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OPTIMIZATION OF EXTRUSION PROCESS OF ALLOY 6063 USING TAGUCHI TECHNIQUE

A. CHENNAKESAVA REDDY

Abstract

The yield and ultimate tensile strengths and ductility decrease with increase in the section thickness of extruded products. T6 imparts larger strengths. 15% of area of deformation gives maximum ultimate tensile and yield strengths. Heat treatment T6 results in lower ductility. The ductility decreases with increase in percent deformation of extruded specimens. The fracture energy decreases with the increase in the section thickness. The fracture energy for heat treatment T4 and T6 are higher than that of T5. The fracture energy decreases with deformation of extruded specimens. The increase in the tensile strength and yield strength is due to vacancies assisted diffusion mechanism and formation of metastable β'' and β' precipitates. Extrusions of larger cross-sections, which contain Mg_2Si particles, have lower strengths. T6 reduces microsegregation by diffusion of magnesium and silicon throughout the structure and transforms the insoluble eutectic phases to the equilibrium phase α-AlFeSi.Mg_2Si particles large enough have low ductility.

Keywords : 6063, extrusion, mechanical properties, Taguchi technique

1. INTRODUCTION

Alloy 6063, one of the most popular alloys in the 6000 series, provides good extrudability and a high quality surface finish. This is being used to produce standard architectural shapes, custom solid shapes, as well as seamless and structural tubes and pipes [1]. The rails and posts are normally in the T6 temper and formed elbows and bends are T4. T4 temper 6063 aluminium is also finding applications in hydroformed tube for chassis.

Alloy 6063 can be strengthened through precipitation of several metastable phases [2]. The understanding and control of precipitation during aging is therefore critical for achieving optimal properties. It is well known that homogenized aluminium alloys billets extrude easier and faster and give a better surface finish than as-cast billets. Structural aluminium alloys contain inclusions of brittle phase dispersed in a ductile matrix [3]. Damage initiation occurs in such alloys by decohesion or fracture of these inclusions. The Fe bearing intermetallic particles such as β-Al_5FeSi and α-$Al_{12}(Fe, Mn)_3Si$ have a significant influence on formability [4]. The brittle plate-like monoclinic β phase is associated to poor hot workability. This unfavourable effect can be improved by performing a long homogenization treatment at high temperature, by which the β phase transforms to the more rounded, metastable, cubic α phase.

The metallurgical process that produces precipitates in heat treatable aluminium alloys is a two steps procedure: first a supersaturated solid solution is produced by heating the material at a temperature where the phase diagram exhibits a maximum solubility, generally an eutectic temperature, followed by rapid quenching at room temperature. This step is then followed by an ageing procedure consisting in maintaining the sample at a room temperature (T4) or a higher temperature generally around 200°C (T6).

It is known that the main components of heat treatable 6xxx series Al alloy are Mg and Si, and 6xxx derives its strength from the precipitation hardening phase, Mg_2Si. The volume fraction of Mg_2Si is affected primarily through the level of Mg within the alloy, but the Si content is also important. The increase of Si in 6xxx type alloys increases strength in the T4 and T6 tempers [5].

The objective of this paper is to study the influence of wall thickness, aging, and percentage of deformation while manufacturing the structural tubes using the extrusion process.

2. EXPERIMENTAL PLANNING

The alloy 6063 type of aluminum alloy is used for the hot extrusion purposes. The chemical composition of alloys is given in Table 1.

Table 1 : Chemical composition of alloys

Alloy	Composition determined spectrographically, %								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
6063	98.8	0.271	0.325	0.0047	0.0376	0.52	0.0076	0.076	<0.0005

The extent of deformation is one of the decisive factors in the extrusion. The deformation is given in terms of the percentage reduction based on the cross-sectional areas of the container (A) and the die aperture (a), $\left[{(A-a)}/{A} \right] \times 100$ or extrusion ration (A/a). In this work the deformation is considered in terms of percentage reduction. The effect of deformation behavior prior to heat treatment must be investigated. For this purpose, the hot extrusion process prior to heat treatment was carried out. Rods were hot extruded so that 10%, 15%, and 20% deformation (for instance, 25 mm diameter reduced to 22.5, 21.25 and 20 mm diameter) could be established.

