Effect of Grain Refinement on Microstructure and Wear Behavior of Cast Al-7Si Alloys

P.C.Meena, A. Sharma, S. Singh

The present work deals with the study of wear of Al-7Si alloys without and with the addition of grain refiners such as, Al-5Ti-1.25C, Al-5Ti-0.8C and Al-5Ti-1B individually. Grain refiner additions have shown grain refinement in the cast Al-7Si alloys. Microstructures showed morphological changes in α- Al phases from dendrite to equiexed. These changes in structure showed improvement in wear resistance of Al-7Si alloys.For this, pin-on-disc test has been performed on Al-7Si alloy samples with varying addition level of grain refiners. The worn-out surfaces of the samples were characterized by SEM studies in order to understand the wear mechanism of Al-7Si alloys against steel disc. Worn-out surfaces of Al-7Si alloys pins exhibited different surface morphologies. Although it has been found that wear mechanism was same for both without and with grain refined Al-7Si alloys. However untreated samples exhibits higher wear loss than that of grain refined samples. It was noticed that with addition of grain refiner, the samples gave smaller debris particles. This showed less wear loss during such conditions.

Keywords: Al-7Si alloy - Grain refinement - Solidification - Microstructure - Wear

INTRODUCTION

Most common applications of Al-Si alloys are components like connecting rods, pistons, engine blocks, cylinder liners, air conditioner compressors, brake drums etc. These cast components are subjected to wear loss during service. Therefore, there is a need to improve tribological properties of Al-Si alloys. The improvement in tribological properties of Al-Si alloys depend on number of material-related properties like shape, size and size distribution of the second phase particles in the matrix and microstructure. In addition to the above factors operating conditions such as sliding speed, sliding distance, temperature, load etc. also play role on tribological properties of the materials. The high wear resistance is mainly attributed to the presence of hard primary silicon particles distributed in the matrix. Due to the presence of the hard primary silicon phase, these alloys have serious machinability problems. In order to obtain the best machinability and low wear rate, the size of silicon phase is to be controlled through melt treatment. Al-Si alloys can be strengthened by adding small amount of Cu, Ni or Mg and the presence of silicon also provides good casting properties. Various studies have been reported on the dry sliding wear behaviour of the cast Al-Si alloys. A.D.Sarkar and J.Clarke[1] investigated the dry sliding wear behaviour of Al-Si alloys using pin-on-disc wear and friction machine and concluded that Si composition in aluminium alloy does not appear to be a dominant factor in the calculation of wear resistance. B.N.Pramila Bai and S.K.Biswas [2] investigated the wear behaviour of Al-Si alloys and concluded that wear rate of an alloy without silicon is significantly higher than the binary modified alloys containing silicon composition between 4% and 24%. Sarkar[3] studied the wear of Al-Si alloys against hardened steel disc and gray cast iron and reported that the wear rate of hyper-eutectic alloys is more than the hypo-eutectic alloys. Shivanath et al.[4] reported that wear resistance is good for the hyper eutectic Al-Si alloys. Somi Reddy et al.[5] investigated the wear and seizure behaviour of Al-Si alloy containing silicon composition upto 23wt% using pin-on-disc wear and friction testing machine under various loads. It was observed from the results that wear and seizure resistance increases with the addition of silicon to aluminium

A.D.Sarkar and J.Clarke[1] conducted experiments on Al-Si alloys and suggested that wear fragments are produced from the transferred material and high Young's modulus of the hypereutectic cast alloys increases their propensity to wear. C.Subramanian[6] studied the effect of sliding speed on wear behavior of Al-Si alloys and reported that the wear rate decreases with increasing sliding speed upto a critical speed. A.S.Anasyida et al.[7] has investigated the effect of element additions on the dry sliding wear of Al-Si alloys .P.K.Rohitgi and B.C.Pai[8] investigated the effect of microstructure and me-

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chanical properties on the seizure resistance of aluminium alloys and concluded that seizure resistance of aluminium can be improved by alloying with silicon and nickel. This is due to the precipitation of hard particles in the matrix. Ashok Sharma et al.[9] studied the worn out test pin surface topography, sub surface damage and debris by SEM. The worn-out test pin surfaces for all the alloys showed a multitude of distinct topographical features in the SEM images. It was found that a number of wear processes, such as delamination, adhesion and abrasion take part in removal of metal as debris, and no single wear process was responsible for metal removal from sliding surfaces. D.K.Dwivedi et al. [10] reported that the addition of alloying element and inoculants to the Al-Si alloy reduces the wear rate and increases the transition load. Taking into account all the earlier findings a systematic study of wear rate without and with addition of grain refiners individually in Al-7Si alloys are carried out and reported in the present paper.

EXPERIMENT PROCEDURE

Synthesis of Cast Alloy

Experimental alloy was prepared by careful melting and dilution of master alloy of Al-20% Si in combination with Al of 99.99% purity in the electric resistance furnace at 720°C provided with ± 5°C accuracy by a digital temperature controller. Necessary allowances for melting losses were also taken into account in computation of charges. After proper mixing, the molten alloy was cast in metallic moulds. The nominal compositions of base alloys were Al-7%Si and Al-7Si-0.45Mg. All the compositions have been expressed in wt. %.The compositions of Al-7Si alloys studied in the present investigation are shown in table 1. The LM25 alloy was selected in addition to Al-7Si alloy to understand the grain refining efficiency of Al-Ti-C and Al-Ti-B master alloys in the presence of Mg.
Al-7Si alloys were grain refined with the addition of 0.2wt%, 0.6 wt%,1wt% and 1.4wt% of Al–5Ti-0.8C, Al–5Ti-1.25 C and Al–5Ti-1B master alloys individually in the melt.

Metallography

Samples for microstructural studies were cut from ingot castings. Specimens were polished by standard metallographic procedure using a series of emery papers from 1/0 to 4/0 grade and finally polished on sylvet cloth using fine alumina powder. Polished samples were etched with Keller's reagent. Worn out pin surfaces and wear debris generated during wear test were subjected to SEM study.

