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Influence of Melt Treatments on Dry Sliding Wear Behavior of Hypereutectic Al-15Si-4Cu Cast Alloys

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Abstract

The purpose of the present work is to investigate the microstructure and dry sliding wear behavior of hypereutectic Al-15Si-4Cu cast alloys with grain refinement, modification and/or refinement. Pin-On-Disc wear tests were conducted under dry sliding conditions on the hypereutectic Al-15Si-4Cu cast alloy after various melt treatments for varying loads ranging from 20N to 100N with constant sliding speed of 1 m/s and for a constant sliding distance of 1000m. Tests were also conducted on the hypereutectic Al-15Si-4Cu cast alloy for sliding distance of 2000m with constant sliding speed of 1 m/s and at a normal load of 60N. Results indicate that the addition of grain refiner (Al-1Ti-3B), modifier (Sr) and refiner (P) to the hypereutectic Al-15Si-4Cu unmodified cast alloy converts large α-Al grains in to fine equiaxed α-Al grains and forms fine fibrous silicon particles and fine CuAl2 particles in the interdendritic region. This improves the wear properties of the cast alloy.

Keywords: Modification; Grain refinement; hypereutectic Al-15Si-4Cu cast alloys; Wear rate; sliding distance

1. Introduction

The development of aluminum silicon alloys is very important due to their high strength to weight ratio, high wear resistance, low coefficient of thermal expansion, high thermal conductivity, high corrosion resistance, good cast performance, good weldability etc which makes them attractive candidate material in many tribological applications, aerospace and other engineering sectors where they can successfully replace ferrous components in heavy wear applications. These applications demand the study of techniques to improve the wear properties of these alloys. For this purpose, many researches had been done to enhance their wear properties. Al-Si alloys are mainly used in cast form in important components like pistons , engine blocks , cylinder liners, rocker arms, air conditioner compressors, brake drums etc. The improvement in the sliding wear resistance and mechanical properties depends on number of material related properties like shape, size and size distribution of the second phase particles in the matrix and microstructures in addition to the operating conditions such as sliding speed , sliding distance , temperature load etc. With the development of automobile industry, the need of hypereutectic Al-Si alloys increasing greatly. Al-Si alloys containing more than 13 wt% silicon are known as hypereutectic Al-Si alloys. The hypereutectic Al-Si alloys contain hard primary particles of non-metallic silicon embedded in an Al-Si eutectic matrix. These alloys have serious machinability problems due to the presence of the hard primary silicon phase which acts as abrasives. In order to obtain the best machinability and low wear rate the size of silicon phase must be controlled through melt treatment. Wear rate of the material decreases with increase in hardness of the material. It should be noted that it is the hardness of the contacting asperities that will improve the wear resistance.

Wear resistance in Al-Si alloys is primarily due to the presence of silicon in the aluminum matrix. Increasing the silicon content in Al-Si alloys increases the wear resistance and strength at the expense of machinability. Aluminum silicon alloys can be strengthened by adding small amount of Cu, Ni or Mg and the presence of silicon provides good casting properties. Copper results in the precipitation of CuAl2 particles in the structure. A very important finding is that alloys with the same chemical composition can have different microstructures and mechanical properties due to variations in the casting process, the use of a refiner, modifier and grain refiner. This means that different processing techniques can result in a range of mechanical properties, which affect the wear resistance of the alloys. A number of studies have been reported on the dry sliding wear behavior of the cast Al-Si alloys. These reports are very conflicting in nature.

A.D.Sarkar and J.Clarke [1] investigated the dry sliding wear behavior of aluminum silicon alloys using pin-on-disk wear machine and reported that silicon composition in aluminum alloy does not appear to be a dominant factor in the calculation of wear resistance. B.N.Pramila Bai and S.K.Biswas [2] studied the wear behavior of aluminum silicon alloys and concluded that wear rate of an alloy with out silicon is significantly higher than the binary modified

