International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:7, No:6, 2013

Influence of Ti, B, and Sr on Microstructure, Mechanical and Tribological Properties of as Cast, Cast Aged, and Forge Aged A356 Alloy – A Comparative Study

R. V. Kurahatti, D. G. Mallapur, and K. Rajendra Udupa

Abstract**—**In the present work, a comparative study on the microstructure and mechanical properties of as cast, cast aged and forged aged A356 alloy has been investigated. The study reveals that mechanical properties of A356 alloy are highly influenced by melt treatment and solid state processing. Cast aged alloys achieve highest strength and hardness compared to as cast and forge aged ones. Ones treated with combined addition of grain refiners and modifiers achieve maximum strength and hardness. Cast aged A356 alloy possesses higher wear resistance compared to as cast and forge aged ones. Forging improves both strength and ductility of alloys over as cast ones. However, the improvement in ductility is perceptible only for properly grain refined and modified alloys. Ones refined with 0.65% Al-3Ti shows highest improvement in ductility while ones treated with 0.20% Al-10Sr exhibits less improvement in ductility.

Keywords**—**Forged A356 alloy, Grain refinement, Modification, Wear.

I. Introduction

ALUMINUM is one of the most important non-ferrous metals. Aluminum based alloys are widely used in automotive and aerospace industries due to their low densities, attractive physical and mechanical properties. They are light in weight, cheaper to produce with stand casting technology. They are easy to machine and have good recycling possibilities (up to 95%). Due to these facts their applications in automotive and other industries increase [1]-[4].

A356 alloy with a composition Al (91.1% - 93.2%); Si (6.96% - 7%); Cu (Max 0.2%); Ti (Max. 0.2%); Mg (0.3% - 0.45%); Fe (0.50%); Mn (0.30%); Ni (0.1%); Zn (0.10%); Pb (0.10%) and Sn (0.05%), possesses excellent foundry characteristics such as good castability, weldability, good thermal conductivity, high strength at elevated temperatures and good corrosion resistance.

Binary Al-7Si% commercial A356 (7% Si) alloys find widespread applications in automotive, aerospace and general engineering industries where they are used for cylinder blocks, cylinder heads and other body parts due to their excellent combination of properties such as good fluidity, low coefficient of thermal expansion, high strength to weight ratio and good corrosion resistance. The physical and mechanical properties attainable are strongly influenced by chemical composition, presence of trace elements, melt treatment, solidification rate and heat treatment [5]-[8]. Microstructural appearance of A356 alloy consists of coarse columnar α-Al dendrites and plate/needle like eutectic silicon. The quality of casting can be improved by grain refinement, which reduces the size of primary α-Al grains/dendritic structure in the casting. The literature reveals that Al-Si alloys containing $\geq$7%Si respond poorly to the grain refinement by Al-5Ti-B master alloy. Al-1Ti-3B master alloy shows better response towards grain refinement of Al-7Si/A356 alloy when compared to Al-5Ti-1B master alloy [7], [8]. To improve the mechanical properties of these alloys, a common practice is to refine the microstructure. Refinement of grain structure is achieved by controlling casting process parameters and / or melt chemistry (i.e. grain refinement, eutectic modification). Grain refiners are materials added to alloys to aid in nucleation and lead to the production of fine and uniform grain sizes. Fine equiaxed grain structure in as cast Al alloys can be achieved by small additions of number of elements like Ti, B, Zr, Nb, V, W, Ta, Ce etc. Modification treatment is needed to change the morphology of silicon from angular platelets into fine fibers by the addition of sodium or strontium to improve the mechanical properties. The modifying agents commonly used for chemical modification of A356 alloys are sodium and strontium. It has been observed that strontium (Sr) is an effective modifier for as cast hypoeutectic and eutectic Al-Si alloys. The slower Sr has one or two hours longer incubation time and also oxidation problem is less severe [8]-[12].

