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RESEARCH ARTICLE

Influence of rotational speed during centrifugal casting on sliding wear behaviour of the Al-2Si alloy

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Abstract The microstructures and dry sliding wear behaviour of an Al-2Si alloy cast centrifugally are studied. Results indicate that at optimum speed the cast has a microstructure consisting of uniformly distributed α-Al grains and fine eutectic silicon grains. The cast exhibited better wear resistance compared to the same cast prepared at different rpms. This paper attempts to investigate the influence of the microstructural changes in the Al-2Si alloy by varying the rotational speed of the mould and its combined action on the dry sliding wear behaviour.

Keywords rotational speed, dry sliding wear, Al-Si alloy

1 Introduction

One of the major driving forces for the development of Al-Si cast alloys is the superior wear resistance, low coefficient of thermal expansion (CTE), high corrosion resistance, high strength to weight ratio, excellent castability, etc., which makes them potential candidate materials for a number of tribological applications in automobiles and other engineering sectors. The improvements in sliding wear resistance and mechanical properties are dictated by the type, shape, size and size distribution of second phase particles in the matrix and matrix microstructures. Hardness is usually thought of as a wear controlling property, i.e. the higher the hardness, the greater the wear resistance of the material. However, it should be emphasized that it is the hardness of the contacting asperities and not the bulk hardness that will control the wear rate. The addition of hard second phase particles to the matrix improves both wear and mechanical properties [1–4]. In this sense, from a wear resistance point of view, it is interesting to minimize the occurrence of soft-hard contact between sliding surfaces, which produces localized wear and would lead to premature failure.

Micro structural tailoring allows for optimizing of the wear resistance by obtaining a fine and homogeneous dispersion of α-Al grains and hard silicon particles. Centrifugal casting is one of the pressure casting methods which enables the pouring of the molten metal into the mould assembly due to the rotational motion. The principal advantage of centrifugal casting is good mould filling combined with good microstructural control, which usually results in improved mechanical properties. However, a complete description of the influence of rotational speed on the mechanical properties of the cast has not yet been fully given.

In order to understand the sliding wear mechanisms of metallic materials, a thorough analysis of their running-in (Break-in) behaviour has been advocated [5]. It is during this initial stage in sliding that surfaces and their underlying microstructures are markedly altered. Such adjustments frequently involve variations in friction coefficients and/or rates of wear. Many poly phase alloys are in use as wear resistant materials. Improvements in their performance can be attempted through clear understanding of their wear behaviour. Fundamental studies of metallurgical effects on sliding wear have largely involved pure metals and single phase alloys. Numerous studies have been reported on the wear behaviour of cast Al-Si alloys [6–10]. Somi Reddy et al. [11] investigated the wear and seizure behaviour of Al-Si alloys containing silicon content up to 23 wt.% using a Pin-On-Disc machine under a wide load range 15–200 N. It was observed that the addition of silicon to aluminium improves wear and seizure resistance. Eyre has also investigated alloying effects on the wear of Al-Si alloys [12]. He found that varying the amount of copper and Fe in the alloy changes the load at which a transition from mild (Oxidative) wear to severe (Metallic) wear occurs.

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It is clear that sliding wear behaviour of polyphase alloys are complex and not just a simple function of composition. The aim of the present work is to investigate the influence of rotational speed of the mould on sliding wear behaviour of Al-2Si in dry sliding against a hardened steel counter face by using a Pin-On Disc wear test tribometer.

2 Experimental details

The centrifugal casting process was carried out at various rotational speeds (200, 400, 600, 800 and 1600 rpm), while the pouring temperature of the material was set at 900°C. The cylindrical sample obtained was 81 mm in diameter, 140 mm in length and 6 mm in thickness. The sample had been cut in the radial direction and microstructure evaluation for the outer, middle and inner regions of the final casting was done. The sliding wear test was carried out using a Pin-on Disc tribometer (TR-20, DUCON-PIN-ON-DISC). The wear test was carried out for the inner surface of the specimen. The specimen was cut in a square of size 8 mm×8 mm. The inner surface of the specimen was made flat by rubbing with sand paper to bring it to a roughness of 0.1 μm (as per ASTM 99 standard). The disc was made up of steel, having a 100 mm diameter and 8 mm thickness. It was rubbed with the sand paper to make a surface finish of 0.1 μm. The disc and the inner surface of the specimen were then degassed with Acetone.

