Deformation behaviour of A356, Al-11Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe alloys forged under different processing conditions

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Abstract: The present paper aims to investigate the feasibility of bulk processing of Al-Si alloys under different processing temperatures. Three different compositions of Al-Si alloys (namely A356, Al-11Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe) have been forged between flat die platen at 300 and 500ºC processing temperatures. High-speed forging was performed with the help of power hammer. The results obtained are discussed critically to illustrate the interaction of various processing parameters associated with the processing of the alloys. The results reveal severe crack generation on the outer periphery of forged billets, while it reduced with low amount of silicon in the alloy. During processing, microstructural refinement and improvement in the mechanical properties were observed. The present work provides valuable insight into producing complex formed products of Al-Si alloys for extensive industrial applications.

Keywords: A356 alloy; Al-11Si-2.5Cu-0.6Fe alloy; Al-18Si-2.5Cu-0.6Fe alloy; deformation behaviour; forging; processing temperature.

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1 Introduction

The stringent requirements of automotive and aerospace industries have prompted the design of newer materials with high strength to weight ratio, low coefficient of thermal expansion and high wear and corrosion resistance. Because various automotive components are subjected to severe wear under the close contact situations. It reduces the power transmission, working efficiency, and catastrophic failure of the components. Therefore, numerous efforts have been made to produce materials with excellent wear resistance characteristics. These efforts comprise the variety of alloying elements, different production techniques, and surface treatment. Aluminium-silicon alloys are such material which possesses high strength-low weight, good castability, low density and excellent tribological properties. So, it has successfully used in making different automotive components and aerospace engine parts (Wang et al., 2016; Lu and Zhang, 2017; Yang et al., 2018). Al-Si alloys have attracted the attention of many researchers due to its industrial significance.

The hard silicon particles dispersed in the soft aluminium matrix, which enhanced the tribo-mechanical performance of the alloy. It can be increased with increase in silicon content in the alloy; therefore the alloys with higher silicon weight (hypereutectic) could be technological interest to the researchers. However, the conventional casting of Al-Si alloy produces a microstructure with needle-shaped eutectic silicon phase along with coarse primary silicon (in hypereutectic alloy) or Al dendrites (in hypoeutectic alloy). This characteristics adversely affect the tribo-mechanical properties (Kaya and Aker, 2017).

Therefore, numerous investigations have been performed to alteration of these microstructures by using different modifiers and/or refiners or various heat treatment techniques (Jigajinni et al., 2013; Shivaprasad et al., 2015). But, the components produced through this technique have insufficient strength and required long heat treatment cycles. Secondary alloying elements such as Cu, Fe, Mg, Zn, etc. in the composition play an important role in determining the tribo-mechanical properties. Copper improves tensile strength and corrosion resistance, whereas iron strengthens the material by modifying the silicon phase by forming intermetallic phases (Al-Fe-Si) (Zheng et al., 2015; Yang et al., 2015).

Processing of Al-Si alloy through bulk metal forming techniques such as forging (Murali and Yong, 2010; Cai et al., 2015), extrusion (Ke et al., 2010; Liang et al., 2016), rolling (Umezawa and Nagai, 1999), etc. is a convenient way to produced sound products with excellent mechanical properties. Bulk processing improves the tribo-mechanical performance of the alloy by changing the coarse microstructural features to refined particles. However, bulk processing of alloy is very difficult due to the presence of hard silicon particles as it reduces the ductility of the alloy and often produces surface cracks on the products (Kang et al., 1999). Therefore, the parameters such as amount of alloying elements, processing temperature, deformation speed, etc. play an important role in bulk-forming of Al-Si alloys.

In the present work, A356, Al-11Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe alloys have been selected to examine the feasibility of bulk processing. The solid cylindrical billets were deformed between flat die platen at different elevated temperatures. The obtained results were critically illustrated to study the interaction of processing parameters. In addition, present study provides valuable insight into understanding the bulk processing of the Al-Si alloy and thus helpful in developing intricate formed components with excellent tribo-mechanical properties.

