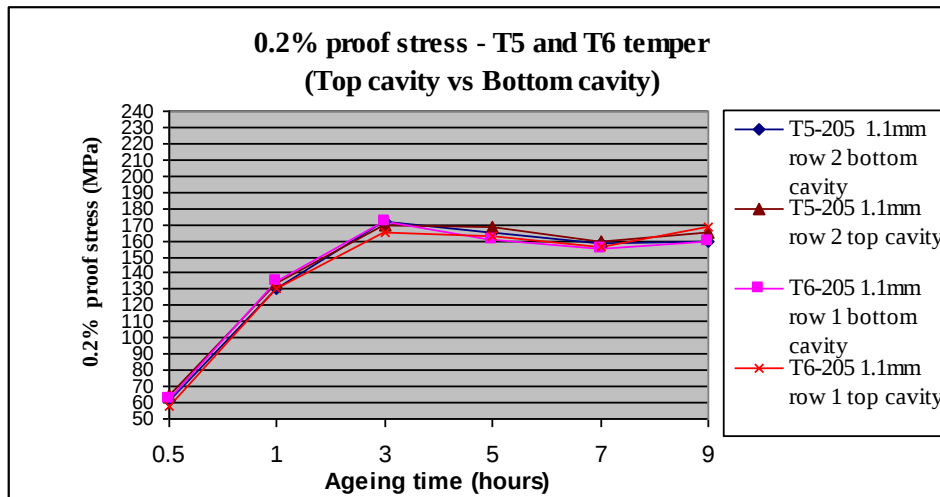


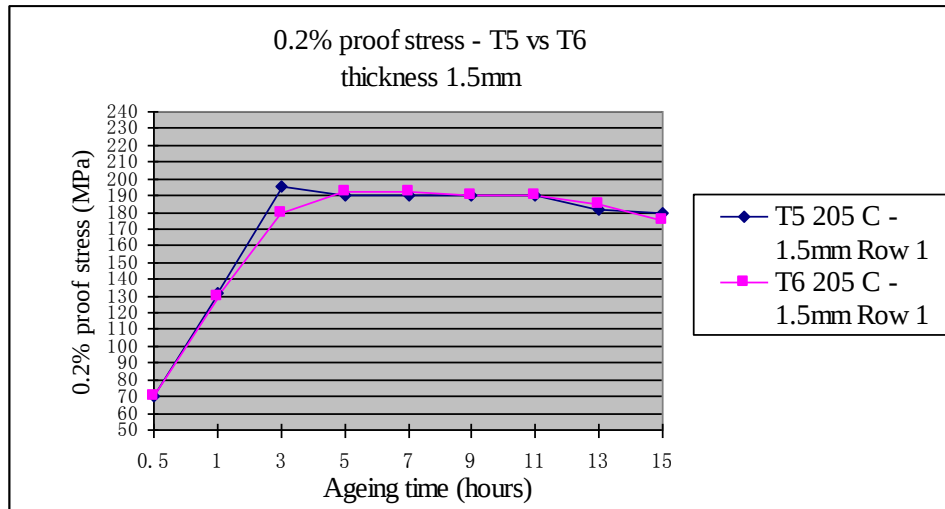
Figure 4-6 Strength of extrudate at mid-length at top and bottom cavities for shape 1

*** Shape, Cavity and Row number of shape 1 – see Figure 3-1 (a)**

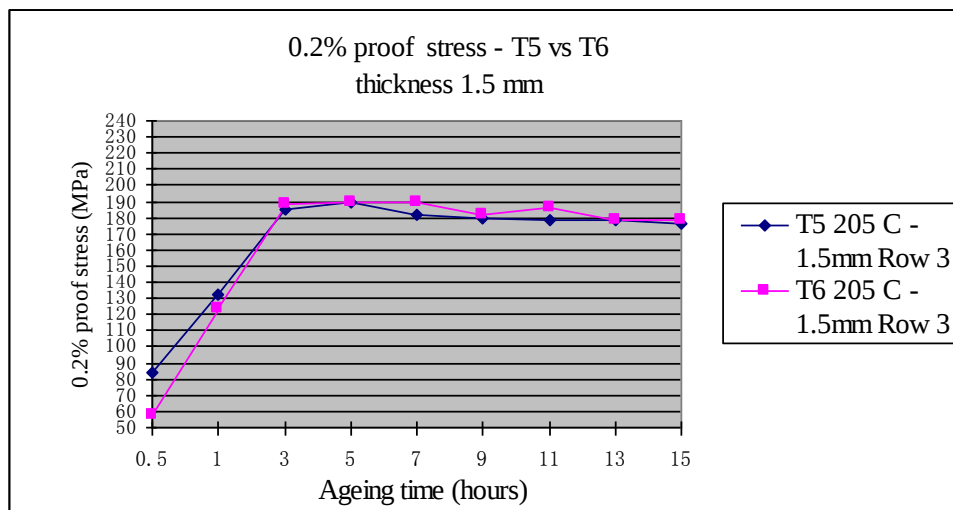
The values in curves for T5 and for T6 are very close to each other. It would imply that, because the thermal history was the same during extrusion, then balanced material flow was achieved.

4.1.2 Thickness 1.5 mm

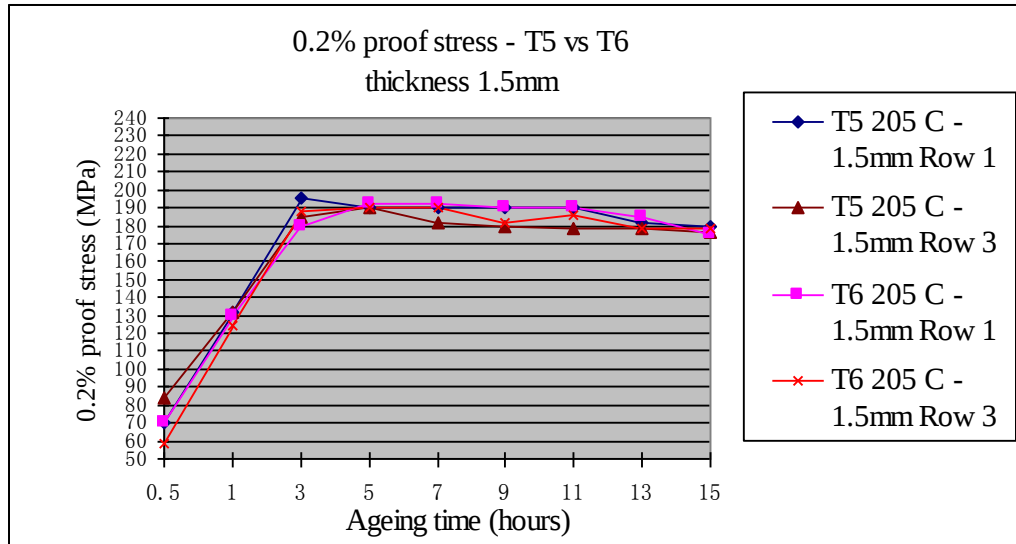
Figures 4-7 (a) and (b) show that yield strength in T5 reaches a peak of 195 MPa at Row 1 when the alloy is aged for three hours and 190 MPa at all rows when aged for five hours at 205° C .



(a) In Row 1



(b) In Row 3

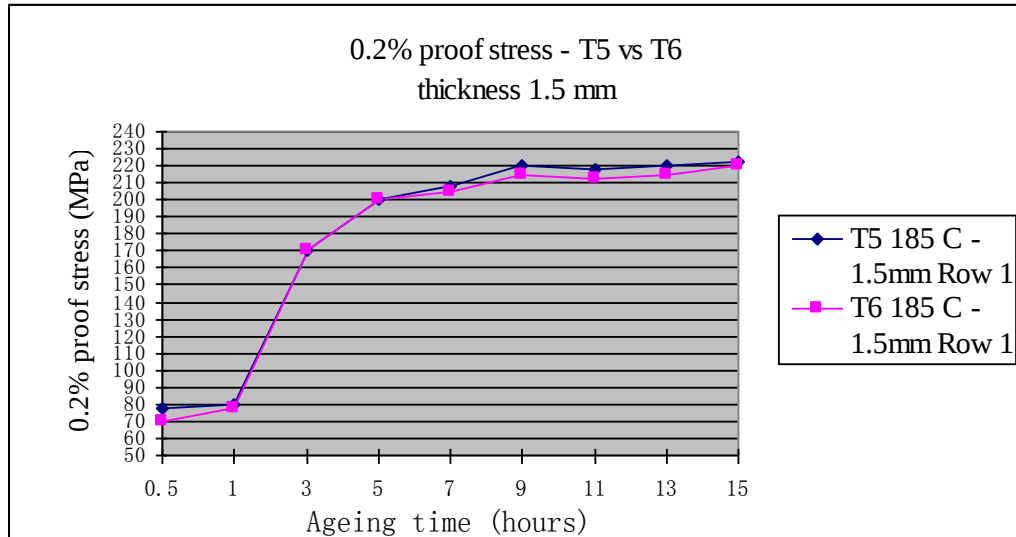


(c) Combination of graphs (a) and (b)

**Figure 4-7 Strength of extrudate at mid-length for thickness 1.5 mm
aged at 205° C for different times
* Location of Row number - See Figure 3-1 (b)**

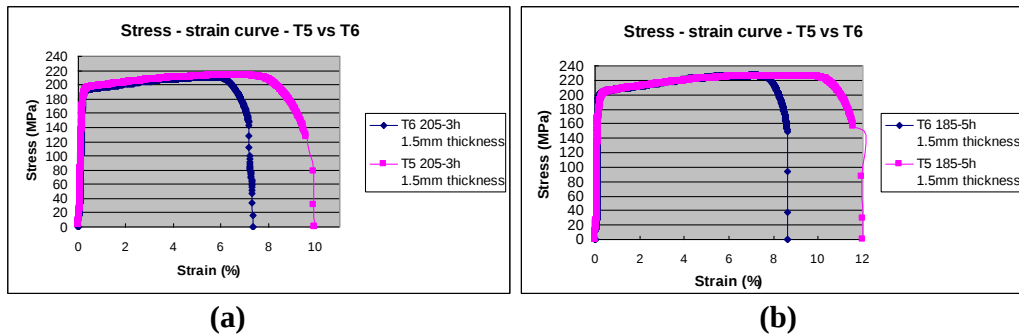
Curves for T6 show the same behaviour as for T5 temper. Both values for yield strength after the same ageing time is quite close. After reaching the peak and holding for two hours all curves started to decrease gradually, which is shown in Figure 4-7 (c). It can be seen that the greatest difference on yield strength, under the same age conditions but in different rows, is 14 MPa, when aged for half hour in T5 temper. In general, yield strength differences among those rows for both T5 and T6 are small. Strength in cross-section shows an almost even distribution. Yield strength reached above 180 MPa at 205° C when aged from three to nine hours for both T5 and T6 temper.

Curves for T5 and T6 temper aged at 185° C for thickness 1.5 mm in Figure 4-8 show the same behaviour in Figure 4-3. Yield strengths are almost the same when aged for the same hours from one to seven hours in Figure 4-8. Yield strength reached above 180 MPa when aged for five hours. After five hours, curves for both T5 and T6 temper, keep increasing gradually.



