Effect of Phosphorus Addition on Friction-Interface Temperature and Wear Behaviour of Hypereutectic Al-Si Alloys

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The effect of phosphorus addition on friction-interface temperature and wear behaviour of hypereutectic Al-Si alloys (Al-13, 14, 15, 17 and 20 Si) are experimentally investigated. Pin-on-disc wear testing machine is used to conduct wear and friction tests under dry sliding conditions, by varying normal pressures and sliding velocities. Interface temperatures are recorded with non-contact type Infrared thermal imaging camera. Friction–interface temperature and wear rates are greatly influenced by normal pressure, sliding velocity and microstructure of the material. Wear rate, frictional force and interface temperature increase with increase in normal pressure. Whereas wear rate decreases with increase in sliding velocity, frictional force and interface temperature increases with increase in sliding velocities. It has also been reported that addition of phosphorus decreases wear rate, frictional force and interface temperatures, at varying normal pressure and at varying sliding velocities. Worn surface and wear debris analysis is also carried out to understand the wear mechanisms operating under varying wear parameters.

Keywords: Wear, hypereutectic Al-Si alloys, worn surface, wear mechanisms.

Introduction

Hypereutectic Al-Si alloys have excellent wear resistance, low thermal expansion coefficient, castability, good fluidity and machining characteristics. However, tool life is affected by hard Si phase present in the matrix. Primary and eutectic silicon are the key components of microstructure. Hard primary and eutectic silicon particles in hypereutectic Al-Si alloys induce high strength and wear resistance. However, coarse primary and eutectic silicon leads to brittleness and hence premature crack initiation and fracture in tension[1]. Shape, size, composition and distribution of silicon in hypereutectic silicon alloys are of great concern for researchers. In one of the earlier works, it had been concluded that with increase in percentage of silicon to near eutectic composition, there is an increase in wear resistance[2]. It is also reported that with increase in silicon content above the eutectic composition results in higher wear rates[3]. In selecting wear-resistant material, it is very necessary for the designers and engineers to have the sound knowledge of microstructure and its significance on wear rate. It is known that sliding of two surfaces on one over the other results in conversion of frictional work into heat. The temperature rise due to this phenomenon results in change of mechanical, metallurgical properties and wear behaviour[4].

Apart from microstructure and mechanical properties, wear behaviour of Al-Si alloys depends upon a number of operating conditions[5-7]. Earlier studies indicate that increase in contact pressure results severe wear due to formation and dislodging of oxide film[5-7].

Dheerendra Kumar Dwivedi[8] reported that wear rate and frictional force are inversely proportional to sliding velocity upto a critical value, however with increase in sliding velocity above the critical value, there is an increase in wear rate, while frictional force decrease. It is also reported that as sliding velocity increases, there is proportional increase in interface temperatures.

Venkataraman and Sundararajan[9] reported that tribological properties of Al-Si and Al-SiC alloys is highly dependent on development of mechanically mixed layer (MML) and its fracture rate as compared to bulk properties of the material. K. Lepper conducted experiments to study the tribological properties of certain Al-Si alloys and concluded that testing environment plays an important role in deciding the wear rate as compared to composition and microstructure[10]. In general, wear behaviour is governed by surface properties of the material; that is why mechanical layer formed during dry sliding wear plays a vital role in forecasting wear rate and wear properties. Perrin and Rainforth[11] concluded that intensity of wear surface damage and wear rate can be directly related to each other. Although ample investigations are carried out on the tribological behaviour of as-cast hypereutectic Al-Si alloys, only a few researchers paid attentions in analysing the effects of elemental additions and other treatments on the wear behaviour of hypereutectic Al-Si alloys[15-21]. Considering the literature, experiments are carried out to study the effect of minor additions of Phosphorus (P) on friction-interface temperature and wear behaviour of hypereutectic Al-Si alloys with varying normal pressures and sliding velocities. In addition, worn surface and wear debris analysis is also carried out to understand the wear mechanisms operating under varying wear parameters.

Materials and Methods

Preparation of the Alloys

Hypereutectic Al-Si alloys are prepared via foundry technique. Calculated quantities of CPAL (99.7wt% purity) and A1-20Wt% Si master alloy are melted in a furnace. Cover flux is used to prevent any chances of oxidation. Hexacloroethane is added to the melt which acts as a degasifier. After the degasification of the melt, cup granules are added for refinement of primary silicon and the melt is stirred for 30 seconds. The melt is held in the furnace for about 5 minutes and then it is poured into graphite mould for preparation of wear pin specimens.

Friction and Wear Behaviour

Experiments are performed using pin-on-disc machine as per ASTM G99 standards to study the wear and friction behaviour. Wear pins of 30 mm length and 8 mm diameter were machined from the cast specimen. Wear losses were recorded by weight loss method. Tests were conducted to study the tribological wear behaviour of hypereutectic Al-Si alloys under varying normal pressure and sliding velocities.

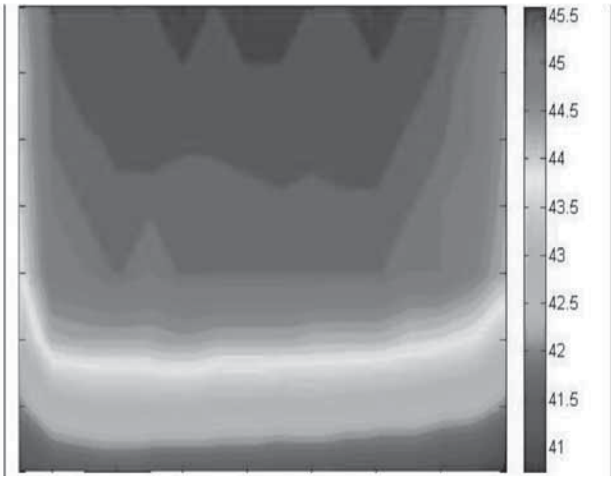

Fig.1: Thermal image and temperature distribution along the length of the wear pin.

Temperature Measurement

Measurement of pin temperature during dry sliding had been carried out with infrared thermal imaging camera. The sliding surface temperature thus measured will be referred as interface temperature in the subsequent sections. It is well-known fact that material, mechanical properties and surface oxidation are greatly affected by temperature hence making it essential to measure the interface temperature during dry sliding. Figure 1 shows temperature distribution along the length of the pin during dry sliding.

Results and Discussion

Microstructural Studies

Figure 2 shows SEM photomicrographs of Phosphorus-treated and as-cast hypereutectic Al-Si alloys. From Fig. 2, it is observed that as-cast (untreated) Al-13, 14, 15, 17 and 20 Si alloys contain large primary silicon particles with broadly distributed needle-like eutectic silicon. The various forms of coarse primary silicon particles are hexagonal, star-shaped and quadrilateral with sharp corners in an unrefined condition and are segregated at one place. But the phosphorus-treated SEM photographs clearly show refinement of primary silicon inhibition of growth of eutectic silicon. Fracture in tension and premature crack initiation is due to brittleness of large size primary and eutectic silicon.