The 12.5, 18.75 and 25.0 mm diameter billets were then hot extruded by using a hydraulic press and a graphite-based high temperature lubricant at a ram speed of 1mm/s and the temperature of 450ºC. Schematic diagram of extrusion equipment used in the present work is shown respectively in figure. 1.

T4 is the solution heat treatment at 520^{0}C for 1 hour followed by water quench. Other tempers are accomplished by aging. Aging is done at a temperature of 175^{0}C for 8 hours for T 6 temper. Ageing at 175^{0}C for 3 hours gives T5 temper.

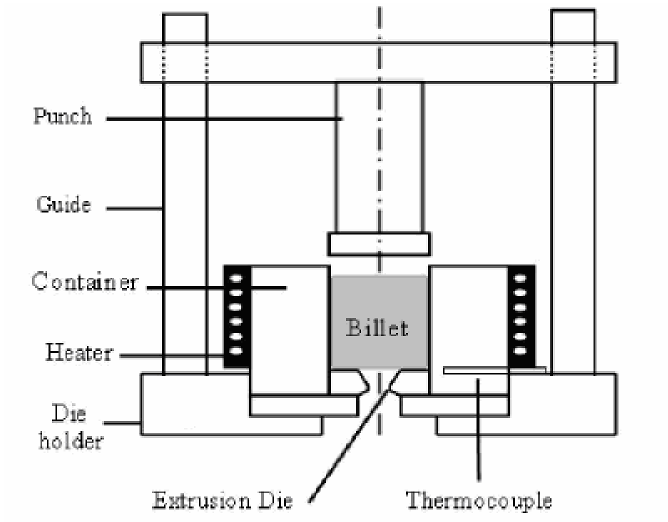

Figure 1 : Schematic diagram of hot extrusion process

2.1 Selection of the Quality Characteristics

The selection of quality characteristics to measure as experimental output greatly influences the number of tests that will have to be done to be statistically meaningful. The quality characters, which were selected to influence the mechanical properties of the alloy 6063, are: yield strength, ultimate tensile strength, tensile ductility (%elongation), and fracture energy.

2.2 Selection of Process Parameters

The parameters, which influence the performance of the alloy 6063, are:

- Section size of round rods (D): 12.5, 18.75 and 25.0 mm
- Percentage of deformation by hot extrusion process (E):10%, 15% and 20%
- Heat treatment (H): T4, T5 and T6

The objectives at the end were developing good mechanical properties. The important parameters were optimized by Taguchi's method. Taguchi techniques offer potential saving in test time and cost.

2.3 Selection of Levels for Control Parameters

Control parameters are those parameters that a manufacturer can control the design of the product, and the design of process. Each of the three control parameters was studied at three levels. The chosen control parameters are summarized in Table-2.

Table 2 : Parameters and Levels for Al_2O_3 reinforced composites

Factor	Symbol	Level – 1	Level – 2	Level – 3
Diameter, mm	D	12.5	18.75	25.0
Heat treatment	H	T4	T5	T^
Deformation, %	E	10	15	20

Table 3 : Orthogonal Array (L_9) and control parameters

Treat No.	D	H	E	DxH
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.4 Assignment of Parameters in Orthogonal Array (OA)

The orthogonal array, L_9 was selected for the present work. The parameters were assigned to the various columns of O.A. The assignment of parameters along with the OA matrix is given in Table – 3. One interaction among section size and heat treatment of alloy (DxH) was also considered.

2.5 Conduction of Tests

The following tests were conducted on the metal matrix composites:

- Tensile test for yield strength, ultimate tensile strength and %elongation
- Fracture energy
- Microstructure analysis
- Scanning electron microscopy

Round tensile samples were machined along the extrusion direction according to ASTM E8 and room temperature. The shape and dimensions of a standard round tensile specimen is shown in figure 2. Uniaxial tension tests were carried out in a fully automated universal tensile testing machine at a constant cross head speed of 1mm/s. The extensometer was used to measure the elongation. The load v/s deflection graph was also obtained for each specimen from the computer attached to the machine. Two specimens were used for each trial. The area under stress- strain curve was calculated to obtain the value of absorbed energy for fracture.