**Figure 4-8 Strength of extrudate at mid-length for thickness 1.5 mm
aged at 185° C for different times – In Row 1
* For Row 1 of shape 2 - See Figure 3-1 (b)**

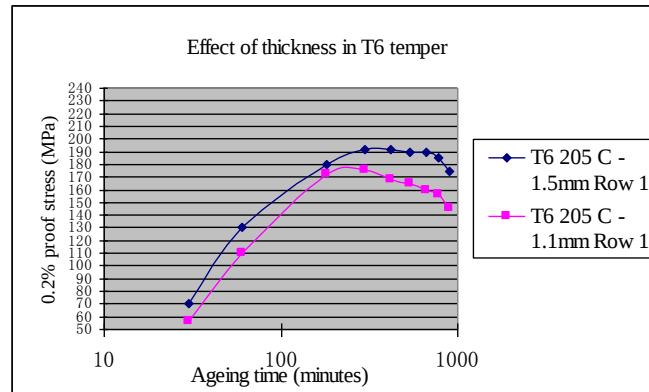
Figure 4-9 shows the stress-strain curves for thickness 1.5 mm when aged at 205° C for three hours and aged at 185° C for five hours for both T5 and T6 temper. 0.2% proof strength reached above 180 MPa for those curves. Ductility was the same as for thickness 1.1 mm in Figure 4-5.



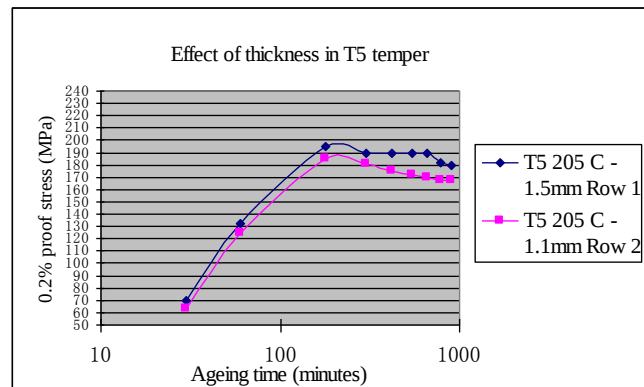
**Figure 4-9 Engineering stress-strain curve (1.5 mm)
(a) ageing at 205° C for three hours
(b) ageing at 185° C for five hours**

4.1.3 1.1 mm versus 1.5 mm

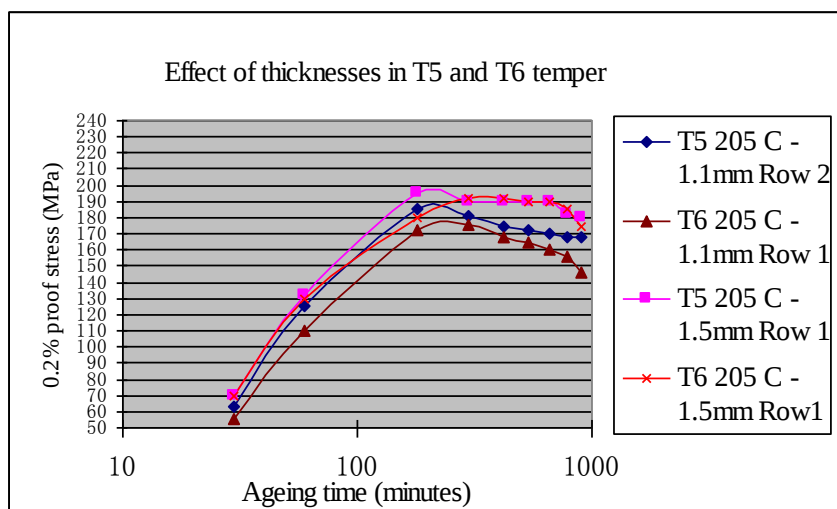
Figure 4-10 and Figure 4-11 show the effect of temperature and time on yield strength for different thicknesses 1.1 mm and 1.5 mm.



(a) T6 temper

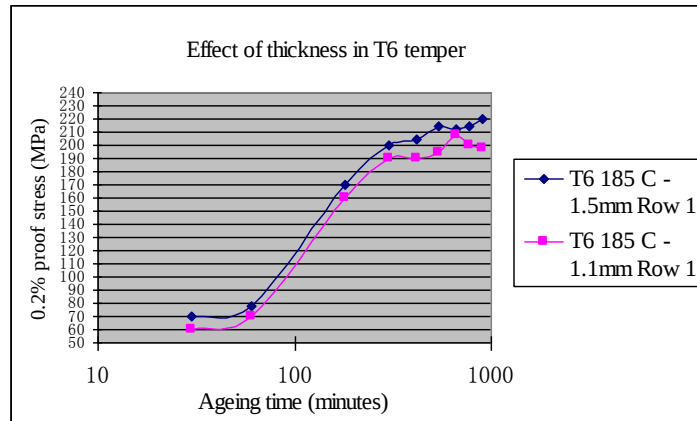


(b) T5 temper

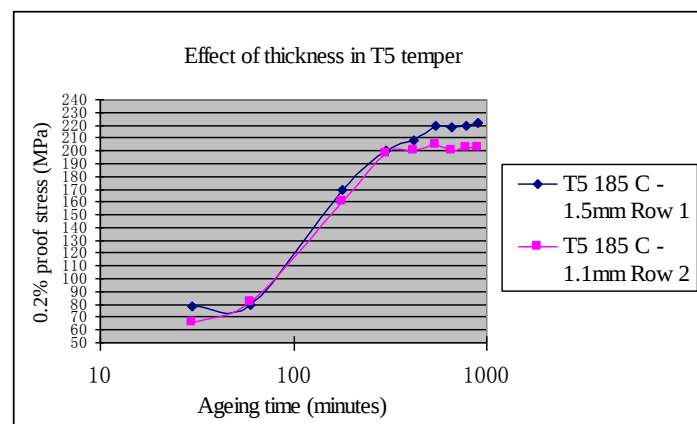


(c) Combination of graphs (a) and (b)

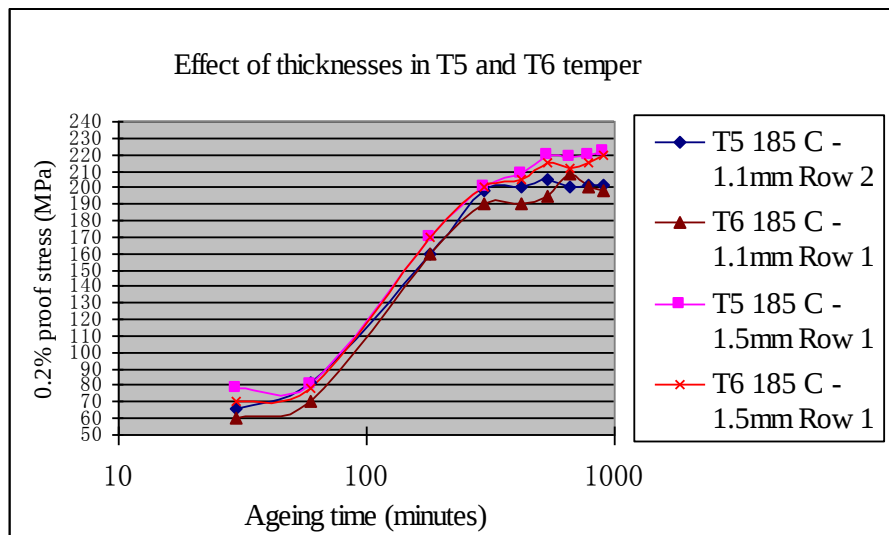
**Figure 4-10 Strength of extrudate at mid-length (1.1mm vs 1.5mm)
aged at 205° C for different times
* For Shape and Row number – See Figure 3-1**



(a) T6 temper



(b) T5 temper



(c) Combination of graphs (a) and (b)

Figure 4-11 Strength of extrudate at mid-length (1.1 mm vs 1.5 mm)

aged at 185 °C for different times

* For Shape and Row number – See Figure 3-1

Generally, yield strength for thickness 1.5 mm is either equal or slightly higher than thickness 1.1 mm at all age conditions regardless of T5 or T6 temper. The slight difference could be due to a slight variation in chemical composition within the specifications.

4.1.4 Summary

From the results presented in 4.1.1 and 4.1.2, it can be concluded that yield strength for T5 temper is basically equal to T6 temper for thicknesses of 1.1 mm and 1.5 mm. This implies that Mg and Si were in a super-saturated state in extrudate prior to age hardening. It confirms that yield strength can achieve the optimal requirement for T6 temper by using the T5 temper process.

4.2 Yield strength over the whole length

Table 4-2 presents yield strength data for extrudate aged at 185° C held for six and twelve hours and at 205° C held for two and four hours in test 2. Table 4-2 has (a) for T6 temper and (b) for T5 temper. Data in test 4 are only for T5 temper that is used in industry practice (Results are provided in Chapter 4.3). Row number represents locations where specimens were taken from the shapes.

Tensile Data (0.2% proof strength MPa)				
Test No.	Test 2			
Profile	Shape 1 (thickness 1.1 mm)			
Location	Row 1	Row 2	Row 1	Row 2
Temperature	205° C		185° C	
Time	2 hours	4 hours	6 hours	12hours
T6 Temper	168	175	195	198
	165	175	196	195
	150	175	195	192
	150	172	198	200
	162	175	196	192
	160	172	190	195
	160	180	192	192
	162	175	190	195
	172	170	194	195
	172	175	192	190
	170	175	190	195
	160	170	192	210

(a) For T6 temper

Table 4-2 Tensile data for experimental test 2 and 4
*** Shape and Row number – see Figure 3-1 (a)**

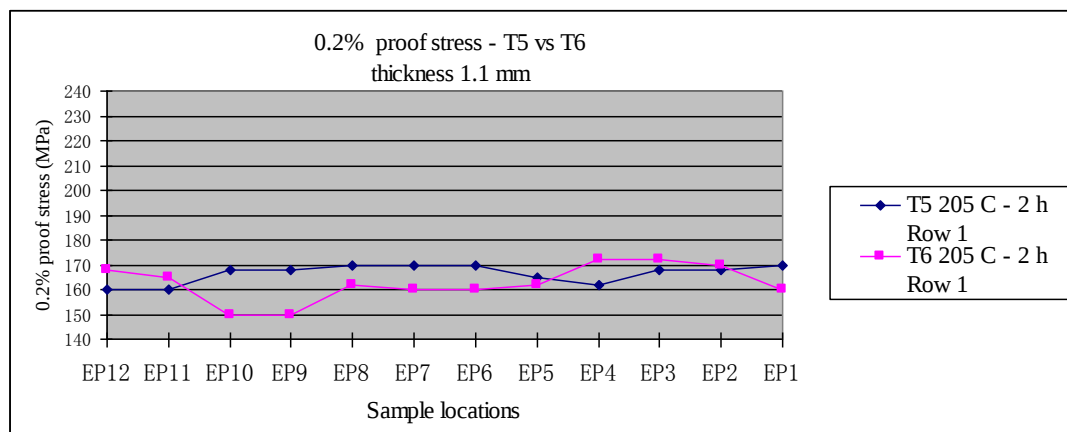
Tensile Data (0.2% proof strength MPa)								
Test No.	Test 2				Test 4 (Industry Practice)			
Profile	Shape 1				Shape 1		Shape 2	
Location	Row 1	Row 2	Row 1	Row 2	Row 1	Row 1	Row 1-* (Left top)	Row 1- *(Left Bottom)
Temperature	205° C		185° C		205° C	185° C	205° C	
Time	2 hours	4 hours	6 hours	12 hours	2 hours	6 hours	2 hours	2 hours
T5 temper	160	172	190	200	156	188	185	188
	160	172	182	198	157	184	188	188
	168	175	190	198	164	184	186	190
	168	170	181	200	156	182	183	190
	170	168	180	200	158	182	192	186
	170	168	185	202	160	182	190	186
	170	170	182	198	160	188	186	188
	165	170	192	198	158	186	190	182
	162	178	188	195	157	184		
	168	170	190	192	160	185		
	168	165	188	195	160	182		
	170	170	190	196	159	183		

