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Effect of T6 treatment on the grain size and mechanical properties of as cast, cast aged and forge aged Al-14Si-13Mg-5Fe-2.5Cu alloy

D. G. Sondur[1, a*], M. D. Harlapur[2, b], D. G. Mallapur[3, c]

[1*]*Department of Mechanical Engineering, Rural Engineering College, Hulkoti, 582205, Karnataka, India,*

[2]*Department of Mechanical Engineering, Rural Engineering College, Hulkoti, 582205, Karnataka, India,*

[3]*Department of Industrial and Production Engineering, Basaveshwar Engineering College (Autonomous), Bagalkot - 587103,*

email: dgsondur_tce@yahoo.co.in, email: mdhrechulkoti@gmail.com, email: dmallapur@gmail.com

Abstract

In the present paper effect of T6 treatment on the grain size and mechanical properties of aluminium alloy under dry sliding condition has been investigated. Aluminium alloy in the form of rods are selected to produce heat treated tensile test specimens. Compositions, morphologies and microstructures of worn surfaces are characterized by scanning electron microscopy (SEM) and energy dispersive spectroscopy analysis (EDS). Microstructure characterization revealed the modification in the size and shapes of the precipitates formed during the homogenization process. This modification increases the anisotropy of the microstructure and the stresses in the as cast structure. Also it is observed that increasing the aging hours facilitates the easy dissolution of Fe in the aluminium matrix. Apart from forming the precipitates of Fe with Al, Si, Cu and Mg in the matrix the alloy shows grain boundary segregation of Al-Fe-Si phases that strengthens the grain boundaries improving the mechanical properties in the plasticity range. Effect of forging and aging gives the best combination of mechanical properties. Increase in the hardness of aged and forge aged alloy is due to the partial recrystallization, fragmentation and redistribution of primary Mg_2Si phase, precipitation of fine θ, Q phases. The high volume fractions of uniformly dispersed hard β-particles greatly increase the flow stress and provide an appreciable impediment to plastic deformation. Thus, increasing the hardness of the alloy.

*Keywords:*Anisotropy, hardness, flow stress, plastic deformation,precipitates and friction coefficient.

1.0 Introduction

Aluminium alloyed with silicon (Si) is the material of tremendous industrial importance. The Al-Si alloys have a number of favorable characteristics including good wear resistance, low thermal expansion, ease of weld-ability, increase in the strength and stiffness without increasing the density. Various casting processes including high pressure die casting, permanent mold casting, sand casting exhibit excellent productivity, mechanical and physical properties in these alloys. The strength and quality of Al-Si alloy castings are determined by the appropriateness of their microstructure, viz., the fineness, size and morphologies of the micro-constituents present there-in, as well as the amount of porosity produced in the casting.

6000 series aluminium alloys are being used for applications in automotive industries for their light weight and strength. This strength comes mainly from their ability to age artificially. Copper is added to these aluminium alloys in different proportions which leads to the formation of different phases as well as precipitates with unique properties. In case of Al-Mg-Si alloys the hardening phases are β' and β" whereas in case of Al-Mg-Si-Cu alloys more number of hardening phases appear that makes the response to the artificial aging process more complex. Among all the phases present in these alloys 'Q' phase is an important one which forms as an equilibrium phase. In this paper the thermodynamic stability of the 'Q' phase is discussed against other coexisting phases. A metastable type of this phase has been reported to exist at the peak age temper that may be useful in understanding the overall precipitation hardening mechanism.