2 Experimental procedure

To study the deformation behaviour of the Al-Si alloys during forging, the following experimental work has been performed.

2.1 Materials and methods

The casting of alloys were done with the help of electric muffle furnace. The different composition of Al-Si alloy was produced, by melting of high purity aluminium along with different weight% of silicon and copper at 730ºC in a furnace. The molten metal at 700ºC was poured into a preheated copper mould (~200ºC), and allowed to solidify at room temperature. After cooling, the cast ingots were removed from the mould and prepare to make cast billets. An atomic emission spectrometer (FOUNDRY MASTER, S/N 01J0054) was used to analyse the chemical composition of the cast alloys and is shown in Table 1. The phases present in the cast alloys were identified using X-ray diffraction (XRD) analysis (Rigaku X-ray diffractometer).

Table 1 Chemical composition of the as-cast alloys

Elements (*Wt.%*)	*A356 alloy*	*Al-11Si-2.5Cu-0.6Fe alloy*	*Al-18Si-2.5Cu-0.6Fe alloy*
Si	7.40	11.0	18.0
Cu	2.50	2.50	2.50
Fe	0.70	0.62	0.60
Mg	0.05	0.04	0.60
Zn	0.14	0.05	0.30
Mn	0.12	0.02	0.02
Cr	0.04	0.02	0.03
Al	Balanced	Balanced	Balanced
Designation	Alloy A	Alloy B	Alloy C

The cylindrical shaped test samples were machined from cast ingots having dimensions 40 × 40 mm. The test samples were heated to corresponding processing temperature in a furnace (approximately one hour) for chemical homogenisation prior to forging. The test samples were forged at 300ºC and 500ºC processing temperatures, and the solid graphite powder was used as lubricant. The high speed forging was performed between flat top and bottom die platens using pneumatic power hammer. All the test samples were forged up to 200 kN load at a strain rate of 20 s^{-1}.

2.2 Microstructural characterisations and hardness test

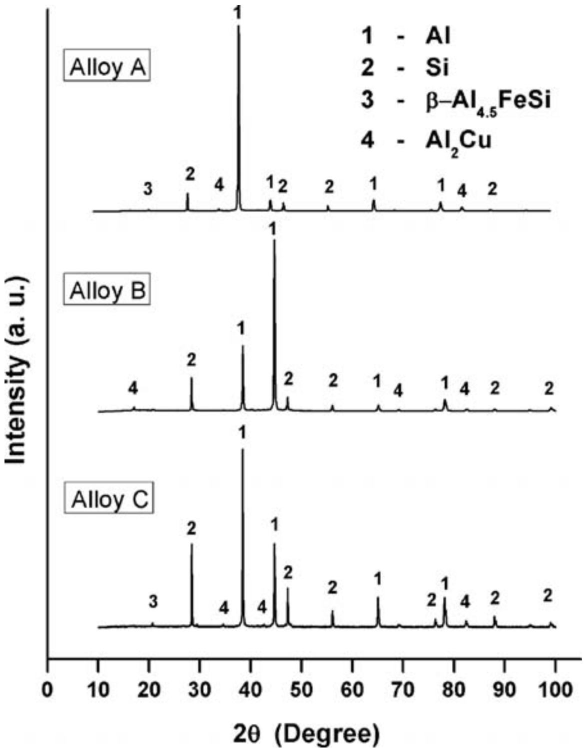
For purpose of characterisation, samples were cut from the forged billets, and prepared for microstructural studies and hardness test using standard metallography technique. Keller's reagent was used as an etchant. These investigations were conducted in a centre position of the test samples. The optical microscopy (ZEISS) was used for microstructural examinations. Hardness test of forged sample were conducted on a semi-automatic Vickers Microhardness Tester with 100 g indentation load and 10 sec. dwell time.