(b) For T5 temper

Table 4-2 Tensile data for experimental tests 2 and 4
*** Shape and Row number – see Figure 3-1**

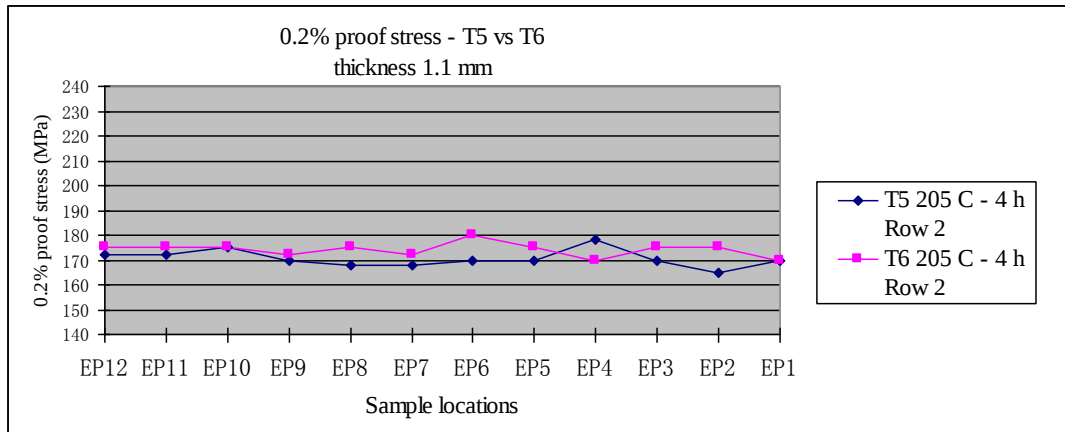
In experimental test 2, twelve specimens for each age condition were taken to investigate strength over the whole length of extrudate for shape 1. This was because non-uniform strength over the whole length had been found by the aluminium manufacturer. This trial was conducted with extrusion speed at 44 m/min, and pre-heating temperature at 380°C , held for 40-45 minutes. The average exit temperature was 541°C . Results are shown in Figure 4-12 and Figure 4-13.

In Figure 4-12 (a) average yield strength over the length for T5 was higher than for T6 when aged at 205°C held for two hours. However, all yield strengths for both tempers was lower than 170 MPa. Yield strength fluctuation over the length for T5 temper was 10 MPa. For T6 temper the fluctuation was 20 MPa. The lowest value of 150 MPa was at positions of EP9 and EP10 while the highest values around 170 MPa were located between EP2 and EP4. Although the experimental tests were carefully controlled, there is always the possibility of unknown processing errors influencing the results. Nevertheless, yield strength seems more non-uniform for T6 temper. Average yield strength over the length for both tempers, aged at 205°C for four hours in Figure 4-12 (b), was similar. Yield strength fluctuation for T5 was 15 MPa, and for T6 was 10 MPa. All yield strengths when aged at 205°C and held for four hours were higher than for two hours except the one at EP2, which was aged at 205°C held for 4 hours. All yield strengths were below 180 MPa shown in Figure 4-12 (c).

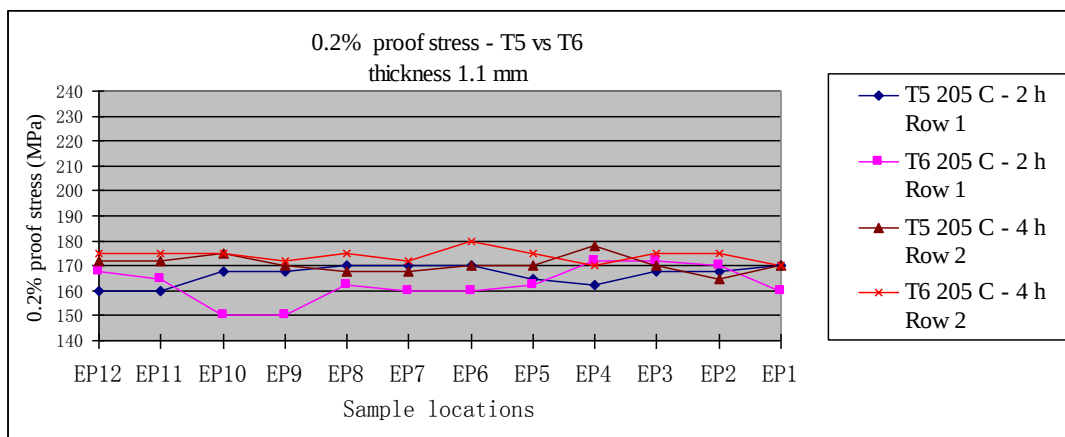


(a) For two hours

Figure 4-12 Strength of extrudate over the whole length for thickness 1.1 mm (T5 vs T6) aged at 205°C for different times
* Row number - See Figure 3-1 (a)



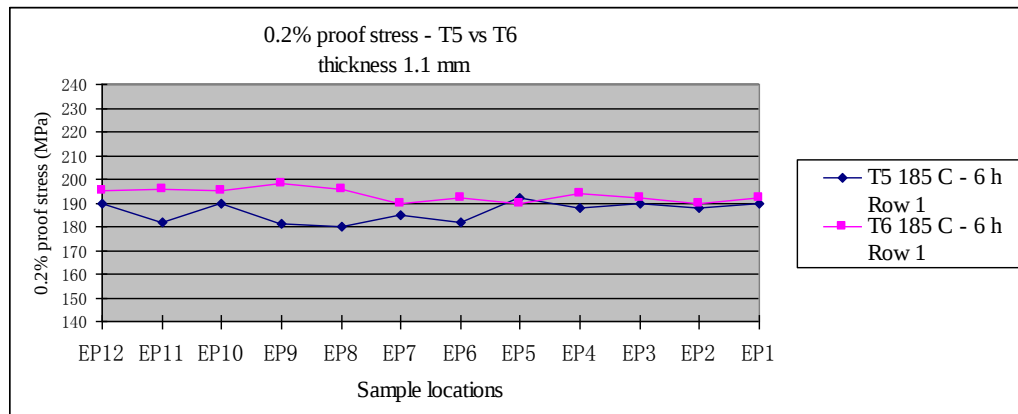
(b) For four hours



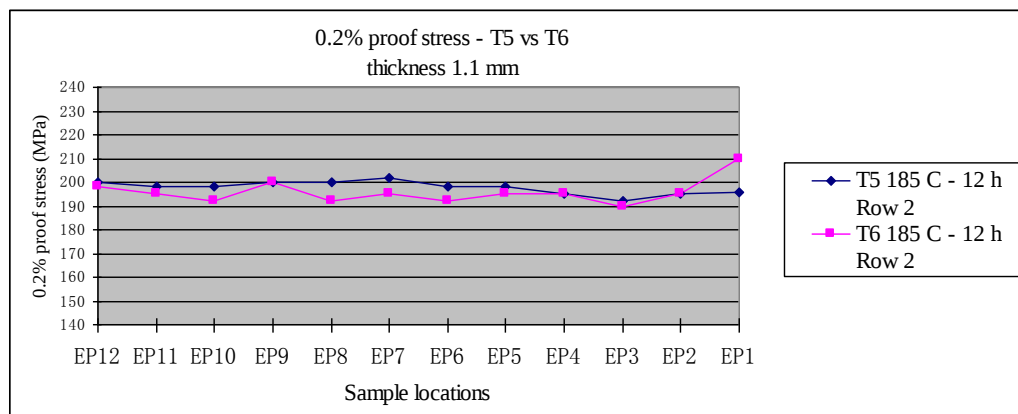
(c) Combination of graphs (a) and (b)

Figure 4-12 Strength of extrudate over the whole length for thickness 1.1 mm (T5 vs T6) aged at 205°C for different times
*** Row number - See Figure 3-1 (a)**

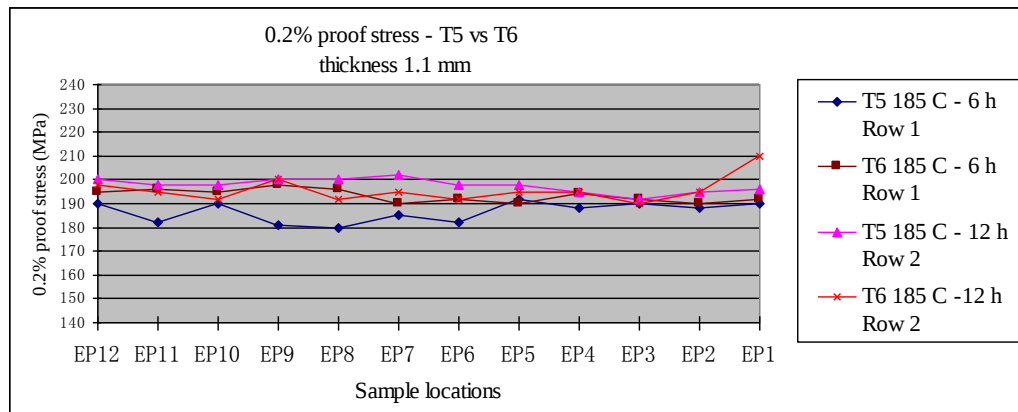
Figure 4-13 shows ageing at 185°C held for six or twelve hours. All yield strengths for both tempers in Figure 4-13 (a) were above 180 MPa. Yield strength for T6 temper was higher than for T5 temper under these conditions. Yield strength for T5 temper still reached the 180 MPa requirement. The behaviour of yield strength in Figure 4-13 (b), aged at 185°C held for twelve hours, was similar to when held for six hours in Figure 4-13 (a). However, all yield strengths under these conditions were above 190 MPa. Figure 4-13 (c) shows the overall yield strengths of Figure 4-13 (a) and (b).



