

Evaluation study of cast Al–SiC_p composites

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The present work is concerned with the wear properties of aluminium matrix–SiC particles cast composites. It was found that introduction of SiC particles into Al alloys causes a drastic reduction in the wear rate. With SiC content above 13.5 wt. %, however, the wear rate starts to increase again. The particle size of 25 µm is optimum for the improvement of wear resistance compared to other sizes (1 and 125 µm). The friction coefficient and sliding surface temperature decrease with increasing particles content.

Key words: *Al–SiC_p composite; wear rate; friction coefficient; temperature*

1. Introduction

In tribological applications, aluminium alloys are desirable because of their low densities and cost, but their relatively poor wear resistance has impeded progress in this direction. Therefore, the development of aluminium–ceramic particulate composites could significantly increase wear resistance, assuring these composites considerable applications in industry [1, 2].

Mechanical properties of particle-filled metal-matrix composites are not considerably enhanced, but the tribological properties are clearly improved. Soft solid lubricant particles like graphite and mica improve the antiseizing properties of aluminium alloys. The most promising application of cast graphitic–aluminium composites is for bearings that would be cheaper and lighter in addition to being self-lubricating when compared to the bearings currently made of alloys containing Cu, Pb, Sn, and Cd. The use of graphite in automobile engine pistons considerably reduces the wear of cylinder liners as well as improves fuel efficiency and reduces frictional horse power losses.

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Hard particles like SiC, Al₂O₃, WC, TiC, ZrO, and BC greatly improve the abrasive resistance of aluminium alloys, especially at elevated temperatures. Such composites find applications in a number of components, including impellers, pistons, piston rings, cylinder liners, connecting rods, machine shrouds, brake systems, and other tribological systems that run at relatively high temperatures. They have also been tried as turbocharger impellers that run at high temperatures [3]. Finally, SiC is considered to be an optimal reinforcement phase for aluminium and its alloys, because it has low density, only one slightly higher than aluminium, a high modulus and strength, and it is readily available at low cost.

The effects of high energy ultrasonic vibrations and other parameters on some properties of Al-SiC_p composites have been studied by Al-Haidary and Al-Kaaby [4]. The present work focuses on the tribological properties (wear rate, friction coefficient, and sliding surface temperature), since the Al-SiC particulate composite has been classified mainly as a tribological material.

2. Experimental

In our previous work [4], several ingots with different combinations of SiC particle contents and sizes have been prepared. These samples were used in this work as well. A pin-on-disc machine (Fig. 1) was used to investigate the manufactured composites.

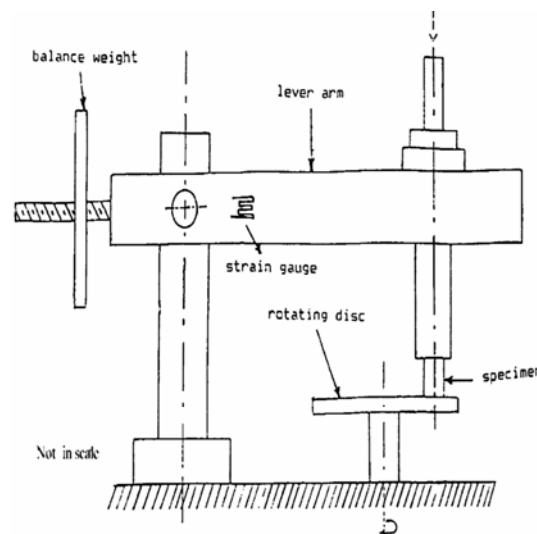


Fig. 1. A scheme of the pin-on-disc apparatus

For this purpose, seven ingots with different SiC contents, three ingots with different SiC particle sizes, and three with various amounts of magnesium in addition to the

base one were prepared, as shown in Tables 1–3. The tests were conducted to study the effect of SiC particle content, size, and Mg wt. % on the wear rate, friction coefficient and sub-surface temperature of the composites under two loads, namely 10 and 20 N.