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alloys containing silicon composition between 4% and 24% and also concluded that there is no systematic trend in wear of aluminum silicon alloys containing 4-24% wt silicon. Shivanath et al. [3] investigated the sliding wear behavior of aluminum silicon alloys reported that wear resistance is good for the hypereutectic aluminum silicon alloys. A.D. Sarkar [4] studied the wear of Al-Si alloys against hardened steel disc and gray cast iron and reported that the hypereutectic alloys wear more than the hypoeutectic alloys. A. Somi Reddy et al [5] investigated the wear and seizure behavior of Al-Si alloy containing silicon content up to 23 wt% using Pin-On-Disc wear testing machine under various loads. It was observed that addition of silicon to aluminum increases the wear and seizure resistance. C.Subramanian [6] studied the effect of sliding speed on wear behaviour of aluminium silicon alloys and reported that the wear rate decreases with increasing sliding speed up to a critical speed. M. Harun et al [7] has investigated the effects of element additions on the wear of Al-Si alloys. S.A.Kori and M.S.Prabhudev [8] investigated on the wear rate of hypoeutectic Al-Si alloys with minor additions of copper at elevated temperatures and concluded that wear rate increases with the normal pressures, sliding speeds and sliding distances at a constant temperature of 3000C. Elmadagli et al [9] have done a parametric study of the relationship between microstructure and wear resistance of Al–Si alloys and concluded that increasing the alloy hardness and Si volume fraction increased the transition loads but did not have a significant effect on the wear coefficients. A.S.Anasyida et al. [10] has investigated the effect of cerium addition to the Al-Si alloys and found that increasing the cerium content up to 2% wt. increases the wear resistance of the alloys and then decreases. T.M.Chandrasehekharaiah and S.A. Kori [11] investigated on the wear resistance of eutectic Al-Si alloys and suggested that wear resistance increases with the addition of grain refiner and modifier. D.K.Dwivedi [12] reported that the addition of alloying element to the Al-Si alloy not only reduces the wear rate but also increases the transition load. K.G.Basava Kumar et al [13] investigated on the wear resistance of hypoeutectic Al-Si alloys using copper and reported that grain refined and modified cast alloys work hardened to a greater extent than the untreated alloys. Ibrahim.S [14] investigated the wear behavior of aluminum silicon alloys under different velocities and temperatures by adding small amount of copper. Y.P.Lim [15] investigated the effects of grain refiner and modifier on the aluminum silicon alloys and found that the mechanical properties improve with the addition of M51 grain refiner and strontium modifier. V.Abouei et al. [16] has investigated the dry sliding wear behaviour of hypereutectic Al-Si piston alloys containing iron-rich intermetallics and reported that the addition of 1.2 wt% Fe to the LM28 alloy increased the wear rate due to the formation of needle beta intermetallics. H.R. Saleh [17] reported that the hardness property could be improved by using Sb as a modifier to the aluminum silicon alloys. M.Babic et al. [18] concluded that the heat-treated alloys improve the tribological properties like wear rate and coefficient of friction over as cast ones for all the loads of sliding conditions. A.K.Prasada Rao et al.[19&20] investigated the wear behavior of hypo eutectic aluminum silicon alloys using grain refiners and modifier and reported that wear resistance depends on the microstructure of the alloys. T.R.Ramachandran et al. [21] proposed the techniques for achieving better refinement along with melt treatment for minimization of hydrogen and dissolved elements such a sodium and calcium. Gang Liu et al. [22] studied the modification response of hypereutectic Al-Si alloys with different Sr additional levels and concluded that wear behaviors are optimal in the range of 0.04-0.06 wt% Sr and concluded that wear volumes of Al-Si alloys are inversely proportional to the hardness.

From the above investigations, it is observed that the dry sliding wear behavior of polyphase alloys is difficult and it is not a simple function of composition. The present work investigates the influence of either grain refiner or modifier/refiner and combined addition of all on dry sliding wear behavior of hypereutectic Al-15Si-4Cu cast alloys against a hardened steel disc by using a Pin-On-Disc wear and friction testing machine.

2. Experimental Procedure

Six different hypereutectic cast Al-15Si-4Cu alloys were used during the present investigation. P-1 was the unmodified one. Cast alloy P-2 was modified with strontium and alloy P-3 was refined with phosphorous. Alloy P-4 was refined and modified with strontium and phosphorus respectively. Alloy P-5 was grain refined with Al-1Ti-3B in addition to the modification and refinement. Similarly, cast alloy P-6 was grain refined with Al-5Ti-1B in addition to the modification and refinement.

