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The tribological characteristics of the Al-20Si-3Cu-1Mg alloy reinforced with Al_2O_3 particles in relation to the hardness of a mating steel

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The application of aluminium in automotive engines requires the material to be strong, stiff and, more importantly, wear resistant, which calls for reinforcement with hard ceramic particles. The resultant wear resistance of an aluminium matrix composite is affected not only by the intrinsic properties of the material but also by extrinsic factors involved in the wear process. Few studies have been conducted on the influence of mating material on the wear resistance of aluminium matrix composites and that of the whole friction couple as a system. This paper presents the results of the pin-on-disk wear tests of a potential piston material, the Al-20Si-3Cu-1Mg alloy reinforced with 10 vol.% Al_2O_3 particles, with the variation of the hardness of a steel counterface from 28 to 58 HRC. The work shows that the wear rate of the composite is significantly affected by the hardness of the counter-specimen. For a higher wear resistance of the composite, the mating steel should also be harder. A soft steel counterface would result in increased wear of both the composite and the steel, and thus increased total wear of the friction couple. The observed change in wear rate with the hardness of the counter-specimen is associated with the predominant wear mechanism. The work also shows that the friction coefficient of the composite specimen is also affected by the hardness of the counter-specimen, in addition to the pressure applied in the wear tests.

1. Introduction

As low weight is nowadays an essential consideration in automobile design for improved fuel economy and cleaner emissions, the specific strength and specific stiffness of material becomes critical. Being light and strengthened through alloying, deformation or heat treatment, aluminium is used for more and more automotive components as an alternative material. However, the use of aluminium in automotive engines still needs extensive research and development in order to make it sure that the material is able to withstand rigorous working conditions, before it can be accepted by the automobile designer. It has been realized that one of the critical factors hindering its use in automotive engines is its poor wear resistance, which in the cylinder/piston/piston ring system, for instance, may lead to dreaded scuffing or seizure of the piston. Therefore, in addition to high specific strength and specific stiffness, further requirements in wear resistance are placed on aluminium for the application in automotive engines.

Reinforcing aluminium with hard ceramic particles to compose aluminium matrix composites can effectively compensate for the inherent shortcomings of monolithic aluminium alloys. The composites are characterised by a number of favourable properties including enhanced specific strength/stiffness and especially improved wear resistance [1–4]. So far, a lot of research has been conducted worldwide with respect to their tribological characteristics. Many of the results are however inconsistent [5–7], especially with regard to the effect of different factors on the wear resistance of the composites. These factors include

- material
  - the type of matrix material, Al, or Al-Si, or 2xxx series, or 6xxx series, or 7xxx series
  - the type of reinforcement, fibres (short or long) or particles (spherical or angular), SiC or Al_2O_3
  - additives (graphite)
  - surface roughness

- processing technique (powder metallurgy, or casting, or infiltration)
- testing condition
  - pressure
  - temperature
  - environment
  - type of relative motion (continuous or reciprocal)
  - sliding speed
  - type of friction (dry or lubricated)

As a matter of fact, the inconsistencies of the obtained results are not surprising. Wear resistance is not a material property. It is not always uniquely correlated with strength or hardness. It depends upon the combination of all intrinsic and extrinsic factors involved in the wear process. Therefore, friction and wear must be considered the general characteristics of the friction couple as a system.

In the friction couple, there is a very important factor, i.e. mating material. This factor is often neglected in comparing the wear resistance of aluminium matrix composites. Sometimes even no mention is made in many publications about the composition, surface roughness, dimensions and mechanical properties of the counterface used in wear tests. The role of the mechanical properties of the mating material in determining the friction and wear behaviour of the composites has rarely been determined.

In the present work, pin-on-disk tests were performed to characterize the friction and wear of an aluminium matrix composite, potentially for the application in automotive engines, in relation to the mechanical properties of mating material. It must be noted that the tests were not intended to simulate the piston/piston ring relative motion but to clarify the effect of mating material on the tribological behaviour of the composite.

2. Experimental details

The matrix material of the composite was provided by Showa Denko K.K. in Japan, in the form of a powder produced by means of air atomization at a mean cooling rate of 10^4–10^6 K/s . The nominal composition of the matrix alloy was 20%Si, 3%Cu, 1%Mg and balance aluminium. The powder had a median size of about 64 μm and an irregular shape. The reinforcement was an aluminium oxide powder with a median size of 6 μm and an angular shape.

The matrix powder and the ceramic powder were mixed in a dry condition to produce a homogenous mixture with 10% Al_2O_3 by volume. The mixed composite was consolidated by using hot extrusion [8], which lead to 100% density. The consolidated composite was then subjected to heat treatment including a solution treatment at 470°C for 1.5 hours, cooling in water and ageing at an ambient temperature for four days and then at 120°C for 24 hours. The heat-treated composite had a hardness value varying from 75.0 to 88.1 HRB. Fig. 1 shows the microstructure of the composite, with the dark particles being the Al_2O_3 reinforcing phase and the grey silicon crystals in the aluminium matrix. It should be noted that the as-extruded structure of the composite is characterised by the aligned distribution of the Al_2O_3 particles in the matrix alloy along the extrusion direction.

