

Effect of thermal exposure on mechanical properties hypo eutectic aerospace grade aluminium-silicon alloy

Nagesh Kumar R^{a*}, T Ram Prabhu^b and C Siddaraju^c

^aDepartment of Mechanical Engineering, EPCET, Bangalore, India

^bCEMILAC, Defence R&D Organization, Bangalore, India

^cDepartment of Mechanical Engineering, MSRIT, Bangalore, India

Email ID: nagi10cmy@gmail.com, nageshkumarr19@gmail.com

Abstract. The effect of thermal exposure on the mechanical properties of a C355.0 aerospace grade aluminum-silicon alloy (5% Si – 1.2% Cu – 0.5% Mg) was investigated in the present study. The alloy specimens were subjected to T6 (solution treatment and artificial ageing treatment) temper treatment to enhance the strength properties through precipitation hardening. The T6 temper treatment involved solution heat treatment at 520°C for 6 h, followed by water quenching and ageing at 150°C. After the heat treatment, the specimens were exposed to various temperatures (50°C, 100°C, 150°C, 200°C and 250°C) for 5 and 10 h to study the structural applications of this alloy to the various Mach number military aircrafts. After the thermal exposure, specimens were tested for tensile, hardness and impact properties (Charpy). The microstructure of the thermal exposed specimens was examined in the optical microscopes and correlated with the mechanical properties results. In summary, an increase of exposure time has a different effect on the tensile and hardness properties of the alloy. For the exposure time 5h, the tensile and hardness properties increase upto 100°C and later decrease with an increase of temperature. In contrast, the tensile and hardness properties linearly decrease with an increase of temperature. Several factors such as matrix grain growth, diffusion rate, Si particles size and distribution, precipitate stability play a key role on deciding the tensile properties of the alloy. Comparing the relative effects of temperature and time, the temperature effects dominate more in deteriorating tensile properties of the alloy. There are no effects of exposure temperature and/or time on the impact properties of the alloy.

Keywords: Al-Si alloy, Mechanical properties, Impact properties, Microstructure, Heat treatment.

1. Introduction

In the present era, every nation wants to have an advanced aircrafts flying at supersonic speed to improve the countries defense mightiness and our country is not exclusion to it. Presently, Al alloys are major structural alloys in the military aircrafts because of the superior strength to weight ratio, corrosion resistance, matured processing technology, less maintenance cost [1, 2]. These alloys have the capability to sustain the heat generated in the subsonic and sonic speed. The application of this to the supersonic speed aircrafts has not been studied yet. At a Mach number of more than 2, it is expected that the aircraft structures are exposed to the temperature in the range of 200-250°C due to the drag (air resistance). Thus, the study of thermal exposure effects on the Al alloys is inevitable. One of the prominent cast Al alloy used in aerospace applications such as gear box housing, cylinder blocks and structural assemblies [3,4,5] is C355.0 aerospace grade aluminum-silicon alloy (5% Si – 1.2% Cu – 0.5% Mg). This alloy has excellent castability, superior corrosion resistance, and high specific strength and specific stiffness properties [5, 6]. The property of this alloy is well established at room temperature and used in the applications where the temperature does not cross over 100°C. This alloy has mainly two constituents in the hypo eutectic compositions: Al matrix and primary Si particles. The size and morphology of Si particles decides the tensile properties, fracture characteristics of the alloy [3, 8-10]. The alloy is refined with Na or Sr to distribute Si particles as fine as possible. This alloy is also amenable to precipitation hardening treatment. The formation of precipitates in the Al matrix improves the strength of the alloy by acting as an effective



obstacle for dislocation motion. Depending on the size and distribution of the precipitates, the dislocation motion is hampered by dislocation by-pass or shearing the precipitates mechanisms. Thus, the strength of the alloy is enhanced. In light of the above facts, the mechanical properties of this alloy are studied for various exposure temperature and time.

2. Material and Methods

The material used for the present work was C355.0 aerospace grade aluminium – silicon alloy. The main alloying elements were determined by spectrographic method in accordance with ASTM E34 standard. The results are given in Table 1. The specimens were given the following T6 heat treatment to improve the strength properties through precipitation hardening.