The main aim is to find the load bearing capacity (wear resistance) of the pin compositions. So experiments were carried out at different loads (20N to 100N insteps of 20N at constant velocity and constant sliding distance) and for a maximum sliding distance of 2 km at a constant speed and load. The details of the alloys, modification, refinement and grain refinement treatment of various alloys are given in Table 1.

Table 1: Test specimens of Al-15Si-4Cu cast alloys.

Sl No	Alloy designation	Alloy composition	Addition level of GR (wt %)	Addition level of modifier and/or refiner (wt %)
1	P-1	Al-15Si-4Cu	-	-
2	P-2	Al-15Si-4Cu-0.04Sr	-	0.04
3	P-3	Al-15Si-4Cu-0.04P	-	0.04
4	P-4	Al-15Si-4Cu-0.04Sr-0.04P	-	0.04
5	P-5	Al-15Si-4Cu-0.04Sr-0.04P-1M13	1.0	0.04
6	P-6	Al-15Si-4Cu-0.04Sr-0.04P-1M51	1.0	0.04

Note: Grain refiners: M13=Al-1Ti-3B,M51=Al-5Ti-1B
Modifier : Strontium (Sr)
Refiner : Phosphorus (P)

Hypereutectic Al-15Si-4Cu alloy was prepared by melting high purity aluminum (99.7%) with master alloys Al-20%Si and Al-30%Cu in graphite crucible in a furnace and the melt was held at 8500C. Melt was degassed with 1% solid hexachloroethane before the addition of modifier/grain refiner. Modification was done by the addition of 0.04%wt strontium in the form of Al-10%Sr master alloy. Refinement of the Al-15Si-4Cu was done by the addition of 0.04%wt phosphorus in the form of red phosphorus. Grain refinement was done with the master alloys Al-1Ti-3B or Al-5Ti-1B. The melt was stirred for 30 seconds after the addition of modifier, refiner and grain refiner. The melt was poured into a cylindrical graphite mould of 25mm internal diameter and 150mm in height.

Table 2 gives the details of the chemical analysis of master alloys.

Table 2: Chemical analysis of master alloys.

Alloy	Composition(% wt)						
	Fe	Si	Sr	Cu	Ti	B	Al
Al	0.15	0.08	-	-	-	-	balance
Al-20Si	0.1	20.2	-	-	-	-	balance
Al-10Sr	0.19	0.12	10	-	-	-	balance
Al-30Cu	0.18	-	-	30.3	-	-	balance
Al-1Ti-3B	0.17	0.16	-	-	1.13	2.25	balance
Al-5Ti-1B	0.17	0.15	-	-	5.62	1.04	balance

A pin on disc type wear and friction machine (TR-20LE, DUCOM, Bangalore) with data acquisition system was used to evaluate the wear behavior of aluminum silicon alloys. Figure1 shows the photograph of the test specimen on the tribometer disc.

