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Studies on the influence of grain refining and modification on microstructure and mechanical properties of forged A356 alloy

D.G. Mallapur[a,*], K. Rajendra Udupa[a], S.A. Kori[b]

[a] Department of Metallurgical and Materials Engineering, National Institute of Technology Karnataka, Surathkal, Karnataka, India
[b] R & D Centre, Department of Mechanical Engineering, Basaveshwar Engineering College, Bagalkot, Karnataka, India

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ABSTRACT

Microstructure and mechanical properties of the forged A356 alloy have been investigated in this paper. Results reveals that at micro level forged structure was more refined than as in the as cast conditions. This is due to the work hardening effect, where the original structure is destroyed during the forging and recrystallization helped in creating large number of nucleating sites leading to fine grain structure. From the investigations on the mechanical properties, we deduce that the PS, UTS and hardness of forged materials are obviously higher than those of the ones treated with as cast condition without and with the addition of grain refiners and modifier.

1. Introduction

Foundry aluminum alloys based on the Al–Si system are widely used in the automotive field since they associate excellent fluidity and castability, good resistance to corrosion and mechanical properties. Al–Si alloys, which comprise 85–90% of the total aluminum-cast parts produced, exhibit excellent castability, mechanical and physical properties [1]. The microstructure and alloy constituents are necessitated to achieve optimum mechanical properties. Some of the critical microstructural features are grain size, dendritic arm spacing and silicon morphology in the eutectic phase [2]. The principal reasons for the usage of Al–Si alloys are high corrosion resistance and low density. A356 alloys are found to provide good results since they have excellent casting characteristics, weldability, pressure tightness, tensile and fatigue properties, and corrosion resistance [3]. A356 aluminum alloys are mostly used as cast hypoeutectic Al–Si alloys to improve flowability of the melt and interfacial properties [4,5]. However, since eutectic Si particles present in the A356 alloys deteriorate strength, ductility, and fracture toughness, processes such as rheo-casting, squeeze casting, and casting–forging have been actively developed for the enhanced distribution of eutectic Si particles [6–9]. Forging processes suitable for producing high-strength parts are restricted to some luxury sedans. In order to address these problems, advanced casting processes like rheo-casting and casting–forging are newly developed, and their pilot products, which are lighter than conventional welded steel plate products by about 20%, are successfully introduced to markets worldwide. Forging of Al alloys are becoming more important in the view of the development in the aviation and transportation industries and hence, it becomes important to study the behavior of the metal which contains second phase particles dispersed in the matrix, when it is plastically deformed. Forging changes the microstructure and mechanical properties both in as cast as well as in grain refined alloys. The fabrication of parts by the forging process is capable of producing products with good mechanical properties, but there are numerous parameters to be considered in the fabrication of complex-shaped parts. Furthermore, a high product cost is involved, due to the increased press capacity required, fatigue failure of the die, etc. [10].

The purpose of the present study was to improve tensile properties and hardness of forged A356 alloy without and with grain refiner and/or modifier and combined addition of both. The application of forging increases the yield strength and an overall improvement in the mechanical properties of the grain refined/modified alloy. The effect of forging process on the observed increase in yield and tensile strength is attributed to the changes in microstructures after forging.

2. Experimental details

In the present study influence of forging on the microstructure, hence the mechanical properties study of grain refined (with 0.65% Al–3Ti and 0.60% Al–3B) and modified (with 0.20% Al–10Sr) A356 alloy is studied. Specimen were cast into billets and then

* Corresponding author. Fax: +91 8354 234204.
E-mail address: drmallapur@yahoo.com (D.G. Mallapur).