- Solution treatment – 520° C for 6 h
- Quenching – Immersion in cold water maintained at 25-30°C
- Artificial ageing - 150° C for 1 h, followed by normal air cooling

The heat treated specimens were given various thermal exposure temperatures (50°C, 100°C, 150°C, 200°C and 250°C) in a electric furnace (capacity: 1550°C). Two exposure times (5 h and 10 h) were selected for each temperature condition. Tensile tests were performed in a TUE-C-1000 universal tensile testing machine at room temperature. The schematics of tensile and impact test specimens with dimensions are shown in Fig 1. The tensile test was carried out according to the ASTM E8 specification. The gauge diameter and length of the specimen were 9 mm and 30 mm respectively. The Charpy test was carried out according to the ASTM E23 specification. The impact test specimen has a length of 55 mm length and a notch radius of 2 mm.

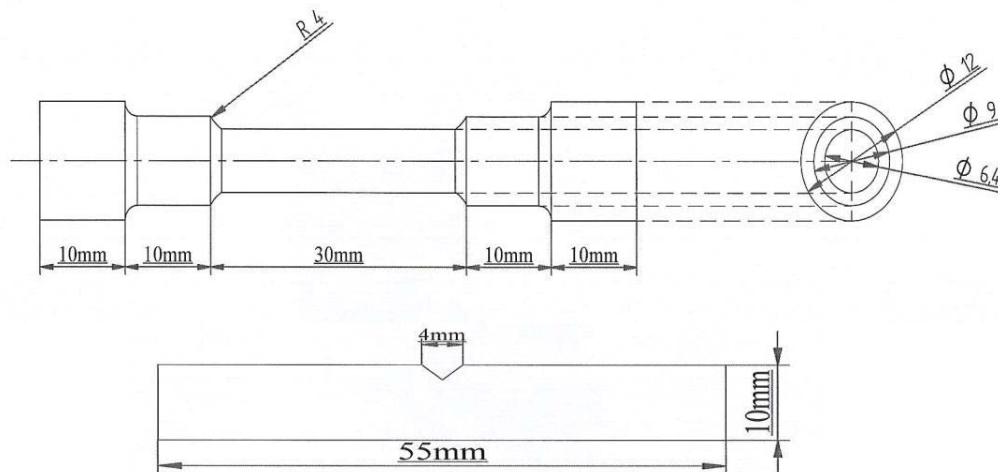


Figure 1. Geometry and dimensions of the tensile & impact specimens

Table 1. Chemical Composition of C355.0 alloy, %wt

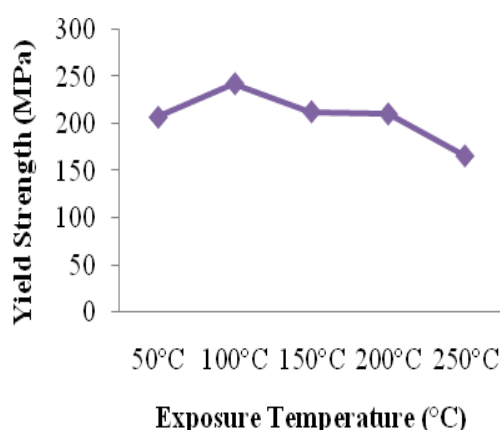
Si	Cu	Mg	Fe	Ti	Mn	Zn	Others	Al
5	1.2	0.5	0.2	0.2	0.1	0.1	0.15	Bal

Hardness test was conducted on Vickers hardness scale and the load used was 50 kgf. Minimum five hardness readings were taken and averaged to report hardness. The samples for microstructure were polished in SiC abrasive emery papers of various grit sizes and followed by diamond paste applied cloth polishing. The polished samples were etched in a Keller's etchant solution (distilled water (190 ml) + nitric acid (5 ml) + hydrochloric acid (3 ml) + hydrofluoric acid (2 ml)) to reveal the microstructure. The microstructure of the thermal exposed samples was characterized in an optical microscope (NIKON Epiphot 200).