With the addition of phosphorus refinement of primary silicon takes place, showing reduction of average sizes of primary silicon from 15.45, 16.93, 24.39, 25.09, 45.03 μm to 6.141, 7.765, 9.230, 9.986 and 22.590 μm respectively for Al-13, 14, 15, 17 and 20 Si alloys. The wear performance of hypereutectic Al-Si alloys is greatly affected by size and shape of the primary silicon particles.

Wear Studies

Effect of Normal Pressure

Figure 3 shows the wear behaviour of hypereutectic (Al-13, 14, 15, 17 and 20 Si) alloys with varying normal pressures (0.19, 0.39, 0.58, 0.78, 0.97 N/mm^2) at a constant sliding distance (565.486m) and at a constant sliding velocity (1.884 m/s) for as-cast and phosphorus-treated conditions. From Fig.3, it is clear that, the wear rate is directly proportional to normal pressure / contact load. It may be due to the fact that surface peaks get deformed under applied external pressure. The contact area between the pin and disc increases with increase in contact load from 0.19 N/mm^2 to 0.95 N/mm^2 which in turn increases the mechanical intimacy and hence increase in wear rate. It is also observed that at lower loads a stable oxide film is formed due to frictional heating

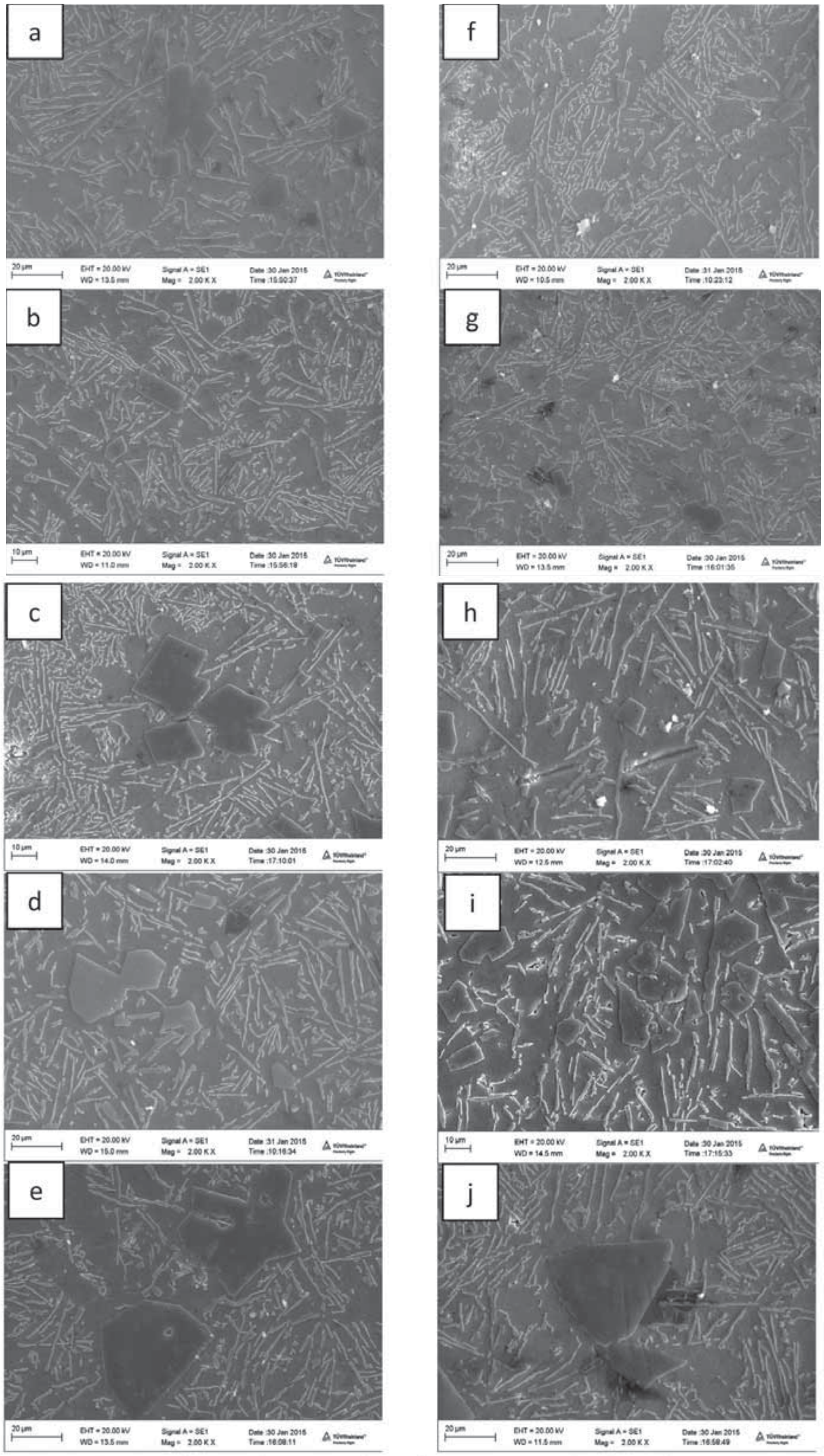

Fig.2: SEM photomicrographs of as-cast and phosphorus-treated hypereutectic Al-Si alloys. (a) Al-13Si (b) Al-14Si (c) Al-15Si (d) Al-17Si (e) Al-20Si (f) Al-13Si+0.02P (g) Al-14Si +0.02P (h) Al-15Si+0.06P (i) Al-17Si+0.06P (j) Al-20Si+0.1P.

which covers the mating surfaces of pin and the disc thus preventing direct metal to metal contact resulting in a lesser wear rate at low loads. Whereas at higher loads pin surface becomes plastic enough to deform due to higher frictional heat generated and fracture in the form of wear debris due to several processes of wear such as abrasion, adhesion and delamination. Similar results were obtained from earlier researchers[13, 14]. Figure 3 also depicts about an improvement in wear resistance of hypereutectic Al-Si alloys treated with P.

It is mainly due to refinement and even distribution of primary silicon and modification of eutectic silicon. As-cast hypereutectic Al-Si alloys have usually polyhedral fractured primary silicon phase which results in crack initiation and propagation at the coarser silicon matrix interface. Due to which primary silicon phase may not bond effectively with the matrix and can be improved with refinement of primary silicon. Phosphorus is the most effective grain refinement element of primary silicon in hypereutectic Al-Si alloys[1]. Phosphorous addition results in refinement of primary silicon and morphology changes from coarse polyhedral to near equiaxial structure with segregation and stunting in growth of eutectic silicon.

