FRICTION AND WEAR OF Al-Si/SiC$_p$ COMPOSITES IN RECIPROCATING SLIDING AGAINST AISI 52100 STEEL

José Ramos Gomes
Universidade do Minho, Departamento de Engenharia Mecânica, CIICS, 4800-058 Guimarães, Portugal
jgomes@dem.uminho.pt

Sérgio Freitas Carvalho
Universidade do Minho, Departamento de Engenharia Mecânica, CIICS, 4800-058 Guimarães, Portugal
sergioc@dem.uminho.pt

Abstract. *Aluminium matrix composites reinforced with silicon carbide particles (Al-Si/SiC$_p$) are characterised by an excellent strength-to-weight ratio, which makes them tribomaterials of high potential for automotive and aeronautic industries, particularly in applications such as cylinder liners, valves and came followers. In those situations the tribological interactions between the mating surfaces occur as a consequence of reciprocating sliding. Therefore, the characterisation of the tribological response of Al-Si/SiC$_p$ composites under this contact situation assumes particular importance.*
In this study, the friction and wear properties of aluminium matrix composites reinforced with distinct content of SiC particles (25.8, 30.5 and 33.4 wt.%) is characterised in unlubricated sliding against AISI 52100 steel. Tribological tests were performed in a ball-on-flat tribometer where a steel ball was loaded against a reciprocating Al-Si/SiC$_p$ composite plate. The stroke length of the reciprocating motion varied between 2 and 10 mm, whereas the normal load and frequency were kept constant (10 N and 1 Hz, respectively). The influence of the stroke length on the friction and wear of Al-Si/SiC$_p$ composites was evaluated and the dominant wear mechanisms were identified. The friction coefficient assumed values between 0.50 and 0.65, whereas the wear coefficient was in the order of 10^{-4} $mm^3N^{-1}m^{-1}$. The wear resistance of Al-Si/SiC$_p$ composites slightly increased with the SiC content, but significantly decreased for higher strokes. Surface fatigue and abrasion were the dominant wear mechanisms identified respectively for aluminium matrix composites and steel worn surfaces.

Keywords*: friction, wear, aluminium matrix composites, steel, reciprocating sliding*

1. Introduction

The demand for inexpensive, lightweight, stiff and strong materials has lead to the development of aluminium matrix composites reinforced with ceramic particles. These composites have been considered to be wear resistant materials because of the hard reinforcement. The wear of aluminium matrix composites has been studied by numerous researchers (Ahlatci *et al*. (2004), Salazar and Barrena, 2004, Sawla and Das, 2004, Shipway P.H. *et al*. (1999)) since these materials are currently being considered as promising tribomaterials with applications in the aerospace, aircraft (Sannino and Rack, 1995) and in particular the automotive industries (Bermudez *et al*. (2001), Bindumadhavan *et al*. (2001)). In fact, the high strength-to-weight ratio of aluminium matrix composites makes it possible that the substitution of steel engine parts by aluminium-based parts in automobiles could result in improved engine efficiency and a reduction in noise and friction (Li and Tandon, 1997).

The degree of improvement of wear resistance of composites depend materials in a great extent on the nature of reinforcement. The use of hard ceramic particles like SiC as reinforcement in aluminium matrix composites have shown to reduce the wear loss as compared to the base alloys (Gomes *et al*. (2000), Chung and Hwang, 1994). This improvement of wear resistance is attributed to the load supporting capability given by the hard ceramic particles. Therefore, the volume fraction of reinforcing particles is a decisive parameter to determine the tribological response of composites.

The tribological behaviour of aluminium matrix composites is also known to be affected by working conditions, such as load, temperature and sliding speed (Gomes *et al*. (2001), Wilson and Alpas, 1997). In applications like cylinder liners, valves and came followers the tribological interaction between the mating surfaces occurs in reciprocating sliding, where the speed vary from zero at the two ends of the stroke to the maximum at the centre of the stroke. Although a large body of literature exists concerning the wear performance of reinforced aluminium matrix composites, most of them consider unidirectional sliding at constant speed. Therefore, a lack exists concerning the tribological response Al-based composites tribologicay loaded under oscillating motion.