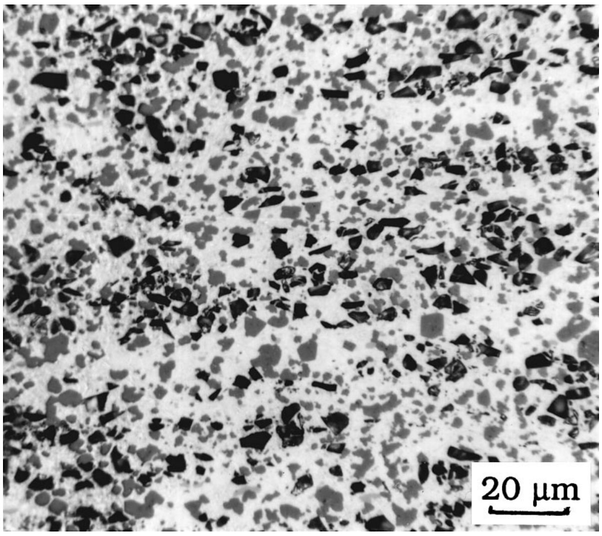

Figure 1 The microstructure of the composite on the plane parallel to the extrusion direction.

The composite specimens for tribological tests were prepared with their friction surface perpendicular to the extrusion direction. They had a diameter of 5 mm and a length of 15 mm.

The mating material used in the wear tests was a steel with the composition of 1.7%C, 12%Cr, 0.4%Mn, 0.4%Si and balance iron. It was hardened and tempered under different conditions to have hardness at distinctly different levels, namely 28 ± 1, 40 ± 1, 58 ± 1 HRC. The mating material was in the form of a disc (counter-specimen) with a diameter of 75 mm. The disc surface (counterface) was ground to Ra ~ 0.32 μm.

The tests were performed on a proprietary test rig with a configuration of pin-on-disc under the conditions given in Table I. No lubrication was applied. The mass loses of the composite specimen (the pin) and the steel counter-specimen (the disk) were measured at regular intervals during continuous sliding after an initial running-in period. The friction of the specimen on the counter-specimen was determined on a circle with a constant diameter of 60 mm. The contact surfaces of the tested specimens and counter-specimens were examined with a scanning electron microscope. In addition, optical microscopy was also performed to analyze the subsurface layers, in an effort to describe the underlying mechanisms of the wear of the composite sliding against the steel with different hardness values.

TABLE I Conditions of pin-on-disk tests

Pressure (MPa)	Sliding speed (m/s)	Sliding distance (m)	Environment	Temperature (°C)	Friction type
0.5	1	12,000	Air	20	Dry
1.5	1	9,000	Air	20	Dry
3	1	6,000	Air	20	Dry

3. Results and discussion

Fig. 2 shows the mass loss of the composite specimen Z_m in the friction couple with a soft counter-specimen (28 HRC), as a function of sliding distance. It can be seen that the mass loss steadily increases with increasing sliding distance. Over the range of the sliding distances covered in the present tests, the mass loss of the composite specimen is almost a linear function of the sliding distance. At a given sliding distance, the mass loss of the composite specimen is significantly higher under a higher contact pressure.

When the counter-specimen is harder (40 HRC), the trend described above remains the same. However, the mass loss of the composite specimen is considerably reduced under the same pressure and at any distance covered during the tests, as shown in Fig. 3.

With a further increase in the hardness of the counter-specimen to 58 HRC, the mass loss of the composite specimen is further reduced, see Fig. 4. This reduction is more obvious at a lower contact pressure. When the wear of the composite is expressed with wear rate I_m, which is defined as the mass loss at a unit sliding distance, it becomes clear that the wear of the composite is indeed reduced with a harder counter-specimen, especially at a lower contact pressure, as shown in Fig. 5.

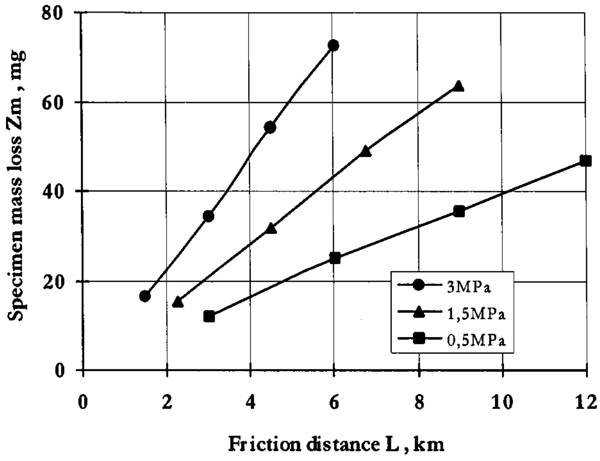

Figure 2 Mass loss of the composite in the friction couple with a 28 HRC counter-specimen.