Research work has been carried out to ascertain the effects of T6 heat treatment on the Al-14Si-13Mg-5Fe-2.5Cu alloy and compare the results with properties of their as cast counterpart. Results from optical microstructure, SEM and EDX tests have been used to ascertained the improvements in artificially aged Al-14Si-13Mg-5Fe-2.5Cu alloy. SEM of as cast structure shows polygonal block like Mg_2Si intermetallic phase with sharp corners, sharp needle form of Fe phase and Chinese script like Al_2Cu precipitates randomly distributed in the aluminium matrix. Aged structure consists of spheroidized Mg_2Si intermetallic phase, blunted edge of Fe intermetallics and high volume of Al_2Cu phase. It is also observed that the precipitation of the intermetallics and their growth increases with increase in the homogenizing hours which leads to improvement in the mechanical properties and wear resistance. Cu, Mg and Fe lead to strengthening of the alloy through the solution and precipitation hardening. The type and the amount of added elements decide the strength developed. This improvement in the properties of hyper-eutectic aluminum alloys comes mainly from their ability to age artificially. Commercial aluminum alloys of Al-Mg-Si have ternary equilibrium phases such as θ, β and S. When Cu is added to Al, Q-phase is formed along with θ, β and S based phases. Control over the microstructure and the resulting improvements in mechanical and tribological properties of the aluminium alloys is possible by carrying out suitable heat treatment. Iron is usually considered deleterious and harmful for aluminium alloys restricting its additions to nearly 1.8% max especially in dies, used in forming the metals. However, in this work it is observed that up to 4% addition of Fe can lead to improvement in mechanical properties reducing the brittleness in as cast condition. Effect of T6 treatment on the mechanical properties of Al-14Si-13Mg-5Fe-2.5Cu alloy was evaluated by conducting mechanical tests on test pieces. Increase in the mechanical properties such as ultimate tensile strength, hardness and % elongation is observed.

2. Experimental details

For the mechanical properties study, commercial grade alloy is used as shown in Table 2.1. Samples of size 30mm lengths and 10mm diameter in the form of pins are used. Mechanical properties of these samples are investigated after the heat treatment process. These samples are covered with cast iron chips to avoid oxidation and subjected to heating above 840°C in a muffle furnace. After soaking for a period of 60 minutes, the samples are allowed to cool down in the furnace itself. Pins from sample are used for hardening process. These pin samples are heated again to 210°C, soaked for one hour for homogenization and cooled to room temperature.

2.1. Qualitative and quantitative analysis of the alloy

Al-14Si-13Mg-5Fe-2.5Cu alloy is procured in an rod form. Qualitative and quantitative analysis is carried out using spark emission spectrometer, Model QSN 750-II

Table 2.1 Chemical composition of the alloy (by wt.%)

Alloy	% Si	% Fe	% Cu	%Mg	%Al
Al-14Si-13Mg-5Fe-2.5Cu	13.68	5.01	2.61	13.2	Balance

2.2 Sample preparation

Ingots of the alloy are cut into small pieces and machined to required dimensions. Samples are prepared for metallographic examination by polishing, using polish papers of grade 4/0, 6/0, 8/0 and then wet polishing is carried out on polishing machine using wet alumina paste of sub-micron grade. Specimens are etched with Keller's reagent and analyzed under optical microscope interfaced with image analyzer.

2.3. Grain size determination

Grain size determination comes under quantitative microscopy.The estimation of grain size is vital for understanding number of properties of metals and alloys. In this study grain size has been determined using Heyn's intercept method in which the number of grain boundaries intercepting a straight line along the microstructure at a given magnification (M) is measured. Grain size will be the length of the intercept / (no. of intercepts x M). It is necessary to take readings in different directions and across different faces to get reliable average size of the grain. Grain size analysis is carried out on as cast, cast aged as well as forge aged samples as per ASTM-E112-13 standard. Results are summarised as follows

2.4 Brinell hardness test
Brinell hardness test is carried out on Brinell Hardness Tester with a ball indenter of 10mm diameter under the load of 5KN as per standard ASTM-E10-12.

2.5 Compression test
Compression test is carried out on UTM 60 T (Traceability: NABL Lab No: C-0199, Certificate no: UT/2016-2017-S/B-092 Date: 02/02/2017) as per the standard ASTM-E9.

