EXTRUSION CHARACTERISTICS OF SOME HIGH STRENGTH AlMgSi ALLOYS

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ABSTRACT

EXTRUSION CHARACTERISTICS OF SOME HIGH STRENGTH AlMgSi ALLOYS. Investigation of the extrusion performance of five high strength 6000 series aluminium alloys with compositions equivalent to commercial 6061, 6070, 6013, 6066 and 6069 alloys has been carried out. Extrusion was carried out using a semi-industrial 750 tonne press at billet temperatures between 400 °C and 500 °C. An extrusion limit diagram was constructed for each alloy. The results show that the limit speed decreases with increasing the alloy concentration. However, the increase of alloy concentrations increases the breakthrough pressure. The high deformation resistance was found in alloys with a high addition of Mg and Cu. Press quenching after extrusion was unable to give a maximum tensile strength of the extruded alloys, especially for the concentrated alloys such as 6066 and 6069.

Key words : High strength AlMgSi alloys, extrusion, extrudability, limit diagram

ABSTRAK

KARAKTERISTIK-KARAKTERISTIK EKSTRUSI DARI BEBERAPA PADUAN AlMgSi KEKUATAN TINGGI. Telah dilakukan pengamatan karakteristik ekstrusi untuk lima buah paduan aluminum seri 6000 berkekuatan tinggi (*high strength alloys*) dengan komposisi setara dengan paduan komersial 6061, 6070, 6013, 6066 dan 6069. Ekstrusi dilakukan menggunakan mesin ekstrusi semi industri berkekuatan 750 ton pada suhu bilet antara 400 °C and 500 °C. Untuk setiap paduan dihasilkan sebuah diagram limit (*extrusion limit diagram*). Hasilnya menunjukkan bahwa laju ekstrusi batasnya (limit *speed*) menurun dengan meningkatnya konsentrasi paduannya. Namun peningkatan konsentrasi paduan meningkatkan tekanan ekstrusinya (*breakthrough pressure*). Resistansi yang tinggi terhadap deformasi ditemukan pada paduan dengan penambahan Mg dan Cu yang tinggi. Pendinginan cepat setelah ekstrusi (*press quenching*) ternyata tidak mampu memberikan kekuatan *tensile* maksimum, khususnya untuk paduan dengan konsentrasi paduan yang tinggi seperti 6066 dan 6069.

Kata kunci : Paduan AlMgSi kekuatan tinggi, ekstrusi, ekstrudabiliti, diagram limit

INTRODUCTION

High strength AlMgSi alloys are normally characterised by the presence of high level of magnesium and silicon as main alloying elements. These two elements are mainly responsible for the strength of alloys by precipitating magnesium silicide (Mg_2Si) as a strengthening agent. Small amounts of other alloying elements such as copper, manganese and/or chromium are added to these alloys to improve the properties.

Although alloying additions are required to increase the strength, it has been suggested that the additions of these alloying elements can be detrimental on extrudability by raising the flow stress of the alloy [1]. Extrudability which can be defined as the ease with which material can be extruded and the degree of deformation it can withstand is strongly dependent on the type and amount of alloying elements present in the alloy. Mg and Cu for example if added in an AlMgSi alloy would significantly increase the alloy's flow stress hence increase the deformation resistance [2-4]. On the other hand Si is considered to be less harmful for extrusion [5]. Several works have been done to study the effect of alloying additions on extrudability and mechanical properties for some medium-strength AlMgSi alloys [2-5]. However none of the investigations on the similar topic has been found to deal with high strength of these alloys.

This paper describes the result of the extrusion tests of some high strength 6000 series alloys: 6061, 6070, 6013, 6066 and 6069. The Mg_2Si concentrations of these alloys vary from 1.34 to 2.25 wt % and each of them has a significant amount of either Mg, Si or Cu additions. Extrudability of the alloys was observed by determining the limit speed and the breakthrough pressure. An extrusion limit diagram was constructed for the five alloys, the tensile strength of the associated alloys was measured and the related microstructures were examined.