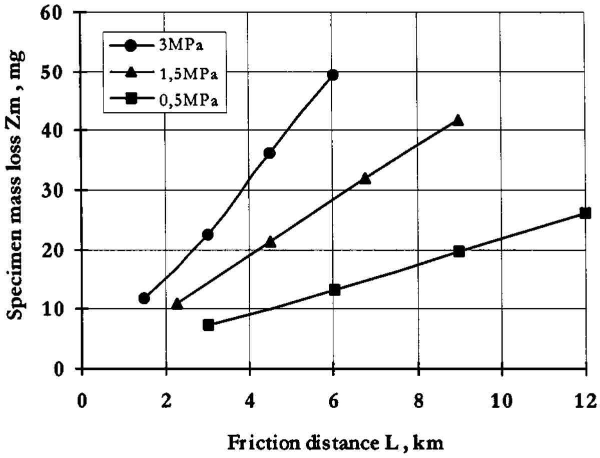

Figure 3 Wear rate of the composite in the friction couple with a 40 HRC counter-specimen.

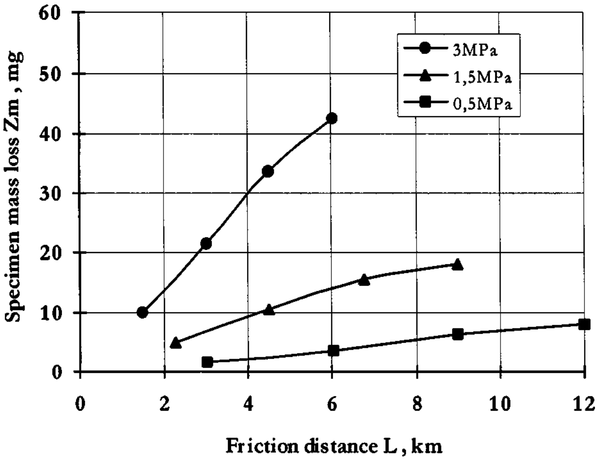

Figure 4 Wear rate of the composite in the friction couple with a 58 HRC counter-specimen.

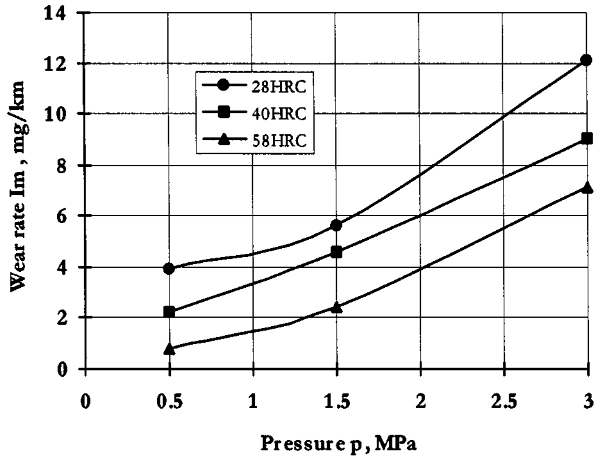

Figure 5 Wear rate of the composite mating the steel with different levels of hardness as a function of contact pressure.

The analysis of the surfaces of the wear-tested specimens and counter-specimens suggests the involvement of several wear mechanisms, namely abrasive wear, adhesive wear, oxidising wear and delamination. However, depending on the condition of the wear tests and the hardness of the counter-specimen, a specific type of wear plays a predominant role in the wear process of the composite.

On the surfaces of the softest counter-specimens, local accretions areas and some material containing reinforcing phase (Al_2O_3 particles) and transferred from the composite specimen were found. These particles, discharged during the wear process of composite, would act as abrasives and thus the predominating wear mechanism was ploughing.

With the increase in counter-specimen hardness, the composite specimen surfaces became less worn out, and the recesses appeared shallower and wider. On the surface of the hardest steel counter-specimens, no build-ups could be found. Only when the highest contact pressure was applied, was some material transfer to the counter-specimen observed. The composite specimen surfaces were smooth. There was no evidence suggesting the shielding of the composite surface by the hard ceramic particles. In this case, the role of abrasion was less important. Instead, flaky debris was found on the worn surfaces of the composite specimens and thus the delamination appeared to be a major wear mechanism. This corresponded to less wear for the composite in comparison with that due to abrasion in the friction couple with a softer counter-specimen.