Wear test

Wear test procedure

Experiments were carried out using at the constant load of 1 Kgf and constant sliding velocity of 1m/s, for a sliding distance of 1800m for each test which was sufficient for highlighting reliable difference among the specimens (Fig. 1). The load was applied by weights. Wear of the test specimens was determined by the weight loss. Tests were conducted at room temperature30±3ºC and humidity 55.The wear volume was studied under the constant sliding distance, load, sliding velocity (sliding distance 1800m, load velocity 1M/s; load 1N/m and 170 rpm) and varying alloy composition. Dry sliding wear tests were conducted on 6 mm diameter and 25 mm long cylindrical wear pins. Wear tests were carried out under given sliding conditions for all sample as shown in Fig.1. The duration of each experiment was 30 minutes. The experiment was performed for all type of alloy (Al-7Si alloys) castings. The flat surfaces of both the test pins and the steel disc were ground to a surface finish about 4 μm. Before each experiment the disc and the test sample were thoroughly cleaned with alcohol and acetone and subsequently dried with warm air to have identical sliding conditions. After each experiment the steel disc was reground to restore the original surface conditions and a new test pin was used for each experiment. Wear was determined by weighing the test samples before and after the test with the help of single pan balance.
An electronic single pan weighing balance (mettler) accurate up to 0.1 mg was used for weighing the samples before and after the test. A new test pin was used for each experiment.

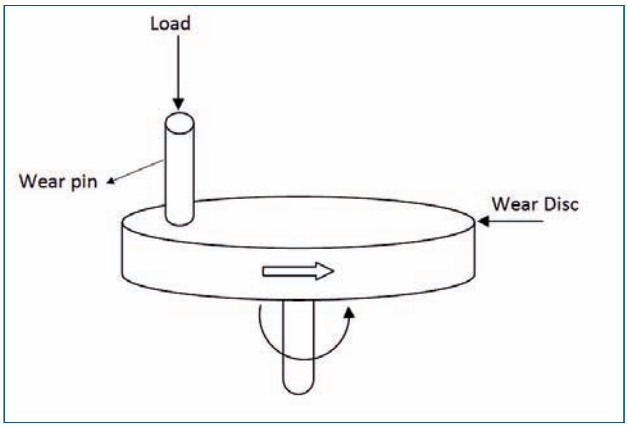

Fig. 1 - Schematic representation of the pin-on-disc wear monitor

Tab. 1 - Chemical composition of the Al-7Si alloys used in the present study

Metal/alloy	Composition (wt %)									
	Si	Fe	Sr	Cu	Mg	Zn	Mn	Ti	Others	Al
Al-7Si	6.9	0.16	-	-	-	-	-	-	-	Balance
LM25(Al-7Si-.45Mg)	7.0	0.20	-	0.20	0.40	0.10	0.10	0.19	-	Balance

RESULT AND DISCUSSION

Microstructure

Fig.2 (a-d) show microstructures of Al-7Si alloy for both without and with addition of grain refiners. From Fig.2 (a) it is observed that α-phase is showing coarse columnar grain structure (grain size 590µm). However when 0.2wt% of different grain refiners are added individually in Al-7Si alloy , the α-phase became finer as shown in Fig.2 (b-d). The dendritic α-phase has converted into equiaxed dendritic structure. The maximum effect of grain refinement is observed in case of addition of 0.2wt% of Al-5Ti-0.8C master alloy grain refiner where grain size reduced to 170 µm. Al-5Ti-1.25C observed minimum effect on α-phase (grain size 210 µm) while Al-5Ti-1B master alloy showed intermediate effect on α-phase (grain size 190 µm). This was attributed to the fact that Al-5Ti-0.8C grain refiner released both $TiAl_3$+TiC particles in the melt, which showed both nucleant and solute effect for grain refinement. The nucluent particles ($TiAl_3$+TiC) released from Al-5Ti-0.8C grain refiner have shown more powerful effect than from $TiAl_3$+TiB_2particles released from Al-5Ti-1B grain refiner. While Al-5Ti-1.25C grain refiner released only TiC particles. Therefore in this case solute effect was missing, hence Al-5Ti-1.25C showed minimum grain refinement effect. Fig.3a shows microstructure of Al-7Si-0.45Mg alloy. In this case also the α-Al phase is having coarser dendrites (grain size 500µm) as shown in Fig.3a for Al-7Si-0.45Mg alloy. The presence of Mg might contribute to some extent the solute effect which in turn contributes to grain refinement effect. Fig.3 (b-d) for 0.2wt% of addition of different grain refiners in Al-7Si-0.45Mg alloys are showing similar trend as is seen in Fig.2 (b-d) for Al-7Si alloy. The grain size with addition of 0.2 wt %. Al-5Ti-0.8C, Al-5Ti-1 .25C and Al-5Ti-1B master alloys are 155µm, 200µm and 170µm respectively. From above results it is understood

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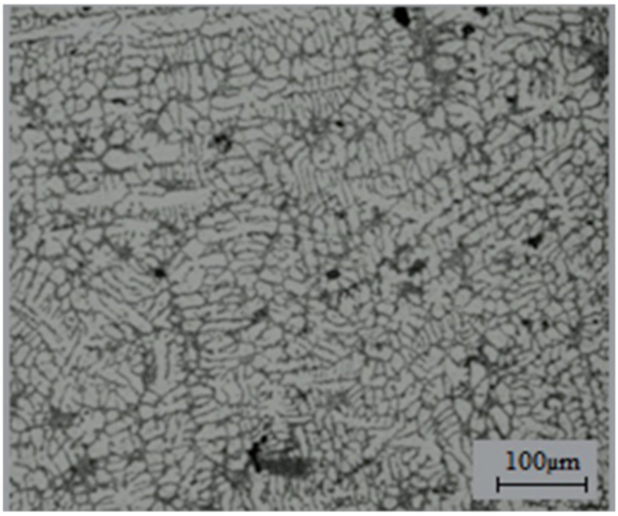

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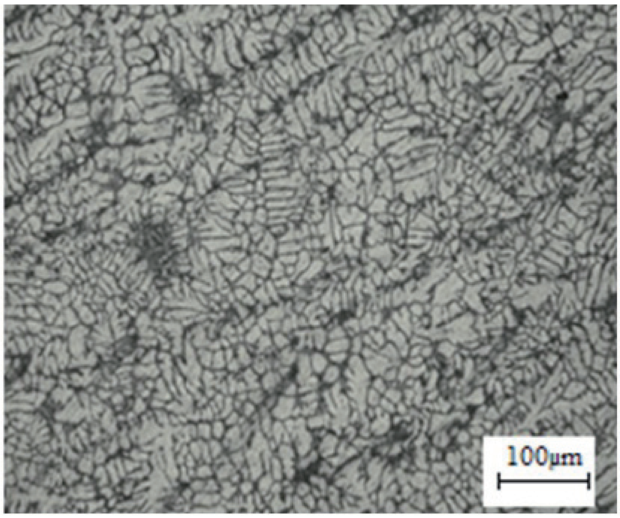