Homogenisation of High Strength 6000 Series Alloys

It has been widely known that homogenisation or extrusion of high strength 6000 series alloys is not a simple matter. This is due to merging of the solvus and solidus point lines in the phase diagram (Figure1) makes a window of possible homogenisation temperature diminishes. In this case, the use of a high homogenisation or extrusion temperature would not be possible due to a risk of alloys liquation if temperature of the billet goes beyond the solidus temperature. On the other hand, the use of a low homogenisation temperature would not be able to dissolve all the Mg_2Si particles unless the temperature of the billet exceeds the solvus temperature. For alloy 6069 in which the Mg_2Si concentration exceeds the maximum solubility limit of Mg_2Si in aluminium matrix, as illustrated in Figure 1, the selection of the apropriate homogenisation temperature would be considerably difficult compared to the less dilute alloy as 6061.

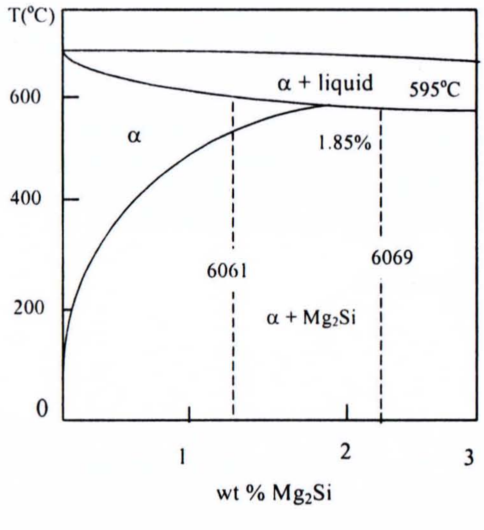

Figure 1. A pseudo binary diagram of Al and Mg_2Si

EXPERIMENTAL

Ingots of 100 mm diameter were direct-chill (DC) cast at Alcan International Ltd. and cut into billets of 150 mm lengths. The chemical composition of the alloys investigated was given in Table 1 [6]. Alloy 6061 which is used as a reference has a relatively moderate composition. Alloy 6070 contains a significant amount of silicon but less copper. While alloy 6013 contains a significant amount of copper. A further increase of magnesium, silicon and copper content was made in alloy 6066. Alloy 6069 is used to observe the effect of high magnesium addition on extrudability and tensile properties. Prior to extrusion the as-received billets were homogenised at 550 °C for 3 hours with a heating rate of 300 °C/hour in a fan-assisted muffle furnace and still air cooled to a room temperature.

For each run the billet was brought to the selected pre-heating temperatures between 400 °C and 500 °C by induction heating at a heating rate of 100 °C min^{-1}. The die, dummy block and container were always preheated to the same temperature as the billet. The breakthrough pressure was recorded for each run. Extruded strips were either water-quenched or forced air-quenched at a cooling rate of 200 °C min^{-1} and 460 °C min^{-1} on the run-out table prior to artificial ageing for 8 hours at 170 °C after a 24 hour storage at room temperature. Tensile testing was carried out on a dog bone-shaped specimen with dimensions of 100 mm x 19 mm x 3 mm at a strain rate of 4.15×10^{-4} s^{-1}.

RESULTS AND DISCUSSION

Alloy and Homogenisation

The high cooling rate during ingot solidification prevents the attainment of equilibrium of the alloy system and causes microsegregation of the alloying elements. The microsegregation is indicated by the presence of magnesium silicide (Mg_2Si) and AlFeSi particles along the cell and grain boundaries of the as-cast alloys. These phases which are thought to have formed by eutectic reactions from the last liquid to solidify [7] would severely limit extrusion speed due to the early onset of surface liquation.

The DSC measurement shows that liquation points (solidus) of alloys 6061, 6070, 6013, 6066 and

Table 1. The chemical composition of the alloys (wt%) [6]

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ti	B	Mg_2Si	ExSi
6061	0.73	0.17	0.35	0.002	0.85	0.06	0.008	0.001	1.34	0.24
6070	1.33	0.20	0.19	0.70	0.86	-	0.009	0.001	1.36	0.83
6013	0.98	0.19	0.88	0.50	0.90	0.01	0.007	0.001	1.42	0.46
6069	0.89	0.20	0.80	0.70	1.43	-	0.009	0.002	2.25	0.007
6066	1.37	0.19	0.97	0.70	1.11	-	0.009	0.002	1.75	0.73

6069 occur at 595, 584, 576, 569 and 579 °C, respectively. The solidus of the alloys was determined from a point where the start of the endotherm occurs or a temperature where the change of slope of the DSC curves takes place. For convenience a homogenisation temperature of 550 °C was selected for all alloys.