The as-cast composites were machined on lathe to prepare 10×25 mm² rod samples. One base of each sample was ground with 1000 grit silicon carbide paper, then polished with 0.25 μm alumina, cleaned with water, degreased with ethanol, and dried. A hardened, 45HRC, carbon steel counterface disc was used.

Table 1. The compositions of Al–SiC composites¹

Code	Mg content [wt. %]	Retention [wt. %]
A1	0.001	13.5
A2	0.45	14.6
A3	0.8	19.1
A4	3.8	21.4
A5	5	21.9
A6	6.6	22.5

¹Average particle size – 25 μm.

Table 2. The composition of Al composites containing SiC particles with three different sizes

Code	Average particle size [μm]	Mg content [wt. %]	Retention [wt. %]
C1	1	0.85	8.1
C2	25	0.9	19.1
C3	125	0.9	14.0

Table 3. The composition of Al-matrix alloys

Code	Mg content [wt. %]
B	0.001
B1	1.2
B2	2.7
B3	4.9

Wear rates were calculated by measuring the weight loss of the sample using a sensitive balance with an accuracy of 0.1 mg. The formula used to convert the weight loss into wear rate is:

$$\text{Wear rate} = \frac{\Delta W}{S} \quad [\text{mg} \cdot \text{cm}^{-1}]$$

where ΔW is the weight difference of the sample before and after the test in mg, S is total sliding distance in cm.

To estimate the friction coefficient, the friction force was measured between the pin and the disc surfaces. For this purpose, two strain gauges were cemented on the vertical faces of the lever arm (Fig. 1) and the elastic bending strain of the lever arm was measured. An estimate of the heat generated at the sliding interface due to friction was obtained by impeding a thermocouple head in a deep hole near the rubbing surface of the pin by about 1 mm. The readings of the thermometer can be used for comparing between different composites and metal cases as particle content and size are changed, and thereby their role in generating heat at the rubbing surface.

3. Results and discussion

The effect of magnesium additions alone (base aluminium, that with 1.2, 2.7 and 4.9 wt. % Mg) on the wear rate were also taken into account. Figure 2 shows the positive role of adding Mg on the wear rate of Al. This is due to the solution hardening of Mg in Al. As a consequence, the wear resistance of the alloys increased somewhat.

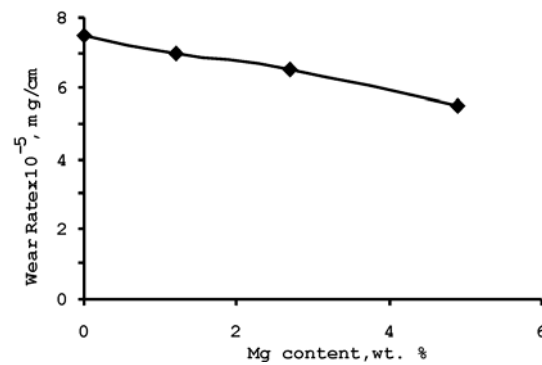


Fig. 2. Wear rate vs. Mg content (wt. %) in Al at a 10 N load. The wear rate values were taken at a steady state, i.e. after 180 min

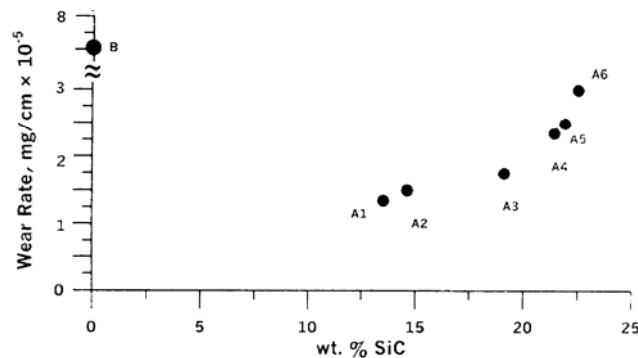


Fig. 3. Wear rate vs. SiC content for various Al-alloy matrices (load – 10 N, SiC average particle size – 25 μm , wear rate values taken after 180 min of sliding time)

The main indication which can be noticed from Fig. 3 is that the introduction of SiC particles (25 μm) to the matrix alloy (B) reduced the wear rate drastically. Increasing SiC content from 13.5 wt. % to 22.5 wt. % by adding Mg, however, increased the wear rate to some extent.