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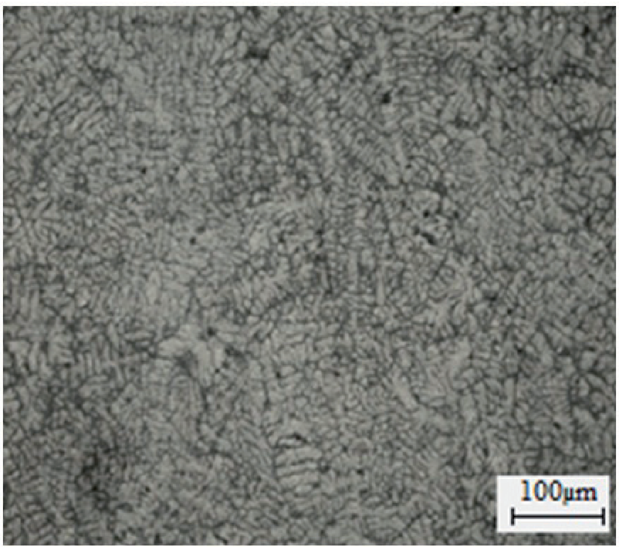

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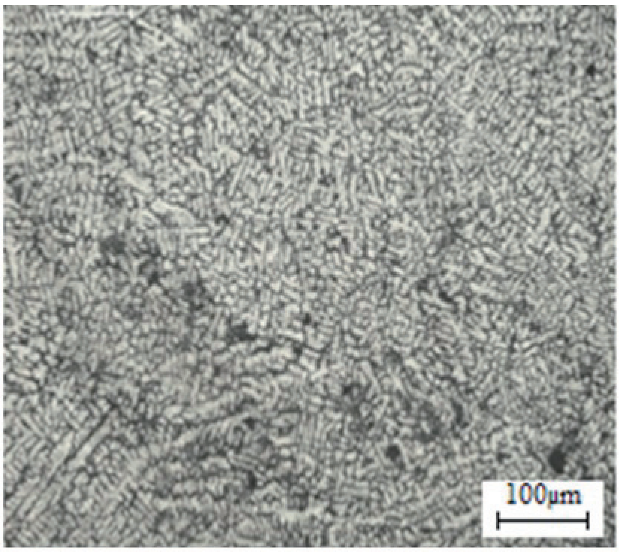


Fig. 2 - Microstructure of Al-7Si alloy without addition of grain refiner (a) at 0 min. and with addition of 0.2wt. % of (b) Al-5Ti-1.25C (c) Al-5Ti-0.8C (d) Al-5Ti-1B grain refiners at 2 mins. of holding time.

a) b) c) d)

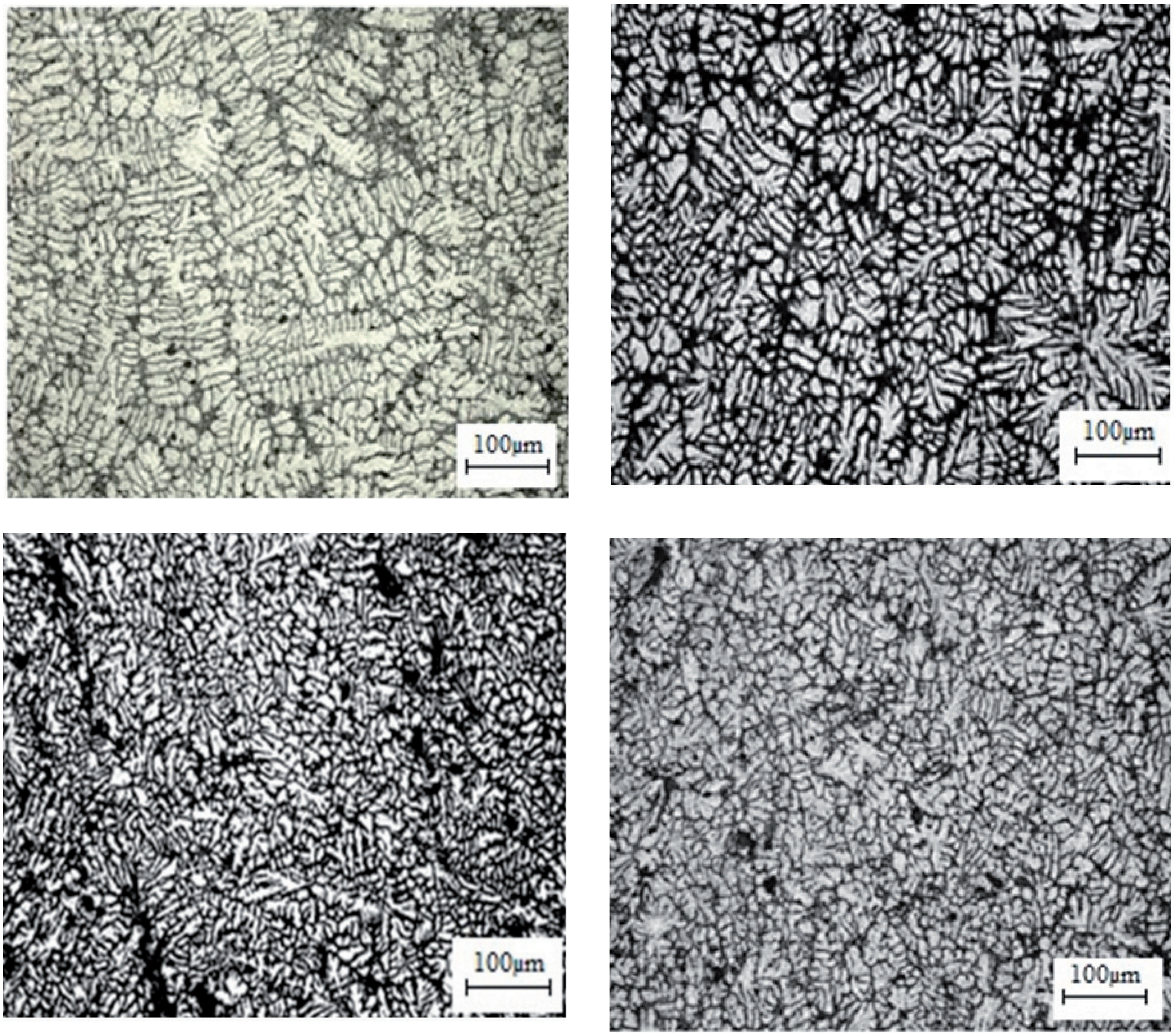


Fig. 3 - Microstructure of Al-7Si-0.45Mg alloys without addition of grain refiner at (a) 0 min. and with addition of 0.2wt% grain refiner of (b) Al-5Ti-1.25C (c) Al-5Ti-0.8C (d) Al-5Ti-1B at 2 mins. of holding time.