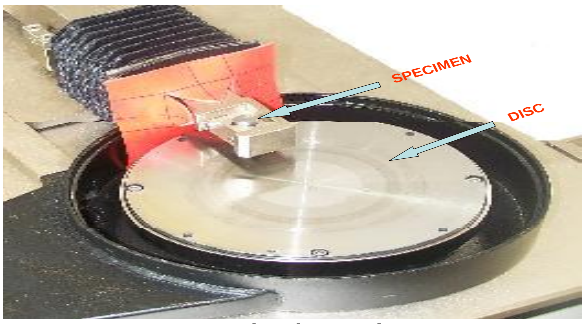


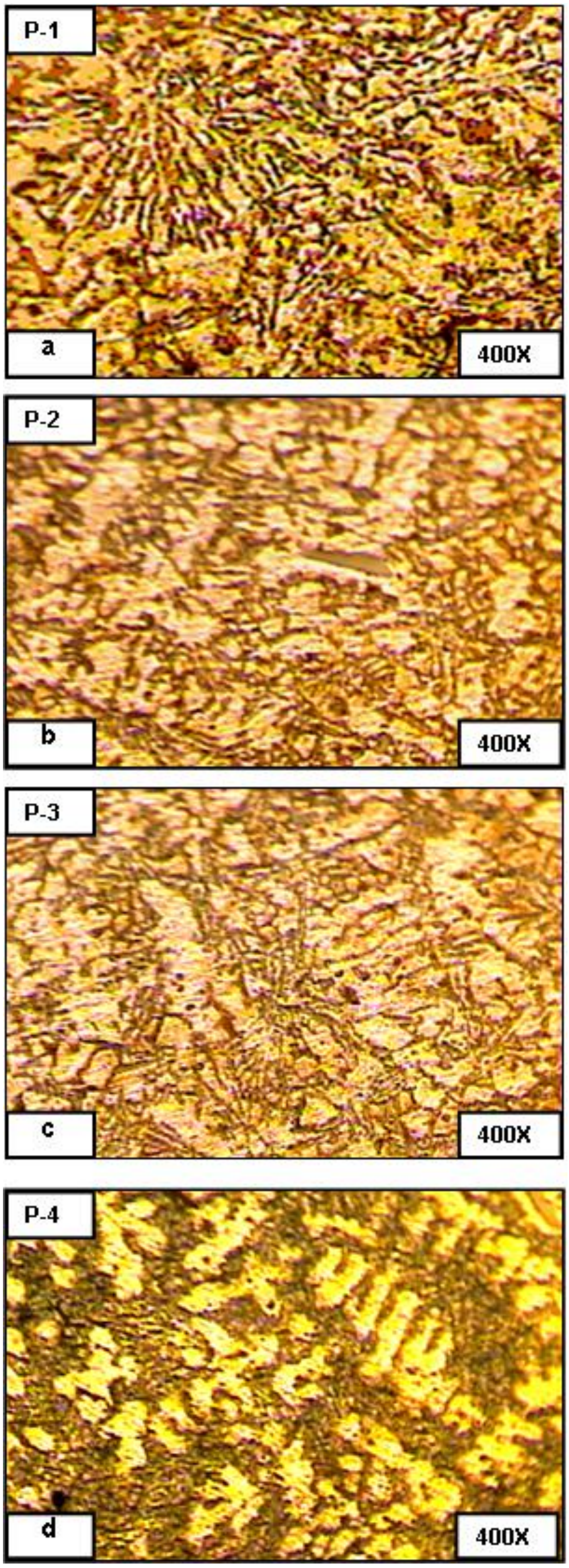
Figure 1: Test specimen on the tribometer disc.

The pins of 8 mm diameter and 25 mm length were fabricated from castings against hardened ground steel (En-31) disc having hardness of HRC 62 and surface roughness (Ra) 0.1µm. The wear tests were carried under varying loads (20, 40, 60, 80 and 100N)) with sliding speed 1 m/s and for a constant sliding distance of 1000m. Track diameter of 100 mm was selected for the analysis. During sliding change in the height of the specimen was recorded using linear variable differential transformer (accuracy ±1 µm with maximum displacement of ±2 mm). The friction force was recorded during the experiment by using a load cell. It has a maximum load capacity of 200N and measures the frictional load at an accuracy of ± 0.1 N in the load range of 0-200N. Frictional force (N) was measured as a function of time. The pins were weighed before and after each test to measure the change in weight for wear loss calculations. Before the test, the polished pins were cleaned and degreased using ultrasonic cleaner, first with water and soap, followed by ethanol and finally with acetone. Cleaned samples were dried in an oven for 30min at 800C. Figure 2 shows the photograph of the controller of the pin on disc wear and friction testing machine.

Figure 2: Controller of the wear and friction-testing machine.

