Interface Temperature under Dry Sliding Conditions

Dheerendra Kumar Dwivedi¹, Ashok Sharma² and T. V. Rajan²

¹Mechanical Engineering Department, Ashok Engineering College, Hamirpur, H.P., Pin: 177005, India
²Metallurgical Engineering Department, Malviya Regional Engineering College, Jaipur, R.J., Pin: 302017, India

In present paper, the influence of sliding speed, contact load, sliding time and microstructure on interface temperature during the sliding of eutectic Al–Si alloy (LM13) and hypereutectic Al–Si alloy (LM28) has been investigated. Sliding test was conducted under dry sliding conditions against hardened steel En-32 counter surface over a range of sliding speed from 0.2 to 5.0 m/s and contact load from 10 N to 30 N. It was observed that the interface temperature is a function of contact load, sliding speed, microstructure and thermal softening characteristics of sliding metal. Heat treatment of LM28 alloy decreases frictional heating and hence interface-temperature, however that of LM13 alloy does not affect the interface temperature especially under severe sliding conditions. Wear of aluminium alloys has close relationship with interface temperature. There is a critical temperature for each alloy corresponding to transition from mild to severe wear. LM28 alloy shows higher value of the critical temperature than the LM13 alloy under identical alloy conditions.

(Received December 11, 2001; Accepted July 12, 2002)

Keywords: sliding speed, interface temperature, microstructure, cast aluminium alloys

1. Introduction

In recent years, use of cast Al–Si alloys as a tribological component has been expanding widely in military, automobile and general engineering industry.¹–³) The wear of components made of these alloys depend on number of material related parameters i.e. shape, size, composition and distribution of micro constituents in addition to the operating conditions such as load, sliding speed, temperature, environment and counter surface.³,⁴) When two surfaces slide together, most of work is done against friction, which eventually converts into heat.⁵) Rise in temperature affects the mechanical and metallurgical properties of sliding surface besides the surface oxidation or even fusion/melting depending up on the interface temperature.³,⁵,⁶) Owing to the potential influence of frictional heating on tribological behaviour and failure of sliding components, the surface and near surface temperature has been an attractive topic for many years.

Number of attempts³–⁸) has been made by researchers to study the variation in temperature of sliding surfaces. Subramanian³) studied the temperature of sliding surfaces of Al–12%Si alloy, at different velocities (0.1–10 m/s) against different counter surfaces (die steel, copper alloy and aluminium alloy). Prasad et al.⁵) studied the rise in temperature for very short duration of sliding i.e. 5 min, at various sliding velocities 1–5 m/s. Literature survey have revealed that limited work has been reported on interface-temperature and their influence on wear behaviour. Little efforts have been made so far to study the affect of microstructure on interface temperature.

To fill up this gap present work was undertaken, it will assist in understanding the phenomenon related with variation in interface temperature of sliding body from initial fast rise to steady state temperature and to find critical temperature above which severe wear occur. In this work, effect of microstructure, load, sliding velocity, sliding time on interface temperature and wear of aluminium alloy (LM13 and LM28) has been investigated.

2. Experimental Procedure

2.1 Material

Experimental alloys LM13 and LM28 were prepared by controlled melting of high purity aluminium, Al–28%Si, Al–10%Mg, Al–10%Ni and Al–50%Cu master alloys in a graphite crucible using a muffle furnace and cast in metallic mould of size 25 mm × 25 mm × 150 mm. Nominal composition of LM13 and LM28 alloy was Al–12Si–1Ni–0.8Cu–0.6Mg and Al–17Si–1Ni–0.8Cu–0.6Mg respectively. LM13 alloy was modified by addition of 0.015% strontium, in form of Al–10%Sr and LM29 alloy was modified by addition of 0.01%P in form of red phosphorous. Rods of Φ25 mm section of LM13 and LM28 were solutionized at 500°C for 7 h followed by quenching into warm water (60°C) and age hardening at 165 ± 5°C for 12 h. Wear test pins (cylindrical) of diameter 6 mm and length of 20 mm were prepared by turning and one end of pin was polished.