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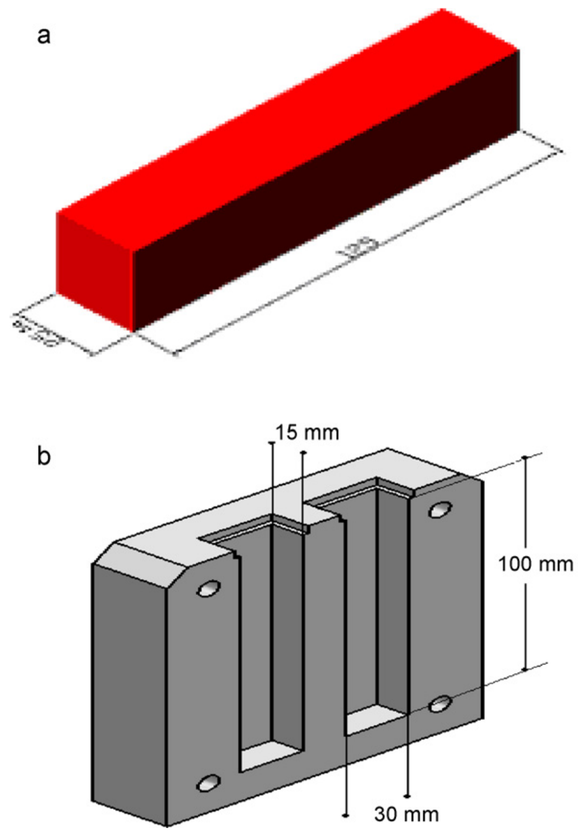

Fig. 1. (a) and (b) Forged specimen (25 mm × 25 mm × 125 mm length) and a split type square graphite mould for the preparation of forging specimens (15 mm × 30 mm × 100 mm length).

Fig. 2. Pneumatic power forging hammer.

forged to the required dimensions. Fig. 1(a) and (b) shows the forged square bar and mould used for preparing the cast billets. These billets were forged to rectangular shape of the dimension 25 mm × 25 mm × 125 mm.

2.1. Forged specimen preparation

The forged test specimen as shown in Fig. 1(a) is a square bar with flat surface having a dimension of 25 mm × 25 mm × 125 mm length. The square forged test specimen bar was forged using a pneumatic power forging hammer of Model MS 412 at Fitwel Tools and Forgings Pvt. Ltd., Tumkur, Karnataka, India. The pneumatic power forging hammer as shown in Fig. 2 is capable of delivering minimum blow energy of 250 kg m. After forging, the bars were then machined into 10 mm diameter × 50 mm gauge length for the preparation of tensile test specimen, for the mechanical properties study.

Forging is carried out at a temperature level of 0.45Tm where Tm is the melting point of the alloy. Considering the melting point of the alloy to be 660 °C, the forging temperature was fixed at 350 °C and forging ratio was 17%. Forging was carried out on both grain refined and modified as well as unrefined and unmodified cast billets. These forged coupons were subjected to aging treatment according to standard T6 heat-treatment process, the parameters of which are presented in Table 1. T6 Heat Treatment is a specific heat treatment process which may be applied to aluminum/copper/silicon alloys, to increase the strength of the alloy. In the case of T6 heat treatment, the process occurs in two phases. The First Phase of T6 heat treatment is called the Quench Phase and the second phase the Aging phase. The T6 heat treatment (solution treatment at 530 °C for 8 h and aging at 170 °C for 4 h). T6 is solution heat treated and artificially aged.

2.2. Specimen preparation for microstructure studies

Standard metallographic techniques were used to prepare the samples for microstructural analysis. These prepared samples were etched using Keller's reagent ($2.5\%HNO_3 + 1.5\%HCL + 1\%HF + 95\%H_2O$ by volume). The polished specimens were taken for optical microscopy, SEM/EDX analysis.

2.3. Specimen preparation for mechanical properties study

From the forged coupons, for the mechanical properties study, a standard tensile testing specimen shown in Fig. 3 was prepared. Mechanical properties (0.2% Proof stress, Ultimate tensile stress, % Elongation, % Reduction in area, Young's modulus and Vickers hardness number) of forged A356 alloy were evaluated before and after grain refinement and modification. Tensile tests were carried out using computerized universal testing machine (UNITEK 9450PC, Blue Star India Ltd., Bangalore). For each composition three specimens were prepared and the value reported is the average of three consistent readings.

Table 1
The standard specifications for T6 heat-treatment process.