(a) For six hours



(b) For twelve hours



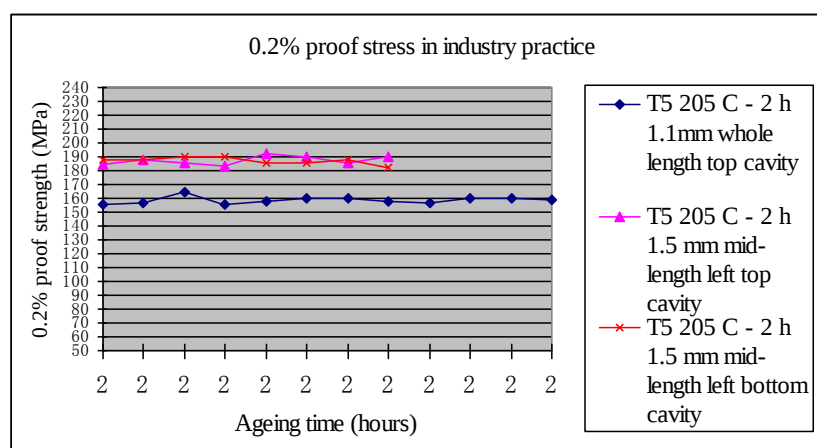
(c) Combination of graphs (a) and (b)

**Figure 4-13 Strength of extrudate over the whole length for thickness 1.1 mm (T5 vs T6)
aged at 185° C for different times
* Row number - See Figure 3-1 (a)**

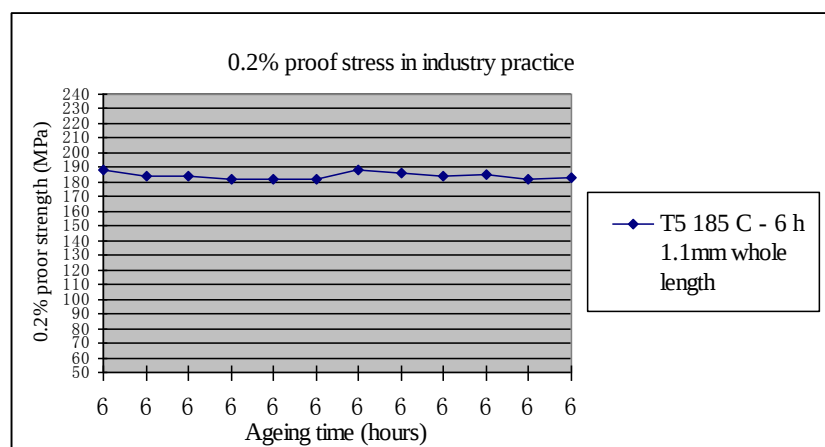
The results suggest that the yield strength of extrudate in T5 temper would equal that of T6 temper for the whole length of extrudate, provided ageing conditions were chosen appropriately.

4.3 Yield strength of samples aged in industry oven

Yield strength for specimens age hardened at the aluminium manufacturer was investigated separately. This was in order to verify if industry reports were correct. Experimental test 4 had all specimens age hardened in the industry oven, and then tensile tested in the AUT laboratory. This is in contrast to the other experimental tests that were all age hardened in the AUT laboratory. Yield strength in industry practice (factory-aged) for shape 1 (1.1 mm) and shape 2 (1.5 mm) were investigated. The results are shown in Figure 4-14. The extrusion conditions of these two trials were under the same billet pre-heating conditions (pre-heating temperature $384\text{--}387^{\circ}\text{C}$, pre-heating time 40–45 minutes). Extrusion speed was 45 m/min for shape 1 and 40 m/min for shape 2. Exit temperature was 536°C and 546°C for shape 1 and shape 2, respectively.



(a)



(b)

Figure 4-14 Strength of extrudate in industry practice

(a) Aged at 205°C for two hours; (b) Aged at 185°C for six hours

Extrusion conditions for two shapes of 6060 alloys were similar. Results in Figure 4-14 demonstrate that yield strengths for thickness 1.5 mm reached over 180 MPa for T5 temper when aged at 205° C for two hours. Thickness 1.1 mm did not reach 180 MPa . It required ageing at 185° C for six hours. Yield strength fluctuations over the whole length for all age conditions in Figure 4-14 were about 10 MPa . These results are similar to the results for T5 temper shown in Figure 4-12 (a) and Figure 4-13 (a) that were done in the laboratory.

4.4 Magnesium distribution

For a given alloy, extrudability can be improved by optimizing the various heat treatments such as homogenization and the pre-heating treatment of the aluminium billet to extrusion temperature. The present chemical tests investigated the Mg distribution in pre-heated billet, and butt and whole length of extrudate. This was to analyse the Mg_2Si transformation during extrusion processing, as Mg and Si content determines the solidus temperature of the alloys and impacts deformation resistance. Mg and Si concentration in extrudate reveals whether the cooling rate is sufficient to prevent coarse Mg_2Si forming after it leaves the die. Dissolved Mg and Si in extrudate determine whether the 180 MPa requirement for T6 temper is achieved by using the T5 temper. In this study only Mg concentration was investigated as the test to determine Si was unsuccessful (See Figure 3-14, Chapter 3).

4.4.1 Pre-heated billet

The results of Mg concentration in billet after pre-heating were presented. Figure 4-15 shows where specimens were taken from the pre-heated billet. The pre-heating temperature was 380°C and pre-heating time was 40-45 minutes.

Figure 4-16 shows curves of Mg% for three axes. The composition of Mg in this alloy is 0.36 - 0.38%. The range of Mg% in results is from 0.338% (location r3-P7) to 0.379% (location r1 – P4).

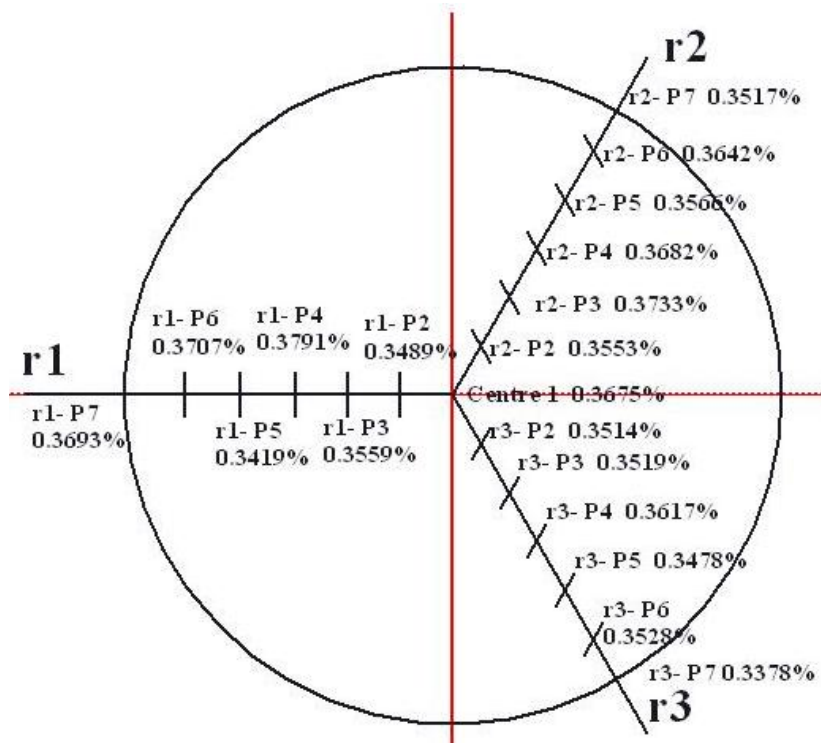


Figure 4-15 Locations and Mg percentage in pre-heated billet determined using ICP-AES

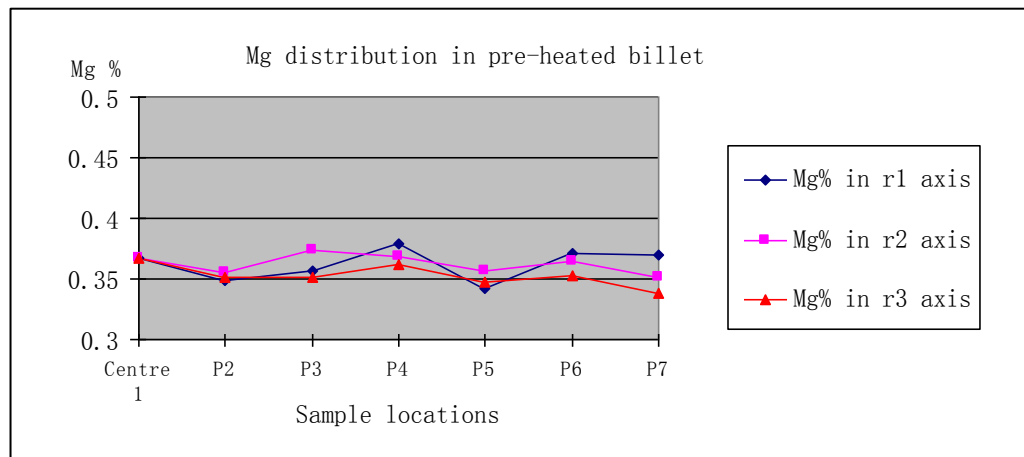


Figure 4-16 Curves of Mg% for three axes in pre-heated billet

For better analysis, the pre-heated billet was divided into six layers. The average Mg percentage for each layer was calculated by adding up values in the same layer then dividing by three. The average Mg% is between 0.3487% - 0.3697% (shown in Figure 4-17).

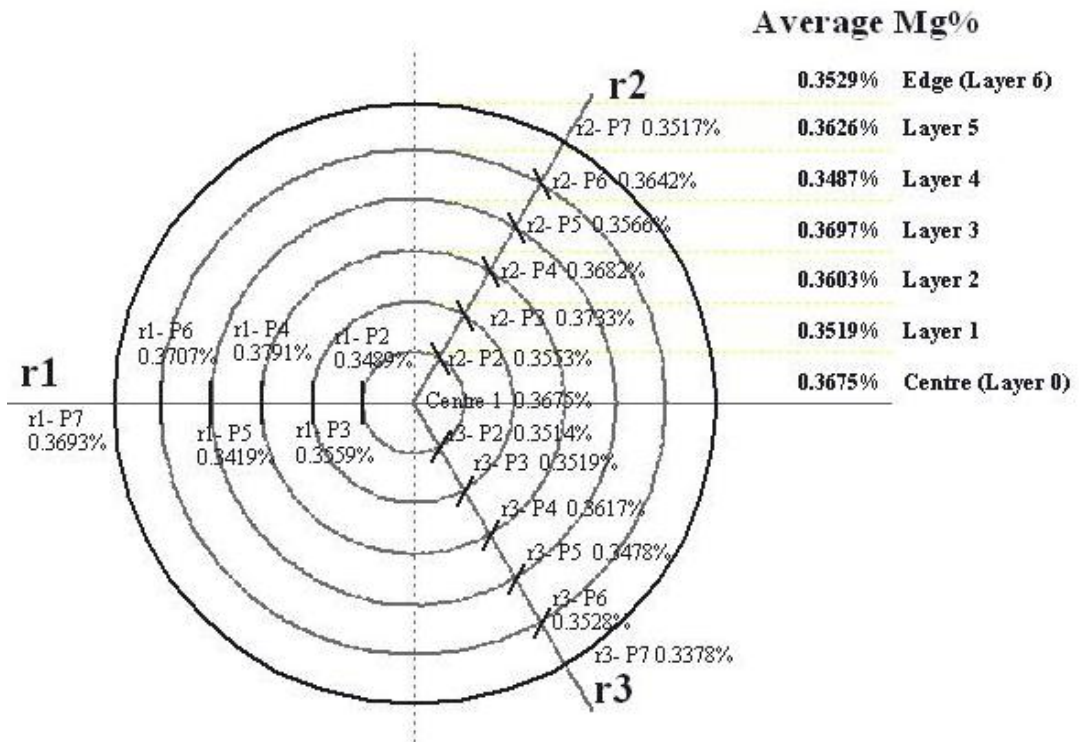


Figure 4-17 Average Mg% distribution in pre-heated billet

The results showing Mg distribution in pre-heated billet in Figure 4-17 indicate that from centre to edge Mg percentages were quite evenly distributed. The largest difference is 0.021% between the layers 3 and 4. Mg% was all less than 0.38%. The literature indicates that possibly little Mg_2Si remains in the pre-heated state. Mg and Si fully dissolved in solid solution in billet would increase resistance to deformation during extrusion, requiring higher pressure.