2.6 Tensile test

2.6.1. As-cast and cast aged samples
Specimens for tensile test are machined as per ASTM 8E 602-78T standard. These specimen samples are cast aged for 1, 3, 5 and 7hr respectively. Uniaxial tension test is done on universal testing machine.

2.6.2. Forge aged samples
Tensile test samples in as-cast condition are forged at the temperature of 300^0C followed by aging.

3. Results and Discussions

3.1. Grain size determination

Table 3.1. Grain size determination test results

SN	Condition	No. of lines	Before compression			After hot compression		
			No. of intercepts	ASTM		No. of intercepts	ASTM	
				Grain size No.	Grain size mm		Grain size No.	Grain size mm
1	As cast	10	406	5.356	0.05	154	3.385	0.090
2	Aged 1hr	10	237	3.792	0.086	250	7.485	0.032
3	Aged 3hr	10	264	4.11	0.077	265	9.473	0.012
4	Aged 5hr	10	234	3.758	0.087	301	7.859	0.021
5	Aged 7hr	10	221	4.426	0.069	348	9.242	0.013
6	*FAg 1hr	10	242	3.982	0.079	256	8.856	0.018
7	FAg 3hr	10	253	4.320	0.059	276	9.156	0.015
8	FAg 5hr	10	286	4.632	0.0563	323	8.523	0.017
9	FAg 7hr	10	302	4.764	0.0531	366	9.230	0.014

*FAg is forge aged

Fig. 3.1 shows the bar chart of grain size measured before and after the test. It is observed that the grains have smaller size after the test compared to the grains before the test. As seen from Table 3.1 the grains appear to have fractured under the compressive load due to the brittleness and no elongation takes place because of lack of ductility. Under the peak cast aged condition precipitates are dispersed after they breakup and the distance between them appears to have grown [1, 2].