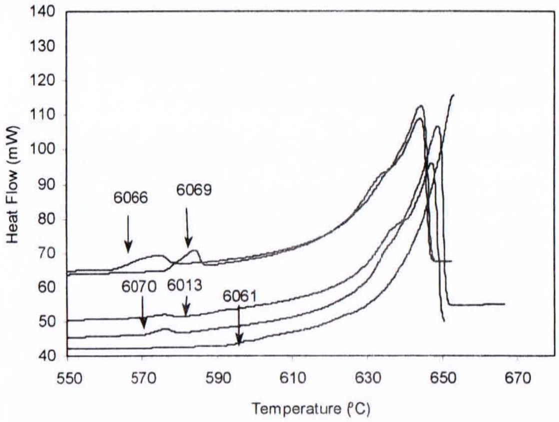

Figure 2. DSC trace of the alloys heated at 10°C/minute

Homogenising at 550 °C for 3 hours removed micro segregation by dissolving the intermetallic phases, breaking up the grain boundary networks and redistributing Mg and Si throughout the grains. During air cooling from the homogenisation temperature some Mg_2Si particles reprecipitated. Figure 3 shows the coarse Mg_2Si particles which precipitated at the grain boundaries. It can be seen from the micrographs that the number of the Mg_2Si. particles increases as the Mg_2Si content in the alloys increases. The sizes of the particles are so big that they would be difficult to be solutionised during extrusion and would be detrimental to the final mechanical properties

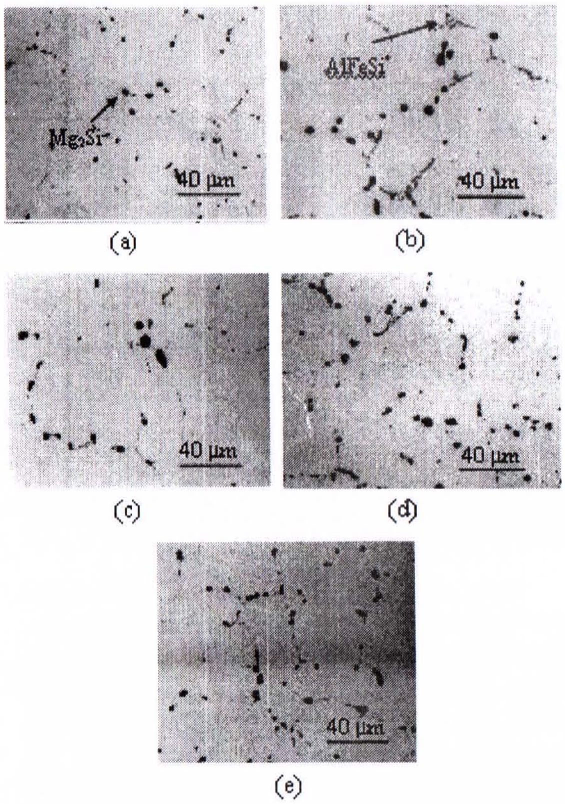

Figure 3. Optical micrographs of the homogenised alloys: (a) 6061, (b) 6070, (c) 6013, (d) 6069 and (e) 6066. Homogenisation was made at 550°C for 3 hours and still air-cooled.

Extrusion Testing

The extrusion performance of the alloys can be observed through the extrusion limit diagrams, Figure 4a and b. The limit diagrams, exit speed vs. billet temperature, of alloys 6070, 6013, 6066 and 6069 are presented with reference to that of alloy 6061. The maximum limit speeds were determined by extruding the billet with increasing speeds until tearing (cracks) was visually observed at the corner of the extruded section. The limit speed for each alloy at a given billet temperature was presented in the diagram by a star data point.

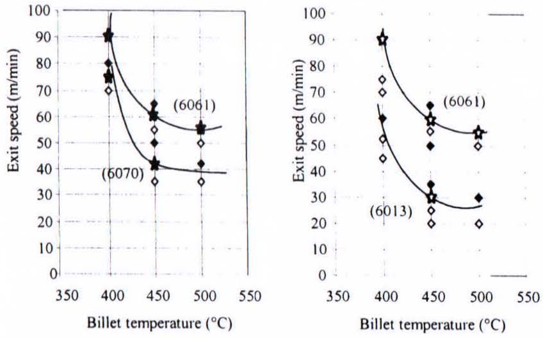

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Figure 4a. Limit diagram of alloys 6070 and 6013 with reference to alloy 6061