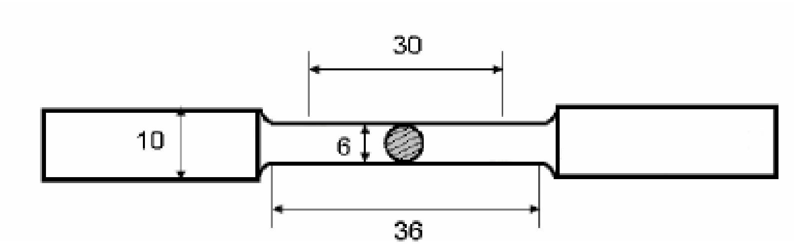

Figure 2 : Tensile specimen

For microstructural analysis, specimens were ground with emery papers from 600 to 1200, and polished with 1 μm diamond paste. As an etchant, a mixture of HF, H_2SO_4 and H_2O in the composition 1:2:17 was used. For characterization, optical microscopy and a scanning electron microscope were used.

3. RESULTS

The experiments were scheduled on random basis to accommodate the extrusion and heat treatment impacts.

3.1 Effect of process parameters on the yield and ultimate tensile strengths

Table – 4 gives the ANOVA (analysis of variation) summary for the yield strength. The Fisher's test column establishes all the parameters (D, H, E, and DxH) accepted at 90% confidence level. The percent contribution indicates that the section size, D (diameter) contributes 0.61% of variation, heat treatment, H aids 88.10% of variation, deformation, E (% area of reduction) influences 9.21% of variation, and interaction between parameters D and H contributes 1.88% of variation.

Table 4 : ANOVA summary of the yield strength

Column No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	D	1053	1039	995	305.34	2	152.67	33.93	0.64
2	H	724	954	1409	40508.34	2	20254.17	4500.93	88.1
3	E	901	1114	1072	4243.01	2	2121.51	471.46	9.21
4	DxH	970	1064	1053	880.34	4	220.09	48.919	1.88
5	Error	----	----	---	31.47	7	4.5	33.93	0.17
6	T	----	----	----	45968.5	17	--------	--------	100

The summary of ANOVA (analysis of variance) for the ultimate tensile strength (UTS) is shown in Table 5. The Fisher's test column confirms only three parameters (D, H, E and DxH) accepted at 90% confidence level influencing the variation in ultimate tensile strength. According to the analysis of variance, there are two strong parameters, which influence UTS. Looking at the ANOVA table, parameter, H (heat treatment) has the largest effect (78.43%), parameter, E (% area of reduction) the second largest effect (15.29%). Parameter, D (section size) and the interaction between section size and heat treatment have the least effect on the ultimate tensile strength.

Table 5 : ANOVA summary of the ultimate tensile strength

Column No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	D	326666.7	315104.2	292604.2	486.12	2	243.06	12.99	1.63
2	H	221568.2	280800.7	453200.2	21680.12	2	10840.06	579.37	78.43

Column No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
3	E	258752.7	360150	319242.7	4256.45	2	2128.23	113.75	15.29
4	DxH	288204.2	338912.7	307813.5	1041.45	4	260.36	13.92	3.5
5	Error	----	----	---	130.97	7	18.71	1.00	1.15
6	T	----	----	----	27595.11	17	--------	---------	100

Figure 3 shows the influence of section size on the yield strength (YS) and ultimate tensile strength (UTS) of Al 6063 alloy. It can be seen that the YS and UTS decrease with increase in the section thickness of extruded products. The only difference is that the UTS values are higher than the YS values. The ultimate tensile and yield strengths increase as the ageing changes from natural to artificial (figure 4). T6 imparts larger strengths. 15% of area of reduction (deformation) gives maximum ultimate tensile and yield strengths (figure 5). The interaction between section thickness and heat treatment has considerable effect on the yield strength (figure 6) and ultimate tensile strength (figure 7).