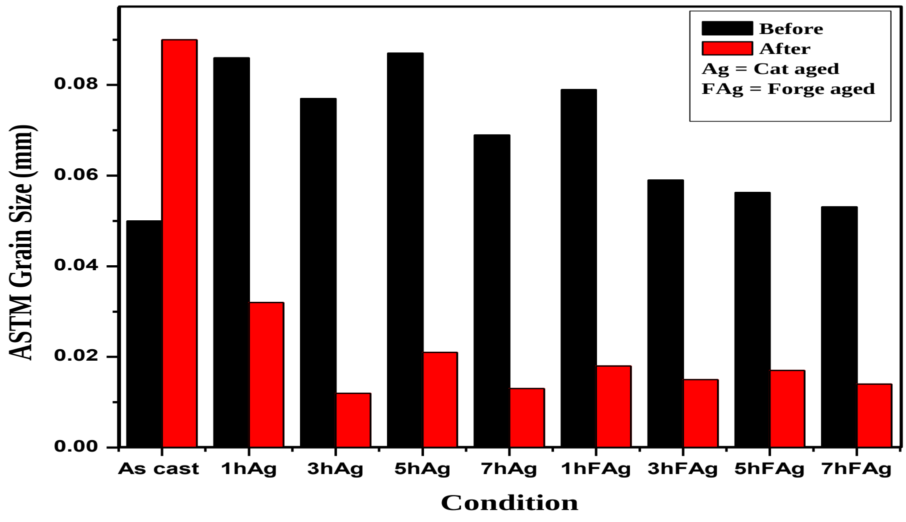

Fig. 3.1 Bar chart results of Grain size test

3.2 Brinell hardness test

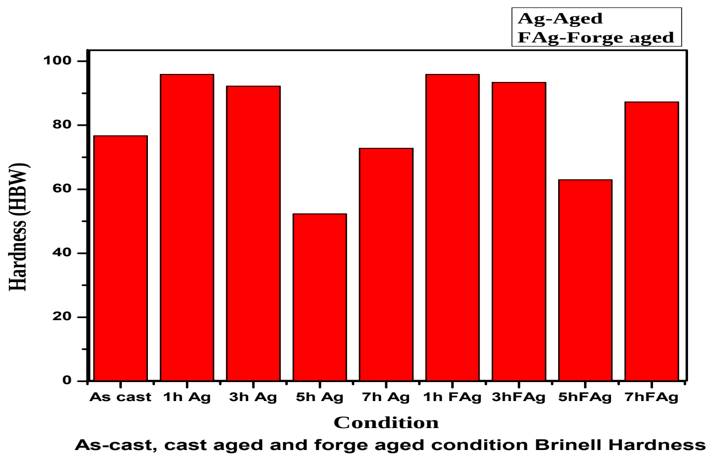

Fig. 3.2 Bar chart results of Brinell hardness test

As seen from Fig.3.2 and Table 3.2 results of hardness test show that hardness is maximum at 1hr cast aged condition. This hardness decreases for 3hr and deteriorates sharply for 5hr cast aged sample. It also means that with increasing aging hours grain coarsening takes place, also precipitates increase in size. Ultimately these precipitates break. All these events together lead to decrease in the mechanical properties which is prominently evident at 5hr cast aged condition showing the over aging effect.

Table 3.2 Brinell hardness test results

SN	Sample condition	Observations					Average
		1	2	3	4	5	
1	As cast	76.2	75.9	77.5	77.8	75.6	76.6
2	Cast aged 1hr	93.2	96.9	95.3	94.0	97.8	95.4
3	Cast aged 3hr	91.8	92.3	95.1	91.8	92.5	92.2
4	Cast aged 5hr	51.3	53.2	54.4	50.9	53.7	52.3
5	Cast aged 7hr	74.3	73.2	72.8	72.5	73	72.8
6	Forge aged1hr	96.2	97.1	95.8	95.3	96.5	96.3
7	Forge aged3hr	94.6	93.7	92.9	93.2	93.5	93.35
8	Forge aged5hr	63.2	64.1	62.7	62.04	63.8	62.92
9	Forge aged7hr	85.8	86.5	86.7	86.4	88.1	87.25

3.3 Microstructure results

As seen from Fig.3.3 as-cast structures have complex intermetallic phases. These phases are formed due to the addition of Cu and Fe and they offer resistance to plastic deformation. With increase in the applied normal load they fracture easily [3]. As the aging hour increases there is decrease in mechanical properties as seen for 5hr aging sample results. However, the properties increase for 7hr cast aged samples which is due to the uniform distribution of hard β-particles that increase the flow stress. Also the amount of Mg_2Si, fine θ, Q-phases increases. This will resist the dislocation movement [4, 5, 6].

It is also observed that coarse Fe rich needles dissolve in the Al matrix leading to increase in the mechanical properties [7]. As the aging time increases small sized precipitates of meta stable β-Mg_2Si and θ-Al_2Cu phases form in large numbers having increased coherency with respect to the α-Al matrix. This reduces the stresses at the interface and the tendency to form the crack, increasing the strength and the hardness [4, 8-10]. With further increase in the aging time coherency of the precipitates with the matrix decreases. This happens due to the coming together of the finer precipitates forming clusters that grow into coarser precipitates that decreases the surface energy. Dislocations find it easier to pass through the passages between the coarser precipitates. Thus, it further decreases the shear stress and the hardness [3, 10-12].