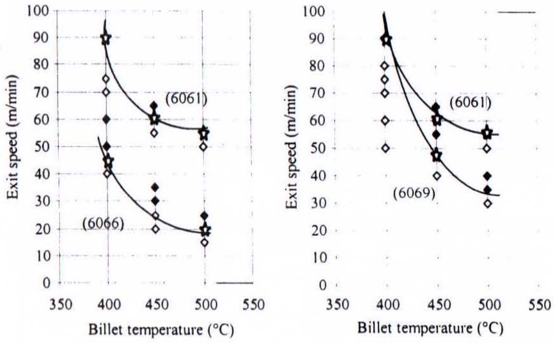

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Figure 4b. Limit diagram of alloys 6066 and 6069 with reference to alloy 6061

Tearing, in this case, is believed to be caused when metal failed due to high tensile present at the die/extrudate interface. It could also be initiated by melting of the liquation of Mg_2Si eutectics which occurred when the temperature rise during extrusion exceeded the eutectic temperature. The decrease of the limit speed by increasing billet temperature was associated with the increase of the surface temperature at a higher billet temperature, therefore at a higher billet temperature a lower extrusion speed was sufficient to bring the temperature beyond the eutectic temperature at which tearing took place.

It can be seen from Figure 4a and Figure 4b that the limit speeds of alloys 6070, 6013, 6066 and 6069 are lower than that of the reference alloy 6061. The limit speed of alloy 6070 decreases by 17 to 30% with reference to alloy 6061. A further decrease of limit speed by 54% is found in alloy 6013. For the concentrated alloys such as 6066 the decrease of limit speed is up to 64%. However, it is found that a high Mg or Mg_2Si content in alloy 6069 does not adversely affect the limit speed, the reduce is only 42%. The reduce of limit speed with alloy content in these alloys is consistent with their eutectic temperatures shown in Table 2. The eutectic temperatures were identified by the points where the small peaks (blips) in the DSC curve start to appear (see Figure 2).

Table 2. Eutectic and solidus temperatures of the alloys measured

	6061	6070	6013	6066	6069
Eutectic Temp.	-	573°C	568°C	564°C	577°C
Solidus Temp.	595°C	584°C	576°C	569°C	579°C

Breakthrough Pressure

Since the flow stress of alloy is strain rate sensitive [4,8] the breakthrough pressure of the alloys can only be compared using the data taken at the same extrusion speed. The breakthrough pressure for the five alloys at the extrusion speed of 40 mmin^{-1} is shown in Figure 5. It can be seen from this curve that the deformation resistance of the alloy increases as the alloy content increases. Compared to alloy 6061 the breakthrough pressure of alloy 6070 which contain high Si is 5 to 8% higher. The breakthrough pressure of alloy 6013 with high Cu content is 10-12% higher. The high concentration of alloying elements in alloy 6066 gives a further increase of deformation resistance to the alloy. The highest deformation resistance is found in alloy 6069 which contains 1.43wt% Mg, the breakthrough pressure increases by up to 25%. It is found that the breakthrough pressure increases as the Mg_2Si concentration in the alloy is raised. The decrease of the breakthrough pressure with billet temperature is associated with the decrease of the flow stress of the alloys by increasing billet temperature.

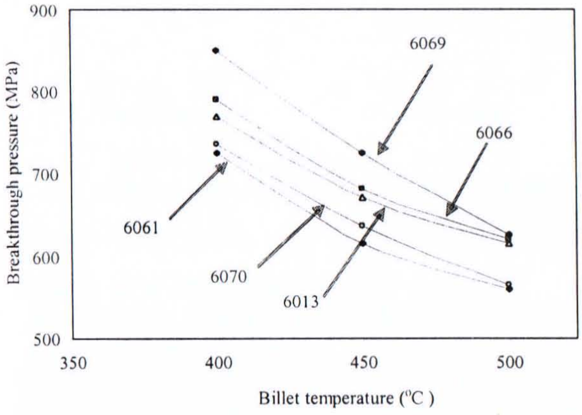

Figure 5. Breakthrough pressures of the five alloys at the extrusion speed of 40 mmin^{-1}

Mechanical Properties (Tensile Testing)