Process	Temperature	Time (h)	Cooling condition
Solution treatment	535 °C	8	Quenching in hot water about 75 °C
Aging	160 °C	4	Cooled in switched off furnace

3. Results and discussion

3.1. Microstructural studies

At micro level, it is observed from Fig. 4(a)–(e), that the forged structure was more refined than in the as cast conditions. This is due to the work hardening effect, where the original structure is destroyed during the forging and recrystallization helped in creating large number of nucleating sites leading to fine grain structure. Fig. 4(a) shows the SEM photomicrograph of forged A356 alloy in the absence of grain refiner and modifier. From figure it is clear that in the absence of Al–3Ti master alloy the silicon needles vanish and highly refined grains are observed. Also, the elongation of the grains is clearly observed in the direction perpendicular to the force of forging. With the addition of 0.65% of Al–3Ti master alloy, the forged A356 alloy shows response towards grain refinement in the refined structure. It is clearly observed that the Si needles have broken into small pieces and eutectic is refined into smaller sizes. Distribution of Si is more uniform in Ti refiner as shown in Fig. 4(b). With the addition of 0.60% of Al–3B master alloy, more elongated grains with slight refinement is seen in the structure. The distribution of the Si particles is along the grain boundaries and in the matrix as clearly observed in Fig. 4(c). Further, as observed in

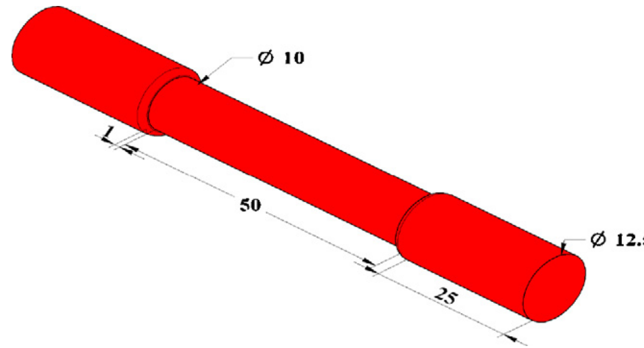

Fig. 3. A tensile test specimen (10 mm × 50 mm gauge length).