3 Results

3.1 Microstructures of Al-2Si alloy of 6 mm thick rotated at various rotational speeds

The microstructures of the Al-2Si alloy across three regions of the section for the various rotational speeds are

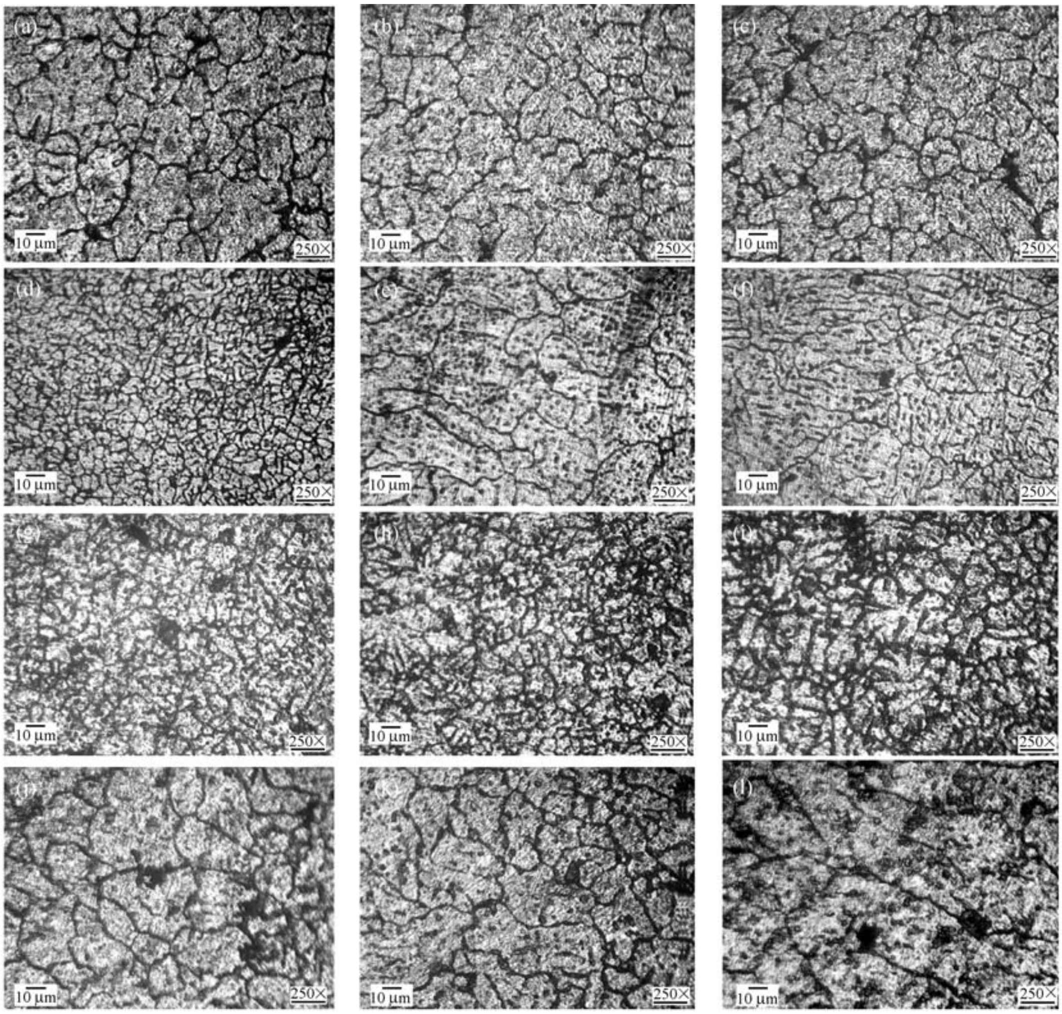

Fig. 1 Microstructure of 6 mm thick Al-2Si at **(a)** 400 rpm outer surface, **(b)** 400 rpm middle surface, **(c)** 400 rpm inner surface, **(d)** 600 rpm outer surface, **(e)** 600 rpm middle surface, **(f)** 600 rpm inner surface, **(g)** 800 rpm outer surface, **(h)** 800 rpm middle surface, **(i)** 800 rpm inner surface, **(j)** 1600 rpm outer surface, **(k)** 1600 rpm middle surface and **(l)** 1600 rpm inner surface

shown in Fig. 1. It can be observed that the rotational speed has a profound influence on the microstructures of the Al-2Si alloy. Figure 1(a)–(c) shows the microstructures of the centrifugal tube rotated at 400 rpm. The section consists of large primary α-Al grains (soft phase) and needle shaped silicon in the interdendritic region. Figure 1(d)–(f) shows the microstructures of a centrifugal cast rotated at 600 rpm. Fine equiaxed α-Al grains at the outer region and long primary α-Al grains at the middle and inner regions are observed. At 800 rpm, fine equiaxed α-Al grains are formed at all the regions of the section in the cast tube. Again, at 1600 rpm, fine structures are observed at the outer region and long aluminium grains are observed at the middle and inner regions of the specimen.