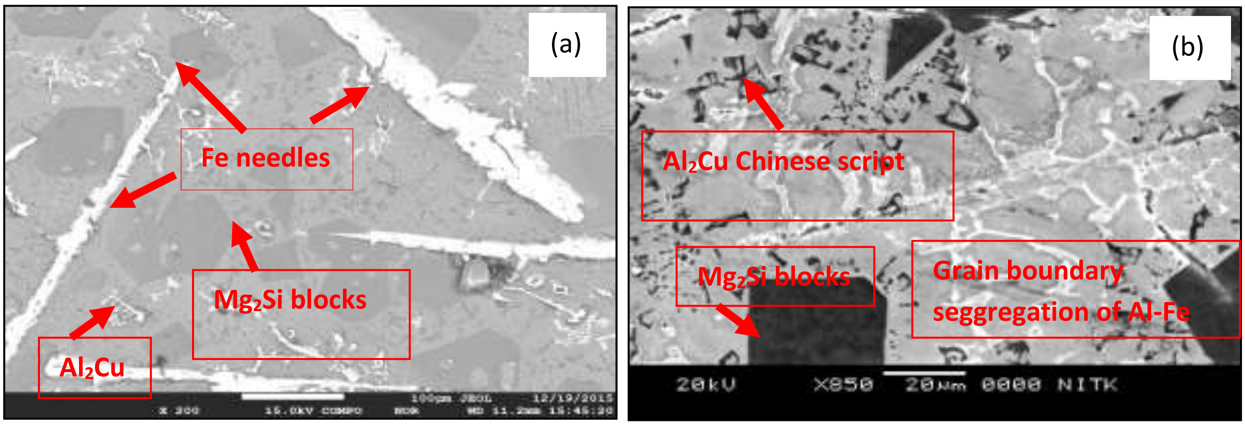

Fig. 3.3 SEM image for as cast alloy (a) 850X and (b) 330X

3.4. Compression test

As seen from Fig. 3.4 and Fig. 3.5 and Table 3.3 it is observed that both hardness and compression strength of 1 and 3hr cast aged as well as forge aged samples show high value indicating higher flow stress.

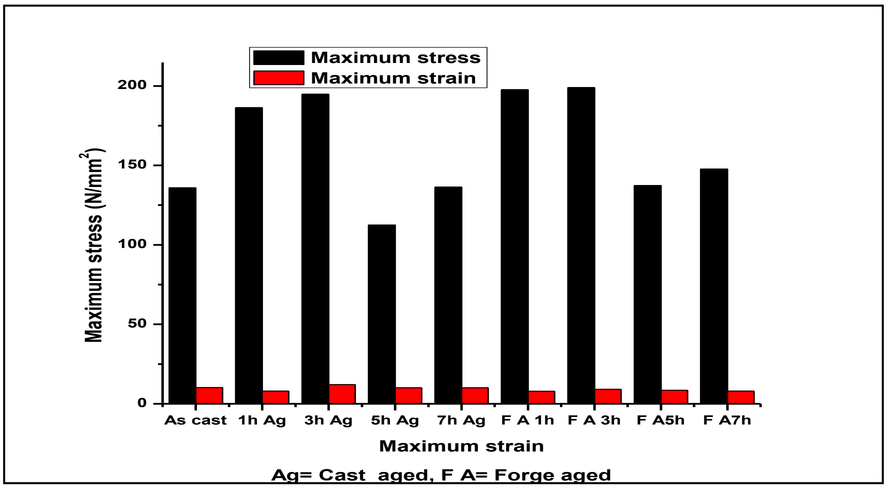

Figure 3.4 Bar chart results of compression test

This is mainly due to the effect of aging and rounding off of the sharp corners in case of Mg_2Si blocks and formation of precipitates in large numbers. More obstacles are created for the movement of dislocations which strengthens the matrix. In case of 5hr aged and forge aged samples both hardness and compressive strength are poor. This may be due to the grain coarsening, and dispersion of the precipitates over a longer distance that weakens the matrix, lowers the hardness and the flow stress.

Table 3.3 Compression test results

SN	Sample condition	Parameter		
		Maximum stress N/mm^2	Maximum Strain	Strain at Fm
1	As cast	135.93	10.16	9.68
2	Cast aged 1hr	186.24	8.04	9.96
3	Cast aged 3hr	194.74	12.08	10.12
4	Cast aged 5hr	112.46	10.04	8.8
5	Cast aged 7hr	136.36	10.04	9.4
6	Forge aged1hr	197.66	7.92	9.56
7	Forge aged3hr	198.91	9.12	9.2
8	Forge aged5hr	137.40	8.48	9.6
9	Forge aged7hr	147.69	8.04	8.92

3.5 Tensile test

3.5.1. As-cast and cast aged samples

Uniaxial tension test results are recorded as shown in Table 3.4. Mechanical properties in aluminium alloys improve due to the formation of precipitates which are intermetallic in nature. These precipitates create obstruction for the movement of dislocations when they try to overcome them. Dislocations pile up and increase the stress level in the matrix, which increases the tensile strength and the overall hardness of the alloy.