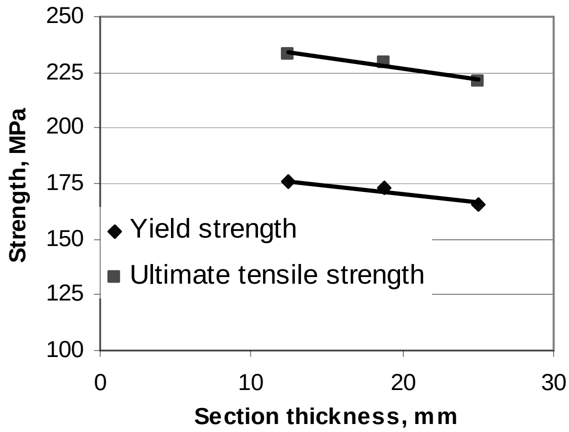

Figure 3 : Influence of section thickness on the yield and ultimate tensile strengths

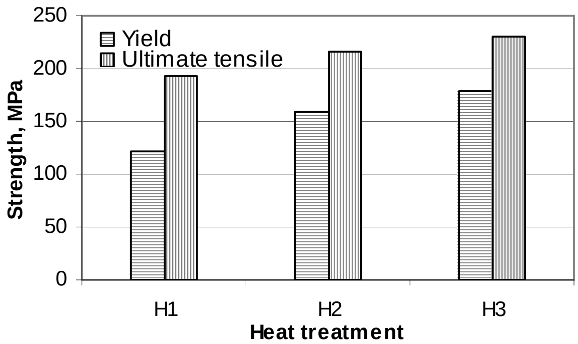

Figure 4 : Influence of heat treatment on the yield and ultimate tensile strengths

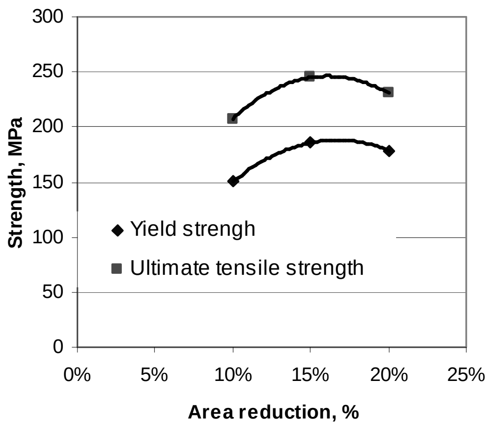

Figure 5 : Influence of area of reduction on the yield and ultimate tensile strengths

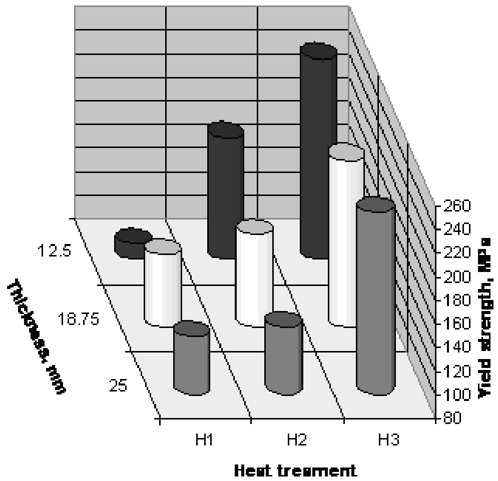

Figure 6 : Influence of interaction between section size and heat treatment on the yield strength

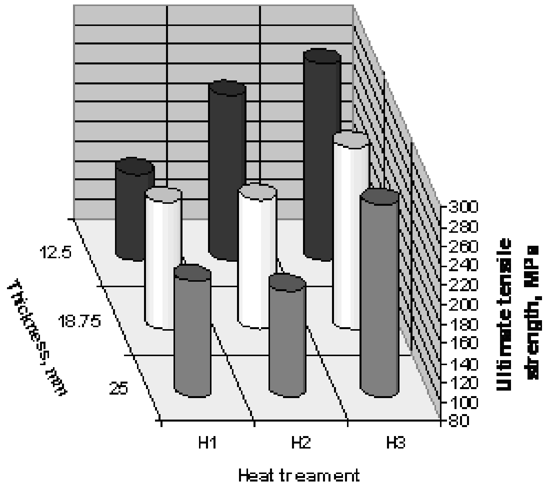

Figure 7 : Influence of interaction between section size and heat treatment on the tensile strength

Table 6 : ANOVA summary of the ductility

Column No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	D	106	75	81	60.12	2	30.06	23.48	40.03
2	H	96	92	84	12.45	2	6.22	4.86	6.88
3	E	102	94	76	59.12	2	29.56	23.09	39.34
4	DxH	94	88	90	3.12	4	0.78	0.61	-1.39
5	Error	----	----	---	8.97	7	1.28	1.0	15.14
6	T	----	----	----	143.78	17	--------	---------	100