The present experimental work confirms that, with an increase in rotational speed, the Al-2Si alloy significantly refines the coarse columnar primary α-Al grains to fine equiaxed α-Al grains. When the mould is rotated at 400 rpm, the molten metal has a laminar flow. Upon pouring the molten metal into the rotating mould, a lot of crystals nucleate on the cold wall mould as a result of super cooling. These chill the crystals form the outer skin of the casting. This structure in the outside wall depends on the thermal fluctuation of the liquid metal. The metal then gradually solidifies towards the inner region. Hence, the metal will be under cooling at the middle and inner surface of the castings. At the inner surface, deflections of columnar grains are frequently observed in the centrifugal casting when the casting is prepared at low rotational speed. It becomes turbulent when the rotational speed is increased to 600 rpm and the formation of long grains begins to break down. Here centrifugal force dominates and lifts the molten metal outwards, leading to increase in cooling rates and hence, the size of the grain structure is less predominant. At the optimised speed of 800 rpm, the melt remains stationary and a fine equiaxed structure is clearly seen in the outside surface of the casting due to the chilling effect of the metal coming in contact with the mould. The chilling effect on the casting depends on the thermal mass of liquid metal and relative movement between the liquid metal and inner surface of the mould. The metal moves in streamline along the axis and simultaneously gets lifted, forming a uniform cylinder. The metal remains stable in its place during solidification and hence the solidification rate is greater. Hence, fine equiaxed structures are also seen on the middle and inner surfaces of the casting tube. With an increase in speed to 1600 rpm, the metal, rather than spreading out along the axis, moves along the circumferential direction of the mould due to a very high centrifugal force. The metal remains stable after being lifted by the mould due to an increase in viscosity, and the casting formed will have a thick section on one side and a thin section on the other side. Taking the microstructure across the thick section, fine structures are seen at the outer surface due to the chilling effect of the molten metal. The solidification process at the middle and inner region takes place through conduction, and long grains of primary α-Al are formed at these regions of the casting.

3.2 Effect of load on wear

When the load on the pin is increased, the actual area of contact would increase towards the nominal area, resulting in increased frictional force between the two sliding surfaces. The increased frictional force and real surface area in contact will bring higher wear. The influence of rotational speed on the sliding wear behaviour of the Al-2Si alloy under different loads (30, 40, 50, 60, 70 and 80 N) with a constant sliding distance of 752 m and sliding speed of 1.256 m/s are shown in Fig. 2(a)–(c). It is noticeable that the coefficient of friction and volumetric wear rate was greater for the cast tube fabricated at lower rpm. The wear test could not be carried out for the higher load due to the possibility of seizure. The coefficient of friction was found to increase linearly with increasing load. However, at optimised speed the coefficient of friction and volumetric wear rate was lesser with increasing loads. The hardness of the worn samples was determined and the data are reported in Table 1. The hardness of the samples increased with increasing nominal loads.

3.3 Effect of various sliding speeds on wear

The sliding wear behaviour of Al-2Si alloy under a rotational speed of mould of 800 rpm under various sliding speeds (0.837, 1.25 and 1.674 m/s) with varying loads is shown in Fig. 3. It is noticeable that the coefficient of friction decreases, which in turn reduces volumetric wear rate with the increase in sliding speeds. Reduction in coefficient of friction is possibly due to increased contamination of the sliding interface by decreased oxide layer breakup in less contact time. The presence of the oxide layer reduces the chance of direct metallic contact and therefore asperities interaction is also reduced. Moreover, increasing the sliding speed also increases the interface temperature. This rise in temperature within limits increases the ability of the soft aluminium matrix to accommodate the hard and brittle second phase silicon particles. High seizure resistance is possibly due to the presence of fine grain size, which resists the thermal softening particularly at high speed and contact load.