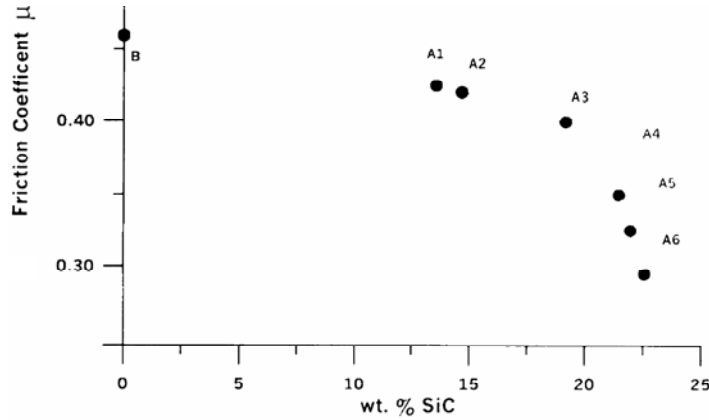


Fig. 4. Friction coefficient vs. SiC content for various Al-alloy matrices (load – 10 N, SiC average particle size – 25 μm , the values of the friction coefficient were taken after 180 min of sliding time)

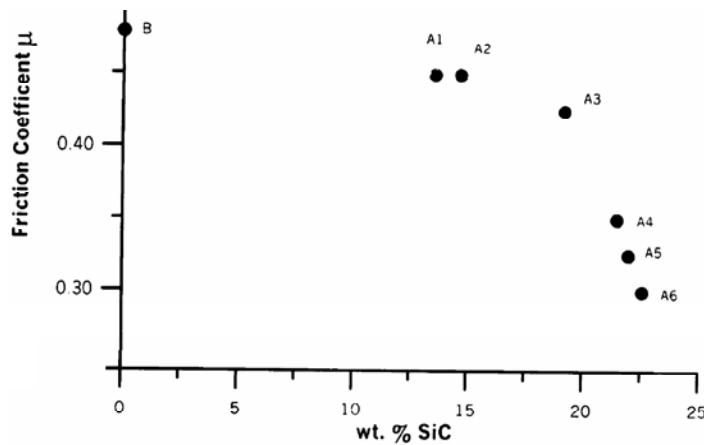


Fig. 5. Friction coefficient vs. SiC content for various Al-alloys matrices (load – 20 N, SiC average particle size – 25 μm , the values of the friction coefficient were taken after 180 min of sliding time)

The improvement in wear resistance accompanying the presence of ceramic particles in the aluminium matrix is due to an increase in average hardness [5, 6] and to reduction of the friction coefficient (Figs. 4, 5). This has been confirmed by Sato and Mehrabian [5] and Hosking et al. [6] for the aluminium matrix–Al₂O₃ system, by Rohatgi and Surappa [7] for the aluminium matrix–SiC system, by Rohatgi et al. [8] for the aluminium matrix–SiO₂ system, and by Rohatgi et al. [9, 10] for the aluminium matrix–zirconia system. The change in behaviour of the curve in Fig. 3 accompanying

the increase in SiC content from 13.5 wt. % to 22.5 wt. % can be explained by the fact that delamination is the dominating mechanism in the wear of matrix alloys (Fig. 6a) and composites (Figs. 6b–6d) where worn surfaces of samples B, A1, A4 and A6 are shown.