Forging of Al alloys are becoming more important in view of the development in aviation and transportation industry and hence, it is important to study the behavior of the metal which contains second phase particles dispersed in the matrix, when it is plastically deformed. The forged microstructure has a more uniform distribution of eutectic silicon in comparison to as cast microstructure. Forging changes the microstructure and mechanical properties both in as cast and in grain refined alloys. The microstructure of the hot forged alloys possess reduced number of particles of eutectic silicon and other

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phases indicating that particles exhibit interfacial debonding and cracking, while almost no cracking damage can be seen in the as cast ones. The application of forging increases the yield strength and overall improvement in the mechanical properties of the grain refined/modified alloy. The effect of forging process on the observed yield and tensile strength is attributed to the changes in microstructure after forging. In the forged microstructure, the reinforcing particles and eutectic silicon particles are more homogeneously distributed in comparison to the as cast specimen.

Tribological properties of forged A356 alloy mainly depend on the shape and size of the α-Al dendrites and the eutectic silicon morphology. The coarse silicon plates/needles of the unmodified acicular silicon structure act as internal stress raisers in the microstructure and provide easy paths for the fracture. From the literature it is observed that, addition of grain refiners (Al-Ti and Al-B) to A356 alloy converts predominantly columnar dendritic structure into fine equiaxed dendritic structure and addition of modifier (Sr) changes plate like eutectic Si into fine particles which leads to the improvements in tensile properties and wear behavior of the product. The wear behavior of Al-Si alloys depends on a number of mechanical properties (hardness, ductility and toughness) and microstructure (such as eutectic silicon morphology, dendrite arm spacing (DAS), grain size, composition, distribution of microconstituents in addition to load, speed, temperature and counterface [13]-[14].

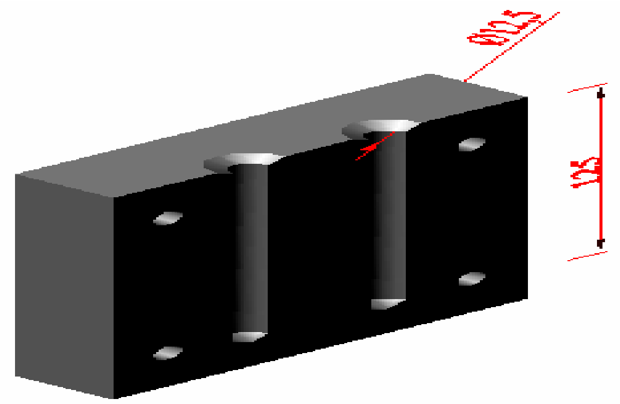
Hence, in the present work, a detailed attempt has been made to study the individual addition of Ti, B, and Sr to A356 alloy and an effort is made to study in depth investigation on microstructural changes and in turn their influence on mechanical and tribological properties of the A356 alloy in as cast, cast aged and forge aged conditions.

II. Experimental Details

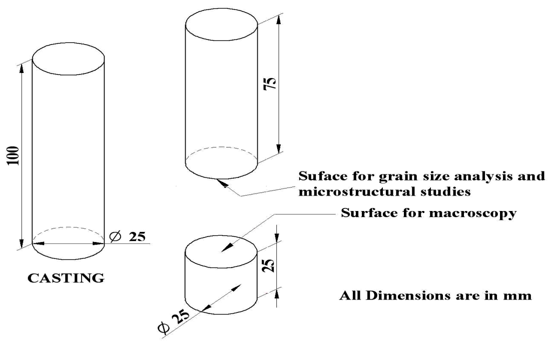
The as cast specimens were prepared by melting A356 alloy in induction furnace (Make: Cereratherm International Pvt. Ltd). After degassing with solid hexachloroethane (C_2Cl_6), the melt was poured into a split type cylindrical graphite mould (Fig. 1 (a)). The casting dimensions are shown in Fig. 1 (b). Some of the castings for the preparation of cast aged and forged samples are given standard T6 heat treatment, the parameters of which are given in Table I.