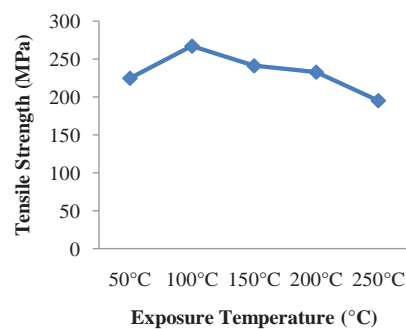
3. Results and Discussion

The relation between tensile properties at different thermal exposing temperatures (50°C, 100°C, 150°C, 200°C and 250°C) for 5 h is shown Fig 2(a, b & c). For the case of thermal exposure time of 5 h, the yield and tensile strength slightly increase upto 100°C and then decrease with the increase of temperature. The rate of decrease is large at the temperature between 100-200°C. The maximum yield and tensile strength recorded for 100°C are 242 MPa and 267 MPa. The hardness results for the 5 h exposure time correspond well with the tensile properties, as seen from Table 2. The optical micrographs of thermal exposed C355 aluminium alloy at 5 h are shown in Fig 3 (a,b,c,d & e). The distribution of primary Si particles and precipitates decides the strength. For the case of 50°C, 150-250°C thermal exposure conditions, the Si particles are distributed mostly along the grain boundaries. Close alignment of particles along the grain boundaries serve as a stress concentration site for crack initiation during tensile loading conditions. Any crack forms on the particles easily propagates along the grain boundaries resulting in intergranular fracture. Further, the size of the Si particles is relatively thicker above 150°C due to increase of diffusion rate of Si with the increase of temperature. Thick particles crack easily under the tensile load. Thus, the strength of the alloy degrades with the increase of temperature above 150°C. Above 150°C, the strength giving precipitates ripen by overageing process resulting the loss of strength. The increase of temperature upto 100°C is beneficial in the case of 5h exposure time. At this temperature, the diffusion rate is optimal to redistribute the Si particles and avoids the thickening or clustering at the grain boundaries which otherwise degrades the properties by stress localization. Further, the precipitates are also stable at 100°C and do not grow at 100°C because the ageing temperature is higher than 100°C. Another important fact is to note that the increase of exposure time and/or time accelerates the Al matrix growth resulting in loss of strength. The increase of temperature tries to minimize the energy of the system by reducing the grain boundaries. The grain boundaries are eliminated by temperature along with time activated diffusion. The increase of temperature promotes the atom transport to grain boundaries and removes the curvature by changing the atomic structure from amorphous to regular. Thus, the grain grows with the increase of temperature and/or time. Below the equicohesive temperature, the grain boundaries are stronger than the grains. As all the selected temperatures are below the equicohesive temperature of C 355 Al alloy, the loss of grain boundaries leads to loss of strength properties according to Hall-Petch equation. The Hall-Petch equation relates the strength/hardness inversely with the grain size. Thus, the strength decreases with the increase of grain size. All these factors (optimum diffusion rate, proper distribution of Si particles, Al matrix grain growth and stability of the precipitates) contribute to the increase of strength properties upto 100°C. The rate of decrease of hardness properties are higher in the temperature between 100-200°C. Interestingly, the impact energy does not change significantly with the exposure temperature for 5h exposure time, as seen in Table 2. This result implies that the size and distribution nature of Si particles and precipitates do not affect the impact energy absorbed by the alloy as the test was carried out at very high strain rate, in other words, at a short time. As the Al alloys have face centered cubic crystal structure, the sensitivity of the structure to the impact loading is very less. Thus, the alloy is not susceptible to catastrophic fracture.