This study aims to contribute to the understanding of the friction and wear behaviour of Al-Si/SiC$_p$ composites with different SiC content in reciprocating sliding against a steel counterface.

2. Materials and experimental procedure

The aluminium matrix composites selected for tribological characterisation have three distinct silicon carbide content of reinforcing particles and were tested against AISI 52100 steel ball bearing. The diameter of steel balls was 10 mm. Table 1 presents the chemical composition, volume fraction of reinforcing particles and hardness of the composites. Table 2 presents the chemical composition and hardness of AISI 52100 steel ball bearing.

Table 1. Chemical composition, volume fraction of reinforcing particles and hardness of Al-Si/SiC_p composites.

Material	Composition (wt%)	Particle Fraction Area (%)	Hardness (HV(30))
Composite A	8.5-9.5% Si; 0.45-0.65% Mg; 0.2% Ti; 0.2% Fe (max) 0.2% Cu (max)	25.8	80
Composite B		33.4	89
Composite C		30.5	85

Table 2. Chemical composition and hardness of AISI 52100 steel ball bearing (Guo and Liu, 2002).

Material	C (%)	Mn (%)	P_{max} (%)	S_{max} (%)	Si_{max} (%)	Cr (%)	HRc
AISI 52100 steel	0.98-1.10	0.25-0.45	0.025	0.025	0.15-0.30	1.30-1.60	58-63

Tribological tests were performed in a ball on flat geometry using an AISI 52100 steel ball bearing against Al-Si/SiC_p plates. A Plint TE 67/R tribometer with a reciprocating plate adapter was used where the stroke length of the reciprocating motion assumed the values of 2, 4, 6, 8 and 10 mm. During sliding, in air and without lubrication, the normal applied load remained constant with the value of 10 N and the frequency of the oscillation motion was 1 Hz. The total sliding distance was x=40 m for all tests. The evolution mode of the friction coefficient along each test was evaluated and the average steady-state friction coefficient value and the wear coefficient of both matting triboelements were calculated.

The steel ball and composite flat specimens were ultrasonically cleaned in ethyl alcohol before and after the reciprocating sliding experiments. The amount of wear was evaluated using a microbalance with an accuracy of 10 µg. The wear volume was calculated from the weight loss and the density of the material. Scanning electron microscopy was used to examine the morphology of the wear surfaces in order to identify the dominant wear mechanisms.

3. Results and discussion

Figure 1 shows the average friction coefficient values, µ, obtained for all steel/composite pairs tested with different strokes. The average friction coefficient was characterised by values between 0.50 and 0.65 and increased with the stroke length from s=2 to s=6 mm. For strokes above 6 mm, no net effect of this test parameter was observed on the average friction coefficient values. On the other hand, contacts involving composites B and C, which are characterised by the higher SiC content, reveal higher friction values than composite A. This behaviour can be explained by the increasing of the mechanical component of friction due to the ploughing effect promoted by ceramic particles acting as two-body or three-body abrasive agents.