3. Results and Discussion:

The microstructures of the test samples that had been cut in the longitudinal direction were studied. Dry sliding wear behavior of Al-15Si-4Cu cast alloys depends on the size, shape of the silicon particles, size distribution of the α-Al grains and CuAl2 particles in the interdendritic region. Figure 3 (a) shows the microstructure of unmodified Al-15Si-4Cu alloy. The microstructure contains needle/plate type silicon particles. Unmodified acicular silicon acts as internal stress riser in the microstructure and provides easy path for fracture. Figure 3(b) shows the microstructure of Al-15Si-4Cu alloy after modification. The addition of modifier (Sr) to Al-15Si-4Cu cast alloy changes the needle like silicon to fine particles in the interdendritic region, while α- Al grains remain dendritic. In hypereutectic alloys, refinement is also achieved through the addition of phosphorus. The phosphorus has a marked effect on the size, shape and distribution of the primary silicon. The addition of phosphorus to Al-15Si-4Cu alloy significantly refines the coarse platlet, star-like and irregular primary silicon to fine and uniformly distributed silicon particles possibly due to aluminum phosphide (Al P) acting as nucleating agent for silicon. This is shown in the Figure3(c). After the addition of refiner and modifier (Figure 3(d)), the microstructure shows fine fibrous silicon particles. Grain refiners are materials added to alloys to aid in nucleation, and lead to the production of fine and uniform grain size. There are several types of grain refiners available for aluminum–silicon alloys, based on aluminum-titanium or aluminum-titanium-boron master alloys, and titanium or titanium-boron containing salt tablets for hypereutectic alloys. Figure 3 (e and f) shows the optical microphotographs of Al-15Si-4Cu cast alloy with grain refiners (by 1% of Al-1Ti-3B and 1% of Al-5Ti-1B master alloys) in addition to the combined addition of modifier (0.04% Sr) and refiner (0.04% P). The additions of grain refiners (Al-1Ti-3B and Al-5Ti-1B), modifier (Sr) and refiner (P) converts large α-Al grains in to fine equiaxed α-Al grains and forms fine fibrous silicon particles and fine CuAl2 particles in the interdendritic region. This improves the wear properties of the cast alloy. The results also suggest that, the addition of Al-1Ti-3B master alloy along with Sr and P to the alloys show more uniformly distributed α-Al grains, fine broken grains of silicon and fine CuAl2 particles in the interdendritic region compared to the microstructure obtained with individual additions of modifier and/or refiner.



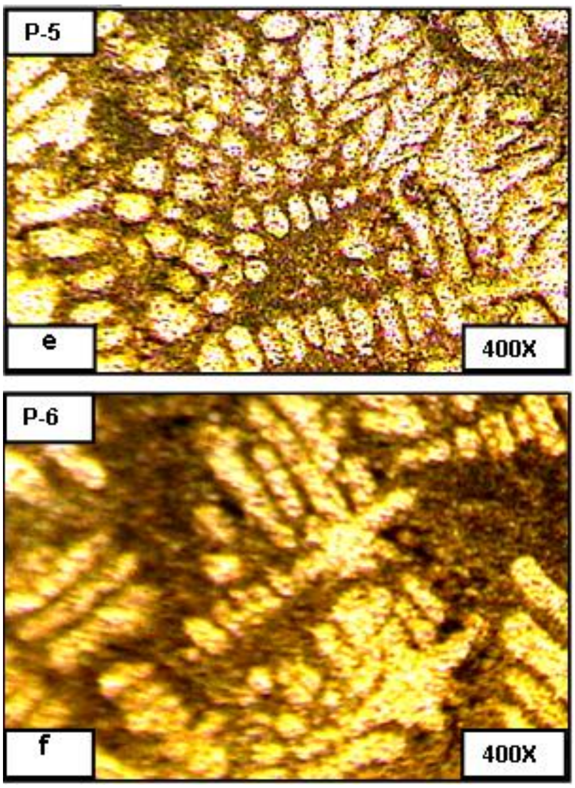
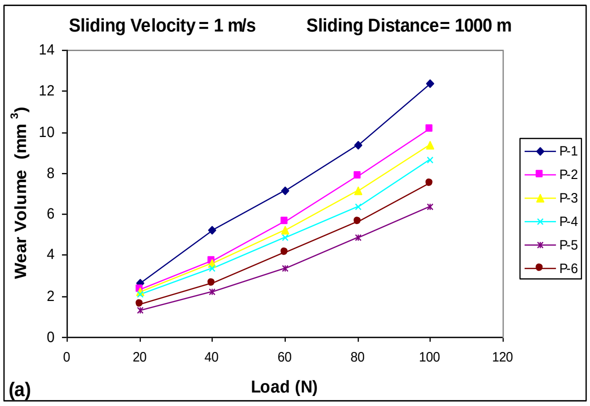