3.2 Effect of process parameters on the ductility

The ANOVA summary of ductility measured in terms of tensile elongation is given in Table-6. The Fisher's test column ascertains only three parameters (D, H, and E) accepted at 90% confidence level influencing the variation in the ductility (tensile elongation). The parameter, D (section size) contributes 40.03% of variation, the parameter, H (heat treatment) aids 6.88% of variation, and the parameter E (% reduction of area) influences 39.34% of variation. The interaction between parameters DxH is not significant over the variation in the ductility of composites. Figure 8 shows the effect of section thickness on the ductility (measured in terms of % elongation). The ductility decreases with increase in the section thickness of extruded workpieces. Heat treatment T6 results in lower ductility (figure 9). The ductility decreases with increase in percent deformation of extruded specimens (figure 10).

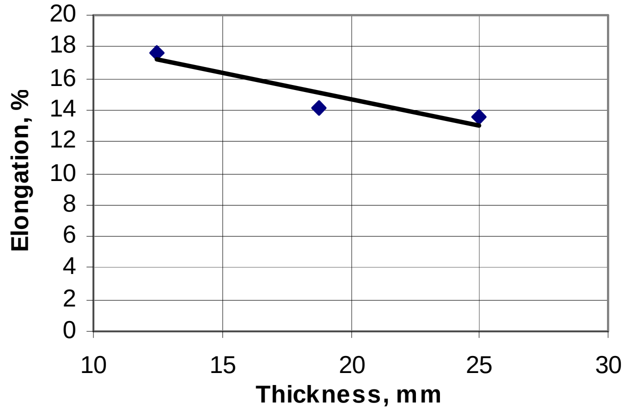

Figure 8 : Influence of section thickness on the ductility.

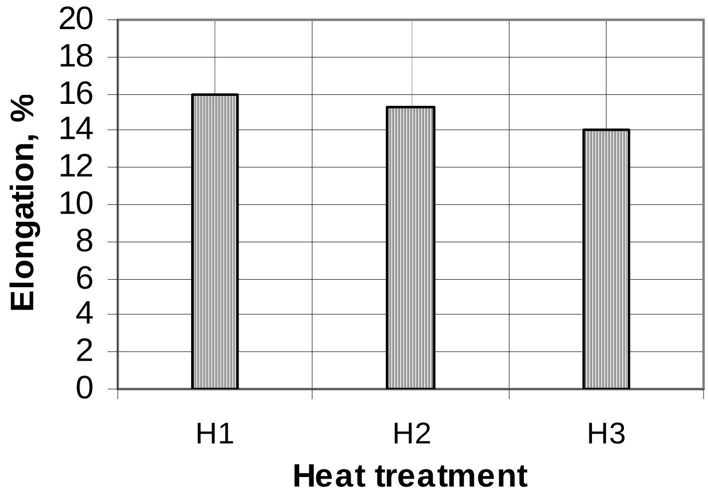

Figure 9 : Influence of heat treatment on the ductility.

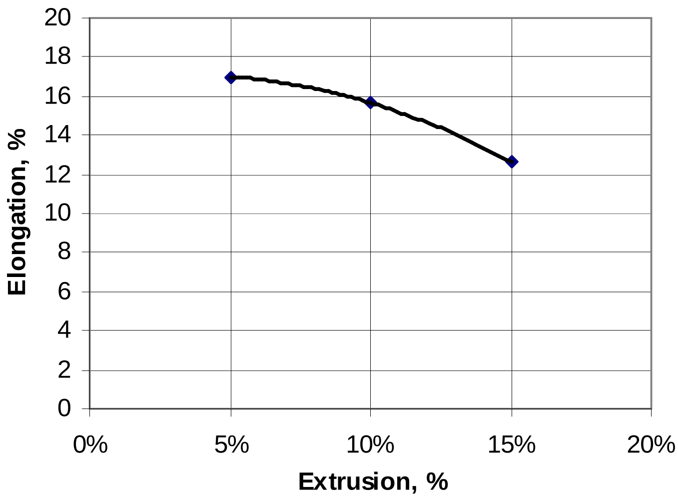

Figure 10 : Influence of area of reduction on the ductility.