that the addition of grain refiners to Al-7Si alloys resulted in the change in the shape of the α-grains from coarse columnar to fine quiaxed [11-14] .
The hardness of cast Al-7Si alloy is 59VHN. The hardness of cast Al-7Si -0.45Mg alloy is 61VHN.With the addition of grain refiners improvement in the hardness is about 10%. Tensile strength of as cast Al-7Si alloy is 160 MPa and yield strength is 80 MPa which increased after addition of grain refiners to about 20%. In case of Al-7Si-0.45Mg alloy, as cast tensile strength is 166 MPa and yield strength is 90MPa which also increased after addition of grain refiners to about 20%.

Wear rate vs wt % addition level of different grain refiners

Al-7Si and Al-7Si-0.45Mg alloys to without and with addition of grain refiners are subjected to wear studied. The results are as given hereinafter;

(i) For Al-7Si alloy

Figure 4 shows wear rate vs wt. % addition level of different grain refiners in Al-7Si alloy at holding time of 2 min. Lowest wear rate is observed in case of Al-7Si grain refined with Al-5Ti-0.8C master alloy in comparison to Al-5Ti-1.25C and Al-5Ti-1B master alloys at all addition level. It was also observed that as the wt. % addition of grain refiners increased there is decrease in wear rate because of decrease in grain size. The wear rate is lowest at 1.4wt.% addition level, which correlates to the lowest grain size obtained under the present grain refining condition. The trend of the graph remains same in all the three cases, wear rate decreases with increasing amount of grain refiner.

(ii) For Al-7Si-0.45Mg alloy

Figure 5 shows wear rate vs wt. % addition level of different grain refiners in Al-7Si-0.45Mg alloy at holding time of 2 min. Lowest wear rate is observed in the case where Al-

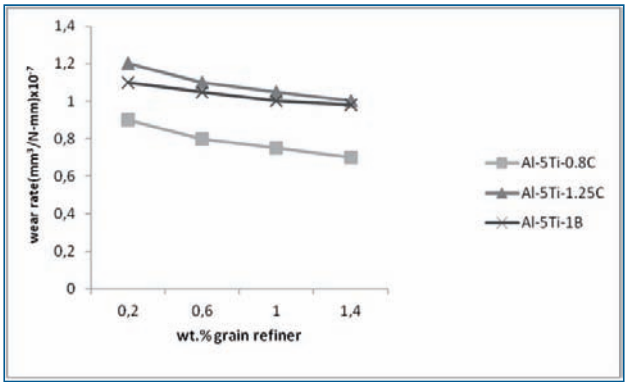


Fig. 4 - The wear rate vs varying wt% addition of different grain refiners in Al-7Si melt at 2 min. of holding time

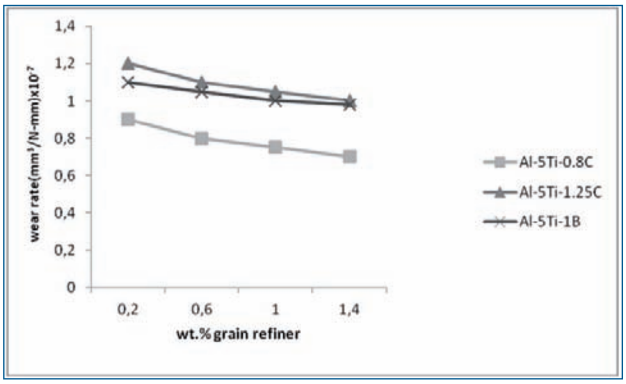


Fig. 5 - The wear rate vs varying wt% addition level for different grain refiners in Al-7Si-0.45Mg melt at 2 min. of holding time

7Si-0.45Mg is grain refined with Al-5Ti-0.8C master alloy in comparison to Al-5Ti-1.25C and Al-5Ti-1B master alloys at all addition level. It was observed that as the wt. % addition of grain refiner increased there is decrease in wear rate because of decrease in grain size. The wear rate is lowest at 1.4 wt% addition level, which correlates to the lowest grain size obtained under the present grain refining condition. The trend of the graph remains same in all the three cases, wear rate decreases with increasing amount of grain refiner.

SEM Study

In order to study the different modes of wear taking place during pin-on-disc test (at 1m/s speed and 1N load), worn surfaces of Al-7Si and Al-7Si-0.45Mg alloy pins were studied by using scanning electron microscope. Figure 6 (a-e) shows worn pin surface morphologies of Al-7Si alloy without any grain refiner (Fig.6a) and with addition of different grain refiners [Fig.6(b-e)] . Fig. 6 (a) shows worn out surface of Al-7Si alloy without adding any grain refiner. The surface layer is seen to be in a state of plastic flow and showing scoring marks, craters and furrows. Figure 6 (b-e) shows various features of worn pin surfaces of Al-7Si alloy with the addition of 1.4 wt. % addition of different grain refiners. These exhibit oxide film, lesser number of craters and loose particles in comparison to Fig.6 (a). White layer is more prominent in Fig.6 (a) which is indicating that due to frictional heat, temperature at the interface was very high.