TABLE I
STANDARD SPECIFICATION FOR T6 HEAT-TREATMENT PROCESS

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



(a)



(b)

Fig. 1 (a), (b) Split type cylindrical graphite mould and castings

Samples are cut from as cast, cast aged and forge aged materials for macro and micro analysis and tensile testing. The dimensions of the tensile test sample are shown in Fig. 2.

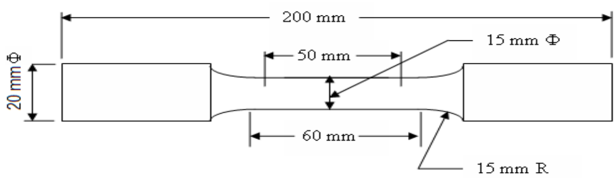
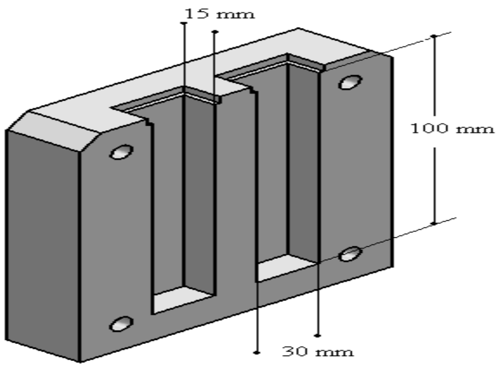
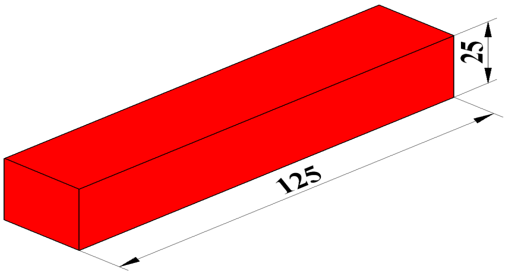


Fig. 2 Tensile test specimen (ASTM E8)

Forging is carried out on billets prepared in the graphite mould. The dimensions of graphite block and the cast billets are shown in Fig. 3. Forging was followed by standard T6 heat treatment. Standard specimens for macro / microstructural studies and tensile testing are machined from these coupons.



(a)



(b)

Fig. 3 Schematic representation of split type square graphite mould for preparation of specimens for (a) forging (15mm x 30mm x 100mm Length) (b) forged specimen (25mm x 25mm x 125mm Length)

The forging process was carried out using pneumatic power hammer of model MS 412 at Fitwel tools and forging pvt. ltd, Tumkur Karnataka, India. The forging was carried out at a temperature level of 350°C well above its recrystallization temperature which happens to be around 300°C for A356 alloys. The prepared wear samples from forged coupons are rounded bars with a flat surface having dimensions of 32mm length x 10mm diameter. After giving T6 treatment process, samples were tested by Pin-On-Disc type wear testing machine (TR-201CL, DUCOM) as shown in Fig. 4.

To evaluate the performance under dry sliding conditions, wear tests were carried out on forged A356 alloy according to ASTM G99 standard [14] using pin-on-disc machine. The flat portion of 10 mm diameter of the specimen is in contact with a rotating disc. The disc material is made of En-32 steel (having diameter 160mm and thickness 8mm) with chemical composition (0.14%C, 0.18%Si, 0.52%Mn, 0.015%S, 0.019%P, 0.13%Ni, 0.05%Cr, 0.06%Mo, balance Fe) and heat treated to get a hardness value of HRc 65 [13]. A constant 90 mm track diameter was used throughout the experimental work. The wear tests were carried out under various conditions such as varying normal pressure, sliding speeds and sliding distances. The details of the experimental parameters are shown in Table II. The weight loss measured in grams was continuously monitored and the frictional force was measured in Newtons using a force sensor. The weight loss and frictional force under various normal pressures, sliding speeds and sliding distances of the specimens are recorded.