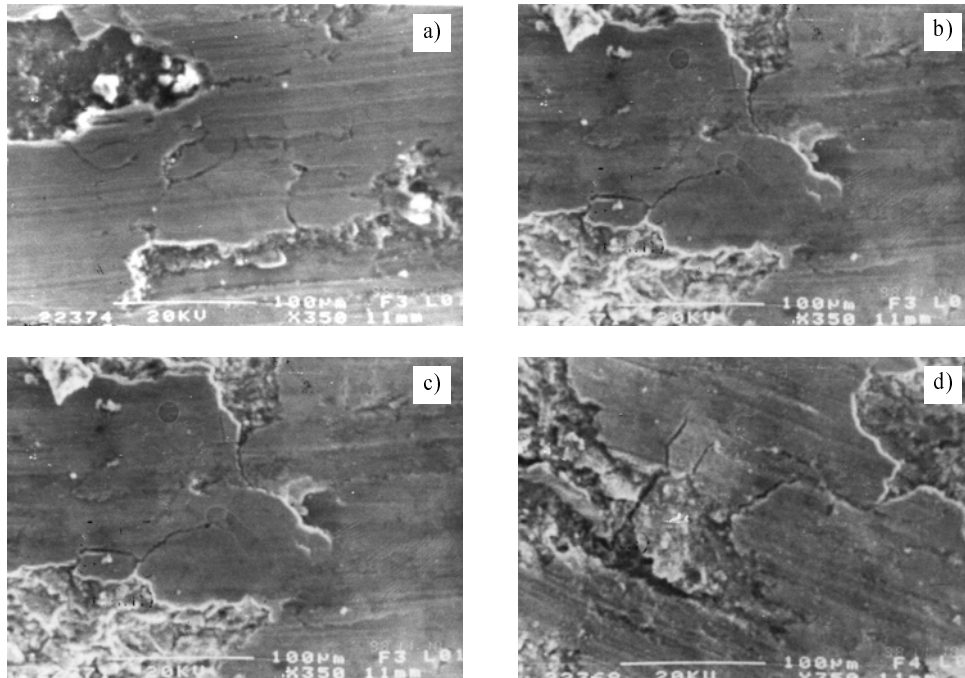


Fig. 6. Worn surfaces of the samples: a) 3, b) A1, c) A4 and d) A6; load – 10 N, sliding time – 180 min, magnification 250×

It is clear that the addition of Mg to the composite improves wettability [4], but generally the adhesion between SiC surfaces and the aluminium matrix is poor due to the formation of a weak Al_4C_3 layer around SiC particles [11]. As a result, the interface will be more or less equivalent to pre-existing cracks. Therefore, although the hardness increases with an increasing volume fraction of reinforcements in the matrix, the wear rate also increases owing to the increasing number of pre-existing cracks and to the decreasing distance that a crack must propagate to link with other cracks. Figure 6 shows the wear tracks of unreinforced alloy (B), the tendency to form delaminated wear flakes, and the final surface cracking. Suh et al. [12–14] have overviewed the mechanism of wear and proposed that the crackings result from the repeated surface tracting exerted by the hard asperities of the steel counterface. They state that plastic shear deformation accumulates with repeated loading, causing the cracks to nucleate below the surface, because nucleation on the surface is not favoured due to compression stress existing just below the contact region. Once the cracks are present (owing either to crack nucleation or to pre-existing voids), further loading and defor-

mation cause cracks to extend and propagate, and join neighbouring ones. Finally, the cracks extend to the surface at certain weak positions. Proof of delamination theory (cracks and holes) are clearly seen in Figs. 6b–6d which show the worn surfaces of composites A1, A4, and A6. This is due to the fact that there are many cracks propagating at the aluminium matrix–SiC interface. These cracks increase with increasing SiC particle content, which causes a reduction in the distance that a crack must propagate to link with others.