2.2 Friction and wear behaviour

A Pin on Disc type wear monitor (DUCOM, TL–20, Bangalore) with data acquisition system was used to evaluate the wear behaviour of aluminium alloys against hardened ground steel (En–32) disc having hardness of Rc30 and surface roughness (R_a) 0.5 μm. Principle diagram is shown in Fig. 1. Load was applied on pin by dead weight through pul-

Fig. 1 Principle diagram of pin on disc wear monitor.
ley string arrangement. The system had maximum loading capacity of 200 N. Disc was rotated by D.C. motor, having speed range 0–2000 rev min^{-1} to yield sliding speed 0–10 m/s. During the sliding, change in height of the specimen was recorded using a linear variable differential transformer (accuracy 2 µm and range 2 mm). This was used as a measure of wear. The friction force was recorded during the experiment by using a load cell (accuracy 0.1 N and capacity 200 N). Counter surface was abraded against carbide polishing papers and cleaned with acetone and dried before each sliding test. Temperature and wear were acquired at rate of 5 samples per second during the 60 min of sliding at various velocities 0.2, 0.5, 0.9, 2.0, 3.0 and 4.0 m/s and normal loads 10, 20, 30 and 40 N. Variation in disc revolution per minute (at 80 mm track diameter) was used to regulate the sliding speed. Sliding conditions when a lot of vibration, noise and gross metal transfer take place has been considered as seizure like conditions.

2.3 Temperature measurement

Temperature measurements of wear pin during the sliding were carried out with chromel-alumel thermocouple. These thermocouples were placed into a hole of 2 mm diameter at 1.5 mm away from sliding surface drilled up at axis of cylindrical pin. Temperature was recorded with help of digital temperature indicator after 2, 5, 10, 20, 30, 45 and 60 min of sliding. It can be important in explaining the friction and wear because mechanical properties of material and surface oxidation are affected by temperature.

3. Results and Discussion

Temperature variation during the sliding of LM13 and LM28 alloy in as cast and heat-treated condition with sliding time at different sliding speeds and 10 N & 30 N load is shown in Figs. 2–5. Two regimes of temperature variation with sliding time were observed in mild wear conditions, first one corresponds to initial steep rise in temperature (reducing rate of temperature rise with the sliding time) and second one is corresponding to steady state sliding shows constancy in temperature. As cast (Fig. 2(a)) and heat-treated (Fig. 3(a)) LM13 alloy at 10 N normal load show this kind of behaviour during the sliding in entire range of sliding speed from 0.2 m/s to 4.0 m/s. While at 30 N load two regimes of temperature variation with the sliding time were observed over a range of sliding speed from 0.2 to 2.0 m/s only above that three regimes of temperature variation with sliding time were observed (Fig. 2(b) and Fig. 3(b)). Three regimes of temperature variation with sliding time were observed as soon as severe wear conditions develop during the sliding. First two regimes are same as that of earlier case (mild wear), but third regime causes unstable increase in temperature. Seizure like conditions were attained only at 30 N normal load and 3.0 m/s sliding speed during the sliding of as cast and heat-treated LM13. As cast (Fig. 4) and heat-treated (Fig. 5) LM28 alloy shows only two regimes of temperature variation with sliding time at both the loads (10 N and 30 N) and in entire range of sliding speed from 0.2 to 4.0 m/s except the as cast alloy at 30 N load and 4.0 m/s sliding speed. As cast alloy (Fig. 4(b))
at 30 N load and 4.0 m/s sliding speed shows three regimes of temperature variation with sliding time as described above. Alloy condition does not affect the interface temperature appreciably moreover minor decrease in interface temperature was noticed after heat treatment of both the alloys.

Seizure like conditions were attained at lower interface temperature with LM13 than that for LM28 in as cast condition. While heat-treated LM28 alloy (Fig. 5(c)) shows three regimes of temperature variation only at 40 N load and 5 m/s sliding speed, when interface temperature reaches 180°C. Temperature variation with time showed that the most of the temperature (about 70–90% of steady state temperature) rise takes place in first 1–5 min of sliding. Variation in temperature with sliding velocity at different normal loads (after 60 min of sliding or before seizure) is shown in Figs. 6 and 7. Rise in temperature is not significant with the increasing sliding speed from 0.2 to 0.9 m/s velocity for both the alloys LM13 and LM28 in as cast and heat-treated conditions. Increase in the sliding velocity from 2.0 to 5.0 m/s shows continuous & gradual rise in temperature at 10 N load. At 4.0 m/s sliding velocity (30 N load) seizure like condition are attained earlier, just after 30 min of sliding. As and when temperature reaches 110°C transfer of pin material to disc by melting/fusion of as cast and heat-treated LM13 alloy pin starts and gross metal transfer took place in very short duration of sliding. From above it can be concluded that heat-treatment of LM13 alloy does not affect the transition point.