Table 7 : ANOVA summary of the fracture energy

C. No	Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
1	D	93	75	73	40.45	2	20.23	9.77	27.45
2	H	88	74	79	16.79	2	8.4	4.061	9.56
3	E	89	85	67	45.79	2	22.9	11.067	31.49
4	DxH	88	76	77	14.79	4	3.7	1.79	4.92
5	Error	----	----	---	14.46	7	2.07	1.0	26.58
6	T	----	----	----	132.28	17	--	-	100

3.3 Effect of process parameters on the fracture energy

The ANOVA summary of hardness is given in Table-7. The Fisher’s test column ascertains all the parameters (D, H, E, and DxH) accepted at 90% confidence level influencing the variation in the hardness. The percent contribution indicates that the section size, D contributes 27.45% of variation, parameter, H aids 9.56% of variation, parameter, E influences 31.49% of variation, and interaction between parameters D and H contributes 4.92%. Interestingly, the error contributes 26.78% because of computation of area under the stress-strain curve which is a complex contour. The fracture energy decreases with the increase in the section thickness (figure 11). The fracture strength for heat treatment T4 and T6 are higher than that of T5 (figure 12). The fracture energy decreases with deformation of extruded specimens (figure 13).

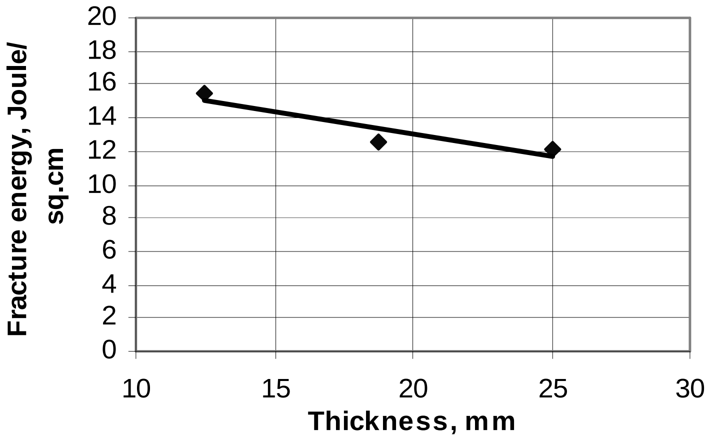

Figure 11 : Influence of section thickness on the fracture energy

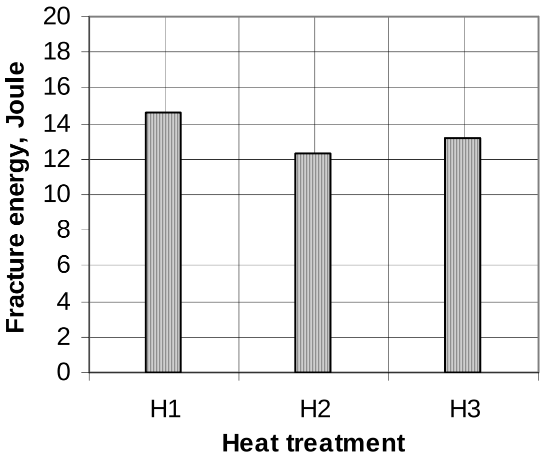

Figure 12 : Influence of heat treatment on the fracture energy

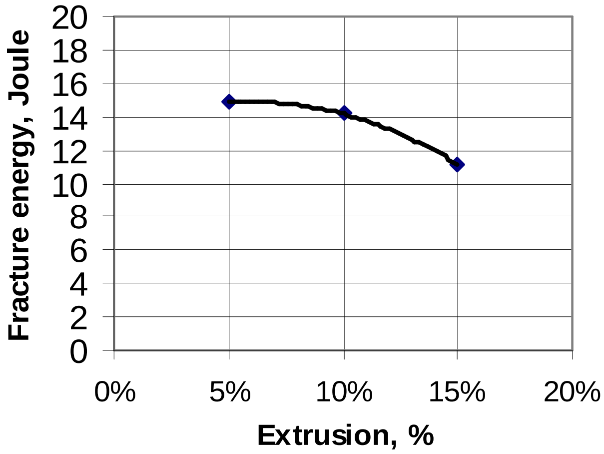

Figure 13 : Influence of area of reduction on the fracture energy

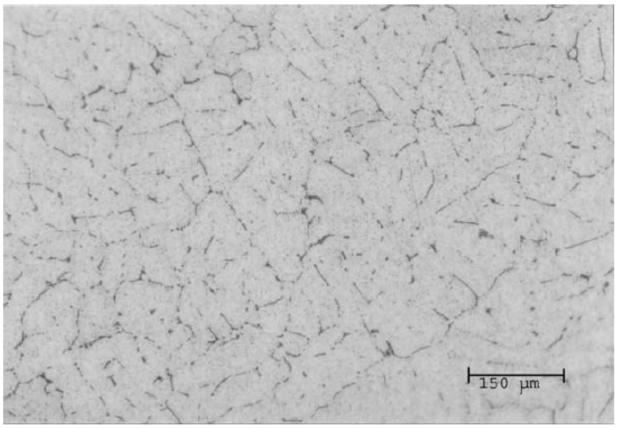

Figure 14 : Microstructure of as-cast 6063 Al alloy

4. DISCUSSION