3 Results and discussions

3.1 Microstructural features of as-cast alloys

Figure 1 shows the XRD spectrum of as-cast A356, Al-11Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe alloys, phases of which were identified by International Centre for Diffraction Data (ICDD) PDF database. The results reveal that the diffraction patterns consist of high intensity peaks of aluminium, and silicon in all the three alloys. However, several low intensity peaks of intermetallic compounds Al_2Cu and β-$Al_{4.5}FeSi$ have been also observed in the XRD pattern of as-cast alloy. The formation of such intermetallic compounds during solidification was due to the presence of silicon, copper, and iron in the alloy. Therefore, the intermetallic compound may be either rich in silicon or copper or iron coexisting in the Al matrix.

Figure 1 XRD spectrum of the as-cast alloys, (a) alloy A (b) alloy B and (c) alloy C



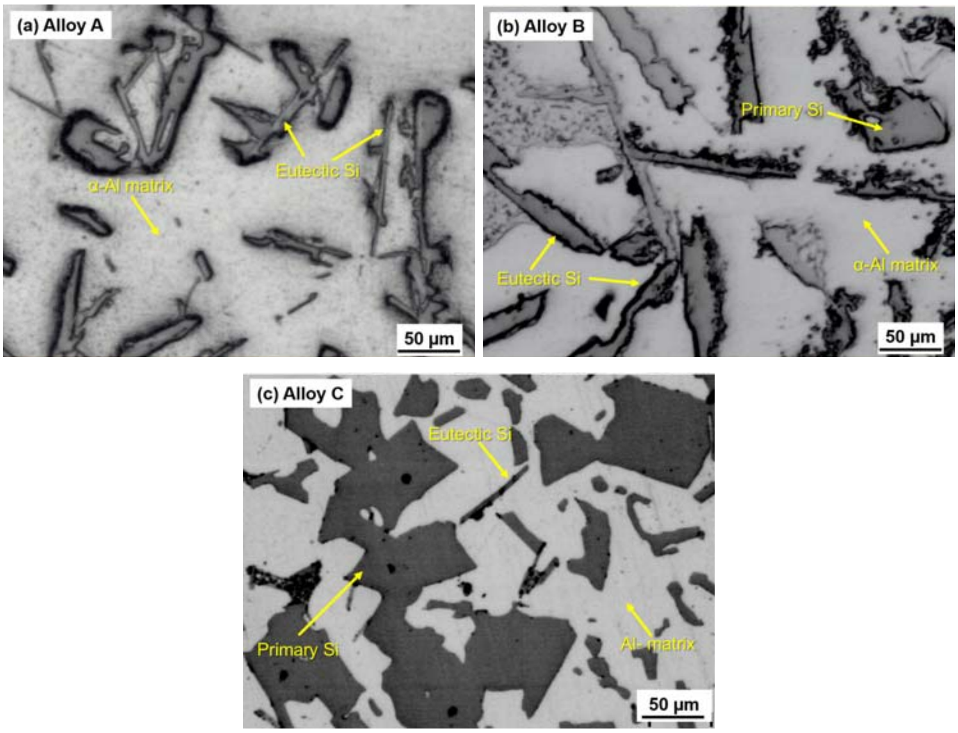
Optical microstructures of as-cast alloy A, alloy B, and alloy C have been presented in Figures 2(a), 2(b), and 2(c), respectively.

The micrograph reveals the presence of long eutectic silicon particles in α-Al matrix in case of alloy A as shown in Figure 2(a). The alloy B also shows the similar morphology as alloy A along with few primary silicon particles as shown in Figure 2(b). The presence of primary silicon particles in the alloy B is attributed to the faster cooling rate during solidification. The presence of primary Si particles along with eutectic Si and α-Al in the alloy is due to skewed coupled zone phenomenon. The alloy C consists of coarse primary and eutectic silicon particle, which were non-uniformly distributed in the Al matrix as shown in Figure 2(c). Table 2 shows the equivalent average length of the different silicon phase. The above mentioned microstructural features in Al-Si alloy reduce the tribo-mechanical properties. Previously, similar morphology was reported in other Al-Si alloys (Shivaprasad et al., 2015; Jigajinni et al., 2013).