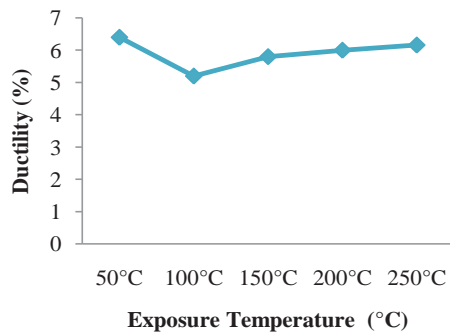
The relation between tensile properties at different thermal exposing temperatures (50°C, 100°C, 150°C, 200°C and 250°C) for 10 h is shown Fig 2 (d, e & f). For the case of thermal exposure time of 10 h, the yield and tensile strength decrease with an increase of temperature. The rate of decrease of the tensile/hardness properties is high from upto 150°C and then gradual with the increase of temperature. The maximum yield and tensile strength are 222 MPa & 237 MPa recorded at 50°C. The hardness results for the 10 h exposure time correspond well with the tensile properties, as seen from Table 2. The optical micrographs of thermal exposed C355 aluminium alloy at 10 h are shown in Fig 4 (a,b,c,d & e). With an increase of exposure time, the diffusion of Si particles increases resulting in shifting of the optimal microstructure to the 50°C. Further, longer exposure time accelerates the growth process of precipitates formed from ageing treatment. As can be seen from Fig 4a & b, the nature of distribution of hard Si particles has a complete change compared to the micrographs of exposure time 5 h at the same temperature. The Si particle segregation along the grain boundaries is significant at and above 100°C. Although the ageing temperature is higher than 100°C, the unduly longer exposure time accelerates the diffusion and provides the malefic effects on the microstructure. Particularly, the size of the Si particles increases with the increase of temperature. The increase of the particle size deteriorates the strength of the alloy by acting as a potential site for defect (crack) formations. Another important fact is to note that the increase of exposure time accelerates the Al matrix growth resulting in coarse grain microstructure, as seen in Fig 4c. The increase of grain size reduces the strength according to the Hall-Petch relation which was already explained in the earlier paragraph. In addition, the reduction of ductility with the increase of temperature, as seen in Fig 4d, supports the malefic effects of Si particle size and distribution and coarse grain size of matrix. The combined effects of time and temperature can be seen in the 250°C and 10 h exposed sample tensile test results, as in Fig 4e. Interestingly, for the case of 10 h exposure time, the impact energy does not change significantly which is similar to the results of the 5h exposure time, as seen in Table 2. This result once again corroborates the implication of insignificant role of the size and distribution nature of Si particles and precipitates in deciding the impact energy absorbed by the alloy. Comparison of relative effects of exposure time and temperature, the exposure temperature has relatively higher effects than the exposure time. It indicates that the rate of diffusion gets accelerated relatively faster by the exposure temperature than the time.



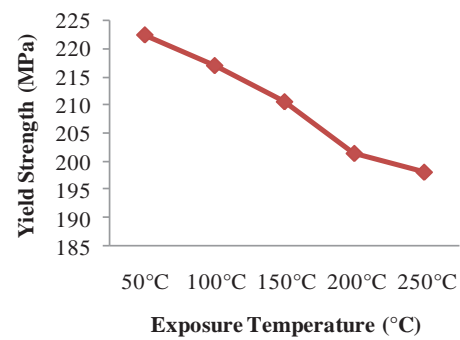
(a)



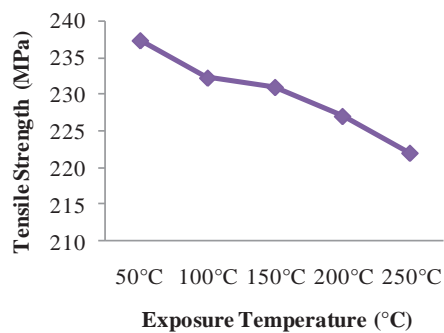
(b)



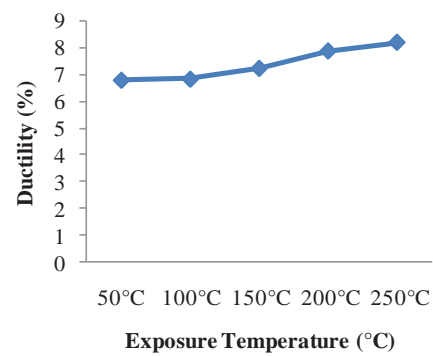
(c)



(d)



(e)