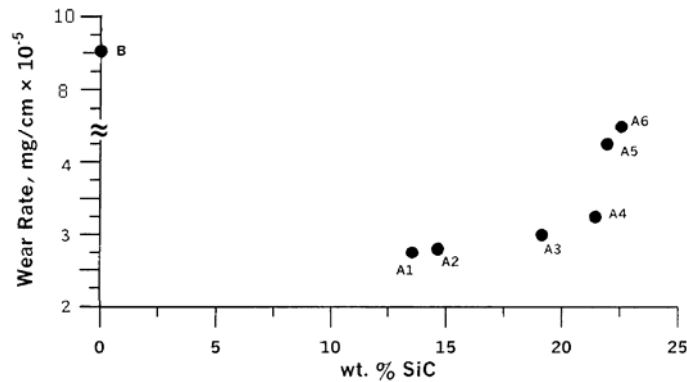


Fig. 7. Wear rate vs. SiC content for various Al-alloys matrices (load – 20 N, SiC average particle size – 25 μm , wear rate values taken after 180 min of sliding time)

Many investigators [7, 6, 15, 17], studied the wear behaviour of various aluminium-matrix composites. They confirmed our results on the reduction of wear rate with the addition of ceramic particles (Figs. 3 and 7), but none of them have stated that wear rate starts to increase again when particle content further increases above a specified limit. This phenomenon may depend on the nature of the particle–matrix interface, which also depends on many other factors, such as the ceramic phase type and shape, manufacturing method, the testing load, and manufacturing conditions.

Returning to Fig. 3, it can be noticed that the aluminium matrix–SiC particulate composites resist adhesive wear better than the matrix alloys (B in Fig. 2) for all volume fractions of SiC particles. Bhansali and Mehrebian [18], on the other hand, stated that composites containing SiC particles offered virtually no or moderate improvement in wear resistance at different loads. They attributed this poor improvement to the brittle interface between SiC particles and aluminium matrix alloy which facilitates shearing unable to resist the action of the adhesive wear under loads.

Figure 8 illustrates the variation of wear rate with particle size under the 10 N load. To prevent confusion resulting from mixing the variations of particle content and particle size, one can return to Fig. 3 and use the effect of particle content on wear rate as a reference when investigating the effect of particle size on wear resistance alone. From Figure 8 it is obvious that a particle size of 25 μm was optimum for improving wear resistance compared to other sizes (1 and 125 μm). The wear resistance improvement of aluminium-matrix composites that accompanied increasing

reinforcement particle size agrees with some previous works [6, 18], since the agglomeration tendency of fine particles (1 μm , Fig. 9) leads to a decrease in the wear resistance due to the reduction of bulk mechanical properties [4], whereas other variables are kept constant.

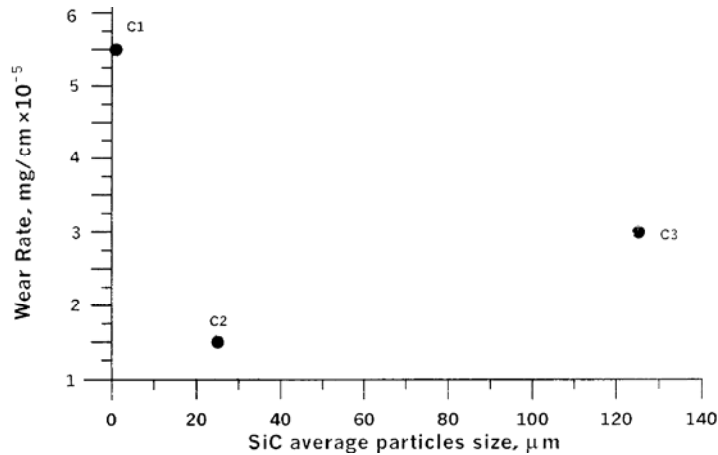


Fig. 8. Wear rate vs. SiC average particle size (load = 10 N, C2 = A3, wear rate values taken after 180 min of sliding time)

The deterioration of wear resistance that accompanied increasing particle size from 25 to 125 μm has not been reported before this study. This can be explained referring again to the delamination mechanism of wear. The crack propagation rate controls the wear rate rather than the crack nucleation rate in materials containing a weakly bonded second phase [14]. Therefore, the coarsening of SiC particles means that the pre-existing crack sizes increase, resulting in the ease of crack propagation and linking with other cracks. The relative wear rate increasing in the 125 μm particle sample can be due to fragmentation fracturing and there may be some dissolution of these particles in the matrix (Fig. 10).