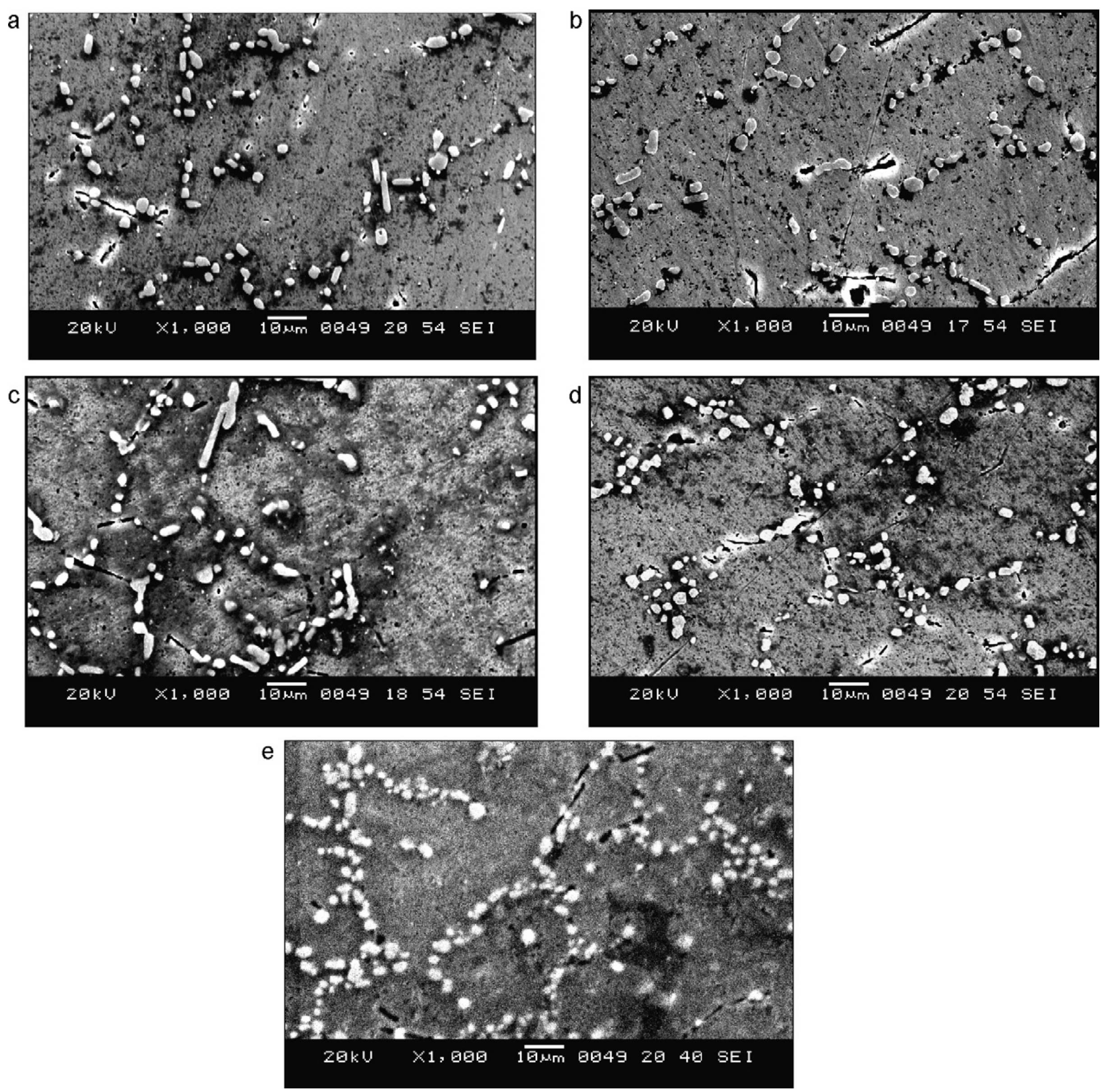

Fig. 4. (a)–(e) SEM photomicrographs of forged A356 alloy (a) as cast alloy; (b) with 0.65% of Al–3Ti grain refiner; (c) with 0.60% of Al–3B grain refiner; (d) with 0.20% of Al–10Sr modifier and (e) combined addition of 0.65% Al–3Ti, 0.60% of Al–3B grain refiner and 0.20% of Al–10Sr modifier.