Table 2 Microstructural characteristics of as-cast alloy

Alloy	*Microstructural feature*	*Average length* (*μm*)
Alloy A	Eutectic Si	32.7
Alloy B	Eutectic Si	38.2
	Primary Si	53.3
Alloy C	Eutectic Si	18.2
	Primary Si	68.5

Figure 2 Optical microstructures of as-cast alloys, (a) alloy A (b) alloy B and (c) alloy C (see online version for colours)



3.2 *Forging of Al-Si alloys*

The test samples of alloy A, B, and C were forged between flat die platens at 300 and 500ºC elevated working temperatures. Figure 3 shows the schematic diagram of forging of Al-Si alloy. During forging of the alloy at elevated temperature, the large axial stresses (compressive) acting on the billet. Due to applied axial stresses, the material flow radially in outward direction and produces radial flow stresses which is tensile in nature.

Since the Al-Si alloy comprises of hard silicon particles and intermetallic phases which reduces the ductility of the alloy, and the material become hard. Forging at elevated temperature induces ductility in the alloy which results the soft Al deforms plastically in outward direction, while hard silicon and intermetallic particles (second phase) fractured and broken down during process. Also the stress concentration generate between second phase particles and Al matrix during forging, which results crack formation at the outer periphery of the test samples. Figures 4–6 exhibit the photographs of forged billets of alloy A, alloy B, and alloy C at 300 and 500ºC elevated working temperatures respectively. In all three different compositions of Al-Si alloy, the test samples forged at 300ºC showed less surface cracks as compared to 500ºC under same applied load (Figures 4–6). It attributed to the substantial softening of the alloy at higher working temperature. As a result, significant plastic deformation of Al matrix takes place, while hard second phase generates stress concentration at flowing Al matrix during forging. Due to this, severe surface cracks developed on the outer surface of the forged billets. Figures 4–6 also revealed that severity of surface cracks increases with increase in silicon content in the Al-Si alloy. Since the ductility of the alloy reduces as increase silicon content, and material became brittle. Due to this, severe surface cracks generates on the finished product during forging.

Figure 3 Schematic diagram of forging of Al-Si alloy (see online version for colours)

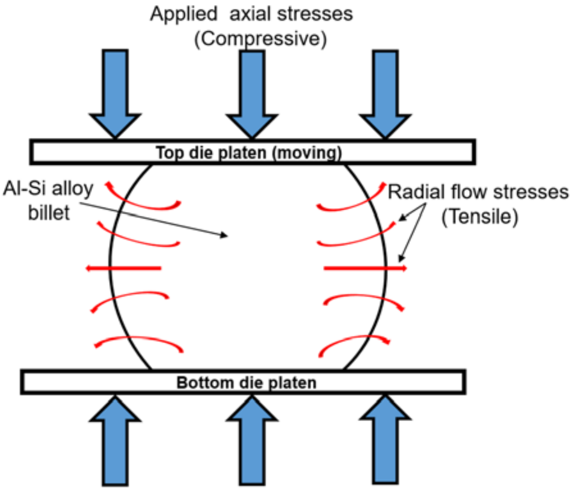


Figure 4 Photograph of the forged alloy A billets (A356 alloy), (a) at 300ºC (b) at 500ºC (see online version for colours)

(a) (b)

Figure 5 Photograph of the forged alloy B billets (Al-12Si-2.5Cu-0.6Fe alloy) (see online version for colours)

(a) (b)

Figure 6 Photograph of the forged alloy C billets (Al-18Si-2.5Cu-0.6Fe alloy) (see online version for colours)


(a) (b)

3.3 Microstructural features of the forged alloys

Figures 7–9 represent the optical microstructures of forged alloy A, alloy B, and alloy C as at 300 and 500ºC working temperatures respectively. Table 3 shows microstructural characteristics of forged Al-Si alloy.