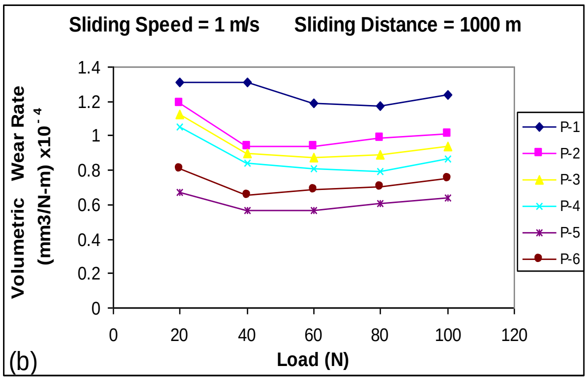
Figure 3 : Optical microphotographs of Al-15Si-4Cu cast alloy: (a) un-modified (b) with modifier (0.04% Sr) (c) with refiner (0.04% P) (d) combined addition of modifier (0.04% Sr) and refiner (0.04% P) (e) with grain refiner (1% of M13) in addition to the combined addition of modifier (0.04% Sr) and refiner (0.04% P) (f) with grain refiner (1% of M51) in addition to the combined addition of modifier (0.04% Sr) and refiner (0.04% P).

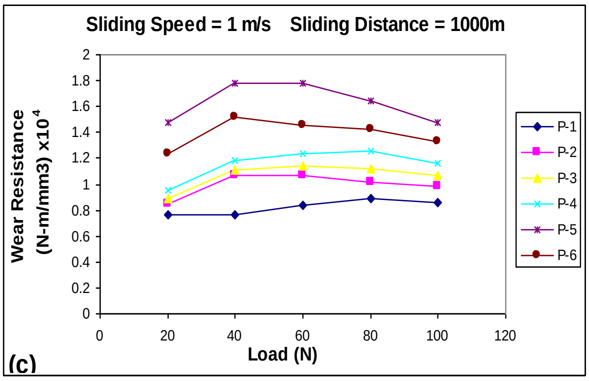
During the test, when the applied load on the pin is increased, the actual contact area would increase towards the nominal area which increases the frictional force between two sliding surfaces. The increased frictional force gives high wear. Figures 4 (a)-(d) show the influence of refinement or modification and grain refinement on the dry sliding wear behavior of the hypereutectic Al-15Si-4Cu cast alloys under different loads varying from 20N to 100N in steps of 20 N with constant sliding speed of 1 m/s for a sliding distance of 1000m.

The wear test of the Al-15Si-4Cu unmodified cast alloy was carried out at the highest load of 100 N. It was observed that seizure does not take place up to this load. Seizure is a phenomenon of the test specimen becoming welded to the wear disc at high loads and higher sliding speeds of the disc due to wear. At seizure there will be more noise and vibrations. Tests were stopped at this load. The wear volume and volumetric wear rate of the alloys under different conditions is shown in Figure 4(a) & 4(b). It is observed that the wear volume and wear rate are more at higher loads for untreated Al-15Si-4Cu alloy. During the test, when the applied load on the pin is increased, the actual contact area would increase towards the nominal area which increases the frictional force between two sliding surfaces. The increased frictional force gives high wear volume and hence high wear rate. The wear volume and volumetric wear rate are less for the combined addition of modifier, refiner and grain refiner. The formation of fine equiaxed α-aluminum grains, fine fibrous silicon particles and fine $CuAl_2$ particles in the interdendritic region due to the addition of grain refiner