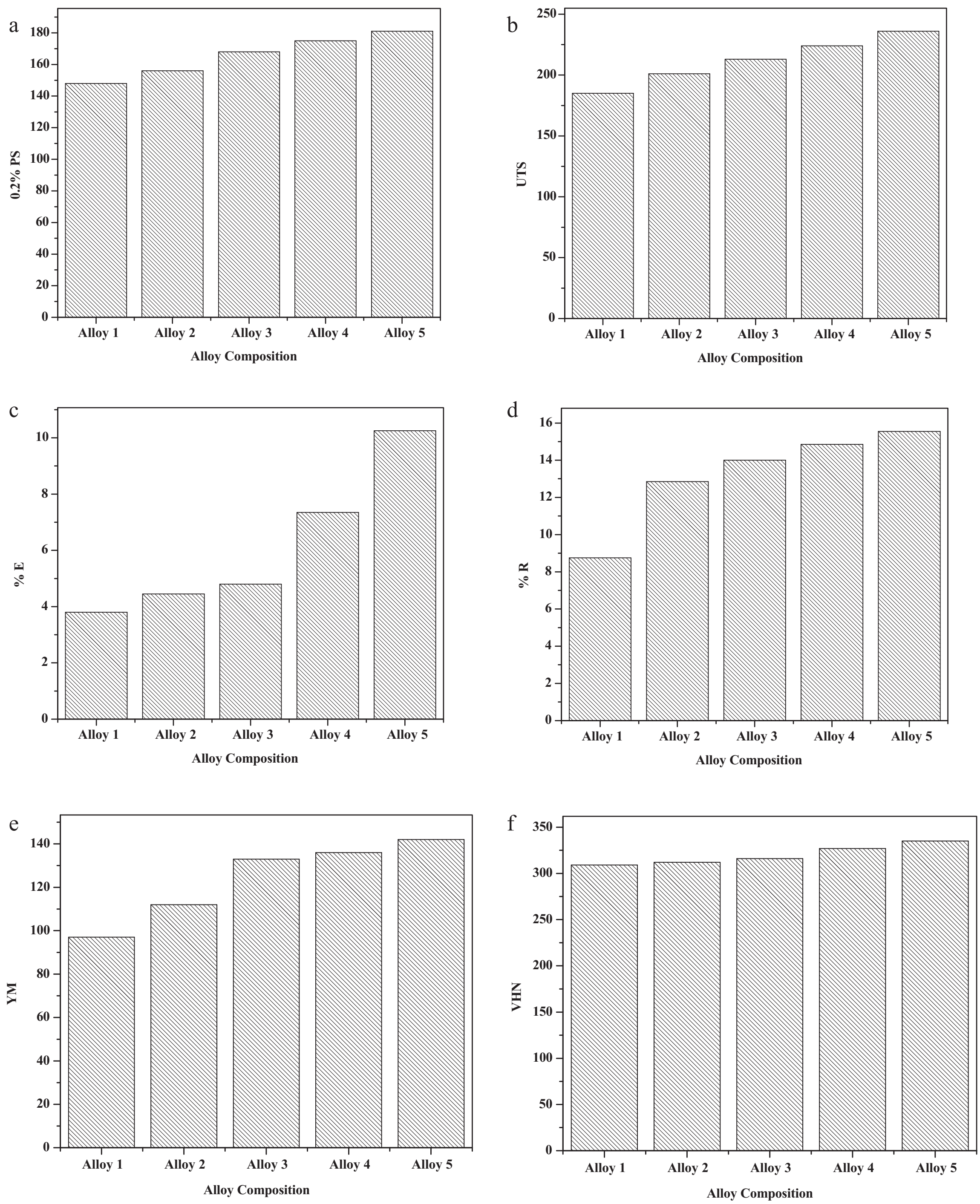

Fig. 5. (a)–(f) Graphical representation of mechanical properties v/s alloy composition of forged A356 alloy.

Fig. 4(d) with the addition of 0.20% of Al–10Sr master alloy, both refinement and modification is observed with respect to the matrix and eutectic Si respectively. However, Fig. 4(e) shows the simultaneous refinement (α-Al dendrites) and modification (eutectic Si) of forged A356 alloy. It is clearly observed that the grains of α-Al is refined to the maximum extent with fine Si particles distributed along the grain boundaries and in the matrix. The Si particles seen are eutectic ones and not primary ones. As Al–Si alloy exhibits disordered eutectic behavior all Si particles are seen over the grain boundaries. If they are modified, morphology of Si changes, if not modified alignment changes due to forging. That is the reason why elongated needles are absent in modified alloy Fig. 4(d) and (e).

3.2. Mechanical properties study

The carts presented in Fig. 5(a)–(f) show the influence of the grain refiner and modifier on the mechanical properties of forged A356 alloy. It is clearly observed from Fig. 5(a)–(j) that these charts are derived from the stress–strain profile generated on the forged materials represented in Fig. 6(a)–(e). The improvement in the mechanical properties such as Proof stress, Ultimate tensile strength, % Elongation, % Reduction, Young's modulus and Vickers hardness number increases with the addition of master alloys containing titanium, boron and strontium. It is also clear that the combined addition of grain refiner and modifier to A356 alloy has