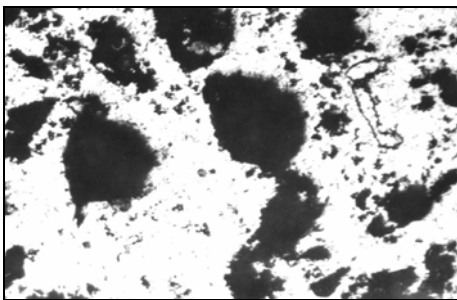


Fig. 9. Agglomeration of fine particles in sample C1, magnification 70 \times

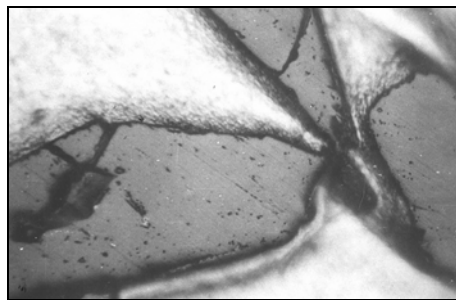


Fig. 10. Fragmentation and possibly some dissolution of large particles, magnification 300 \times

The steady state value of the coefficient of friction μ is plotted against particle content in Fig. 4. The figure shows that, in general, the addition of ceramic particles to the aluminium alloy matrix reduces the coefficient of friction continuously with increasing particle content. This can be attributed to an overall hardening effect that resulted from increasing the ceramic particle volume fraction. An identical result has been reported by Hosking et al. [6].

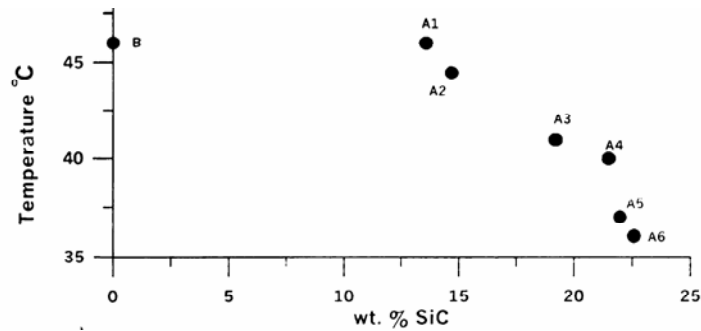


Fig. 11. Rubbing subsurface temperature vs. SiC content for various Al-alloy matrices (load – 10 N, SiC average particle size – 25 μm , temperatures were taken after 27 min of sliding time, i.e. at a temperature steady state)

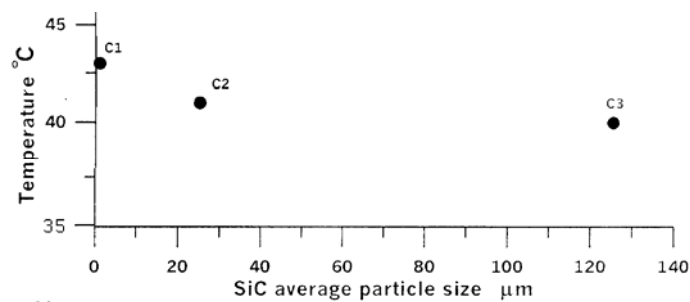


Fig. 12. Rubbing surface temperature vs. SiC average particle size (load – 10 N, C2 = A3, temperatures were taken after 27 min of sliding time)

Figures. 11 and 12 develop the effect of particle content and size, respectively, on the sample near (1 mm) surface temperature during sliding. From Figure 11 it can be seen that the temperature decreases with increasing SiC particle content. This is due to the reduction in the friction coefficient (Figs. 4, 5). Figure 12 shows a narrow range of temperature change. It is not reasonable to attribute this temperature change to the variation in particle size alone, and the particle content should be taken under consideration as well. Figures 5, 7, 13 and 14 describe previous experiments with the 20 N load. They show that the general trend is equivalent, although the applied load is higher.