Effect of Sliding Velocity

Figure 4 shows the wear behaviour of hypereutectic (Al-13, 14, 15, 17 and 20 Si) Al-Si alloys with varying sliding velocity (0.942, 1.884, 2.827 and 3.769 m/s) at a constant sliding distance (565.486m) and at a constant normal pressure of (0.975N/mm^2) for untreated and phosphorus-treated conditions. Figure 4 clearly reveals that wear rate is inversely proportional to sliding velocities, which is varied from 0.942 m/s to 3.769 m/s. This trend is mainly attributed to more resident time at low sliding speeds. However, with increase in speeds the residential time available for the sliding is less, leading

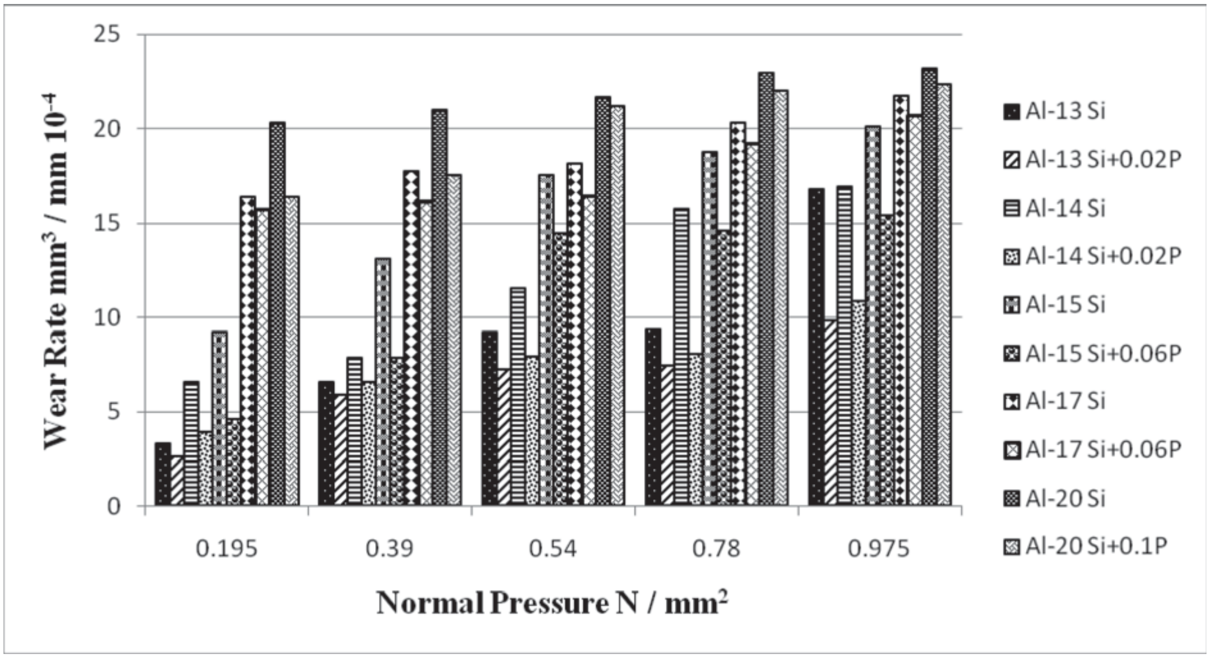

Fig.3: Effect of phosphorus addition on wear rate at varying normal pressure for hypereutectic Al-Si alloys.

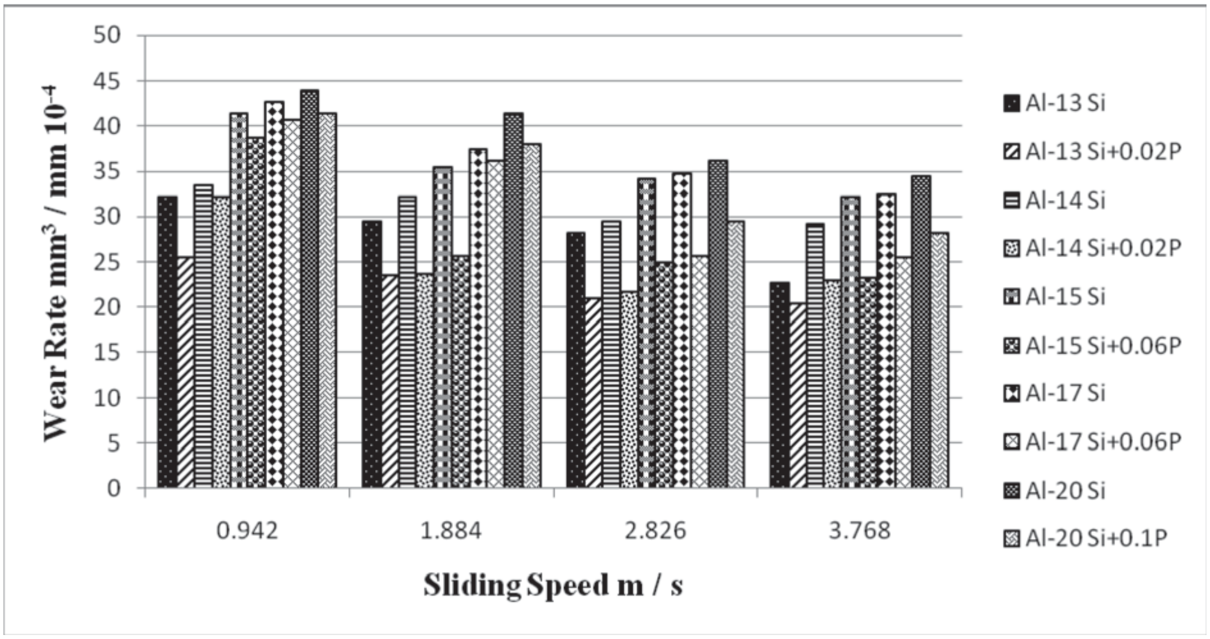

Fig. 4: Effect of phosphorus addition on wear rate at varying sliding velocity for hypereutectic Al-Si alloys.

to lesser wear rate. Reduction in wear rate at higher speed is attributed to formation of stable iron-rich oxide film which may be formed due to high interface temperatures during rubbing which is justified from Fig.8. It may also be concluded from Fig. 4 that wear resistance increases with the addition of phosphorus to as-cast hypereutectic Al-Si alloys and it is due to refinement of primary silicon as explained in earlier section.

Friction and Interface Temperature

Figure 5 and 7 show variation in frictional force and interface temperature with normal pressure (N/mm^2) for constant sliding velocity of 1.884 m/sec and sliding distance of 565.486 m for untreated and phosphorus treated Al-13, 14, 15, 17, and 20Si alloys.