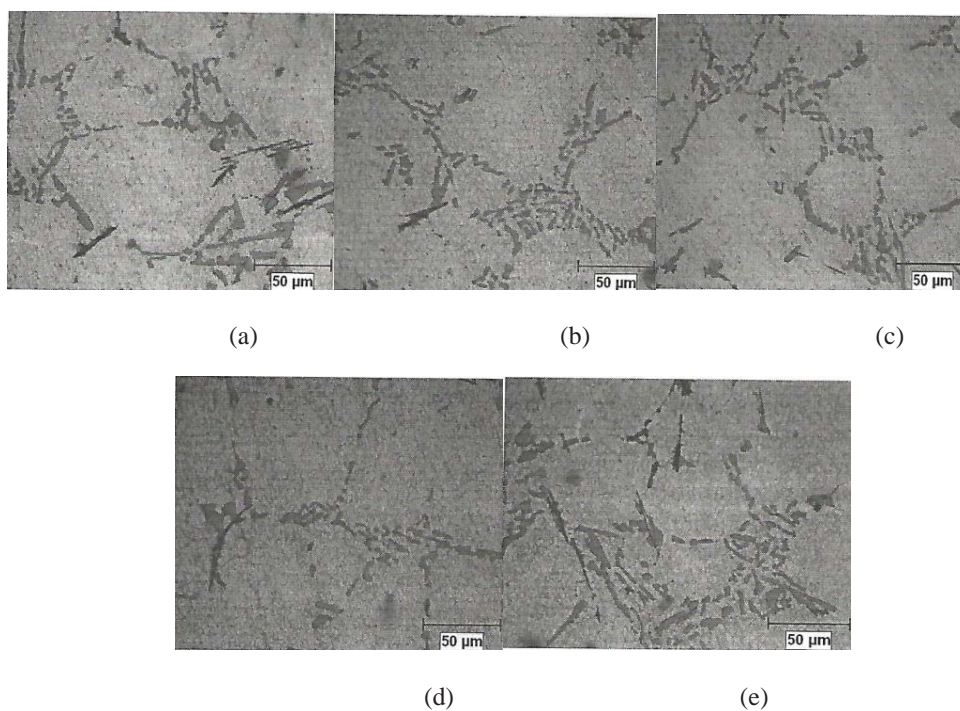


(f)

Figure 2. Graphical plot of (a) Yield strength Vs exposure temp, (b) Tensile strength Vs exposure temp, (c) Ductility Vs exposure temp for 5 h and (d) Yield strength Vs exposure temp, (e) Tensile strength Vs exposure temp, (f) Ductility Vs exposure temp for 10 h.

Table 2. Effects of thermal exposure on impact and hardness properties

Exposure temperature °C	Exposure time, h	Impact Energy (J/cm ²)	Hardness (VHN)	% loss of hardness with respect to 50°C
50	5	20	154	-
	10	20	151	-
100	5	20	167	8.4
	10	20	146	3
150	5	18	137	11
	10	20	134	11.3
200	5	20	130	15.6
	10	19	128	15.2
250	5	20	127	17.5
	10	19	121	19.9

**Figure 3.** Optical micrographs of C355.0 aluminium alloy when it thermally exposed (a) 50⁰ C, (b) 100⁰ C, (c) 150⁰ C, (d) 200⁰ C & (e) 250⁰ C for 5 h