Figure 7 Optical micrographs of the forged alloy A billets (A356 alloy) at (a) 300ºC and (b) 500ºC

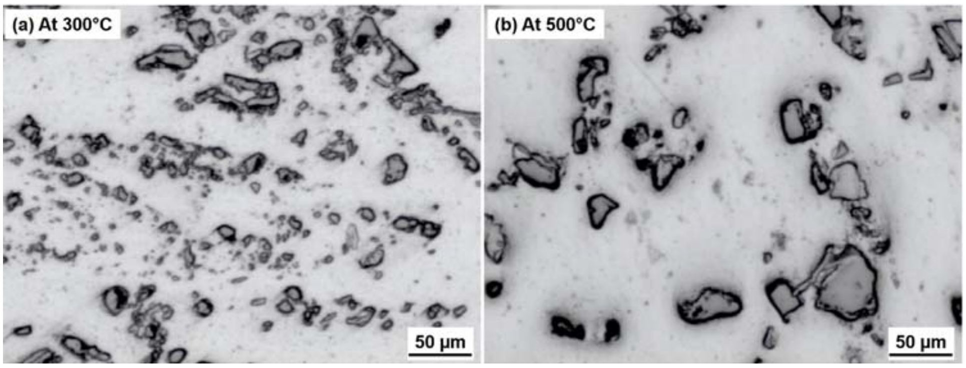


Figure 8 Optical micrographs of the forged alloy B billets (Al-12Si-2.5Cu-0.6Fe alloy) at (a) 300ºC and (b) 500ºC

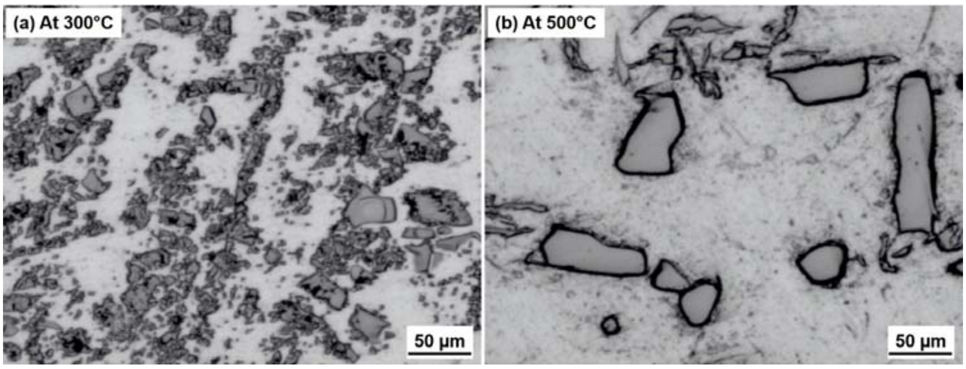


Figure 9 Optical micrographs of the forged alloy C billets (Al-18Si-2.5Cu-0.6Fe alloy) at (a) 300ºC and (b) 500ºC