The influence of particle size on the coefficient of friction under the 20 N load is illustrated in Fig. 15. From this figure it can obviously be recognized that the compos-

ite containing the finer size (1 μm) has a lower friction coefficient compared to other samples, taking the effect of the difference in particle content under consideration (Fig. 5). This is in agreement with the results of Hosking et al. [6]. As a result of the agglomeration tendency of the fine particles, they are easily pulled out of the matrix and produce three-body abrasive wear conditions or a ceramic particle separating layer between the two sliding metals, which obviously results in a reduction of the friction coefficient.

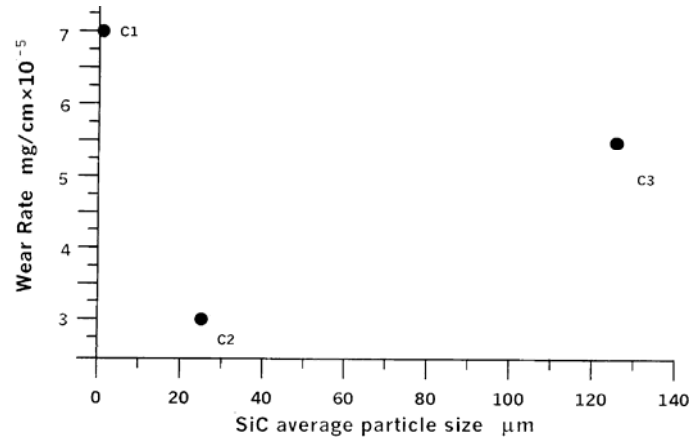


Fig. 13. Wear rate vs. SiC average particle size (load – 20 N, C2 = A3, wear rate values were taken after 180 min of sliding time)

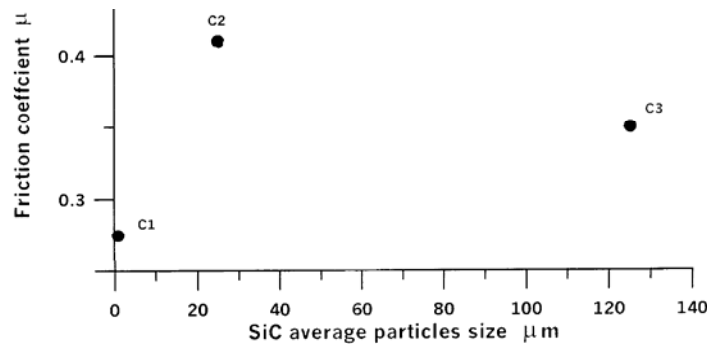


Fig. 14. Friction coefficient vs. SiC average particle size (load – 20 N, C2 = A3, the values of the friction coefficient were taken after 180 min of sliding time)

Finally, when concentrating on the micrographs of the worn surfaces (Figs. 6b–6d), it can be noticed that SiC particles disappear. This can be attributed either to the coating of these particles with a viscous aluminium film, resulting from localized fusion at the sample surface during rubbing, or to the particles being embedded in a soft matrix, since the heating effect of rubbing and normal load promote such phenomena.

4. Conclusions

- Addition of SiC particles to the Al-alloy matrix clearly improves wear resistance. Above the content of 13.5 wt. % of SiC, however, the wear resistance begins to decrease under both 10 N and 20 N loads.

- The friction coefficient decreases with increasing SiC particle content under both 10 N and 20 N loads.

- The particle size of 25 μm is optimum for improving the wear resistance when compared to other sizes (1 and 125 μm) under both 10 N and 20 N loads.

- The surface temperature decreases with increasing SiC particle content.

- The finer particle size (1 μm) gives a lower friction coefficient compared to the other sizes (25 and 125 μm).

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