LM28 alloy shows different frictional heating than the LM13 alloy in as cast and heat-treated conditions. LM28 alloy in as cast condition causes maximum temperature of 80°C, 90°C and 150°C that for heat-treated alloys is 68°C, 75°C and 110°C on sliding at 30 N load and 2, 3 and 4 m/s sliding speeds respectively. LM28 in heat-treated condition attains maximum temperature of 120°C at 5 m/s speed and 30 N load. As cast LM28 alloy seizes at 4.0 m/s velocity and 30 N load, where as heat-treated LM28 alloy on sliding at 30 N load, 4 and 5 m/s velocity generates maximum 110 and 120°C temperature respectively. Sliding velocity and load at which heat-treated LM28 seizes are 40 N and 5.0 m/s respectively (until interface temperature of 180°C is generated).

Wear of heat-treated LM13 and LM28 alloy at various

---

**Table:**

<table>
<thead>
<tr>
<th>Sliding Time, t / min</th>
<th>Temperature, T / °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 0 2 0 3 0 4 0 5 0 6 0</td>
<td>0.2m/s</td>
</tr>
<tr>
<td>0.5m/s</td>
<td></td>
</tr>
<tr>
<td>0.9m/s</td>
<td></td>
</tr>
<tr>
<td>2.0m/s</td>
<td></td>
</tr>
<tr>
<td>3.0m/s</td>
<td></td>
</tr>
<tr>
<td>4.0m/s</td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 5** Temperature variation with sliding time at different velocities for heat-treated LM28 alloy at (a) 10 N, (b) 30 N and (c) 40 N load respectively.

**Fig. 6** Temperature variation with sliding speed at 10 N and 30 N load for LM13 alloy in (a) as cast and (b) heat-treated conditions respectively.

**Fig. 7** Temperature variation with sliding speed at 10 N and 30 N load for LM28 alloy in (a) as cast and (b) heat-treated conditions respectively.
loads and a constant sliding velocity 4.0 m/s is shown in Fig. 8. It is observed from Fig. 8(a) that at 10 N normal load wear volume of LM13 alloy increases with increase in sliding time and there is linear relation between two in the steady state. Mode of wear under these conditions appears to be oxidative during the entire 60 min of sliding. While at 20 N and 30 N normal loads wear takes place rapidly after traverse of certain time. It appears that mode of wear is severe and metallic in nature under these conditions. LM28 alloy showed linear relation between wear and sliding time in steady state at all three (10 N, 20 N and 30 N) experimental loads constant sliding speed of 4.0 m/s and this is evident from the Fig. 8(b). Mode of wear appears to be oxidative type although wear increases with increasing normal load. Wear-sliding time relation for heat-treated LM28 alloy at constant 40 N normal load and varying sliding speed is shown in Fig. 8(c). It may be seen that wear takes place at constant rate after run-in period at 40 N normal load and 4.0 m/s sliding speed. While 40 N normal load and 5.0 m/s sliding speed metallic-wear conditions develop after 20 min of sliding hence wear at increasing rate takes place. This is evident from the SEM image of the wear surface (Fig. 12(b)).

Figures 9 and 10 show the optical microphotographs of LM13 and LM28 alloy respectively in as cast and heat-treated conditions. It is observed from the Fig. 9(a) that the as cast eutectic alloy has eutectic of α-aluminium dendrites and acicular silicon. As cast LM28 alloy shows coarse primary silicon particles in a matrix of eutectic (Fig. 10(a)) as expected from the equilibrium phase diagram. Heat-treated LM13 alloy shows completely spheroidized eutectic silicon crystals in matrix of aluminium; whereas in LM28 alloy corners of primary silicon crystals are rounded off and eutectic silicon crystals are spheroidized same as that LM13 alloy.