(Al-1Ti-3B), modifier (Sr) and refiner (P) reduces the wear volume and volumetric wear rate of the cast alloy. The wear resistance of the un-treated alloy decreased continuously with increasing wear load as shown in figure 4(c). Better wear resistance should be achieved through fine equiaxed primary α-aluminum grains and uniform distribution of the second phase particles. The combined grain refined and modified Al–15Si–4Cu cast alloy recorded higher wear resistance at the highest load. The additions of modifier (Sr), refiner (P) and grain refiner (Al–1Ti–3B) convert large α-aluminum grains into fine equiaxed α-aluminum grains and eutectic silicon plates into fine particles and fine CuAl2 particles in the interdendritic region leading to better mechanical properties and hence improved wear resistance. The overall wear resistance increased due to appreciable work hardening of the grain refined, modified and/or refined alloys. On the contrary, the wear resistance of the un-treated Al–15Si-4Cu alloy (alloy P-1; Fig. 4(c)) continued to decrease with increasing load due to low work hardening rate. The cast alloys, which were only refined and/or modified, have shown the intermediate results. The coefficient of friction increases uniformly with increasing load in most of the cases. The coefficient of friction in the case of the modified, refined and/or grain refined Al–15Si–4Cu cast alloy was lower at all the loads as shown in Fig. 4(d). The rise in the coefficient of friction with the increase in wear load may be attributed to (a) enhanced accumulation of the wear debris consisting of large volume fraction of hard aluminide and silicide particles pulled out of the matrix during wear at the pin and disc interface and (b) oxidation of the wearing surface. Temperature measurement of wear pin during the sliding wear was carried out using thermocouple. Temperature of the pin was recorded with the help of digital temperature indicator of the wear and friction monitor. Figure 5 indicates that the temperature of the pin is more for the untreated Al-15Si-4Cu cast alloy during sliding and is less for the treated alloys. During wear at high loads, the temperature increases (Fig. 5) appreciably lowering the strength of the materials in contact resulting in increased contact area and coefficient of friction. Rise in temperature within limits increases the ability of soft aluminum matrix to accommodate hard and brittle second phase silicon particles.







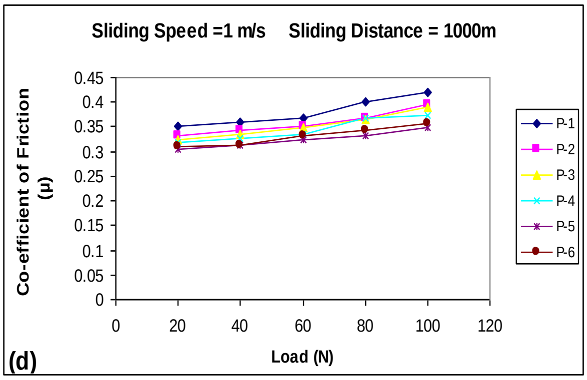


Figure 4: Variation of (a) wear volume (b) volumetric wear rate (c) wear resistance (d) coefficient of friction, with different loads at 1 m/s sliding speed and 1000m sliding distance.

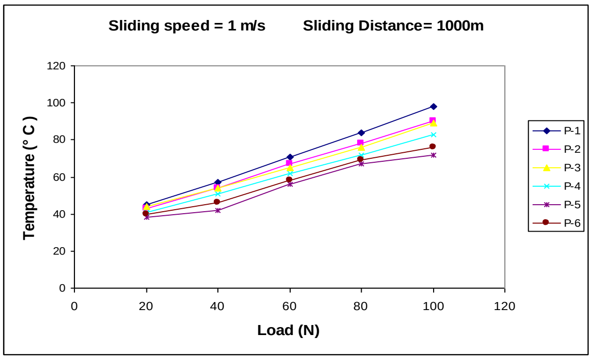


Figure 5: Variation of temperature vs. different loads at 1 m/s sliding speed and 1000m sliding distance.

Dry sliding wear tests were also conducted for load bearing capacity of the pin compositions for a long sliding distance of 2 km with sliding speed of 1 m/s and at a normal load of 60N. Figure 6 (a-c) shows the wear volume, volumetric wear rate and wear resistance of the test specimens for sliding distance of 2000m with sliding speed of 1 m/s and at a load of 60N. Results indicate that wear volume, wear rate are more and wear resistance is less for the untreated Al-15Si-4Cu cast alloy. The additions of grain refiner M13, modifier (Sr) and refiner (P) to the unmodified alloy grain refiner (Al-1Ti-3B), modifier (Sr) and refiner (P) reduces the wear volume, wear rate and increases the wear resistance of the cast alloy. Figure 7 shows one of the photographs of the data acquisition report of the specimen with sliding velocity 1 m/s, normal load 60N and for a sliding distance of 2000m.