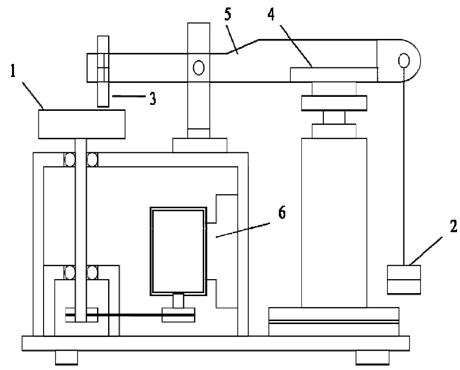


Fig. 4 Schematic diagram of the wear and friction testing machine 1. Disc 2. Load 3. Specimen (pin) 4. Friction force sensor 5. Load beam 6. Electric machine

III. Results and Discussion

The improvements in the wear behavior of forged A356 alloy with and without the addition of grain refiner and modifier under various normal pressures, sliding speeds and sliding distances have been studied. Wear behaviors quantified in the form of wear loss, frictional force and co-efficient of friction are assessed. The difference in wear behavior due to structural variation was revealed only for conditions of higher load, speed and longer distance of testing. At lower ends the difference was marginal.

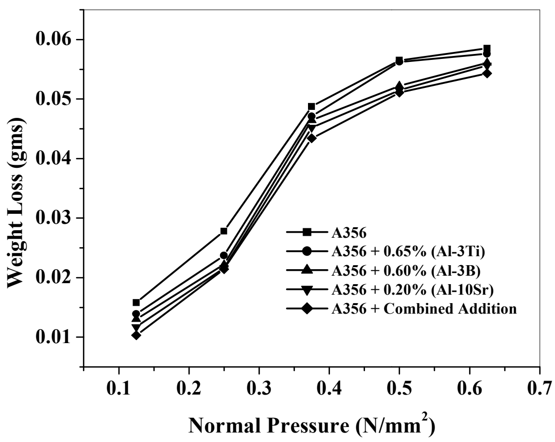
TABLE II
VARIOUS PARAMETERS FOR WEAR STUDIES

Composition of the alloys	Parameters	Variables	Constants
A356 alloy before and after the addition of master alloys (As cast + Cast aged and Forge aged conditions)	Normal pressure N/mm^2	0.13, 0.23, 0.38, 0.50 and 0.63	At constant sliding speed v = 1.88m/s and at constant sliding distance L = 3400 m of A356 Alloy
A356 alloy before and after the addition of master alloys (As cast + Cast aged and Forge aged conditions)	Sliding speed m/s	0.47, 0.94, 1.41, 1.88, 2.35 and 2.82	At constant normal pressure P = 0.63 N/mm^2 and at constant sliding distance L = 3400 m of A356 Alloy
A356 alloy before and after the addition of master alloys (As cast + Cast aged and Forge aged conditions)	Sliding distance m	850, 1700, 2540, 3400 and 4240	At constant normal pressure P = 0.63 N/mm^2 and at constant sliding speed v = 1.88m/s m of A356 Alloy

A. Effect of Normal Pressure

The effect of normal pressure on the weight loss and frictional force of forged A356 alloy under different normal pressures (0.13, 0.23, 0.38, 0.50, and 0.63N/mm^2) with constant sliding distance (3400m) and at constant sliding speed (1.884m/s) is shown in Fig. 5 (a), (b). From Fig. 5 (a), it is clear that, the weight loss of forged A356 alloy with and without the addition of grain refiner and modifier goes on increasing with an increase in normal pressure in all the cases studied and this is due to forging and heat treatment effect wherein the microstructure of forged A356 alloy have a more uniform distribution of SiC particles and the eutectic silicon. However, melt treatment influenced the wear loss with respect to normal pressure to a certain extent (10-15%). Graph presented in Fig. 5 (b) shows the variation of frictional force with normal pressure. Figure clearly indicates that the frictional force increases with increase in normal pressure in all the cases studied up to the addition of grain refiner. However, a sudden decrease in the frictional force with an increase in the normal pressure is clearly indicated which might be due to change in the microstructure from coarse to fine dendrites and plate like eutectic Si into fine particles, which reduces the area of contact of eutectic silicon.