4.4.2 Butt after extrusion

After extrusion the remaining billet is cut off to discard the butt. This is to exclude the possibility of billet skin running into the extrudate. Cutting changes the shape of the butt from circular to oval. Butt thickness was approximately 20 mm. Figure 4-18 indicates Mg distribution in the butt after extrusion. Figure 4-19 shows curves of Mg% for three axes correspondingly.

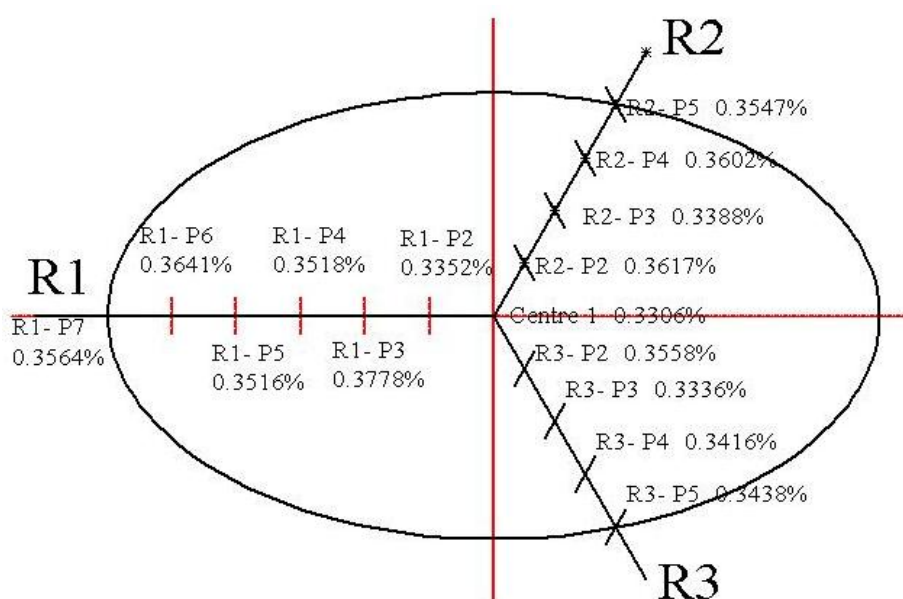


Figure 4-18 Locations and Mg percentage in butt after extrusion

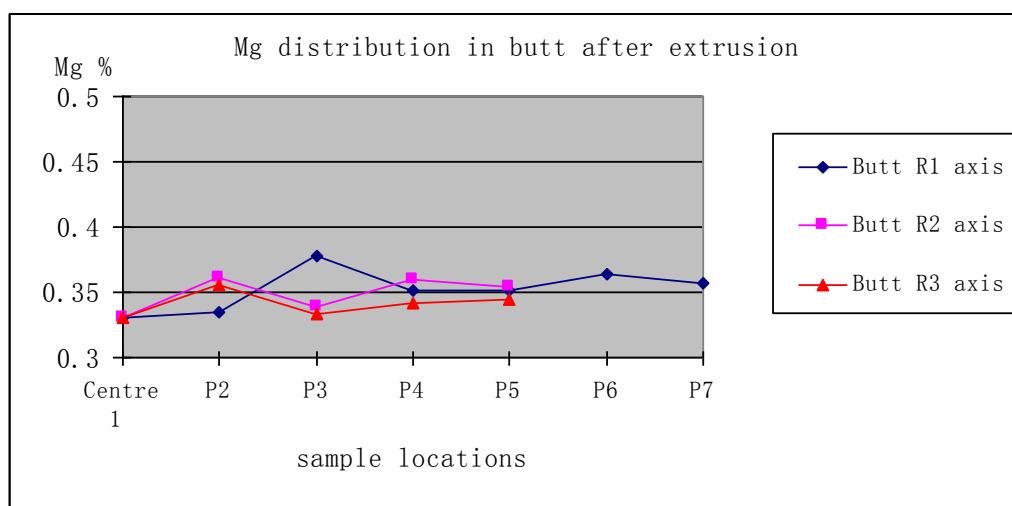


Figure 4-19 Curves of Mg% for three axes in butt after extrusion

Mg distribution in butt was from 0.3306% (Centre 1) to 0.3778% (R1-P3). In comparison with Mg distributions of 0.3378% to 0.3791% in pre-heated billet, it was on average 0.01% less. This could be caused by two reasons. Firstly coarse Mg_2Si precipitates may have formed during extrusion processing before entry to the die. This was described in Figure 2-11 (c) and (d) in Chapter 2. Secondly, MgO may have formed during hot deformation. A higher oxide inclusion count in the remaining billet causes a lower Mg%.

4.4.3 Extrudate over whole length

Specimens for studying Mg% along the whole length were taken from Row 3 of shape 1 (See Figure 3-1 a).

Locations and Mg distribution along the whole length of extrudate are shown in Figure 4-20. Figure 4-21 is the curve showing Mg percentages. Results indicate that Mg% along the length ranged from 0.359% (EP12) to 0.377% (EP1) - a very small difference of 0.018%.

Such a small variation in Mg% along the length suggests that a constant extrusion exit temperature between 530-545°C was achieved by using a pre-heating temperature of 380-390°C and an optimal extrusion speed of 40 – 45 m/min. This condition matches the limitation diagram of exit speed and billet temperature in Figure 2-18 (Chapter 2). The composition of 6060 alloy ranges from 0.36 – 0.38% Mg. Mg% along the whole length was 0.359% to 0.377%. That suggests Mg was almost all in its super-saturated state after it left the die.

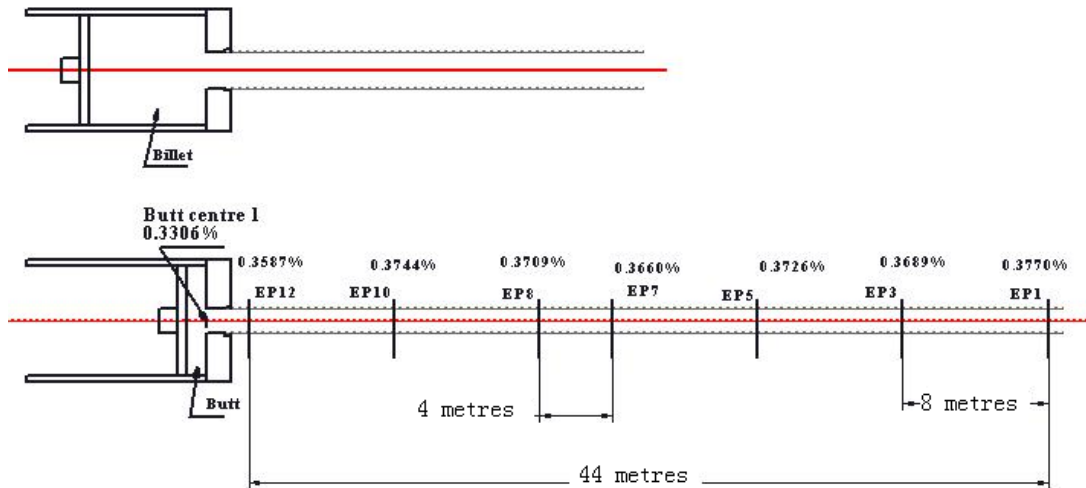


Figure 4-20 Locations and Mg distribution along whole length of extrudate

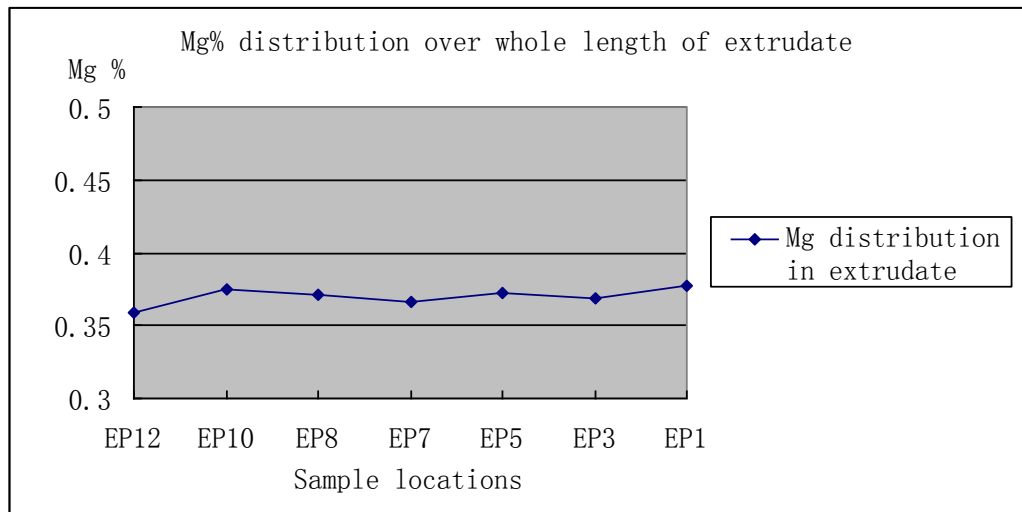


Figure 4-21 Curve of Mg distribution over whole length of extrudate

Specimens for studying Mg% in cross section were taken from front, middle and end of the whole length of extrudate. The locations and Mg% are shown in Figure 4-22. The average Mg% at the end cross-section is 0.3497% (at EP12). Mg% difference between butt centre 1 (0.3306% Mg before undergoing the die) and end position EP12 of extrudate (Figure 4-22) increased by 0.019%. This amount of Mg may have been dissolved by material deformation during the extremely short extrusion period.