4 Discussion

At the optimised speed of 800 rpm, Al-2Si alloy offered the best wear resistance at higher loads. The wear resistance was distinctly inferior to the cast tube formed at low rotational speeds. The long α-Al primary grains are undesirable from the point of toughness and ductility. Further, they did not improve the wear resistance either. At

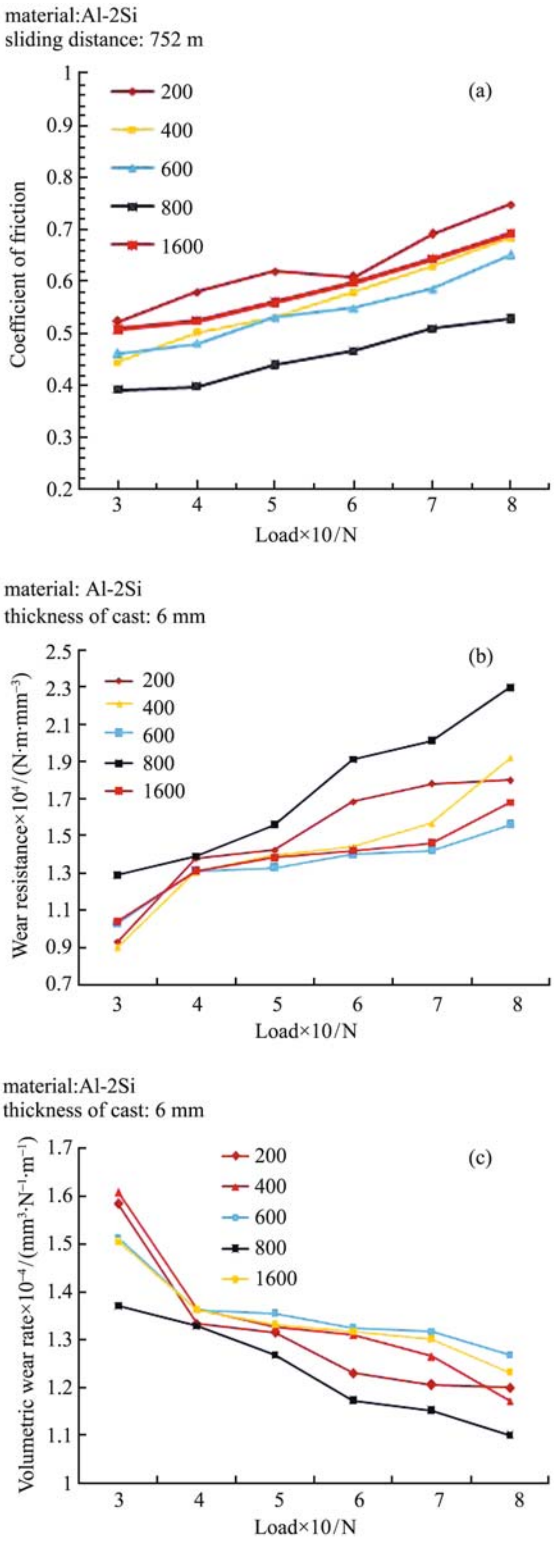

Fig. 2 Wear performance of Al-2Si alloy: **(a)** coefficient of friction with respect to nominal load; **(b)** wear resistance versus varying nominal load; **(c)** volumetric wear rate versus nominal load

Table 1 Hardness (VPN) of the samples under different nominal loads (load 5 kg)

mould rotation /rpm	hardness (VPN)				
	30 N	40 N	50 N	60 N	70 N
200	40	44	46	48	51
400	43	46	48	51	54
600	62	70	81	93	106
800	68	84	98	119	142
1600	63	79	86	99	116

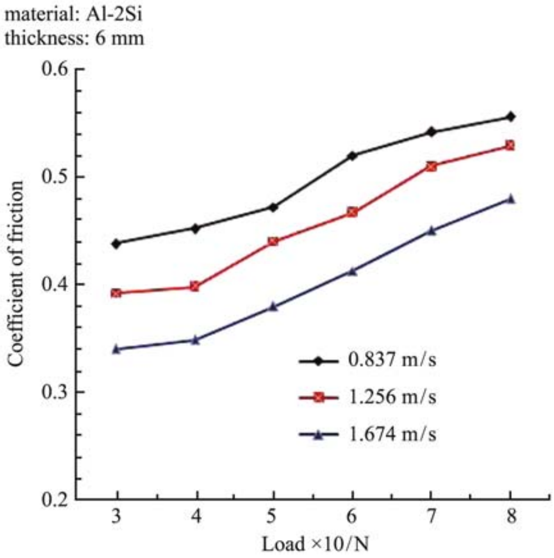

Fig. 3 Effect of various sliding speed on coefficient of friction with nominal load