Figure 6 and 8 show variation in friction force and interface temperature with sliding velocity (m/s) for constant normal pressure of 0.975 N/mm^2 and sliding distance of 565.486 m for untreated and phosphorus-treated Al-13, 14, 15, 17, and 20Si alloys. Figure 1 shows temperature distribution along the length of the pin. From these figures it is clear that friction force and interface temperature for all the alloys taken for study increases with increase in normal pressure and sliding velocity. However, decrease in frictional force and interface temperature is observed with the addition of phosphorus and it may be due to refinement of primary silicon particles. Even though the chemical compositions and microstructure of the alloys taken for study vary substantially, friction force generated during wear of these alloys were remarkably similar in trend with slight variation in their values for both load and speed dependent experiments. It may be concluded that friction behaviour is rather affected by environment rather than changes in chemical compositions [10].

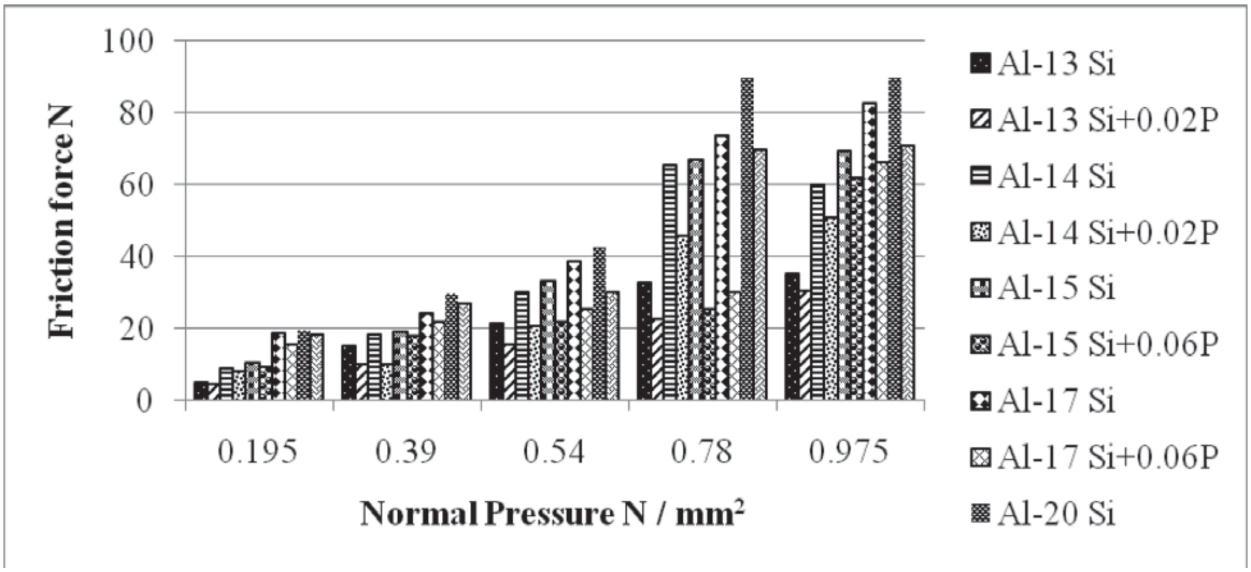

Fig. 5: Variation of frictional force vs normal pressure for hypereutectic Al-Si alloys.

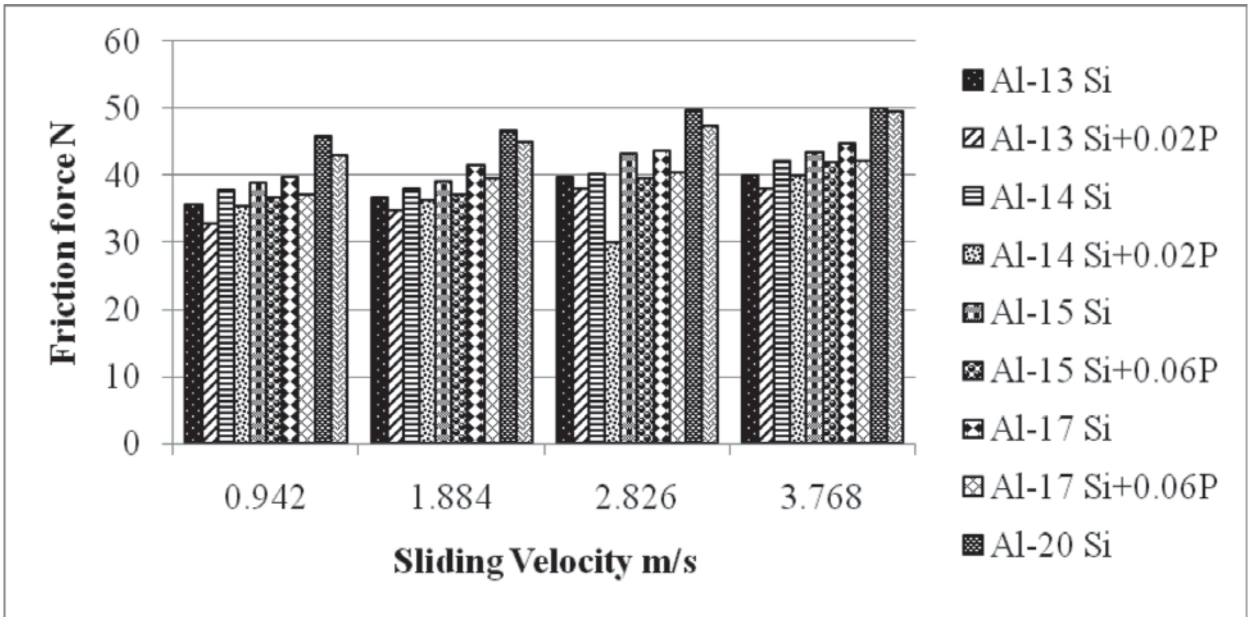

Fig. 6: Variation of frictional force vs sliding velocity for hypereutectic Al-Si alloys.