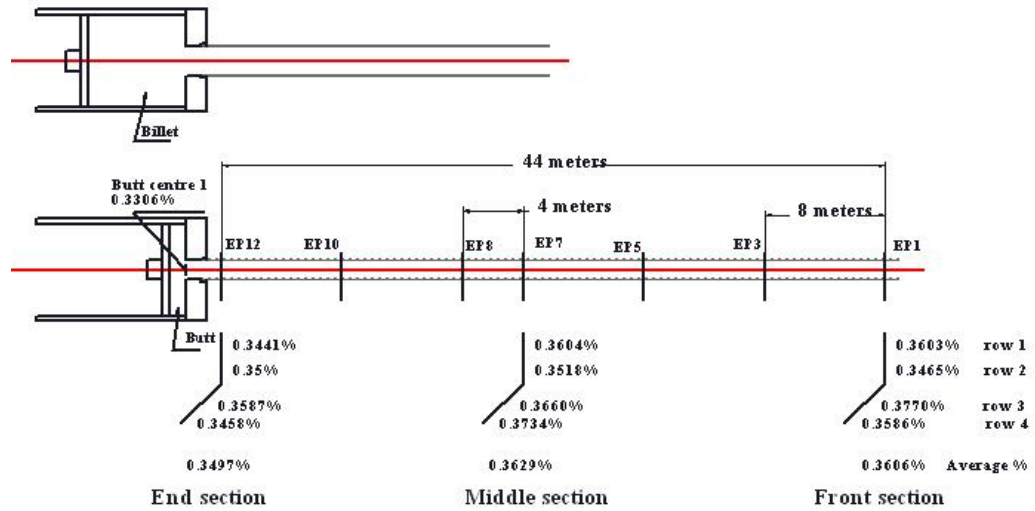


Figure 4-22 Mg composition in cross-section of front, middle and end of whole length of extrudate

Difference in Mg percentage for front, middle and end cross-sections of four rows (See Figure 3-1 a) was 0.03%, 0.02%, and 0.01% respectively. This result may be explained by deformation resistance decreasing gradually during processing. Hence Mg% differences across the section are less at the end cross-section.

The dissolving Mg is free to combine with the clusters of Si atoms to form Mg_2Si that are strengthening particles in Al-Mg-Si alloys. 6060 alloy has excess Si. Therefore the increment of the yield stress, $\Delta\sigma_y$, is determined only by the Mg content [44]. Provided that all the Mg is available for strengthening, $\Delta\sigma_y$ should be proportional to $(Mg)^{1/2}$. Then we can conclude that [44]:

$$\Delta\sigma_y = \text{constant} (Mg)^{1/2}$$

Results indicate that the difference of Mg% along the whole length is 0.018%.

So that along the whole length fluctuation of the yield stress:

$$\Delta\sigma_{y\text{-length}} = \text{constant} (0.00018)^{1/2} = 0.0134$$

The largest difference in Mg percentage in cross-section is in the front section - 0.03%. The fluctuation of the yield stress in cross-section is:

$$\Delta\sigma_{y\text{-cross section}} = \text{constant} (0.0003)^{1/2} = 0.0173$$

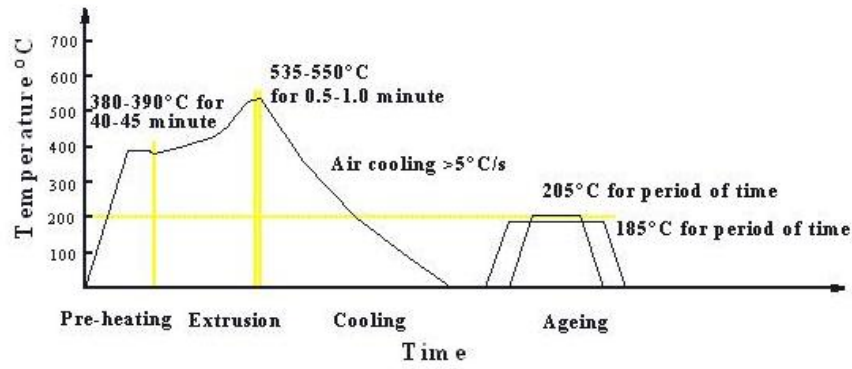
Chapter 5 General Discussion

Experimental test results were described in Chapter 4. This chapter discusses how homogenized billet, extrusion exit temperature, ageing time and temperature conditions affect the yield strength.

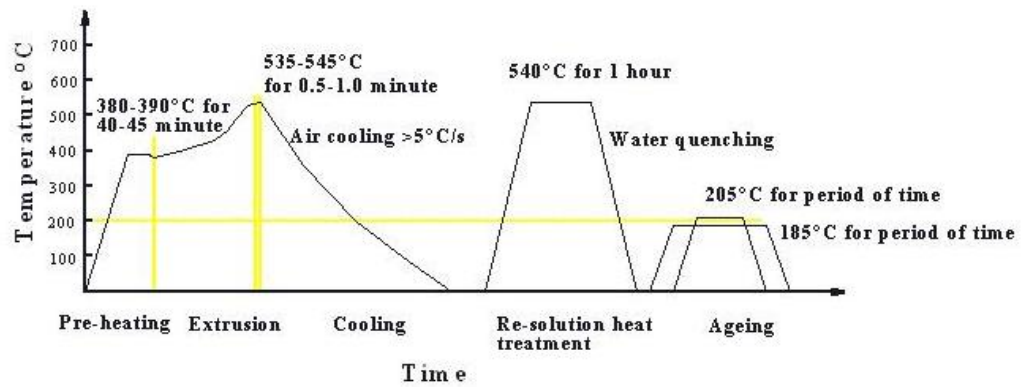
5.1 T5 and T6 temper

Results presented in Chapter 4.1 confirmed that yield strength in T5 temper equals that of T6 temper for thicknesses of 1.1 mm and 1.5 mm.

The thermal history of specimens from T5 and T6 temper used in tests is shown in Figure 5-1. The specimens were extruded with pre-heating temperature 380-390°C held for 40-45 minutes. Exit temperature was controlled between 535-550°C. The cooling rate by air was greater than 5°C/s. This was estimated by a calculation shown in Figure 3-6 and Table 3-3 (Chapter 3). Then the specimens were aged either at 205°C or at 185°C for varying periods of time after exiting from the die for T5 temper. For T6 temper, re-solutionising at 540°C for one hour was performed and then aged under the same conditions as T5.



(a)



(b)

Figure 5-1 Thermal history of examined extrudate in quenching operations
 (a) Simplified solution treatment – T5 temper
 (b) Separate solution heat treatment – T6 temper

Comparing Figures 5-1 (a) and (b), T5 temper eliminates a separate solution heat treatment, but achieves the same results as T6. The key is to retain the maximum amount of Mg and Si in supersaturated form in extrudate prior to age hardening. This requires an optimal homogenized billet and suitable cooling rate after exit from the die. Figure 5-2 explains Mg and Si transformation for specimens at different extrusion stages.

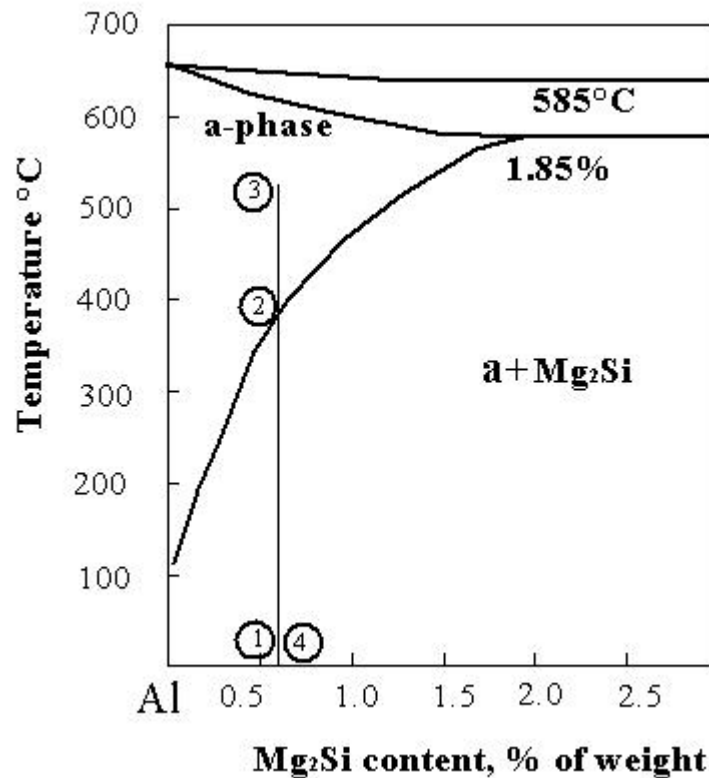


Figure 5-2 Phase diagram of thermal history of examined extrudate

Stage (1) Billet prior to pre-heating

Stage (2) Pre-heated billet

Stage (3) Extrusion process

Stage (4) Extrudate quenched

The phase diagram of the Al-Mg-Si system in Figure 2-19 (Chapter 2) shows that above the solid solubility line with enough holding time, all of the solute would be dissolved into the solution from billet heating. Magnesium in 6060 alloy in this study is between 0.36% and 0.38%. In the correct proportion to fulfil the stoichiometric requirements for Mg₂Si, 0.21% to 0.22% of Si is needed. Therefore, the amount of Mg₂Si would then be between 0.57% and 0.60%. For 0.60% of Mg₂Si (by weight) in 6060 alloys, a vertical line intersects the solid solubility line at about 370°C.

At stage 1 few Mg₂Si particles would be visible in the homogenized billet, where constituents are generally uniformly distributed. Homogenizing is the first thermal treatment applied to extrusion logs to improve the extrudability by transforming β -AlFeSi into α -AlFeSi and dissolving the Mg₂Si. During stage 2 (pre-heating), Mg₂Si particles are further dissolved but some still

remain undissolved until extrusion completion. Mg distribution in pre-heated billet is shown in Figure 4-15. During stage 3 (extrusion), phase transformation of the Al(Fe, Mn)Si-intermetallics takes place and the Mg and Si solute contents increase by dissolution of Mg_2Si particles [42]. In this case Mg_2Si in the pre-heated billets further dissolves at extrusion temperatures greater than $370^{\circ}C$. Extrusion pressure and mechanical properties of the extrudate depend on the condition of Mg and Si before extrusion, defined as the presence of Mg and Si, either as solute, or bound as precipitates. The function of solution treatment can be achieved with a short treatment by raising the magnesium and silicon solute contents to their maximum level and homogenizing their distribution. This function is vital for achieving the maximum level of yield strength corresponding to the alloy composition and the ageing condition used for precipitation hardening.

During extrusion, time spent in the deformation zone and die bearing should be as short as possible to improve productivity. For shape 1, the whole length of extrudate was 45 metres long. The bearing of the die was 5 mm. Extrusion speed was 44 m/min. That is:

$$V_{\text{extrusion}} = \frac{44\text{metres}}{\text{minute}} = \frac{44 \times 100\text{mm}}{60\text{s}} = 7.3\text{mm/s}$$

Extrusion speed was 7.3 mm/s which is greater than the length of the die bearing. Therefore, time going through the die bearing was less than one second.

Time for dissolving Mg and Si to achieve sufficient final strength appears very short. Experimental results in Chapter 4.1 show that yield strength in T5 equals T6 temper. Mg distribution along the whole extrudate length is between 0.359% - 0.377%. This implies Mg is almost all in its super-saturated state, as its composition is 0.36 -0.38% Mg in 6060 alloy. This confirms that such a short diffusion time in the deformation zone, under extrusion speed 44 m/min, with exit temperature $535-545^{\circ}C$, meets the requirement that the solution treatment for T6 does. This is provided that homogenizing conditions were held at $575^{\circ}C$ for two hours. A cooling rate greater than $5^{\circ}C/s$ (See Figure 3-6) at stage 4 for 6060 alloy using air cooling on the running table is sufficient. This prevents Mg_2Si forming in air-cooled extrudate. Figure 4-20 indicates that Mg%

presents in a supersaturated-state along the whole length. Figure 5-3 shows a slow cooling rate allows coarse Mg_2Si to form, which is detrimental to final strength. As the optical microscopy and scanning electron microscopy (SEM) were not used in this investigation, the sizes/shapes of the coarse precipitates in the processing windows were not able to be estimated at this stage.