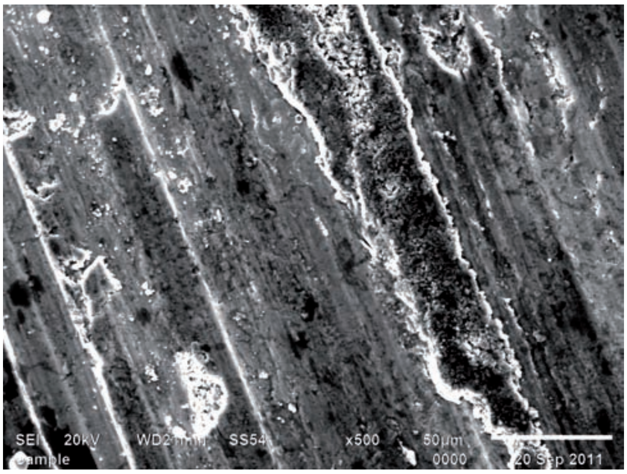
From Fig. 6 (b) it is observed that scoring marks are less prominent in comparison to SEM microstructure shown in Fig.6 (a). The magnified view of Fig.6 (c) has been shown in Fig.6 (d), where due to edge cracking particles are seen in a process of detachment from the edges. Fig. 6 (e) has shown worn out pin surface of Al-7Si alloy grain refined with 1.4wt. % of Al-5Ti-1B grain refiner. The SEM image of pin surface of Fig.6 (e) is comparable with Fig.6(c). From SEM images [Fig.6 (c-e)] it is observed that scoring marks, craters and detached laminates are not so prominent as in the case of Fig.6 (a). This shows that the wear resistance has improved with addition of grain refiners. Fig.6(c&d) has shown lesser number of worn out features in comparison to Fig.6 (a,b&e).

Figure 7(a-d) shows worn out pin surface morphologies of Al-7Si-0.45Mg alloy without any grain refiner (Fig.7a) and with addition of different grain refiner [Fig.7 (b-d)] . From Fig. 7 (a) it is seen that surface layer is in a state of plastic flow with scoring marks and furrows.

The presence of oxide particles, delaminate flake, and craters are also observed. The worn out pin surface is showing deep grooves and smooth strips which are caused by hard metallic particles. Some oxide particles are also seen on the pin surface. The white layered structure on the pin surface indicates that temperature at friction surface was very high. Fig.7 (b) shows worn out surface with the addition of 1.4 wt. % of Al-5Ti-1.25C grain refiner. Fig.7(c) shows worn out pin surface with addition of 1.4 wt. % of Al-5Ti-0.8C grain refiner. Fig.7 (d) shows worn out pin surface grain refined with 1.4 wt. % of Al-5Ti-1B master alloy. Some craters have been seen in Fig. 7(a & b) which might be due to detachment of surface layer from the pin surface. Ploughing features are less prominent in Fig. 7 (b) in comparison to Figs. 7 (a). This clearly shows that with the addition of 1.4 wt. % addition of Al-5Ti-1.25C grain refined wear rate has reduced. Fig.7 (c) shows rough grooves in Al-7Si-0.45Mg alloy wear pin grain refined with 1.4wt.% of Al-5Ti-0.8C master alloy. Fig.7 (d) shows more numbers of grooves, debris particles in comparison to Fig.7(c).

Debris

It is observed that during sliding a black powder gradually generated from wear pin surface and is seen to be piled-up on both the sides of the wear tracks of steel counter face. Since sliding generates frictional heat, oxidation of fresh mating surfaces might have taken place in the working atmosphere. The black powder could be a mixture of oxides of alumina and other constituents with metallic debris along with some fine oxide debris. Representative samples of Al-7Si and Al-7Si-0.45Mg alloy without and with addition of grain refiner are taken for observation under SEM. For comparison purpose only samples after grain refined with 1.4wt. % of Al-5Ti-0.8C grain refiner for Al-7Si and Al-a)



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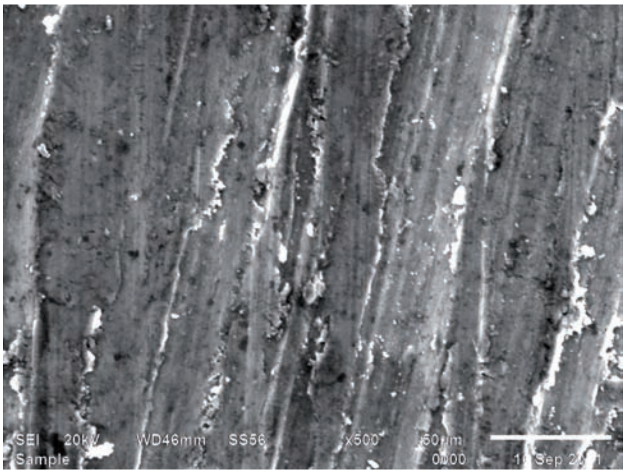

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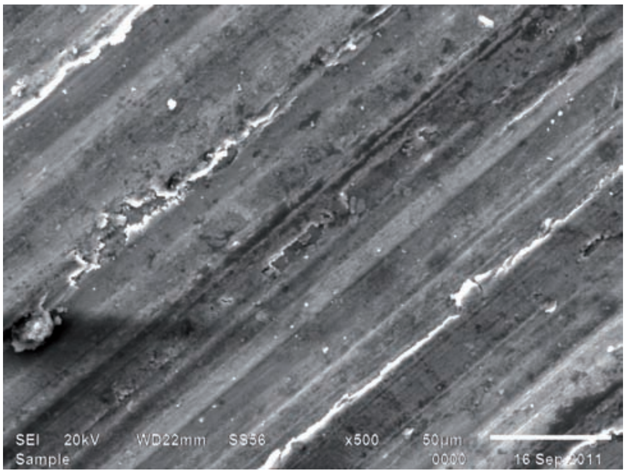

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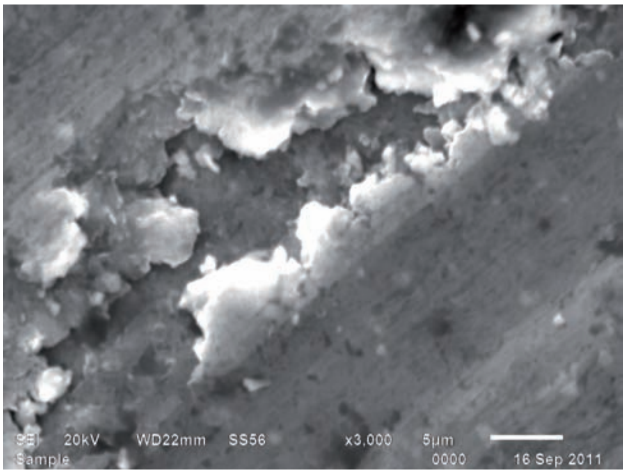