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Table 3.4 Tensile test results for as cast and aged alloy

Condition	Properties			
	Y.S. N/mm^2	U.T.S N/mm^2	% Elongation	% Area reduction
As cast	19.175	53.624	0.12	0.943
Aged 1hr	19.363	78.945	0.399	0.961
Aged 3hr	32.779	56.331	0.439	0.637
Aged 5hr	30.303	50.423	0.16	0.795
Aged 7hr	37.58	62.233	0.04	1.105

3.5.2. Forge aged samples

Tensile test samples in as-cast condition are forged at the temperature of 300^0C followed by aging. Forge aging operation helps in increasing the yield strength of the material hence, an overall improvement in the mechanical properties of the Al-14Si-13Mg-5Fe-2.5Cu alloy is observed as seen from Table 3.5. The forge aged microstructures have more uniform distribution of the Mg_2Si blocks and other precipitates in comparison to as-cast and cast aged microstructures. In this case the microstructures of the hot-forged materials posses reduced size of Fe needles, Mg_2Si blocks and other phases, indicating that particle coarsening has occurred to a certain extent. It is noticeable that after forging, some particles exhibit interfacial debonding and cracking, while almost no cracking damage can be seen in the as-cast materials. In the forge aged microstructures the reinforcing phases and Fe needles are more homogeneously distributed in comparison to the as-cast specimens. All these changes in structure which occur with the application of forging and aging are to increase the mechanical properties of the samples as seen from Fig. 3.5 Microstructural refinements, particularly break down of Fe needles seems to be asserting the major influence in improving the properties on aging. The increase in the hardness of forge aged alloy is due to the partial recrystallization, fragmentation and redistribution of primary Mg_2Si phase. Precipitation of fine θ, Q-phases and reduced porosity due to hot pressing, leads to the improvements in mechanical properties and hardness values in forge aged Al-14Si-13Mg-5Fe-2.5Cu alloy [13-14].

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Table 3.5 Tensile test results for forge aged alloy

Condition	Properties			
	Y.S. N/mm^2	U.T.S N/mm^2	% Elongation	% Area reduction
Forge aged1hr	18.235	62.341	0.287	0.894
Forge aged3hr	30.535	49.231	0.372	0.901
Forge aged5hr	26.103	42.19	0.29	0.82
Forge aged7hr	34.287	53.338	0.32	0.862

Forge aging of Al-14Si-13Mg-5Fe-2.5Cu alloy becomes more important in view of the developments in the aviation and transportation industries. It is observed that forge aging changes the microstructure of unrefined grains of as-cast alloys and brings out the improvement in the mechanical properties in grain refined alloys. Forged and cast aged samples show yield stress and ultimate tensile stress values on par with the cast aged samples.