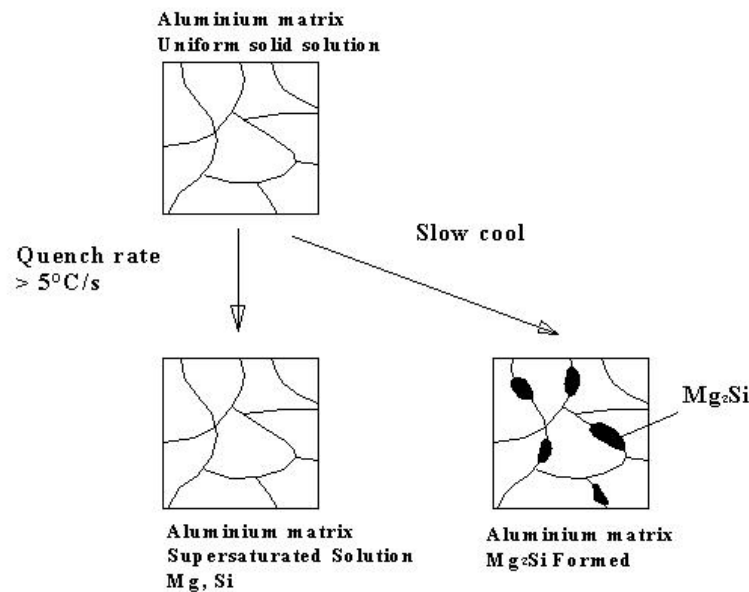


Figure 5-3 Effect of cooling rate for thickness 1.1 mm on 6060 alloy

In conclusion, T5 temper can be used instead of T6 solution treatment without sacrificing mechanical properties. This is provided adequate solutionising takes place during extrusion to achieve the desired final requirement. Simplified solution treatment – T5 temper in industry practice does this. Extrudate is quenched directly after the extrusion process and followed by artificial ageing. This achieves sufficient yield strength in the final product.

T5 temper actually gives slightly higher yield strength with longer elongation than T6 temper for almost all holding times for both temperatures. An explanation of this could be that the extrudate had a fibrous unrecrystallised structure. Some of the deformation substructure such as subgrains and dislocations still remains in the as-extruded profile, giving a significant contribution to the strength of the age hardened material [19]. When separate solution heat treatment is applied to this profile the substructure recovers, and the strength of the subsequently age hardened material decreases accordingly.

5.2 Uniform strength and exit temperature

Results in Chapter 4.2 show that the yield strength difference along the whole length for T5 temper is about 10 MPa . Comparatively uniform strengths were achieved over the whole length of extrudate for T5 temper at 205°C and 185°C for shape 1 in this trial.

To obtain uniform product quality extrusion with a constant exit temperature [1, 13] and extrusion time is required. This gives the same amount of dissolved Mg. Figure 3-5 (Chapter 3) shows ram pressure and ram speed curves for the extrusion cycle in this experimental test. Maximum pressure was 3600 Psi (24.8 MPa) and constant ram speed was achieved at 5 mm/sec for shape 1 after about one quarter of the extrusion cycle was complete. The relationship between exit temperature and ram pressure for shape 1 of 6060 alloy is illustrated in Figure 5-4.

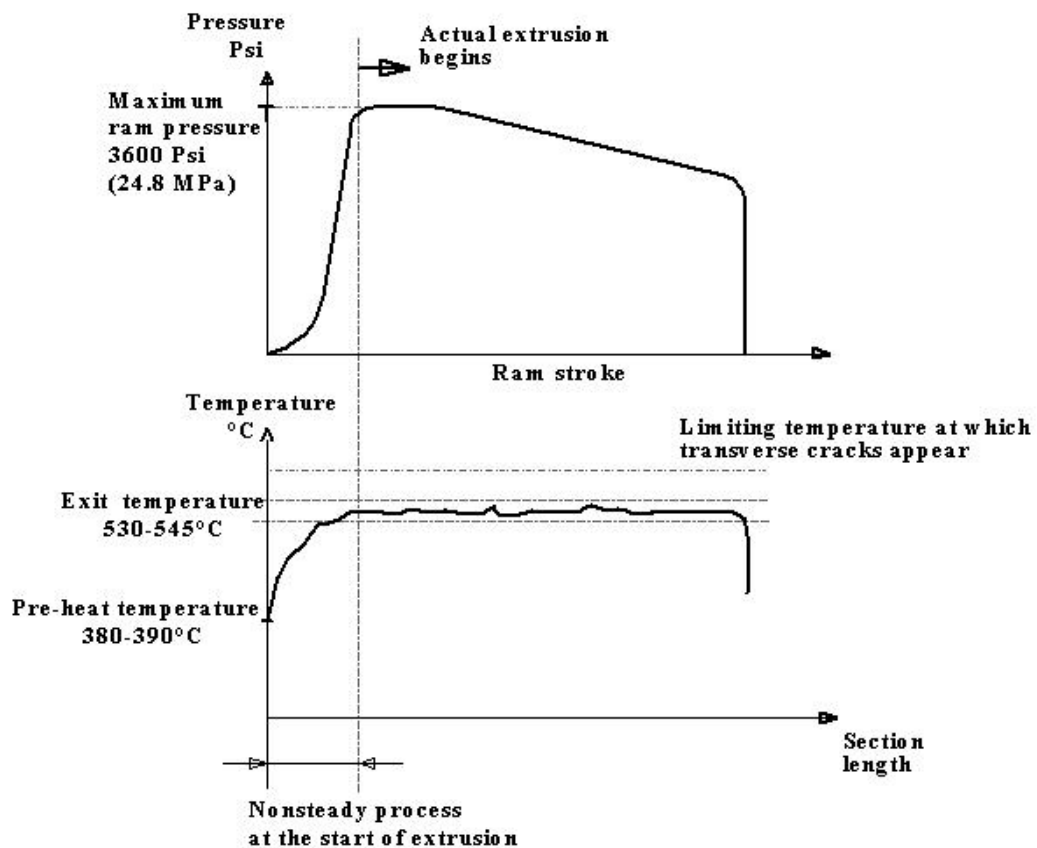


Figure 5-4 Relationship between ram pressure and exit temperature of 6060 alloy

The fast pressure increase at the beginning of the process is accompanied by a dramatic temperature rise in front of the die aperture. In this non-steady process at the start of extrusion, it took one quarter of extrusion cycle (shown in Figure 3-5) to reach a constant exit temperature between 530° C and 545° C. Continued ram pressure raises ram speed to an almost constant 5 mm/sec. Then the pressure drops. The process enters the steady-state stage with a gradual decrease of pressure. This is caused by reducing billet length with resulting reduction in friction at the container-billet interface as well as a gradual temperature increase in the remaining billet [45]. During extrusion, the exit temperature is maintained by varying ram speed based on friction and volume. A constant temperature is achieved. Increased temperature of the emerging extrusion billet consists of three components (presented in Figure 5-5). Firstly, temperature increase ΔT_1 is caused by deformation, which is entirely transferred into heat. Secondly temperature increase ΔT_2 is caused by friction at the container wall. Thirdly, temperature increase ΔT_3 is caused by friction at the die land.

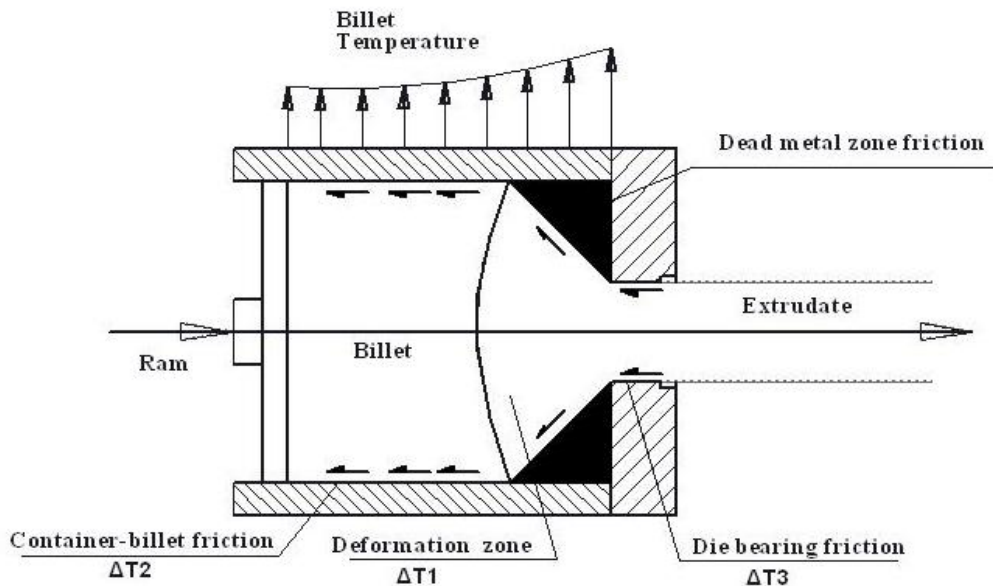


Figure 5-5 Relationship between friction and rising temperatures

If the exit temperature varies during extrusion by an unknown amount, the press speed is usually adjusted in accordance with the maximum optimising temperature.

Based on the results in Chapter 4.1, yield strength differences for T5 temper are small. This is along the whole length of extrudate and between the top and bottom cavities. Mg% differences are similar along the whole length of extrudate and in front, middle and end cross-sections. This may mean that balanced material flow was achieved in shape 1 with two cavities of die configuration shown in Figure 3-2 (a) in Chapter 3.

Figure 5-6 is a sketch of inferred material flow for shape 1 based on combining the information from the literature (Chapter 2.3) and experimental test results mentioned above.

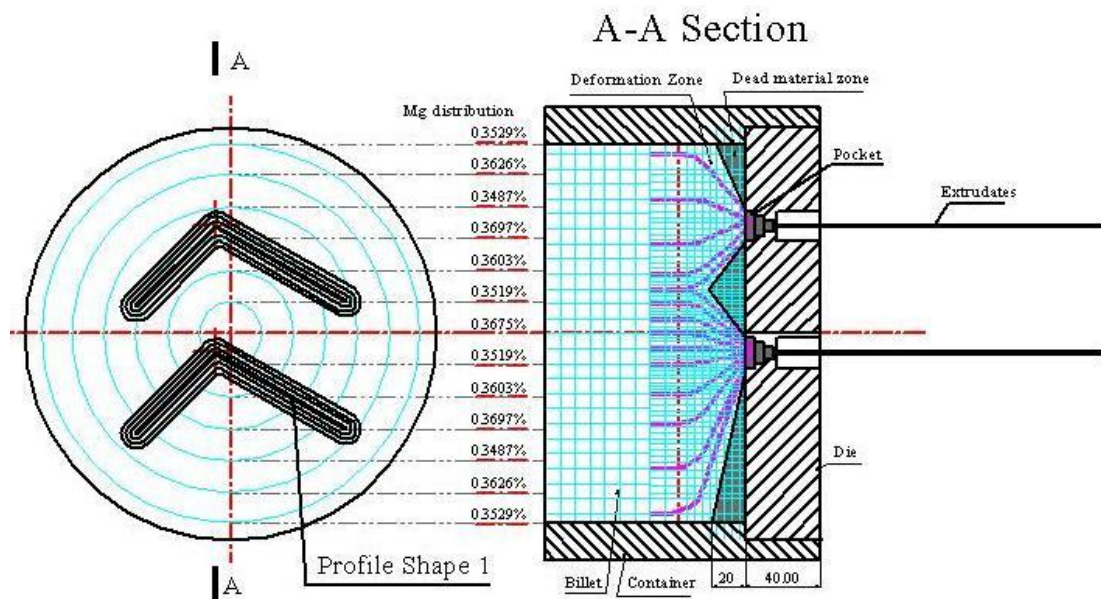


Figure 5-6 Sketch of inferred material flow of shape 1

In conclusion non-uniform yield strength over the extrudate length may be caused by Mg_2Si not being fully dissolved. Variation in exit temperatures may have occurred during extrusion. If yield strength near the end of the extrudate was less, this may have been caused by the back-end effect where the billet skin runs into the material flow.