It is worth noting that delamination as a predominant wear mechanism is not observed on the worn surfaces of aluminium matrix composites based on a softer matrix, for example, an Al-Cu matrix or an Al-Si matrix without going through an ageing treatment [9].

To consider the friction couple a system, one also needs to analyze the wear of the counter-specimen. This is important because it may well happen that the improvement of the wear resistance of an aluminium alloy by adding ceramic reinforcement is actually at the sacrifice of the mating material in the friction couple. In practical terms, what really matters is the total wear of the two mating components, which is often associated with leakage or unacceptable tolerances in a mechanical system. Fig. 6 shows the wear rate of the steel counter-specimen, which decreases as its hardness increases. This is because the Al_2O_3 particles in the composite specimen abrade and roughen the soft counter-specimen, resulting in its accelerated wear. It can also be seen from Fig. 6 that at a specific hardness value, the wear rate of the counter-specimen increases with rising contact pressure. This is again due to the higher abrasive action of the ceramic particles on the counter-specimen when the contact pressure is higher. Combining the wear of both the composite specimen and the steel counter-specimen, one may come to the conclusion that to reduce the total wear of the friction couple with an aluminium matrix composite, it is necessary to have a harder mating surface.

The present wear tests also show that the hardness of the counter-specimen also influences the friction coefficient of the composite at the mating surface. As shown in Fig. 7, the μ value is the lowest at the highest contact pressure and when the counter-specimen is softer. This is probably because the detached material from the composite material is pressed into the soft counter-specimen, forming two-body abrasion and corresponding to a low friction coefficient. However, when the counter-specimen is harder and the pressure is lower, the embedment of the delaminated material would be difficult and, as a result, there would be three-body abrasion leading to a higher friction coefficient.

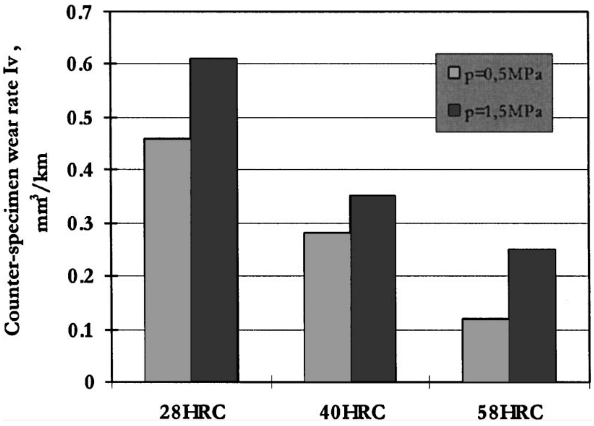

Figure 6 The wear rate of the counter-specimen with different hardness values and under the pressures of 0.5 and 1.5 MPa.

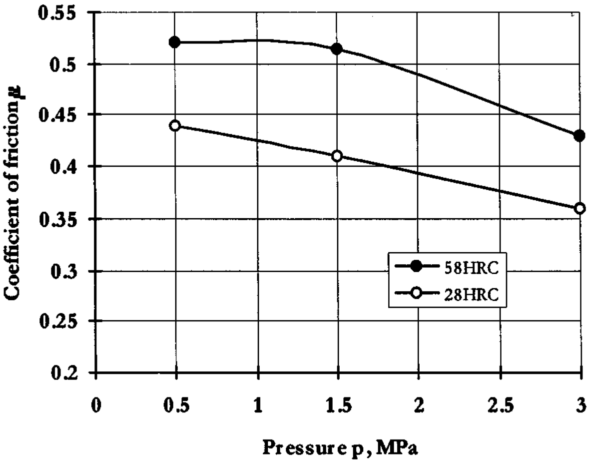

Figure 7 The dependence of the friction coefficient of the composite in the friction couples with the 28 HRC and 58 HRC counter-specimens on contact pressure.

4. Conclusions

The pin-on-disk tests of the piston material, Al-20Si-3Cu-1Mg alloy reinforced with 10 vol.% Al_2O_3, have been performed using the steel counter-specimens with hardness at different levels. The results of the tests lead to the following conclusions.

(1) The wear resistance of the aluminium matrix composite is strongly influenced by the mechanical properties of the mating material used in the wear tests. With a harder mating steel, both the composite and the steel itself will be more wear resistant. In other words, to obtain a higher wear resistance of the composite, one needs to have a harder steel to mate with it.

(2) The influence of the hardness of the mating material is associated with the predominant wear mechanism operating during the wear process. With a soft steel as a mating material, material transfer from the composite to the steel occurs and abrasive action on the composite promotes its wear. With a harder steel counterface, delamination at the friction surface of the composite is largely responsible for its wear.

(3) The friction coefficient of the composite is also affected by the hardness of the counterface, in addition to pressure. With a harder counterface, the friction coefficient is increased, which is likely caused by the difficult embedment of the material detached from the composite in the counterface.

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