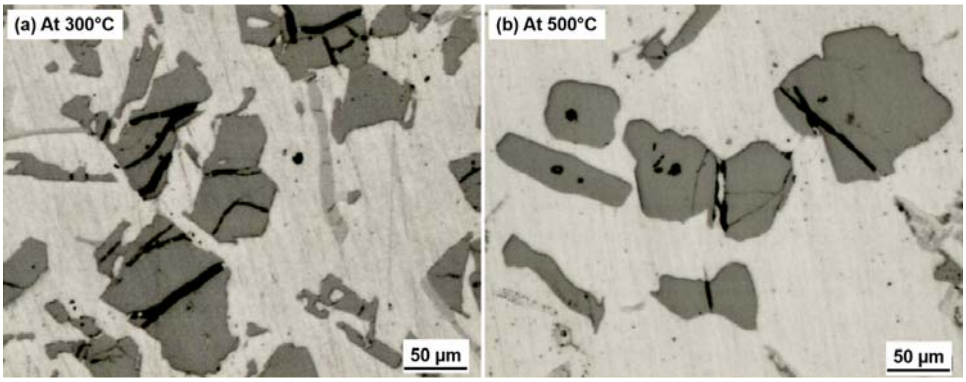


Table 3 Microstructural characteristics of forged alloys

Alloy	*Microstructural feature*	*Average length (μm)*	
		Forged at 300°C	*Forged at 500°C*
Alloy A	Eutectic Si	4.9	12.4
Alloy B	Eutectic Si	6.5	9.6
	Primary Si	20.2	41.5
Alloy C	Eutectic Si	29.2	14.9
	Primary Si	49.5	9.3

The results revealed the microstructural refinement in all three different material namely A356, Al-12Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe alloy during forging at 300 and 500ºC temperatures. The fragmentation of long eutectic particles in both alloy A and alloy B was observed (Figure 7 and 8). It reflects the strong refined structure after the reorientation. Moreover, coarse primary Si particles in alloy C was also cracked and broken down into the small particles during forging (Figure 9). The microstructural refinement during forging attributed to the precipitation of fine particle at elevated temperature prior to forging, whereas coarse and long particles broken down to small splits during forging. Such fine precipitated and split up particles were uniformly dispersed in the Al matrix during forging. It results strong structure of Al-Si alloy as shown in Figures 7–9. It was also observed that coarsening in the silicon particles occurred during forging at 500ºC working temperature. It attributed to the diffusion of the silicon atom at higher working temperature, which results increment in particle size as well as coarsening as shown in Figures 7(b), 8(b), and 9(b). Various authors have also reported the similar trend during processing of other Al-Si alloys (Ke et al., 2010; Cai et al., 2015). Barhoumi et al. (2015) have found coarsening of Si particles at higher working temperature.

3.4 Hardness tests

Table 4 shows the average of the five indentation (random at different locations) of the microhardness values of the as-cast and forged alloy. The result reveals that hardness of the alloy A, alloy B, and alloy C were improved significantly on account of forging at elevated working temperatures. It attributes to the Hall Patch strengthening mechanism (Manu et al., 2017) in which hardness of the material improved due to the formation of strong bonding between fine second phase particles and Al matrix during forging. Also, dislocation immobilising due to the presence of refined second phase particles during forging enhances the hardness of the material. Reduction in hardness of the forged alloys in all compositions were observed during forging at 500ºC due to coarsening of the microstructures as shown in Figures 7(b), 8(b), and 9(b). The results also revealed that hardness of the alloy increased with increase in Si amount. Alloy C exhibits highest hardness as compared to two other alloys. It may due to the presence of harder Si particles in the Al matrix that reduces the ductility of the alloy and make it difficult to deformable, therefore hardness improves significantly.

Table 4 Microhardness values of the as-cast and forged alloys

Alloy	*Vickers microhardness (HV)*		
	As-cast	*Forged at 300ºC*	*Forged at 500ºC*
A356	44.5	57.3	52.6
Al-12Si-2.5Cu-0.6Fe	51.9	68.5	59.5
Al-18Si-2.5Cu-0.6Fe	78.2	94.5	87.7

It can be summarised that the hardness of alloy depends mainly microstructural features, and dislocation density generated during forging. Various authors have confirmed that hardness of the alloy significantly improved due to refinement in morphology and higher dislocation density (Jamaati et al., 2011; Manu et al., 2017).

4 Conclusions

The following conclusions have been drawn from the present study:

1 The morphology of the silicon changes from eutectic to polyhedral Si particles by increasing the silicon weight percentage in the alloy.

2 Forging of the Al-Si alloys between flat die platen is very difficult even at elevated temperature conditions, and the forged products having severe surface cracks.

3 Morphological refinement occurred during forging process due to fragmentation of coarse eutectic and primary silicon particles into fine particles.

4 Significant improvement was observed in hardness of the forged alloy as compared with as-cast alloy in all other different compositions.

5 Hardness of the alloy increased with increase the silicon content.

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