Figure 11(a) shows the SEM image of worn surface of heat-treated LM13 alloy (after 60 min sliding at 4.0 m/s speed and 10 N load) wear scars, craters, and oxides tempting to oxidative wear. Figure 11(b) shows SEM image of worn out surface of as cast alloy (after 60 min sliding at 3.0 m/s speed and 30 N load) smooth strips, severe plastic deformation of surface, and crack indicating the occurrence of metallic wear. Figures 12(a) and (b) show the SEM images of LM28 alloy wear surface after sliding at 40 N load and 4.0 m/s and 5.0 m/s sliding speed. Wear surface shows the oriented overlapping flaky structure shows that asperities have been deformed by adhesion at high temperature (Fig. 12(a)). This feature is normally observed in conditions close to transition from mild to severe metallic wear. Wear surface shows the gross plastic flow of metal metallic fracture of ridges and edge cracking. These features are indicating the occurrence of severe metallic wear.

Oxidation and thermal softening of material with rise in
interface temperature are two main factors, which control the wear and friction response against given counter surface.\cite{3,4,9-13} Performance of sliding component is closely concerned with surface interface temperature since oxidation generally occurs only at real contact areas where surface temperature is highest. Oxide film may or may not be beneficial from friction and wear point of view.\cite{12,14} In case when oxide film is ductile, thick, continuous and adhered to the surface it reduces the direct metallic contact, hence friction and wear, where as brittle and discrete oxide film is detrimental because it acts as hard impurity or particle (third body) between mating surfaces.\cite{10} Heat generated at high load causes more oxidation but that is counteracted by continuous fracture under those conditions.\cite{15}

In general, metallic material’s hardness or shear strength decreases with increase in temperature, material just beneath the surface becomes weaker than the surface material owing to higher temperature and deforms more easily.\cite{10} There may be three different stages during the sliding: (A) Initial stage: It depends on surface finish and nature of oxide film. (B) Intermediate stage: Involves plastic deformation and work hardening of near surface layers. (C) Final stage: Involves constant microstructure or equilibrium of sliding processes resulting from temperature stability and equilibrium of oxide formation and break down.\cite{12} High rate of temperature rise during initial sliding period is attributed to abrasive action of broken oxide particles from sliding surface.\cite{3} Significant increase in interface temperature due to frictional heat with sliding velocity above certain critical velocity is mainly attributed to increase in contact area caused by thermal softening at a given load.

Refinement and modification reduce high temperature strength,\cite{16} which may be important from sliding wear performance point of view particularly at high sliding speed. LM28 in heat-treated condition does not show any sign of transition even up to 5 m/s sliding velocity at 3 kg normal load. LM28 in heat-treated condition shows seizure at 5 m/s sliding velocity and 4 kg normal load. This shows that seizure resistance of LM28 alloy improves significantly with heat treatment. It may be attributed to presence of primary silicon article and increase cohesiveness with matrix due to which it does not soften easily and prevents large-scale plastic flow of metal in presence of primary silicon particles. Earlier Linguard\cite{17} noticed that if large-scale plastic deformation is not allowed then oxidative wear is maintained even under heavy sliding conditions. As cast alloy shows somewhat higher interface temperature than that in heat-treated conditions. Possibly increased hardness and strength resists the yielding of asperities and gross plastic deformation near surface layer that makes oxide protective film more stable and reduce the real area of contact. In as cast condition different phases of alloy act independently that may facilitate the yielding of asperities so increase the actual area of contact. Where as under heat-treated conditions phases act simultaneously against the external load because of increased cohesiveness between various phases, which reduce the actual area of contact hence interface temperature. Actual
area of contact appears to be affected by thermal softening behaviour. More softening at a given temperature would increase the actual contact area owing to reduced hardness and yield strength. Increase in silicon content increases the resistance to thermal softening, as silicon is hard and more stable than the aluminium. That is why high silicon alloy LM28 shows lower sliding interface temperature even under severe sliding conditions. While LM13 alloy under similar sliding conditions higher temperature.

4. Conclusions

(1) Heat-treatment of LM28 reduces the temperature rise and increases the interface temperature corresponding to transitions in wear.

(2) Under mild wear conditions interface temperature remains stable after initial transitions (during the run-in) where as in severe metallic wear conditions temperature increases again after steady state or increases gradually depending up on the load.

(3) There is a critical sliding interface temperature for each alloy at which transition in mode of wear takes place. Increase in silicon content increase the critical temperature. Heat treatment of LM13 alloy does not affect this temperature while that for LM28 alloy increases significantly on heat treatment.

(4) LM28 alloy shows higher critical temperature (140°C) than the LM13 alloy (110°C) under identical conditions.

REFERENCES