5.3 Ageing temperature and time

The results in Chapter 4.3 show that yield strength for thickness 1.1 mm and 1.5 mm was different when aged at 205°C for two hours in T5 temper. Thin shapes (1.1 mm) require ageing at 185°C for five hours to reach above 180 MPa. Ageing time and temperature influence the availability of Mg-Si precipitation during the age hardening process. Complex sequences of time and temperature dependent changes are involved in precipitation processing.

The initial increase in yield strength could be explained by a diffusion assisted mechanism and by hindrance of dislocation by impurity atoms [14]. The time to reach peak yield strength reduces with a greater ageing temperature. As the precipitation temperature increases, the time to form stable nuclei reduces. Dislocation movement is obstructed by GP zones, which require energy to cut through the clusters. Yield strength increases during cluster formation. Peak yield strength lasted for two - three hours, and then decreased when heat treatment continued above five hours at 205°C. This may be because of coalescence of the precipitates into larger particles and bigger grain size causing less obstacle dislocation [14]. However, peak yield strength maintained steady longer at the lower temperature of 185°C. The time to allow stable nuclei increases with increased holding time, when aged at a lower temperature. Energy to pass by the clusters by dislocation movement in GP zones increases, resulting in higher yield strength.

Lower yield strengths for shape 1 (1.1 mm) at 205°C for two hours compared with shape 2 (1.5 mm) could be caused by a different number of small precipitates (nucleation) in the early stages of ageing. One possible reason might be that the amount of nucleation is less for thin cross-sections compared with thicker cross-sections. However, without microstructure this cannot be isolated as a reason. The force/energy required to pass obstacles is less for thin cross-sections. This results in lower yield strength. Nevertheless, when thickness 1.1 mm was aged at 185°C for six hours, the number of small stable precipitates probably increased with increased holding time. It requires more energy to cut through the clusters. Yield strength increases during increased cluster formation.

Chapter 6 Conclusions and Recommendations

Experimental and comparative studies were performed on ageing temperature at 205°C and 185°C for varying time periods for two 6060 alloy extrudates with thicknesses 1.1 mm and 1.5 mm. Based on the results for mechanical performance, the following conclusions could be made:

- Results have shown that Mg% was almost all in super-saturated state after leaving the die, evenly distributed along the whole length, and over the cross-section. A cooling rate greater than 5°C/s is sufficient to prevent Mg₂Si forming during press quenching. Results showed that yield strength for T5 temper is equal to T6 temper for thicknesses 1.1 mm and 1.5 mm. This confirms that the optimal yield strength requirement for T6 temper can be achieved using the T5 temper process. This is provided that homogenizing conditions were held at 575°C for two hours.
- Ageing at 205°C reached peak yield strength faster compared with ageing at 185°C for both T5 and T6 temper. Yield strength of 1.1 mm thick extrudate is very different from that of 1.5 mm extrudate when subjected to the same ageing practice - at 205°C held for two hours. 1.5 mm thick extrudate reached the T6 yield strength of above 180 MPa by doing T5 temper, but 1.1 mm extrudate did not. Yield strength peaked in 1.1 mm extrudate when held for three hours at 205°C and when held for five hours at 185°C.
- Further investigations of yield strength for 1.1 mm thick extrudate are recommended, ageing from two to three hours at 205°C. This could bring savings in ageing time from six hours to five hours at 185°C, or to about three hours at 205°C. It is also recommended to perform microstructure analysis when ageing between two and three hours at 205°C. This could discover the different contributions Mg₂Si precipitates make to strength.

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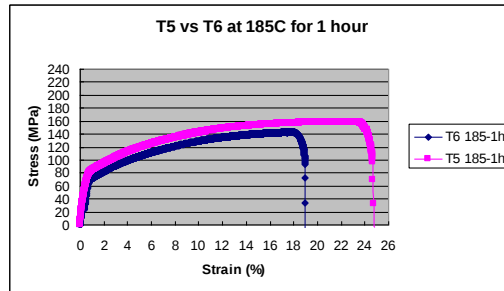
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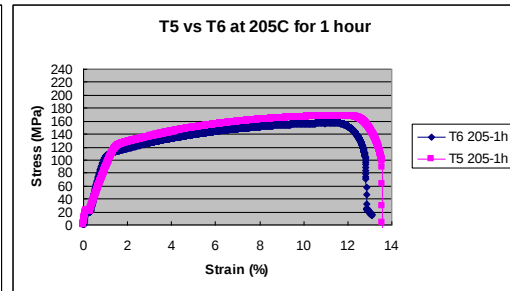
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Appendix 1

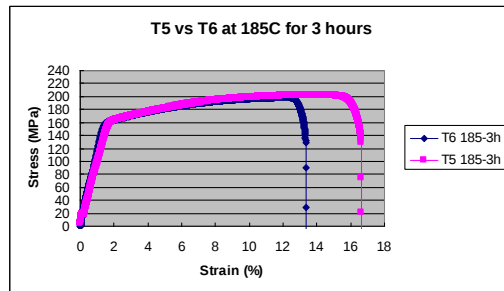
Engineering stress-strain curve - Thickness 1.1 mm



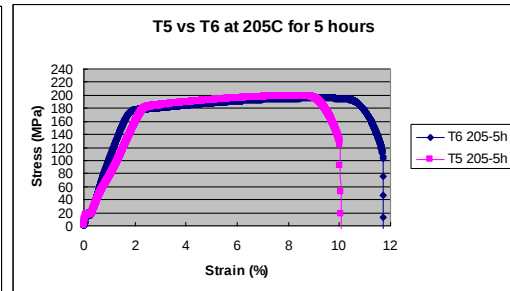
(a) Aged at 185° C for one hour



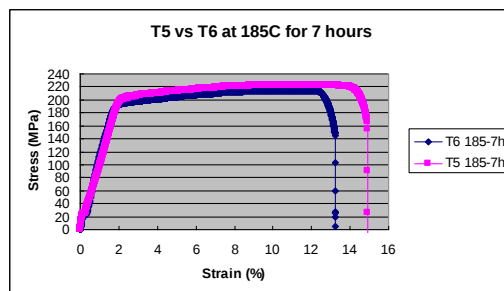
(d) Aged at 205° C for one hour



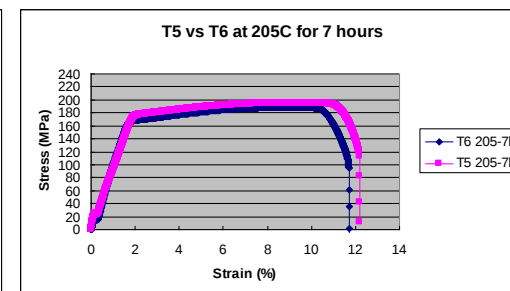
(b) Aged at 185° C for three hours



(e) Aged at 205° C for five hours



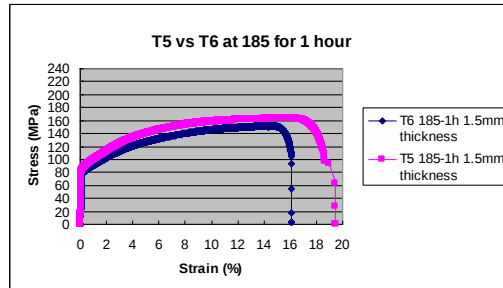
(c) Aged at 185° C for seven hours



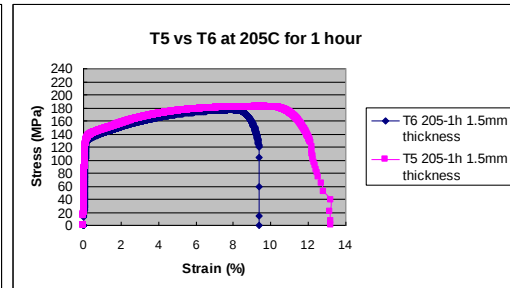
(f) Aged at 205° C for seven hours

Appendix 2

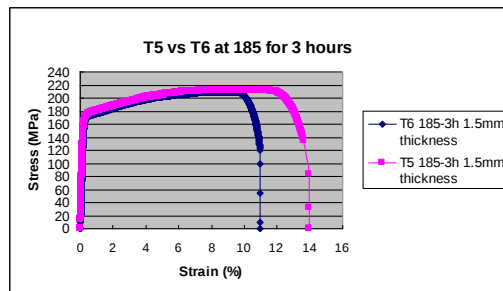
Engineering stress-strain curve - Thickness 1.5 mm



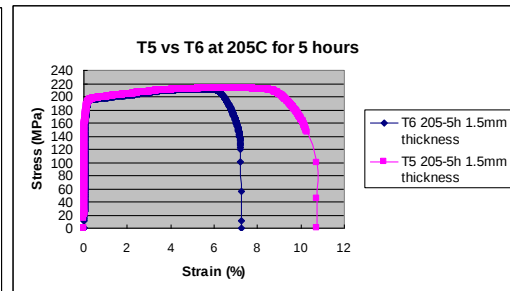
(a) Aged at 185° C for one hour



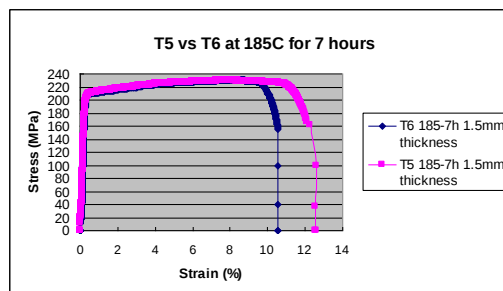
(d) Aged at 205° C for one hour



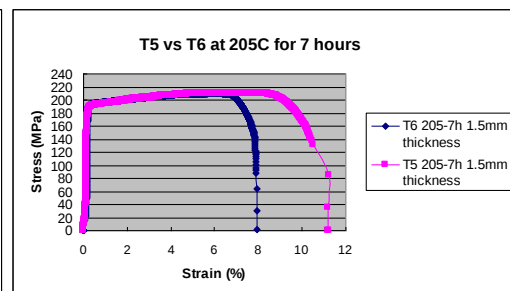
(b) Aged at 185° C for three hours



(e) Aged at 205° C for five hours



(c) Aged at 185° C for seven hours



(f) Aged at 205° C for seven hours