The microstructure of the alloy 6063 in the as-cast state is given in figure 14. In the interdendritic spaces of α-Al solid solution the intermetallic phases are revealed. The revealed particles of the intermetallic phases were formed during casting of the alloy 6063. The typical as-cast structure of examined alloys consisted of a mixture of β -AlFeSi and α -AlFeMnSi intermetallic phases distributed at cell boundaries, connected sometimes with coarse Mg_2Si.

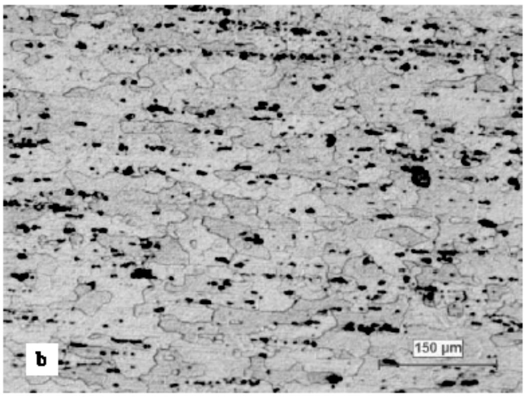

Figure 15 : Microstructure of 6063 Al alloy after hot extrusion

The microstructure of the alloy after hot extrusion process of 25 mm diameter and 20% reduction is given in figure 15. During hot working of ingots, particles of intermetallic phases arrange in positions parallel to the direction of plastic deformation (along plastic flow direction of processed material) which allows for the formation of the band structure. As a result, the reduction of size of larger particles may takes place.

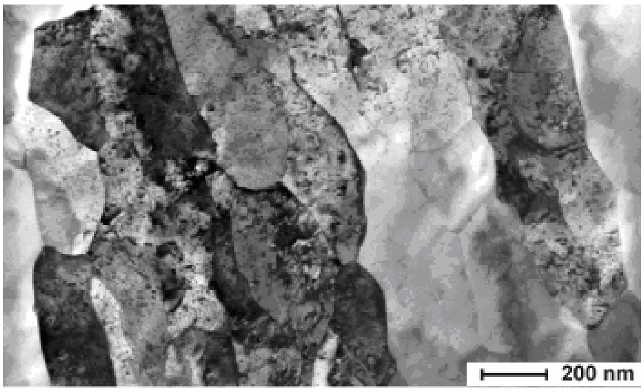

Figure 16 : Microstructure of 6063 Al alloy after hot extrusion

The dark areas represent the newly formed dislocations which accumulate at the grain boundaries and inside the grains, and increase the strength of the material as observed in the SEM of the hot extruded specimen of 25 mm diameter and 20% reduction (figure 16). Light areas indicate no tensions inside the grain. The more the aluminium strengthens due to dislocation accumulations the blurrier is the black-white contrast. Furthermore, there are finest precipitations close to the free dislocations, acting as nuclei, which preserve the strength of the material during heat treatment.