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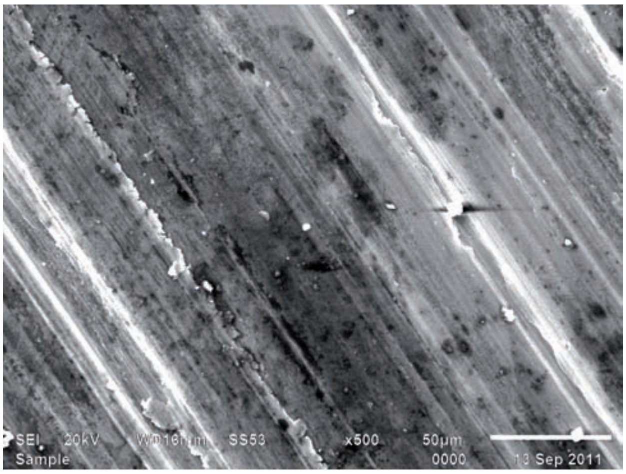


Fig. 6 - SEM photo micrographs of Al-7Si alloy wear pins (a) without grain refiner and with 1.4 wt. % of grain refiners (b) Al-5Ti-1.25C and (c) Al-5Ti-0.8C (d) Al-5Ti-0.8C at high magnification (e) Al-5Ti-1B

7Si-0.45Mg alloy are taken and compared with respective alloys when no grain refiner was added.

Figures 8(a) shows debris generated from as cast worn out pin surfaces of Al-7Si alloy (Fig.8a) and Al-7Si-0.45Mg alloy (Fig.8b). While Fig.8(c & d) show debris generated from worn out pin surface of Al-7Si alloy (Fig.8c) and Al-7-Si-0.45Mg alloy (Fig.8d) grained refined with 1.4wt.% of Al-5Ti-0.8C grain refiner. Debris generated from pin surfaces without adding any grain refiner is larger in comparison to respective grain refined samples. Grain refinement has reduced the wear rate which is quite clear while comparing the debris morphologies.

DISCUSSION

The results show that the wear rate decreases with the decrease in the grain size of Al-7Si alloys at a load of 1 N, sliding distance of 1800 m and sliding velocity of 1 m s^{-1} under dry sliding condition. The results suggest that wear properties also dependent on the addition level and type of grain refiners used. Grain refinement improved the load bearing capacity of Al-7Si alloys. The yield strength of the sample can be estimated according to the Hall-Petch relationship [15],

$$\sigma_s = \sigma_0 + K.d^{-1/2}$$

where σ_s is the yield strength of the sample, σ_0 is the yield strength of a single crystal, K is a constant value related with crystal structure, and d is the size of a grain. According to this equation it is very clear that larger the diameter of the grain, lower will be its yield strength. Therefore the