In addition, change in microstructure leads to the toughness and strength of the alloy leading to lesser frictional force. The linearity in the curve is disrupted by sudden change in the slope which results 3 regimes in the profiles. These 3 regimes could be correlated to the three mechanisms operative under different pressure conditions.



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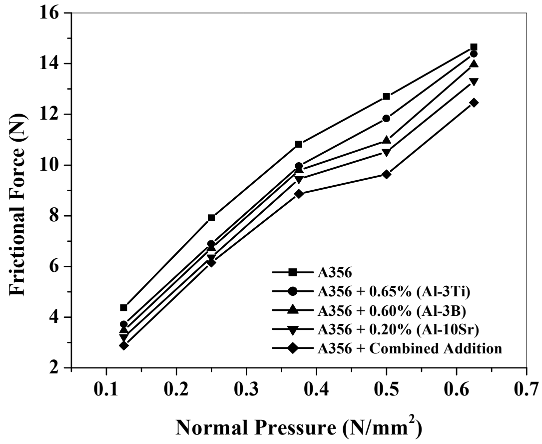


(b)

Fig. 5 (a), (b) The effect of normal pressure on the weight loss and frictional force of forged and heat treated A356 alloy (constant sliding speed v = 1.88m/s and constant sliding distance L = 3400m)

In the low pressure regime loss of metal could be attributed to abrasion wear which is caused by the hard silicon particles scuffed away from the matrix. At higher normal pressure, debris of silicon particles gets embedded into the soft Al matrix leading to a situation where adhesive wear becomes dominant. At intermediate levels of normal pressure, a mixed mode of mechanism prevails which is confirmed by images of worn surface studied under scanning electron microscope (SEM) and are shown in Figs. 6 (a), (b). Fig. 6 (a) shows worn surface of specimen tested at 3kg. Wear tracks are visible indicative of abrasion wear and Fig. 6 (b) shows worn surface of specimen tested at 5kg. Wear tracks are not visible, metal flow and rapture are indicative of adhesive wear.

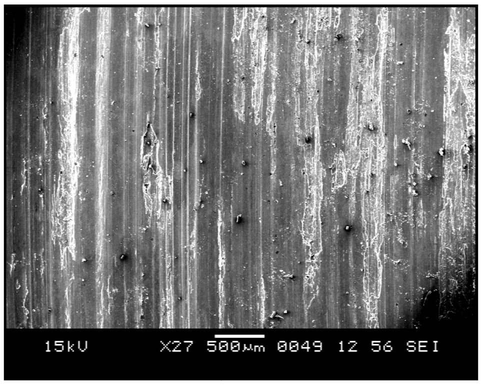


Fig. 6 (a) Abrasion dominant

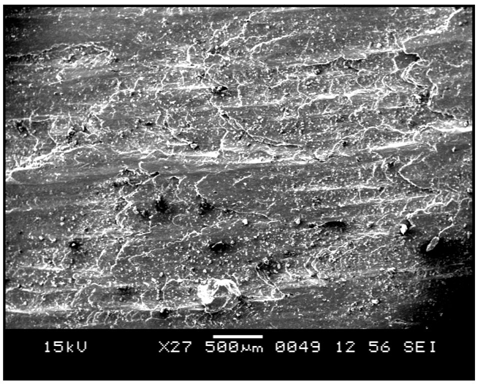
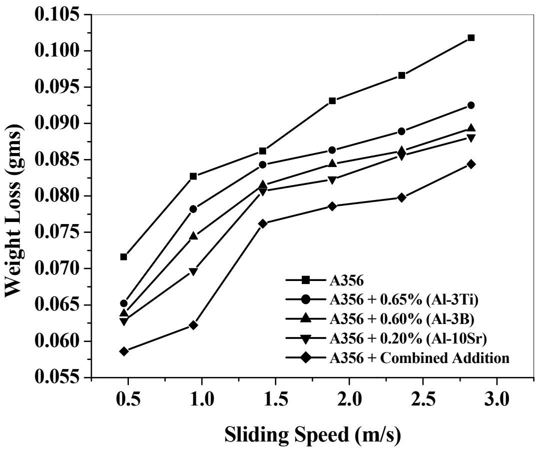