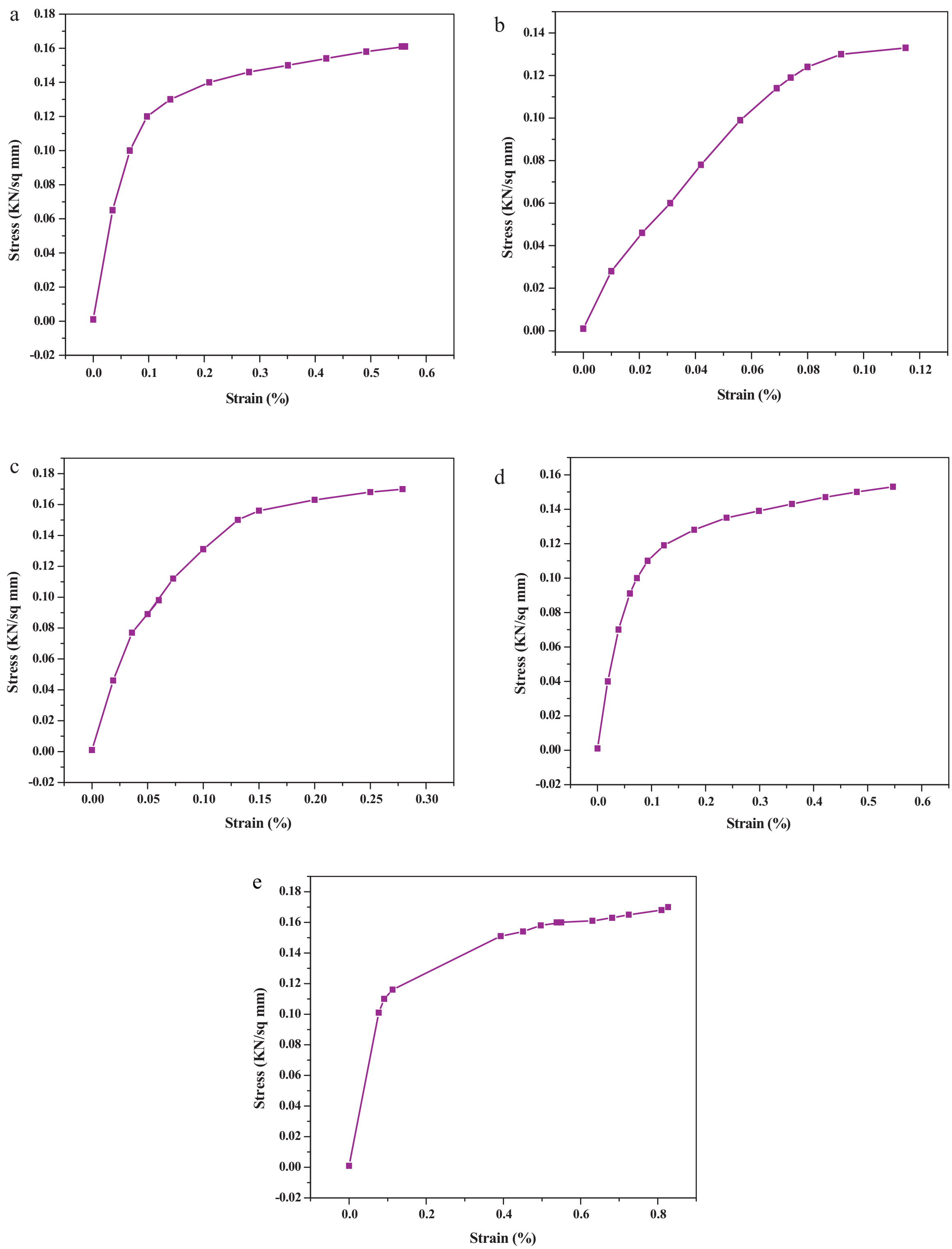

Fig. 6. (a)–(e) The stress v/s strain diagram of forged A356 without and with the addition of grain refiners and modifier: (a) as cast A356 alloy; (b) A356 + 0.65% (Al–3Ti); (c) A356 + 0.60% (Al–3B); (d) A356 + 0.20% (Al–10Sr) and (e) A356 + combined addition.

Table 2
Mechanical property studies on forged A356 alloy.