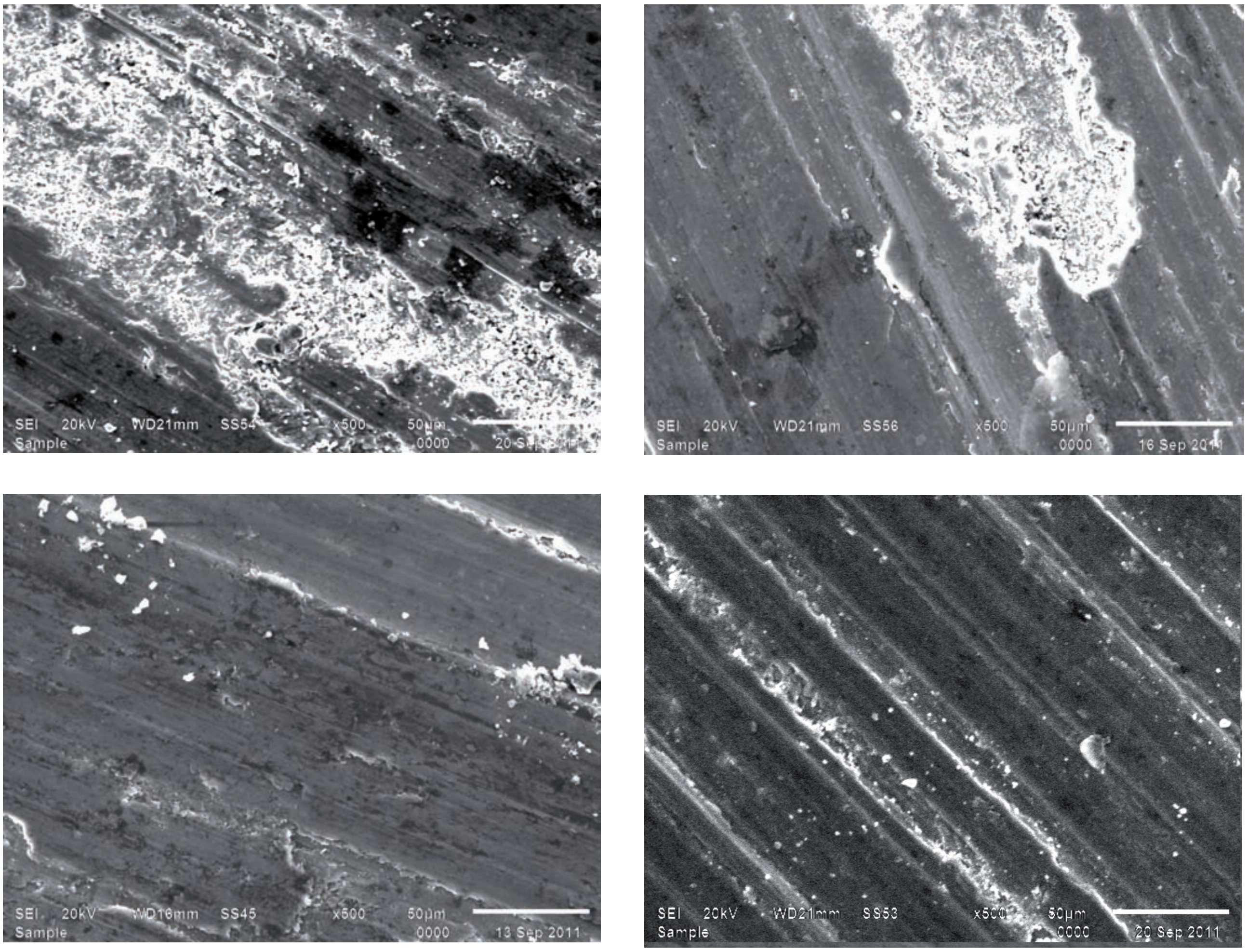


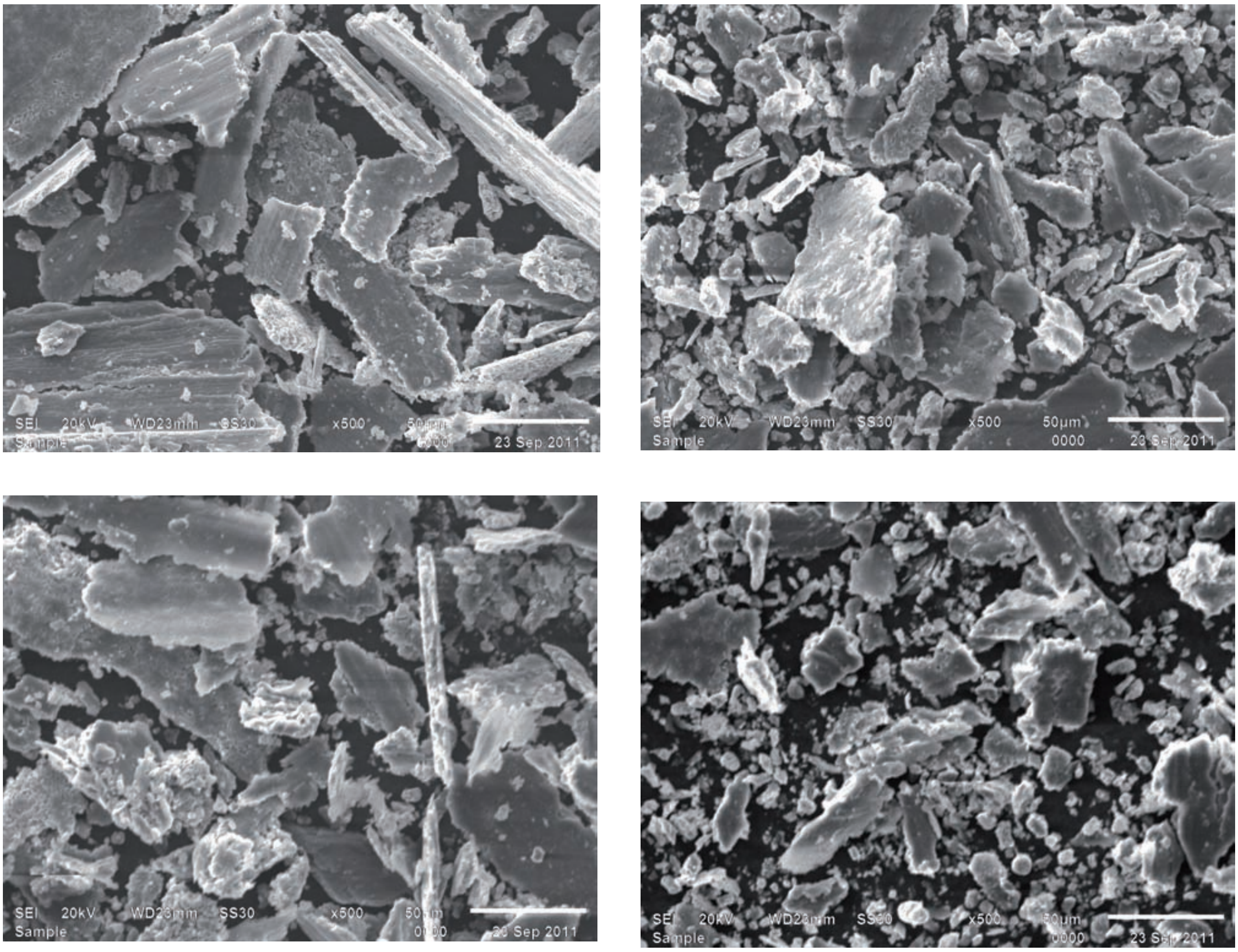
Fig. 7 - SEM photo micrographs of Al-7Si-0.45Mg alloy wear pins (a) without grain refiner and with 1.4 wt. % of grain refiners (b) Al-5Ti-1.25C (c) Al-5Ti-0.8Cand (d) Al-5Ti-1B

maximum yield strength is observed when the grain size is the smallest. This is so because the grain boundaries act as effective obstacle for slip dislocation on initial deformation stage, while the stress on heavy deformation stage is predominantly affected by the interaction and across of dislocation rather than the presence of grain boundary. The behavior of slip dislocation with decreasing grain size was interrupted by numbers of grain boundaries. Therefore, the yield strength and elongation were improved with decreasing grain size. Decrease in grain size increases the grain boundary area and results in improvement of strength. Improvement in strength and hardness resist wear loss during sliding. Therefore, grain refiner additions have shown Improvement in wear resistance of the sliding samples.

Although it has been found that wear mechanism of Al-7Si alloys is same under without grain refiner and with grain refiner addition. However, without grain refinement Al-7Si alloys exhibited greater wear loss than that of grain refined Al-7Si alloys. The wear rate decreased with increase in the weight percentage of grain refiners. This is attributed to the fact that the nucleating particles were able to withstand thermal softening effects due to reduced grain size and the formation of oxidative protective transfer layer.

The wear debris generated during sliding of pin against steel disc is mainly flakes of oxide and particles. Wear debris formed during sliding developed a tribolayer by a process of transfer from one surface to another, which resulted in the consolidation of these plastically deformed and oxidized particles into a hard, protective layer that reduced the overall wear rate. It was reported [16] that this transition in the wear regime was more significant at elevated temperatures, where the wear scar developed a very smooth tribolayer. The material could be transferred back and forth several times during sliding and eventually produce wear debris particles. It was suggested [17-18] that the formation of these wear particles could be a direct result of their work-hardenability. It was further suggested that a critical transfer layer thickness existed for a given sliding situation. At this critical value, wear debris particles were thought to form by delamination at or near the interface between the transferred material and the base material. During dry sliding of Al-Si alloys against steel systems, it was shown by Antoniou et al. [19] that a finely dispersed amphorous iron oxide formed on the wearing surfaces. This was due to the oxidation of a significant proportion of the steel counter face. This phase helped to stabilize

a) b)



c) d)

Fig. 8 - SEM photo micrographs of debris (a) Al-7Si alloy without grain refiner (b) Al-7Si alloy grain refined with 1.4 wt. % of Al-5Ti-0.8C master alloy (c) Al-7Si-0.45Mg alloy without grain refiner (d) Al-7Si-0.45Mg alloy grain refined with 1.4 wt. % of Al-5Ti-0.8C master alloy

the tribolayer on the alloy surface by pinning dislocations. The composition of these layers consisted of an intimate (mechanical) mixture of materials derived from both sliding materials.