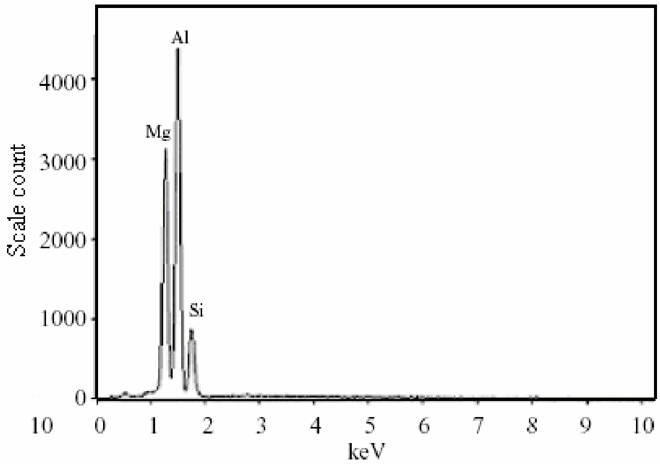

Figure 17 : EDS analysis of extruded material

The increase in the tensile strength and yield strength is due to vacancies assisted diffusion mechanism and formation of metastable β'' and β' precipitates, which disturb the regularity in the lattices. The solution heat treatment can lead to recrystallisation of an unrecrystallised material, or to significant grain growth in a fine-grained recrystallised structure. The EDS analysis of the hot extruded specimen of 25 mm diameter and 20% reduction indicates the presence of Mg_2Si precipitates (figure 17). Extrusions of larger cross-sections, which contain Mg_2Si particles, have lower strengths. T6 reduces microsegregation by diffusion of magnesium and silicon throughout the structure and transforms the insoluble eutectic phases to the equilibrium phase α-AlFeSi. Thus, the yield and ultimate tensile strengths of tensile specimens register for high strengths.

When deformation is increased, it is obvious that the material exposed to higher pressure. This increases strain hardening which reduces the ductility. The local stains increases the strength of the material due to increases amount dislocation tangles with reducing ductility. The 20% deformed specimen has higher dislocation density than the 10% deformed one. Large particles pf Mg_2Si form on slow cooling. Faster cooling retains a substantial amount of Mg and Si in solid solution. Mg_2Si particles large enough have low ductility.

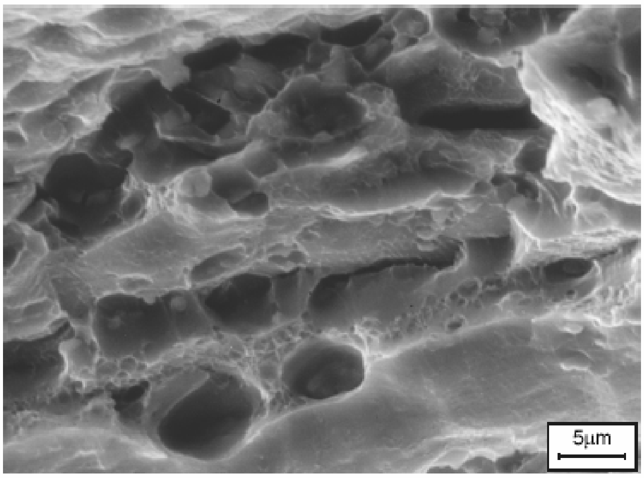

Figure 19 : Fractograph of tensile specimen

Observation of the microstructure and surfaces of the failed samples (of the hot extruded specimen of 25 mm diameter and 20% reduction) showed that the fracture is facilitated by participation of few overlapping processes – nucleation, growth and coalescence of voids (figure 18). Most of the cracks initiated at void clusters.

CONCLUSIONS

The ultimate tensile and yield strengths increase as the ageing changes from natural to artificial. T6 imparts larger strengths. 15% of area of deformation gives maximum ultimate tensile and yield strengths. The ductility decreases with increase in the section thickness of extruded workpieces. Heat treatment T6 results in lower ductility. The ductility decreases with increase in percent deformation of extruded specimens. The fracture energy decreases with the increase in the section thickness. The fracture energy decreases with deformation of extruded specimens. During hot working of ingots, particles of intermetallic phases arrange in positions parallel to the direction of plastic deformation. The increase in the tensile strength and yield strength is due to vacancies assisted diffusion mechanism and formation of metastable precipitates. T6 reduces microsegregation by diffusion of magnesium and silicon throughout the structure and transforms the insoluble eutectic phases to the equilibrium phase. The strain hardening reduces the ductility.

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A. Chennakesava Reddy
Professor of Mechanical Engineering
JNT University College of Engineering
Hyderabad – 500 031, Andhra Pradesh, India
Email : dr_acreddy@yahoo.com