Alloy no.	Alloy composition	0.2% PS (MPa)	UTS (MPa)	% E	% R	YM	VHN
1	A356	148	185	3.80	8.75	97	309
2	A356 + 0.65% Al–3Ti	156	201	4.45	12.85	112	312
3	A356 + 0.60% Al–3B	168	213	4.80	14.00	133	316
4	A356 + 0.20% Al–10Sr	175	224	7.35	14.85	136	327
5	A356 + 0.65% Al–3Ti + 0.60% Al–3B + 0.20% Al–10Sr	181	236	10.25	15.55	142	335

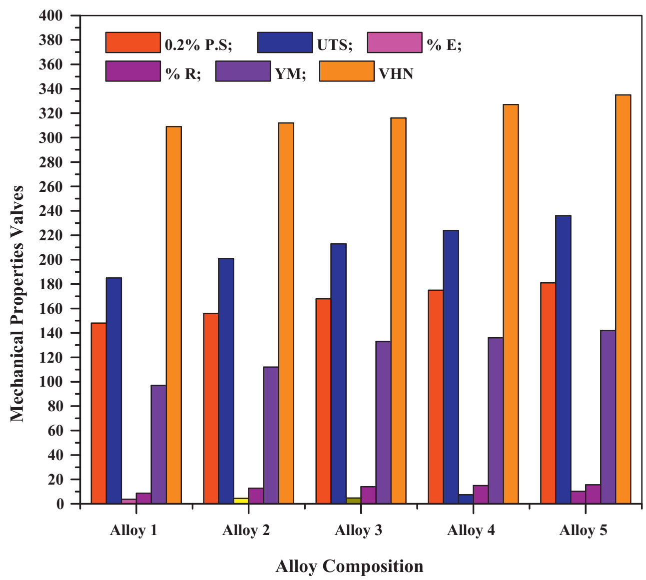

Fig. 7. Combined mechanical properties of forged A356 alloy before and after the addition of grain refiner and or modifier.

resulted in maximum improvement in mechanical properties as compared to the individual addition of grain refiner, modifier and in an untreated forged condition. Tensile properties and hardness valves of the forged materials are clearly presented in Fig. 5(a)–(f). It is observed that the forged materials exhibit superior tensile properties and hardness for all types of treatments. Among the forged materials, the ones treated with combination of grain refiners along with modifier exhibit the best tensile properties and hardness valves. Melt treated materials when forged register higher level of improvement in mechanical property compared to untreated material. Among treated materials, the ones treated with 0.65% Al–3Ti, 0.60% Al–3B and 0.20% of Al–10Sr exhibits highest improvement in the property. Such a materials record 39% improvement in the yield strength when forged. It is indicative of the fact that forging is effective only when Si needles are absent. It is also clear that forging improves both strength and ductility of the materials. However, the improvement in ductility is perceptible only for properly grain refined and modified A356 materials. It is also clearly observed that the ones refined with 0.65% Al–3Ti shows highest improvement in ductility while the ones treated with 0.20% Al–10Sr exhibits 25% improvement in ductility when forged. Microstructural refinements, particularly break down of Si needles seems to be asserting the major influence in improving the properties on aging. Improvements in mechanical properties and microhardness values are obtained due to the addition of grain refiner and or modifier to forged A356 alloy.

To identify the mechanical properties study, combined stress v/s strain diagram of forged A356 without and with the addition of grain refiners and modifier is shown in Fig. 6(a)–(e).

Fig. 7 shows the combined mechanical properties study of forged A356 alloy without and with the addition of grain refiners and modifier. It is clearly observed that with the addition of grain refiner and modifier there is a significant improvement in the mechanical properties of the forged materials. This may be due to the breakdown and distribution of Si particles during the forging process.

Table 2 shows in a tabular form the overall effect on the mechanical properties of forged A356 alloy without and with the addition of grain refiners and modifier. The charts presented in Fig. 5(a)–(j) are obtained by the valves represented in Table 2. The valves represented in Table 2 are obtained after conducting tensile test on the various prepared tensile specimen after the forging and T6 treatment process, with help of a computerized universal testing machine.

4. Conclusions

1. Forging improves the mechanical properties of A356 alloys.
2. The forging benefit is better in grain refined and modified materials. Materials treated with 0.65% of Al–3Ti, 0.60% of Al–3B and 0.20% of Al–10Sr offered the best results.
3. Microstructural refinements, particularly break down of Si needles seems to be asserting the major influence in improving the properties on aging.
4. Improvements in mechanical properties and microhardness values are obtained due to the addition of grain refiner and or modifier to forged A356 alloy.

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