low rotational speed, the wear resistance decreased continuously with the increase in wear load. The coefficient of friction and volumetric wear rate recorded higher at the highest load for the cast tube rotated at 200, 400, 600 and 1600 rpm. Better wear resistance could be achieved through fine equiaxed primary α-Al grains and uniform distribution of the second phase particles. At optimised speed, the long α-Al primary grains were converted into equiaxed α-Al grains, leading to the better mechanical properties and improved wear resistance. Crack nucleation generally occurs at some depth below the surface rather than very near the surface. This leads to a very high hydrostatic compressive pressure acting near the asperity contact [13]. Thus, once a crack is nucleated, its propagation is slow and seizures do not occur owing to the presence of well distributed particles in the matrix.

Increasing test loads leads to greater plastic deformation and wear. Increased work hardening in specimens tested at higher loads is evident from the data on hardness of the worn specimen presented in Table 1. The overall wear resistance was increased due to appreciable work hardening of the grains refined at optimised speed.

In order to investigate the wear mechanisms, the surface of the worn samples were examined under SEM. Under high magnification, for worn samples of 400 rpm, extensive plastic flow and cracking were observed. Cracks may initiate in the highly work hardened layer at the subsurface region. The cracks grow and get interconnected, removing a layer of metal leading to delaminating wear. Figure 4(a) suggests such a mechanism. At 600 rpm, there may be hard dispersoid particles or fractured pieces thereof which are mechanically dislodged during wear. The pinholes so formed act as potential sites for nucleation and growth of cracks, paving the way for delamination wear. These dispersoid particles may act as asperities and continue to support the load until it is levelled off. Table 1 shows that work hardening increases with the increase in the degree of grain refinement. This suggests that a refined grain seen at 800 rpm undergoes greater strain hardening.

The coefficient of friction increased uniformly with increasing load with all the samples. The rise in the coefficient of friction with the increase in load may be due to oxidation of the wearing surfaces or enhanced accumulation of the wear debris consisting of a large volume fraction of hard aluminide and silicide particles pulled out of the matrix during wear at the pin and disc interface. A simultaneous work hardening of the matrix by plastic deformation helped in reducing the extent of wear of the samples at high loads. During wear at high loads, the temperature increases appreciably, lowering the strength of the materials in contact, resulting in an increased contact area and coefficient of friction. The stronger refined grains at optimized speed recorded the lowest coefficient of