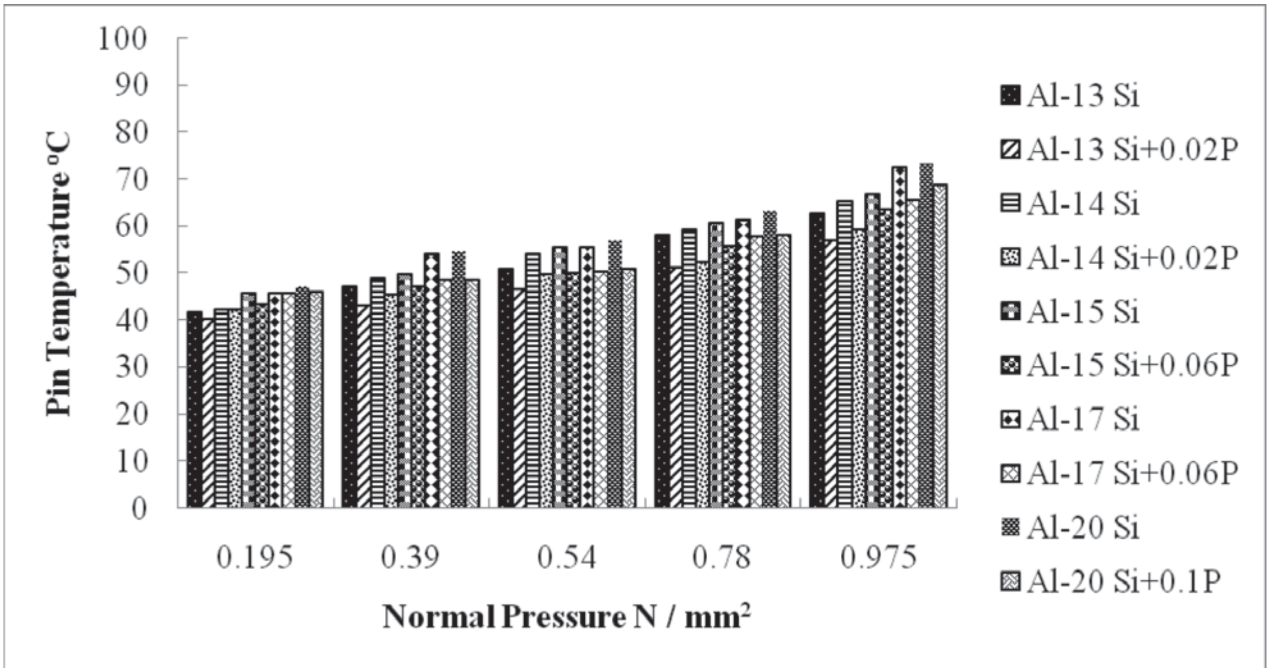

Fig. 7: Variation of interface temperature vs normal pressure for hypereutectic Al-Si alloys.

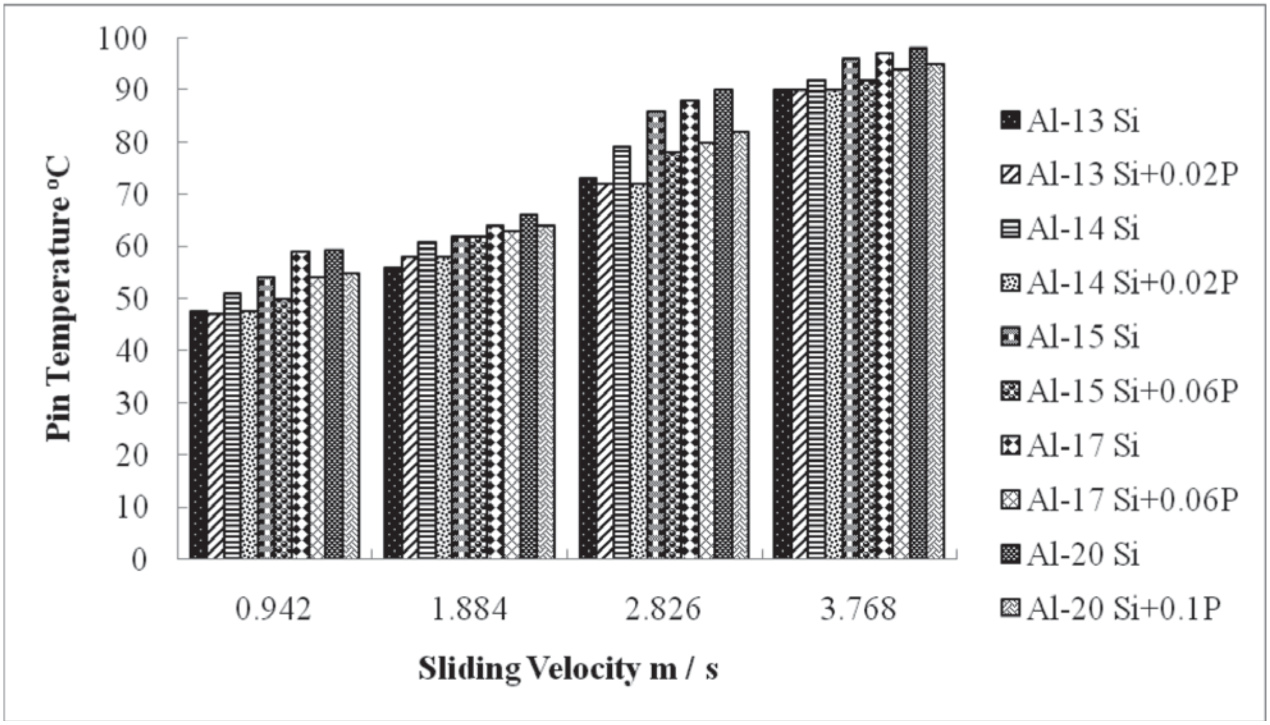

Fig.8: Variation of interface temperature vs sliding velocity for hypereutectic Al-Si alloys.

Worn Surface Studies

Topographic analysis of hypereutectic Al-Si alloys (Al-13, 14, 15, 17 and 20 Si) have been carried out at a normal pressure of 0.975 N/mm² and sliding velocity of 0.942 m/s.

Worn Surface Studies at a Normal Pressure of 0.975 N/mm²

The parameters that govern the wear and friction are oxidation and thermal softening of material. These parameters are greatly influenced by rise in interface temperature.

Figure 9 (a and b) shows topography of as-cast and phosphorus treated Al-13Si alloy at 0.975 N/mm^2 normal pressure, Fig. 9 (c and d) shows EDS microanalysis of as-cast and phosphorus-treated Al-13Si alloy at 0.975 N/mm^2 normal pressure. It is clear that there is formation of unstable oxide film which has ill effects as it acts as hard abrasive particle between rubbing surfaces. In addition, at high load/pressure, interface temperatures are high leading to the formation of large amount of unstable oxide film which gets dislodged due to increased applied normal pressure. Topographical observations reveal presence of depression/dimples on the surfaces of Al-13 Si alloy and also it can be noted that size of the depression/dimples increases as the Si content increases in hypereutectic Al-Si alloys. It is attributed to dislodging of brittle blocky irregular-shaped primary silicon particles from the matrix. Worn surface of Al-13Si alloy at 0.975 N/mm^2 is analysed for its chemical composition using EDX microanalysis. Microanalysis results clearly reveal the presence of Si, Fe and O, indicating an oxidative wear.