The worn surfaces of the specimens were characterized in order to understand the wear behavior of Al-7Si alloys against steel disc. Although it has been found that wear mechanism of Al-7Si alloys is same for both untreated and grain refined alloys. However, earlier exhibited higher wear loss than that of grain-refined Al-7Si alloys. Similar studies were made by Prasad Rao et.al [18] on the influence of grain refinement on the wear mechanism of Al-7Si alloys. The grain refinement of Al by inoculating with Al-Ti or Al-Ti-B grain refiners leads to decrease in the size and aspect ratio of the grains.

Heat is also generated at the interface while sliding take place due to friction. When two asperities are in contact at a given instant and at a location temperature rises ΔT at the interface. This is a function of a few independent variables, like load, sliding velocity, real area of contact type and addition level of grain refiners and the average thermal conductivity of the two contacting bodies. In the adhesive theory of wear, as suggested by Archard [20] , Burwell and Strang [21] and Bowden and Tabor [22] it is assumed that in the absence of lubricant the asperities on the opposing surfaces adhere strongly and form asperity junctions. Subsequent separation of the surfaces occurs either at the interface or inside the bulk of the weaker asperity, depending on the relative strengths of the junction and the materials. When Al-7Si alloys were slide against steel counterface, separation occurs in the asperities and fragments of this material are transferred to the harder surface. Subsequently, this transferred material may become detached and form loose wear fragments. According to Rabinowicz [23] , lump removal is due to material separation over a weak section dissimilar to the original surface of joint. The separated material is to be transferred on to the other surface without formation of free fragments. The adhesion wear is considered as a fatigue process. Abrasive wear shows presence of clean furrows cut by particles causes grooving. During fatigue, in presence of surface or subsurface cracks accompanied by pits and spalls causes sharp and angular edges around pits.

In the delamination theory of wear, proposed by Suh [24] for unlubricated sliding situations, wear particle formation is explained in terms of deformation and fracture of material near the sliding surface. It is suggested that surface and sub-surface deform plastically as a result of surface traction imposed on the sliding surfaces. Consequently, accumulation of incremental plastic strain leads to micro-crack and micro-void formation at a critical depth below the contact surface, where some fracture criteria can be satisfied. Propagation of these subsurface cracks parallel to the surface as a result of stress conditions in the material leads to loose flakes, long and thin sheet-like wear particles are generated. The process of crack formation and propagation has been analyzed by Jahanmir and Suh [25] . Using mechanics of contacts, they found that, under sliding situations, the criteria for generation and propagation of cracks are satisfied at a critical depth below the contact surface. This critical depth is dependent on the material properties, the contact load and the friction coefficient.

From above discussion, it is clear that no single wear mechanism is responsible for the production of material loss from the sliding surface. SEM studies of worn pin surface for all the alloys show a multitude of distinct topographical features. There can in some cases be a direct effect where material is detached by delamination. Delamination wear producing craters is a prominent feature of mild wear regimes and depends upon sub-surface failure. By repeated sliding, fatigue induced cracks initiate at a finite subsurface depth and propagates to the surface causing delamination. Various shapes and sizes of wear debris were found as a result of dry sliding. The debris includes the flakes, chips, and oxide powder. The debris essentially consists of laminates produced by fracturing of compacted material. It shows that during sliding of wear pin, more than one process took part in generation of debris. The generation of laminate debris may be a more delayed event, as it would take several sliding interactions for cracks to initiate and propagate. Morphological observations of worn pin surface indicate that delamination is a main mechanism responsible for removal of material in mild oxidative wear conditions. Failure by a delamination process is clearly indicated by the shape of the debris particles.

It is observed that Al-7Si-0.45Mg alloy grain refined with 1.4wt. % of Al-5Ti-0.8C master alloy could resist adverse conditions of wear better in comparison to Al-7Si alloy under similar conditions. In case of Al-7Si alloy, the presence of Si strengthens the aluminium matrix. In case of Al-7Si-0.45Mg alloy, in addition to the presence of Si, the Mg has also additive role in improving the strength of the matrix. Strengthening of matrix reduces wear rate. It has been established that the addition of grain refiners in Al-7Si alloys result in the change in the shape of the grains from coarse columnar to fine equiaxed. Due to fine grains wear resistance of the material improved and the lower wear rates were obtained in such cases. Numerous potent heterogeneous nucleation particles are added through the master alloys which act as nucleants to Al-7Si alloy. Grain refinement of Al-7Si alloys leads to decrease in the size of the grains [26] . This in turn increases the grain boundary area and results in improvement in strength. The grain boundary strengthening has shown improvement in the wear resistance of Al-7Si alloys. Hence, it is understood that the wear resistance of grain refined Al-7Si alloys increased with the decrease in grain size. Thus finer grain size and equiaxed grain shape both are important parameters for better wear resistance in Al-7Si alloys.

CONCLUSIONS

From the present study following conclusion are drawn;

1. The wear resistance of grain refined, Al-7Si and Al-7-Si-0.45Mg alloys increased with decrease in grain size with respect to without grain refined Al-7Si and Al-7Si-0.45Mg alloys. This was attributed to the fact that due to finer grains, grain boundary strengthing took place.
2. SEM studies of worn pin surfaces for all the alloys showed a multitude of distinct topographical features such as debris, scoring marks and edge cracking. The worn pin surface is simultaneously subjected to more than one mode of metal removal in the form of debris.
3. Debris generated from pin surfaces without adding any grain refiner was larger in comparison to respective grain refined samples.
4. Finer grain size and equiaxed grain shape both are important parameters for better wear resistance in Al-7Si alloys.

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