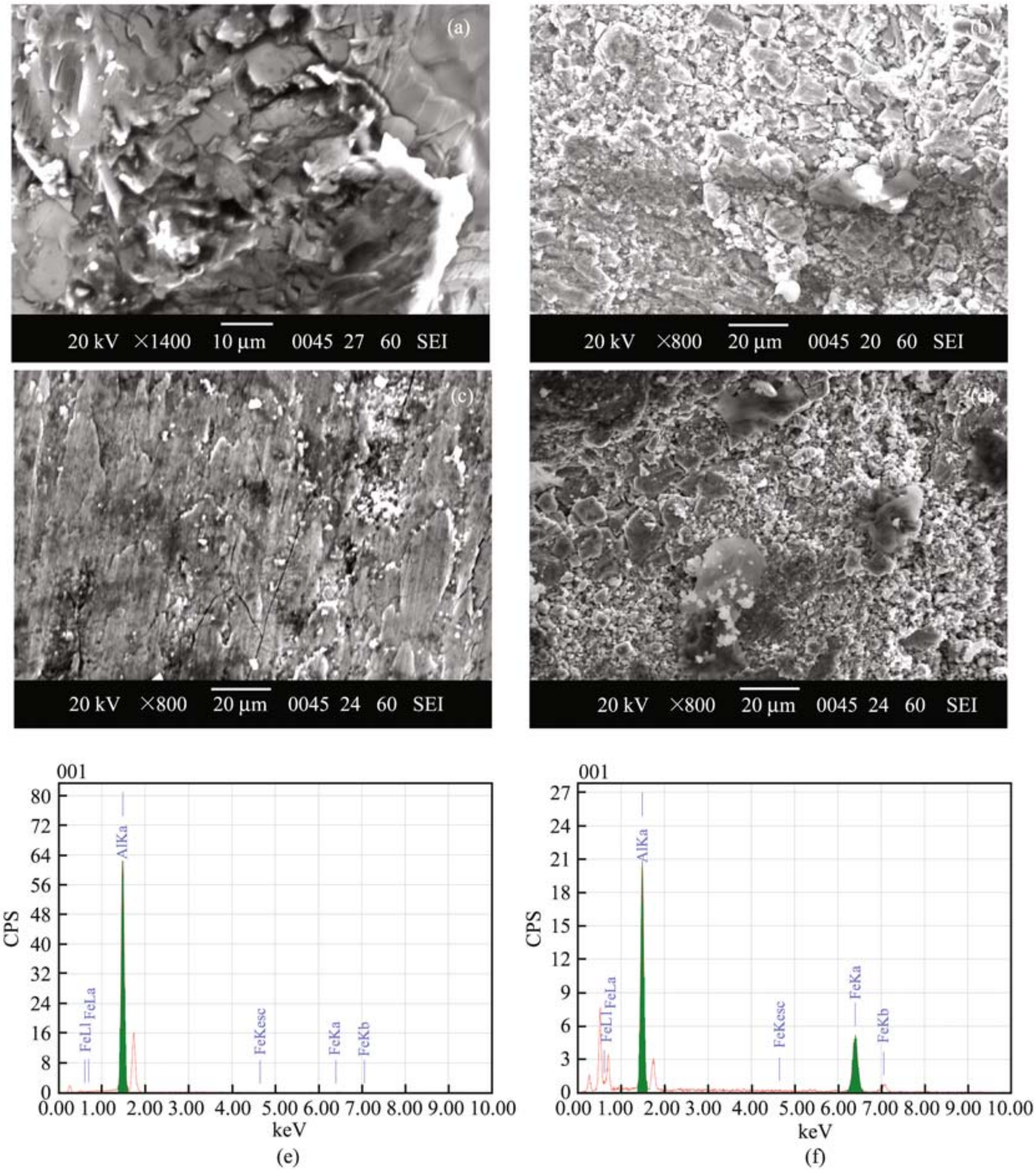

Fig. 4 SEM photograph of worn samples of Al-2Si alloy for mould rotation at **(a)** 400, **(b)** 600, **(c)** 800 and **(d)** 1200 rpm; EDAX analysis for worn sample of **(e)** 400 and **(f)** 800 rpm

friction Fig. 4(c). Due to low work hardening in the sample cast at 1600 rpm, the coefficient of friction was greater and pinholes were observed in the worn sample Fig. 4(d).

Reduction in the coefficient of friction with an increase in sliding speed (Fig. 3) is possibly due to the increased contamination of the sliding interface by the oxide layer. The presence of the oxide layer reduces the chance of direct metallic contact and therefore asperities interaction is reduced. Moreover, the increase in sliding speed makes the soft aluminium matrix accommodate hard and brittle second phase silicon particles [13]. Hence, high resistance is recorded due to the presence of the comparatively more stable aluminium oxide, which reduces the thermal softening at various sliding speeds. The EDAX was done for the worn samples at 400 and 800 rpm for a load of 70 N.

Figure 4(e) shows the EDAX analysis for a worn sample at 400 rpm. Friction mainly depends on the hardness of the material, and with the lower value of hardness opportunities to form a hard inter metallic compound are lesser. The sample showed the presence of Al at about 99% and 0.05% of Fe, indicating that the sample had worn greatly. Figure 4(f) shows the EDAX analysis for 800 rpm. Dispersion hardening in the alloying element may be a possible reason due to the higher seizure resistance. High hardness may shear off some particles on the disc and accumulate in the worn samples. The sample showed the presence of Al at about 70% and Fe of about 30%, indicating that both the sample and disc got worn out.

5 Conclusions

The following conclusions can be drawn from the above investigation:

(1) The influence of rotational speed on the wear behaviour of the Al-2Si alloy was investigated and the wear behaviour was mainly dependent on the size and shape of α-Al grains and silicon particles in the matrix.

(2) The coefficient of friction increased linearly with the increase in load and the value was lesser for the sample at optimum speed due to fine equiaxed aluminium grains. The wear resistance was increased for this sample due to an increase in work hardening rate.

(3) Delamination wear was formed for the sample at a lower rpm and at 1600 rpm due to hard dispersoid particles detaching from the worn surface.

(4) Reduction in the coefficient of friction with the increase in sliding speed may be due to increased contamination of the sliding interface by the oxide layer and increased solid solution strengthening.

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