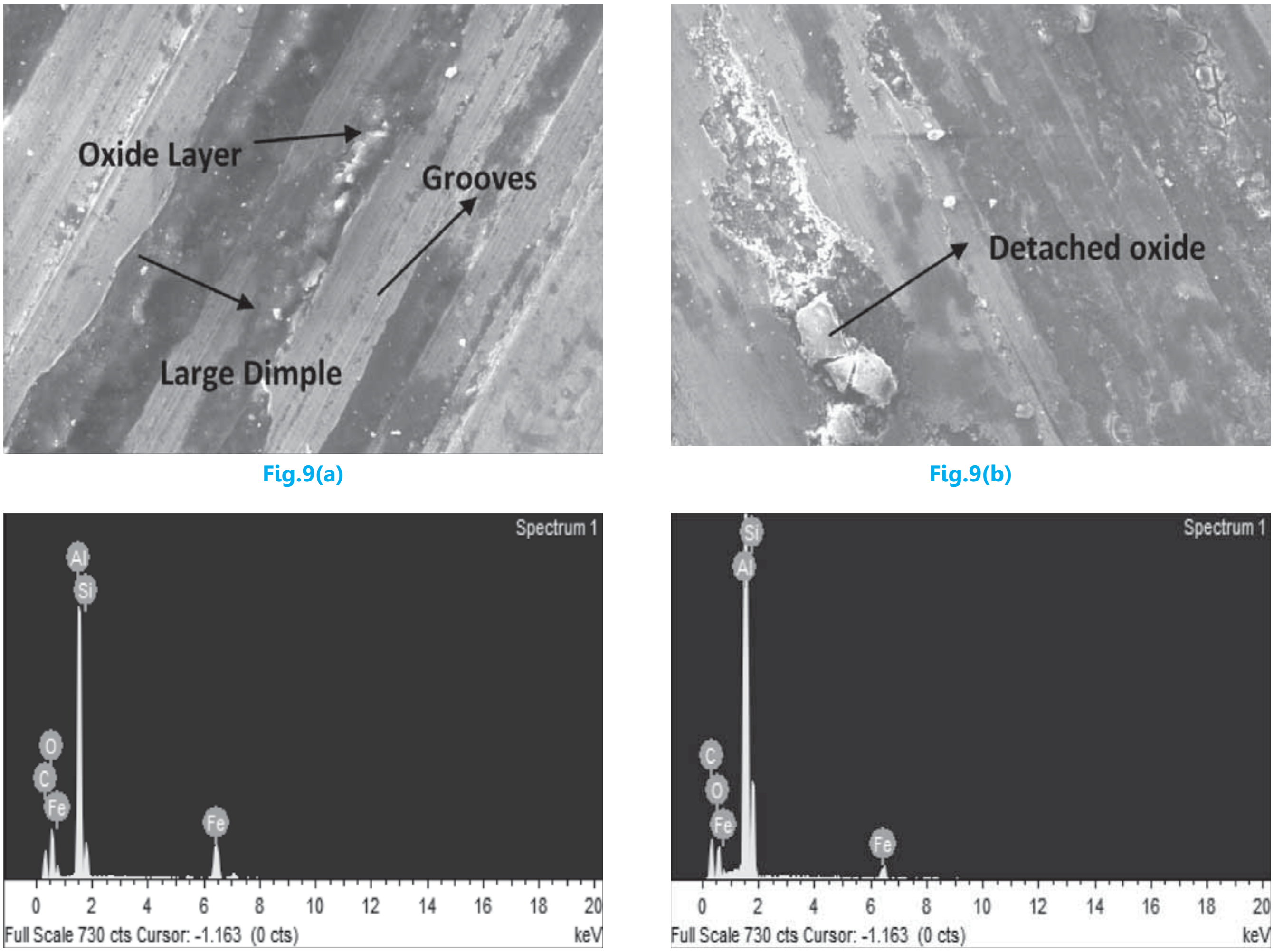

Fig.9(a)

Fig.9(b)

Fig.9(c)

Fig.9(d)

Fig 9 : (a) Worn out surface of Al-13 Si at 0.975 N/mm^2 (b) Worn out surface of Al-13 Si+0.02P at 0.975 N/mm^2 (c) EDX microanalysis of Al-13 Si at 0.975 N/mm^2 (d) EDX microanalysis of Al-13 Si+0.02 P at 0.975 N/mm^2.

Worn Surface Studies at a Sliding Velocity of 0.942 m/sec

Figure 10 (a and b) shows topography of as-cast and phosphorus-treated Al-13Si alloy at 0.942 m/sec sliding velocity, Fig. 10 (c and d) shows EDS microanalysis of as-cast and phosphorus-treated Al-13Si alloy at 0.942 m/sec sliding velocity.