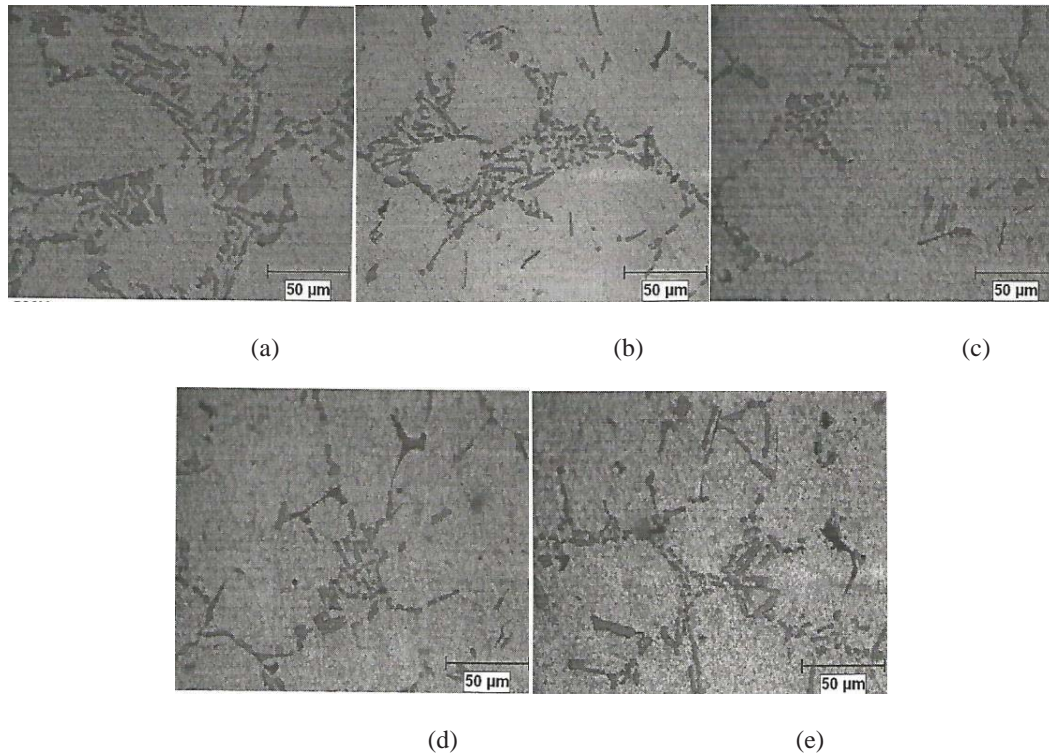


Figure 4. Optical micrographs of C355.0 aluminium alloy when it thermally exposed to (a) 50⁰ C, (b) 100⁰ C, (c) 150⁰ C, (d) 200⁰ C & (e) 250⁰ C for 10 h

4. Conclusions

The present study was focused on the effect of thermal exposure on mechanical properties hypo eutectic aerospace grade aluminium-silicon alloy (C 355). An increase of exposure time has a different effect on the tensile and hardness properties of the alloy. For the exposure time 5h, the tensile and hardness properties increase upto 100°C and later decrease with an increase of temperature. In contrast, the tensile and hardness properties linearly decrease with an increase of temperature. Several factors such as matrix grain growth, diffusion rate, Si particles size and distribution, precipitate stability play a key role on deciding the tensile properties of the alloy. In contrast, the impact properties are insensitive to the exposure temperature and/or time. This is due to the matrix crystal structure effects. Comparing the relative effects of temperature and time, the temperature effects dominate more in deteriorating the properties of the alloy.

5. References

- [1] Ram prabhu T 2015 *Acta Metallurgica Sinica* **28(7)** pp 909-921
- [2] Ram prabhu T 2016 *Archives of Civil and Mechanical Engineering* (In Press, DOI: 10.1016/j.acme.2016.01.003: Elsevier Publication)
- [3] Jabra J et al 2006 *JMEPEG* **15** pp 601-607
- [4] Nikolaos D et al 2011 *Material Science & Engineering A* **528** pp 6303-6312

- [5] Avinash L et al 2016 *Applied Mechanics and Materials* **829** (Trans Tech Publications Ltd: Switzerland) pp 83-89
- [6] Avinash L et al 2016 *Applied Mechanics and Materials* **829** (Trans Tech Publications Ltd, Switzerland) pp 66-72
- [7] Tiryakio glu M 2006 *Materials Science and Engineering A* **427** pp 154-159
- [8] Lloyd D J 1991 *Acta Metallurgica et Materialia* **39(1)** pp 59-71
- [9] Poole W J and Dowdle E J 1998 *Scripta Materialia* **39(9)** pp 1281-1287
- [10] Lloyd D J et al 1995 *TMS* (Warrendale) pp 39–48