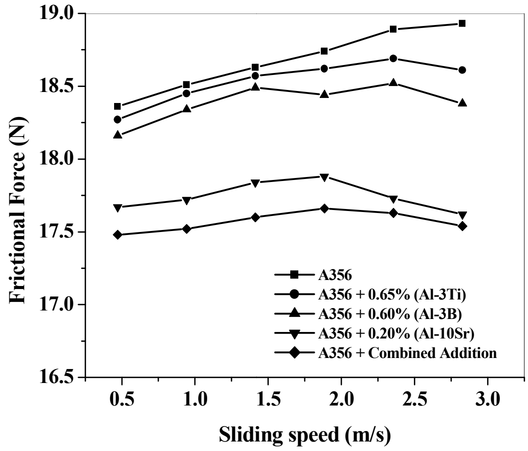
Fig. 6 (b) Adhesive dominant

B. Effect of Sliding Speed

The effect of grain refinement and modification of forged A356 alloy on the weight loss and frictional force under different sliding speeds (0.47, 0.94, 1.41, 1.88, 2.35, and 2.82m/s) with constant normal pressure (0.63N/mm^2) and at constant sliding distance (3400m) is shown in Figs. 7 (a), (b). It is clear from Fig. 7 (a) that with increase in the sliding speed, a sudden increase in the weight loss of forged A356 alloy was observed. This could be due to the forging process creating a large number of micro voids, particularly at the interface of brittle silicon phase and ductile aluminum matrix. Void growth and void coalescence becomes easier at higher speed because, heat generated at higher speeds lowers the cohesive strength between the atoms and tearing becomes easier. In the fracture process it is the nucleation of the void which is the most difficult event requiring higher level of energy. This could be conceived as the reasons for increasing weight loss with sliding speed in the case of forged alloy. It is clear from the Fig. 7 (b) that the frictional force increases with increasing sliding speed from 0.47 to 1.88m/s for forged A356 alloy with and without the addition of grain refiner and / or modifier.



(a)



(b)

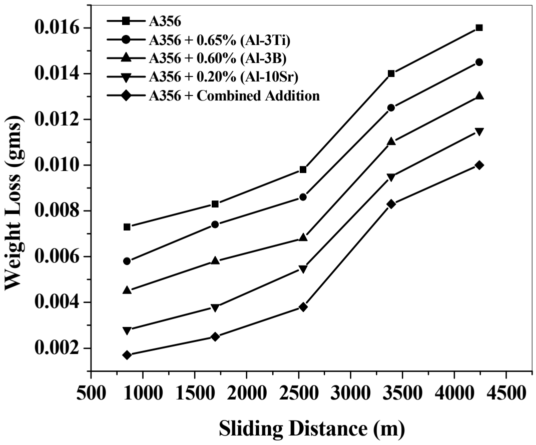
Fig. 7 (a), (b) The effect of sliding speed on the weight loss and frictional force of forged A356 alloy (constant normal pressure P = 0.63 N/mm^2 and at a constant sliding distance L = 3400m)