The tensile and yield strength of the alloys extruded at the limit speed, at a billet temperature of 500 °C press water quenched and aged at 170 °C for 8 hours after a 24-hour storage at room temperature is given in Figure 6. It can be seen from the graph that the tensile strength increases with alloy additions. The reference alloy 6061 has the tensile strength of 330 MPa (UTS) and 300 MPa (YS). The high Si addition in alloy 6070 increases the tensile strength to 370 MPa (UTS) and 340 MPa (YS). The increase of Cu content in alloy 6013 increases the tensile strength further to 400 MPa (UTS) and 350 MPa (YS). A further increase of alloy content in alloy 6066is not accompanied by a significant increase in tensile strength; 415 MPa (UTS) and 370 MPa (YS). The high addition of Mg in alloy 6069 does not give a significant increase to the tensile strength, 405 MPa (UTS) and 350(YS).

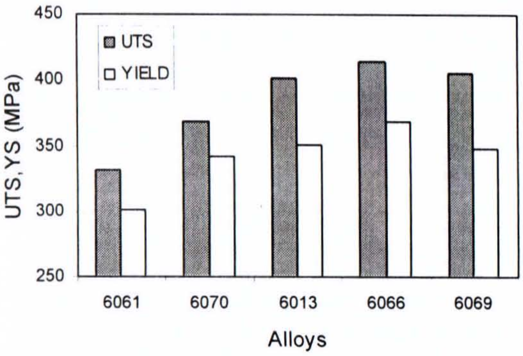

Figure 6. Tensile strength of the alloys extruded at the limit speed, at a billet temperature of 500°C press water quenched and aged at 170°C for 8 hours after a 24 hour storage at room temperature.

Press quenching after extrusion seems to be unable to give a full solution of Mg_2Si during extrusion. This is indicated by the presence of second phase particles, Mg_2Si, in the extruded alloys as shown in Figure 7. Therefore the tensile strength obtained in the press quench condition is not at its maximum. The volume fraction of the undissolved particles increases as the Mg_2Si concentration in the alloy increases. Image analysis (Table 3) reveals the increase of the mean diameter with the Mg_2Si concentration.

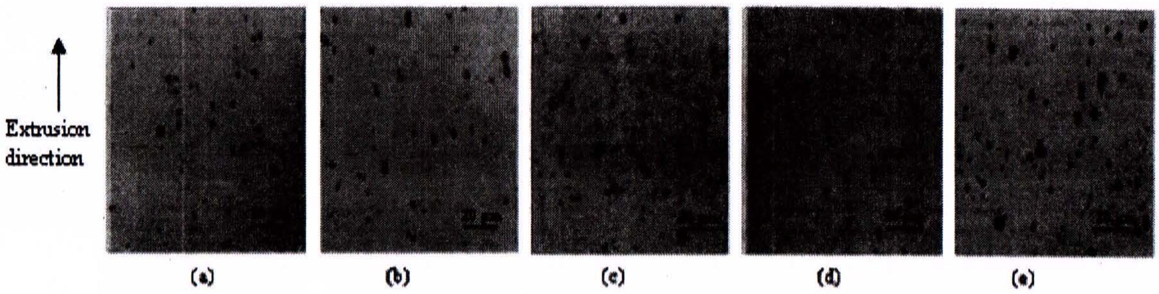

Figure 7. Optical micrographs of the alloys 6061(a), 6070 (b), 6013 (c), 6066 (d) and 6069 (e) extruded at the limit speed at a billet temperature of 500°C water quenched to room temperature

Table 3 The mean diameter and density of the Mg_2Si particles for the five alloys shown in Figure 7 calculated using image analysis.

	6061	6013	6070	6066	6069
Mean diameter (μm)	9.0 ± 5.5	7.0 ± 3.5	7.3 ± 4.6	7.8 ± 4.9	8.6 ± 4.5
Density (%)	1.15 ± 0.08	1.21 ± 0.15	1.47 ± 0.12	2.24 ± 0.07	2.51 ± 0.07