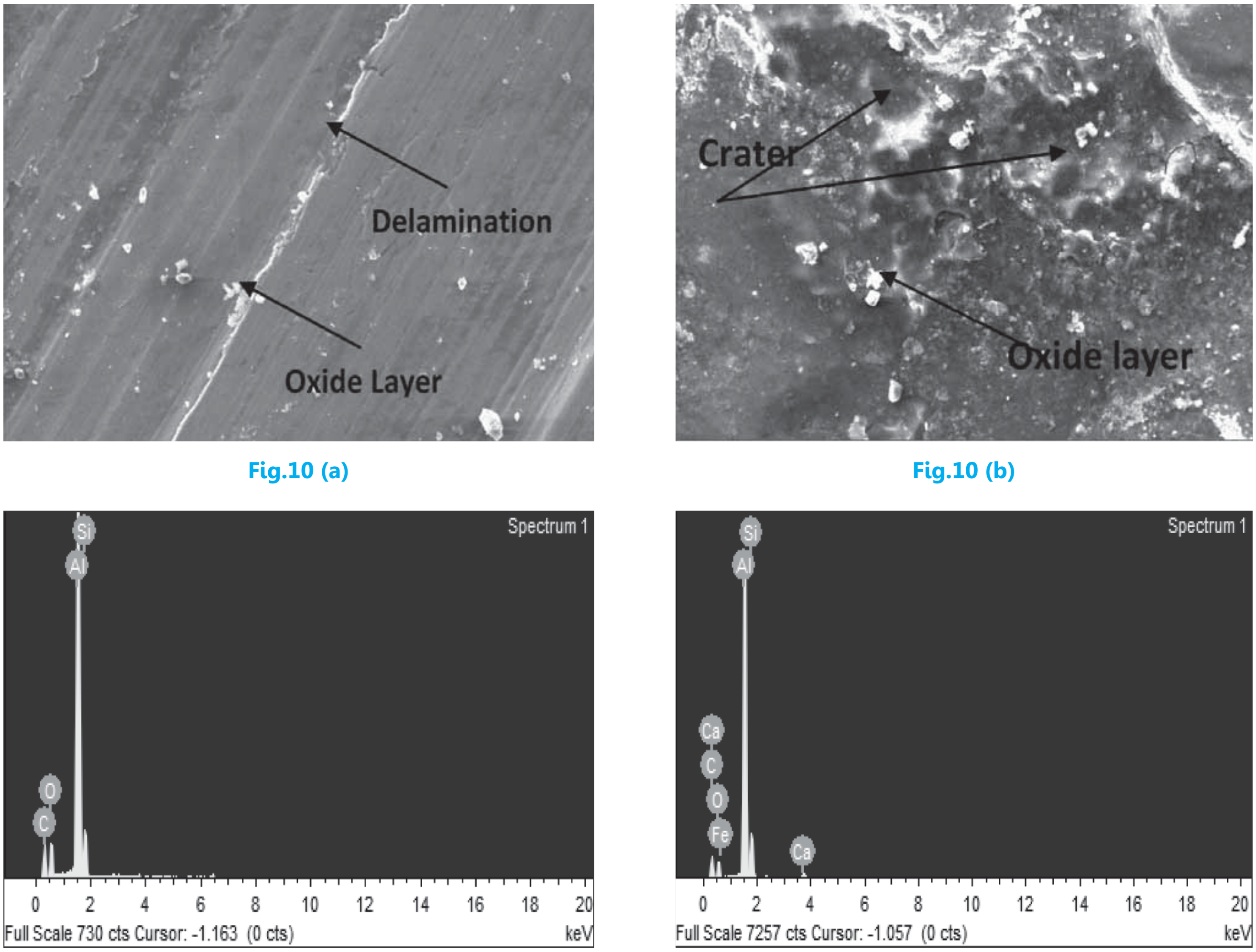

Fig.10 (a) **Fig.10 (b)**

Fig.10 (c) **Fig.10 (d)**

Fig 10 : (a) Worn out surface of Al-13 Si at 0.942 m/sec (b) Worn out surface of Al-13 Si+0.02 P at 0.942 m/sec (c) EDX microanalysis of Al-13 Si at 0.942 m/sec (d) EDX microanalysis of Al-13 Si+0.02 P at 0.942 m/sec.

It is clear from the photographs that scoring, formation of oxide layer, delamination, crater format are the main mechanisms responsible for wear of material. The photographs clearly demonstrate occurance of mild oxidative wear and crater wear which are the characteristics of mild wear [12]. Gross plastic deformation and severe damage to surface is seen on the wornout surfaces. EDX microanalysis of the worn out surface was carried out and it indicates presence of Fe and oxide content. This oxide content decreases with increase in sliding velocity from 0.942 to 3.769 m/sec.

Wear Debris Analysis

Wear debris analysis is carried out to reveal the wear behaviour and wear mechanism of hypereutectic Al-Si alloys using SEM and EDX microanalysis. Wear debris analysis has been carried out for 0.975 N/mm^2 contact load and 0.942 m/s sliding speed of all the Al-13, 14, 15, 17, and 20 Si as-cast and phosphorus-treated hypereutectic Al-Si specimens. Figure 11(a) and b shows wear debris of untreated and phosphorus-treated hypereutectic Al-13 Si alloy and it is composed of mainly metallic particles, confirming wear to be delaminative. EDX microanalysis. Figure 11 (c and d) clearly shows Al, Si and small amounts of aluminium oxides, which confirms it to be an oxidative wear.

Figure 12 (a and b) shows wear debris of untreated and phosphorus treated hypereutectic Al-13 Si alloys at 0.942 m/s sliding velocity. Photographs clearly show that the wear debris consisted of fine powders confirming wear to be oxidative. Figure 12(c) and (d) shows EDX microanalysis of Al-13 Si alloy at 0.942 m/s sliding velocity, it clearly shows that particles mainly composed of Al, Si and small amounts of aluminium oxides that confirms it to be an oxidative wear.