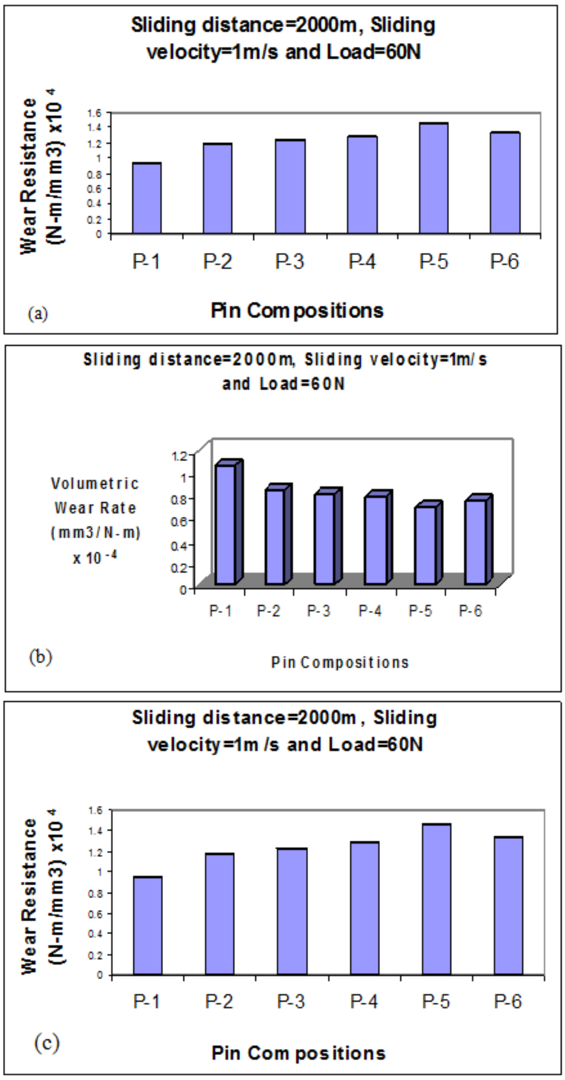


Figure 6 (a-c): Wear volume, wear rate and wear resistance of test specimens for sliding distance of 2000m, sliding velocity of 1m/s and at a normal load of 60N.

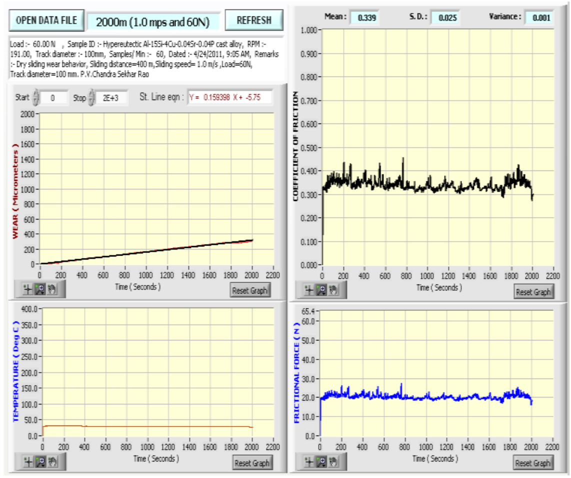


Figure 7: Data acquisition report of the specimen.

4. Conclusions

The influence of grain refiners, modifier and refiner on wear - friction behavior of hypereutectic Al-15Si-4Cu cast alloy was investigated and the following conclusions were drawn:

- Dry sliding wear behavior of the hypereutectic Al-Si cast alloys depend on the size, shape and size distribution of α- aluminum grains and secondary phase particles in the matrix.
- The additions of modifier (Sr), refiner (P) and grain refiner (Al–1Ti–3B) to the unmodified Al-15Si-4Cu alloy convert large α-aluminum grains into fine equiaxed α-aluminum grains and eutectic silicon plates into fine particles and fine CuAl2 particles in the interdendritic region leading to better mechanical properties and hence improved wear resistance.
- Combined modification, refinement, and grain refinement minimizes the oxidation of the matrix. The best combined modification, refinement, and grain refinement (Al-15Si-4Cu-0.04 Sr-0.04P-1M13) alloy recorded minimum coefficient of friction and temperature at high wear load.
- The hypereutectic Al–Si alloys investigated exhibit work hardening and plastic deformation during dry sliding wear testing; the modified, refined and grain refined Al–15Si–4Cu cast alloys work-hardened to a greater extent than the un-treated alloys.

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