Figure 8 shows the relationship between the tensile strength of the alloys at a press quenched condition and billet temperature. Except for alloy 6061, the tensile strength (UTS) of these alloys increases as the billet temperature is increased. The increase of the tensile strength with billet temperature is almost similar for alloys 6069, 6066, 6013 and also 6070. As the billet temperature is increased from 400 °C to 500 °C the UTS of these alloys increased by 18 to 22% . The increase of strength at higher billet temperatures is attributed to the increase of dissolution rate of Mg_2Si as the temperature increases giving rise to the increase of the amount of Mg and Si in solid solution. For alloy 6061, most of the Mg_2Si particles has probably dissolved at a lower billet temperature, so increasing billet temperature does not give any significant effect. Quench sensitivity of the alloys can be seen in Figure 9 which shows the effect of quenching rate on tensile strength. The tensile strength in the press quenched condition exhibits a 90 MPa lower strength following air-cooling than water quenching. However for alloy 6061 no significant loss in properties is found when the quench rate is reduced. The quench sensitivity of the alloys is attributed to the Mn additions. The low quench sensitivity of alloy 6061 is due to the absence of Mn in the alloy.

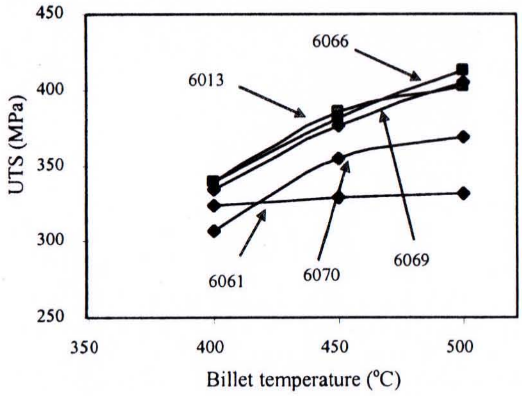

Figure 8. Tensile strength vs. billet temperature for the five alloys.

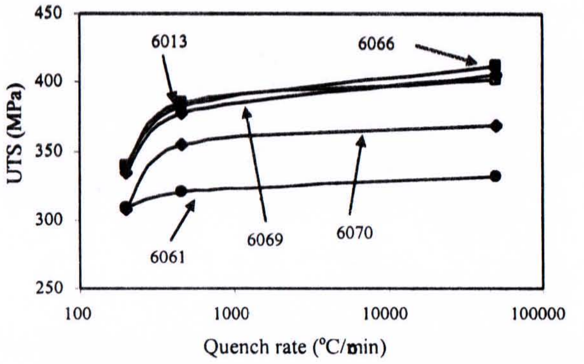

Figure 9. Quench sensitivity of the alloys.

SUMMARY

1. The extrusion performance of the alloys has been successfully evaluated using a limit diagram. The extrusion limit speed decreases as billet temperature is increased and the increase in concentration of alloying elements decreases the limit speed.
2. High amount of Mg in an AlMgSi alloy does not significantly affect the limit speed, but it does increase the breakthrough pressure. The high amount of Mg in solution at the extrusion temperature is thought to be responsible for the increase of the breakthrough pressure.
3. The use of high Mg and Si addition in an extrusion alloys is not recommended since only a portion of

them will be taken into solid solution during homogenisation and extrusion hence the contribution to the alloy strength cannot be maximum.

4. The addition of 0.7 wt% Mn in alloys 6013, 6070, 6066 and 6069 makes the alloys more quench sensitive compared to 6061.

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TANYA JAWAB

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Pertanyaan

1. Apa seluruh *as-cost structure* larut dalam proses *homogenization*.
2. Berapa suhu *solution treatment*.

Jawaban

1. Sebagian besar *dendritic structure*nya larut setelah paduan AlMgSi di homogenisasi pada suhu 550 °C selama 3 jam, namun beberapa partikel seperti Mg_2Si dan AlFeSi masih tertinggal pada paduan setelah homogenisasi. Hal ini disebabkan tingginya suhu *solven* Mg_2Si dari paduan ini sehingga pelarutan total dari Mg_2Si tidak dapat dicapai. Sedangkan sebagian kecil fasa AlFeSi yang tertinggal kemungkinan disebabkan adanya Mn yang terikat pada fasa itu dan membentuk AlFe(Mn)Si. Mn mempunyai koefisien difusi yang relatif tinggi sehingga fasa tersebut hanya bisa larut pada suhu homogenisasi yang tinggi.
2. *Solution treatment* terjadi selama proses ekstrusi itu sendiri sehingga suhu *solution treatment*nya adalah gabungan antara suhu *gillet* : 400 °C sampai dengan 500 °C ditambah dengan suhu yang timbul karena metal deformation yang diperkirakan sekitar 90 °C