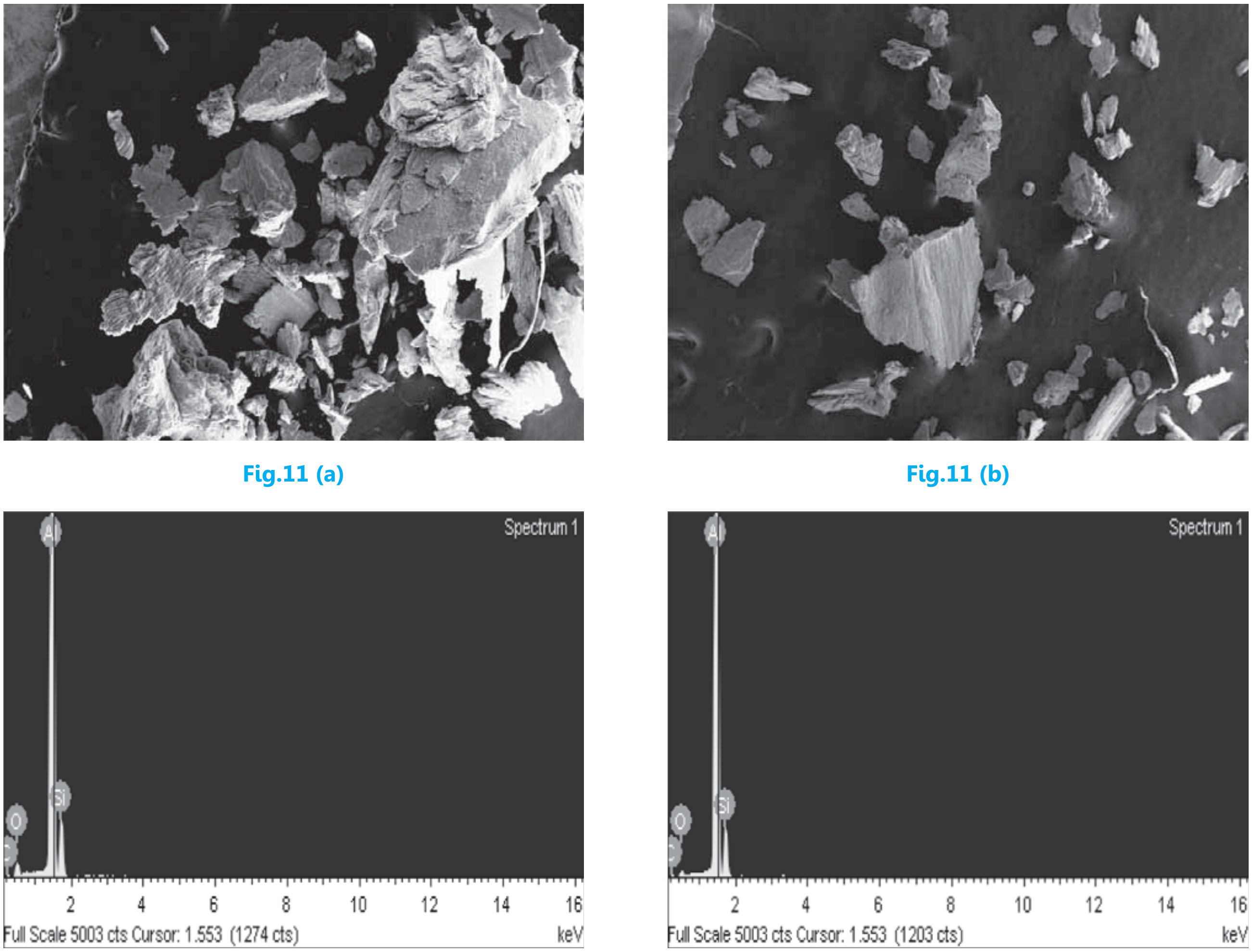

Fig.11 (a) Fig.11 (b)

Fig.11 (c) Fig.11 (d)

Fig.11 : (a) SEM photographs of wear debris of Al-13 Si at 0.975 N/mm^2 (b) SEM photographs of wear debris of Al-13 Si+0.02P at 0.975 N/mm^2 (c) EDX microanalysis of wear debris of Al-13 Si at 0.975 N/mm^2 (d) EDX microanalysis of wear debris of Al-13 Si+0.02P at 0.975 N/mm^2.

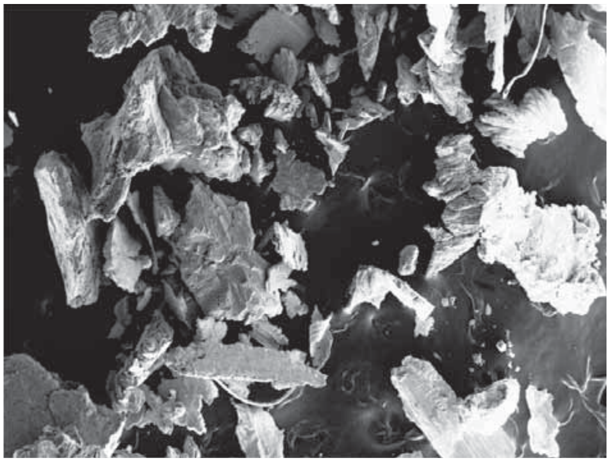

Fig.12 (a)

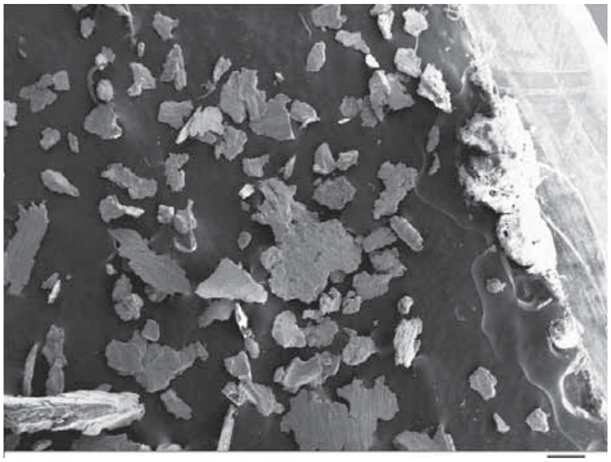

Fig.12 (b)

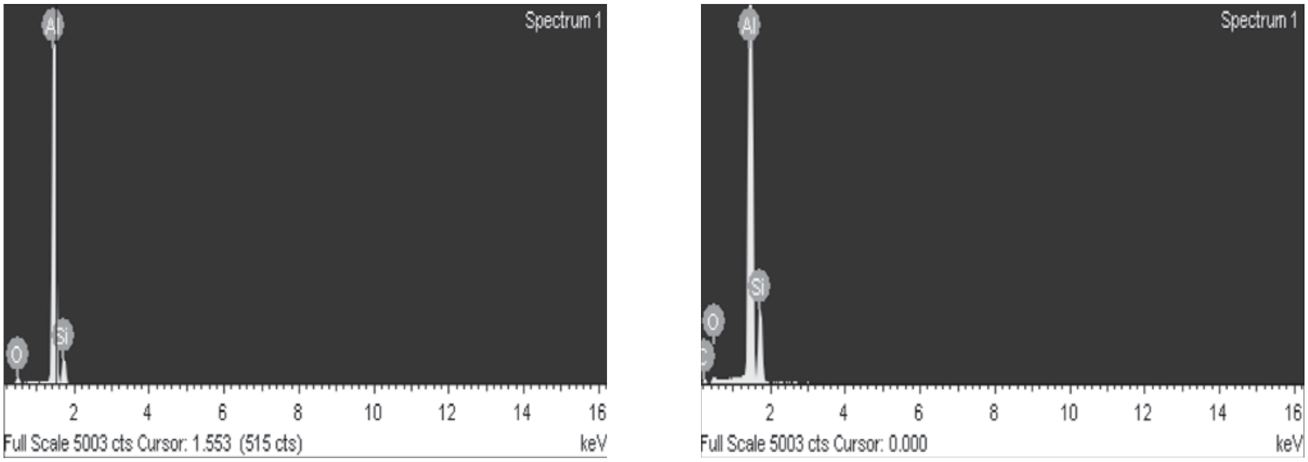

Fig.12 (c) **Fig.12 (d)**

Fig 12 : (a). SEM photographs of wear debris of Al-13 Si at 0.942 m/sec (b) SEM photographs of wear debris of Al-13 Si+0.02P at 0.942 m/sec (c) EDX microanalysis of wear debris of Al-13 Si at 0.942 m/sec (d) EDX microanalysis of wear debris of Al-13 Si+0.02P at 0.942 m/sec.

Conclusions

- Wear rate in terms of volume loss increases with increase in silicon content for hypereutectic Al-Si alloys.
- Wear rate increases with increasing normal pressure and decreases with increasing sliding velocity for both as-cast and phosphorus treated conditions. However, improvement in wear resistance is seen with the addition of phosphorous in Al-Si alloys with the same Si content.
- Frictional forces as well as interface temperature are proportional to normal pressure and sliding velocity, friction and interface temperature behaviour is similar for all the alloys taken for study. Friction and interface temperature behaviour is generally unaffected by changes in composition of hypereutectic Al-Si alloys.
- Worn out surface and wear debris study clearly indicates that oxidative wear is one of the predominant wear mechanism along with abrasion and delaminative wear mechanisms.

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