However, further increase in the sliding speed from 2.35 to 2.82m/s, a decrease in the frictional force was observed. In addition the frictional force is always lower in grain-refined and modified alloys when compared to the untreated alloy. This is due to the fact that strength and hardness of the alloy improved with the addition of grain refiner and modifier when compared to the untreated A356 alloy. This is due to the increase in the temperature in the wear specimen. As the temperature increases in the specimen, the intimate contact between the wearing pin and the rotating disc increases due to which the alloy becomes softer at the wearing surface. Further, it is observed that as the sliding speed increases from 2.33 to 2.82m/s, the frictional force decreases considerably and it is due to the increase in the frictional temperature which causes reducing shear stress at the wearing surface. With the addition of grain refiner the toughness and hardness of the forged alloy increases and leads to less frictional force.

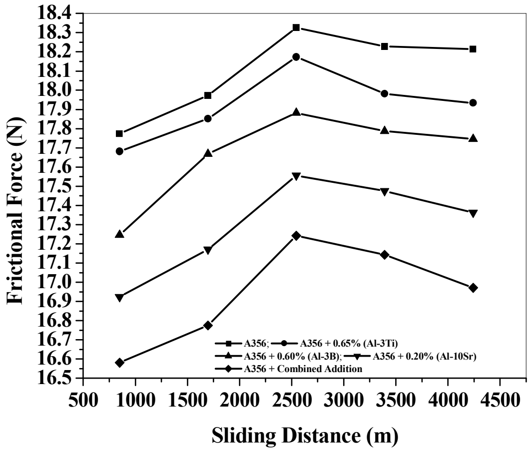
C. Effect of Sliding Distance

The effect of sliding distance on the weight loss and frictional force under different sliding distance (850, 1700, 2540, 3400, and 4240m) with constant normal pressure (0.63N/mm^2) and at constant sliding speed (1.88m/s) is observed in Fig. 8 (a), (b). It is clear from Fig. 8 (a) that the weight loss increases with an increase in the sliding distance in almost all the cases studied. It is obvious fact that weight loss is proportional to the sliding distance and is due to the fact that in the forged and heat treated materials the particles are more homogeneously distributed in comparison to the as cast condition. From Fig. 8 (b), it is clear that the frictional force increases with an increase in the sliding distance up to 2540m and beyond that frictional force decreases drastically. It is probably due to the reduction in friction. Addition of grain refiner leads to decreases in the grain size and results in the formation of more number of grain boundaries. Further reduction in the frictional force with the addition of 0.20% of

Al-10Sr modifier could be due to the conversion of sharp needle/plate like eutectic silicon into fine rounded particles.



(a)



(b)

Fig. 8 (a), (b) The effect of sliding distance on the weight loss and frictional force of forged A356 alloy (constant normal pressure P = 0.63 N/mm^2 and at a constant sliding speed v = 1.88m/s)

IV. Conclusion

1. 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. Ones refined with 0.65% Al-3Ti shows highest improvement in ductility while the ones treated with 0.20% Al-10Sr exhibits less improvement in ductility when forged.
2. In all the cases studied, it was observed that in forged condition a considerable decrease in the weight loss and frictional force was noticed as compared to the untreated condition (as cast A356 alloy) and this would be due to the effect of forging on A356 alloy.
3. It was also observed that, in forged conditions the weight loss of alloy increases with an increase in the normal pressure. However weight loss increases with increase in sliding distance. Wear resistance of forged A356 alloy improved with the addition of (Al-3Ti, Al-3B) grain refiners and/or Al-10Sr modifier to the melt.
4. The effect of the frictional force on forged A356 alloy clearly indicates an increase and later decrease with respect to normal pressure, sliding speed and sliding distance. The reason for the same is due to the effect of addition of grain refiner and modifier either individually or in combined condition.

Acknowledgment

The authors are grateful to Mr. D. R. Subramanya (Managing Director), Mr. Subhash and entire team of Fitwel Tools and Forgings Private Limited, Tumkur, India, for extending the necessary facilities for the conduct of forging processes/operations and preparation of samples for characterization.

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