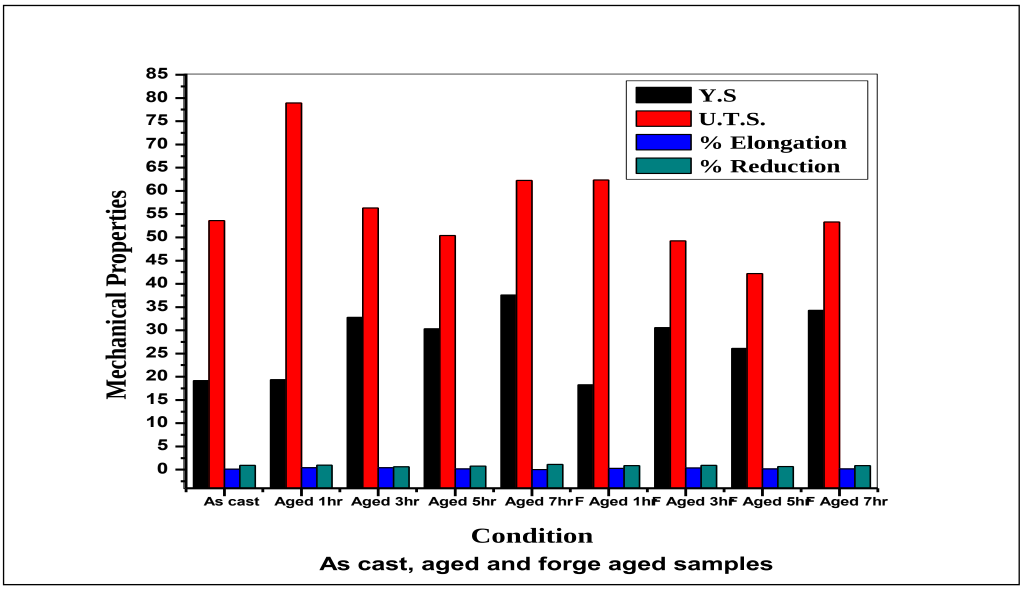

Fig.3.5 Bar chart results of tensile test for as cast, aged and forge aged samples

Forge and cast aged samples show improved mechanical properties mainly due to the effect of recrystallization. Further increase in aging time for forge aged samples leads to grain growth and reduction in mechanical properties. Thus, the fabrication of parts by the forging process is capable of producing products with good mechanical properties. As seen from Table 3.5 ultimate tensile strength value is maximum at 62.341 KN/mm^2 for 1hr forge aged sample. UTS value decreases to 49.231 KN/mm^2 for 3hr cast aged sample. Bar chart results in Figure 3.5 show an increase in the yield stress values. Tensile strength values are maximum for 1hr aging which decreases slightly with increase in the aging time. It is also observed that tensile strength and the yield strength are optimum for 3 and 7hr cast aged samples. However, in case of 5hr cast aged samples tensile strength and the yield strength values deteriorate. This may be due to the grain coarsening and dispersion of precipitates decreasing the flow stress and the hardness. These precipitates transform into metastable phases such as β' and β'' that reduce the tensile strength as seen from the Table 3.5 [15].

4. Conclusions

Study of the results reveal that grains are coarse in as cast and aged condition. Whereas in forge aged condition grains are smaller due to fragmentation as well as refinement because of recrystallization. This increases the mechanical properties of the forge aged alloy than as cast and cast aged alloy.

a. **Forge aged properties -** Hot pressing of the as cast test samples promotes the microstructural refinement, reduction in porosity, fragmentation and redistribution of secondary phases. Microscopic study of the alloy before and after hot pressing shows that only the relatively large Mg_2Si particles and Fe needles suffer obvious fracture. Small Mg_2Si particles in the alloy essentially retain their size and shape after hot pressing.

b. **Hardness -** As cast alloy shows more hardness. The hardness of both the aged, forge aged alloy increases with increasing Mg_2Si content. This increase can be interpreted as an indication that the hardness of alloy is a function of Mg_2Si content in the alloy. The hardness of the aged alloy is approximately 60% higher than that of as-cast alloy.

c. **Compressive strength -** As cast sample shows poor compressive strength. Forge aged samples show better compressive strength than the as cast and aged samples. Due to the refined grains and uniform distribution of broken Mg_2Si blocks as well as the Fe needles. Forge aged sample shows more flow stress.

d. **Tensile strength -** The tensile properties of aged alloy shows higher strength and low ductility over that of the as-cast alloy. Increasing Mg_2Si content in both the 1hr aged and the forged 1hr aged alloy increases Ultimate Tensile Strength.

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