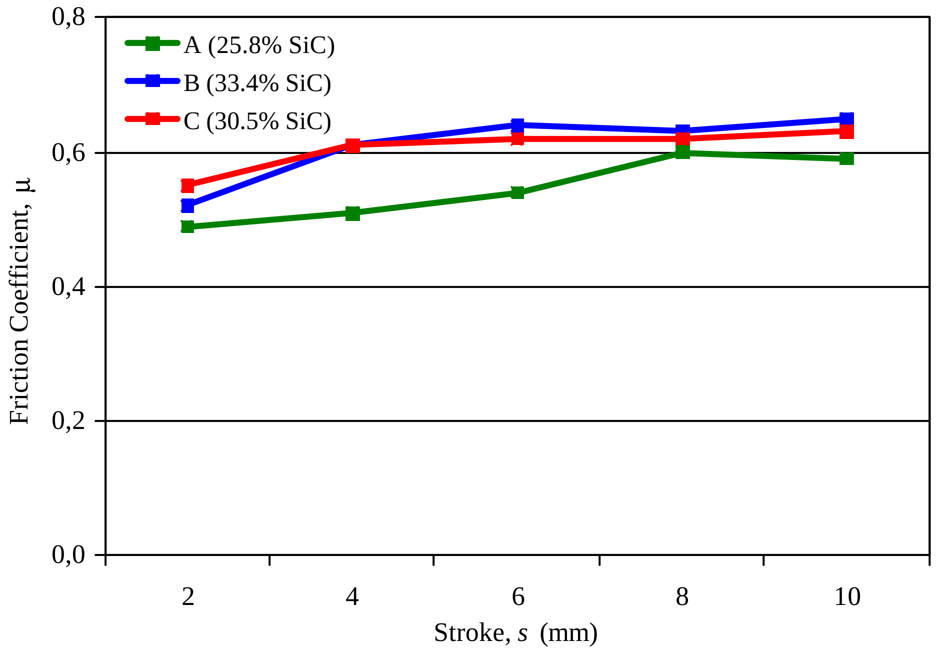


Figure 1. Average friction coefficient values for AISI 52100 steel/composite pairs tested for different strokes

In all tests, the variation of the friction coefficient during sliding denoted the existence of a running-in stage characterised by increasing values of the friction coefficient, followed by a steady-state regime (Fig. 2). Nevertheless, it was observed that the duration of the running-in stage increased with the stroke length. In fact, for s=2 mm, the running-in period was verified to correspond to a sliding distance of almost 5 m, whereas for s=10 mm the running-in regime was remained for a sliding distance of approximately 20 m.

Figure 3 shows the wear coefficient dependence of both steel balls and opponent composite plates with the stroke length, between 2 and 10 mm. The wear coefficient values of composites were always higher than those obtained for the steel balls, which is explained by the superior hardness of this triboelement (Tab. 1 and Tab. 2). In addition, the wear coefficient of composites significantly increases with the rise of the stroke from 2 to 6 mm, but remained almost constant for higher strokes. Composite B, with the higher content of reinforcing particles (33.4%), is characterised by low wear than the other composites, which is in accordance with the results obtained for these composites in continuous sliding conditions (Gomes *et al*., 2000). In a different way of composites, the wear coefficient of steel balls significantly decreases with the rise of the stroke, stabilising as $K \approx 2\times10^{-5}$ mm^{3}N^{-1}m^{-1} for higher strokes (s=8 and s=10 mm). In addition, the wear values of steel are slightly lower after reciprocating sliding contact against composite A, which is characterised by the lower content of SiC particles (25.8%). This result is attributed to a decrease of the ploughing action on the steel surface by the reinforcing ceramic particles present on the composite counterface.

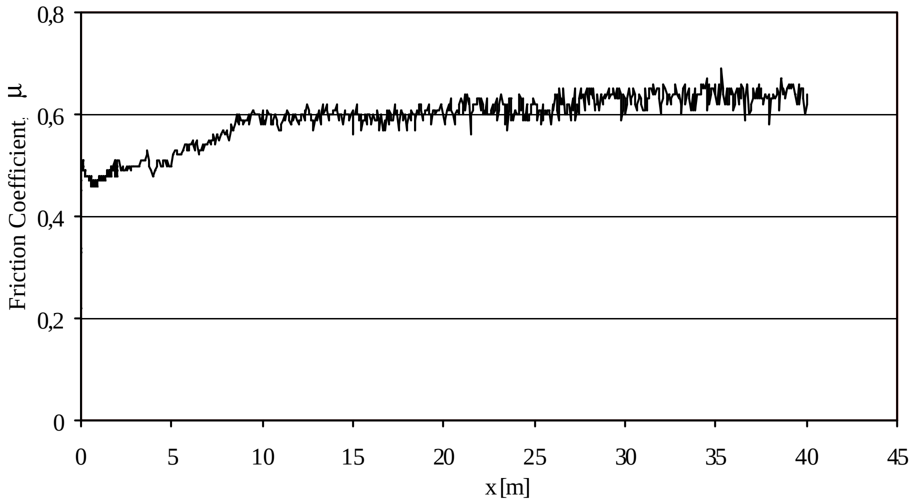


Figure 2. Evolution of the friction coefficient during sliding for the contact AISI 52100 steel / composite B (33.4% SiC) and intermediate stroke, s=6 mm (W=10 N, f=1 Hz).

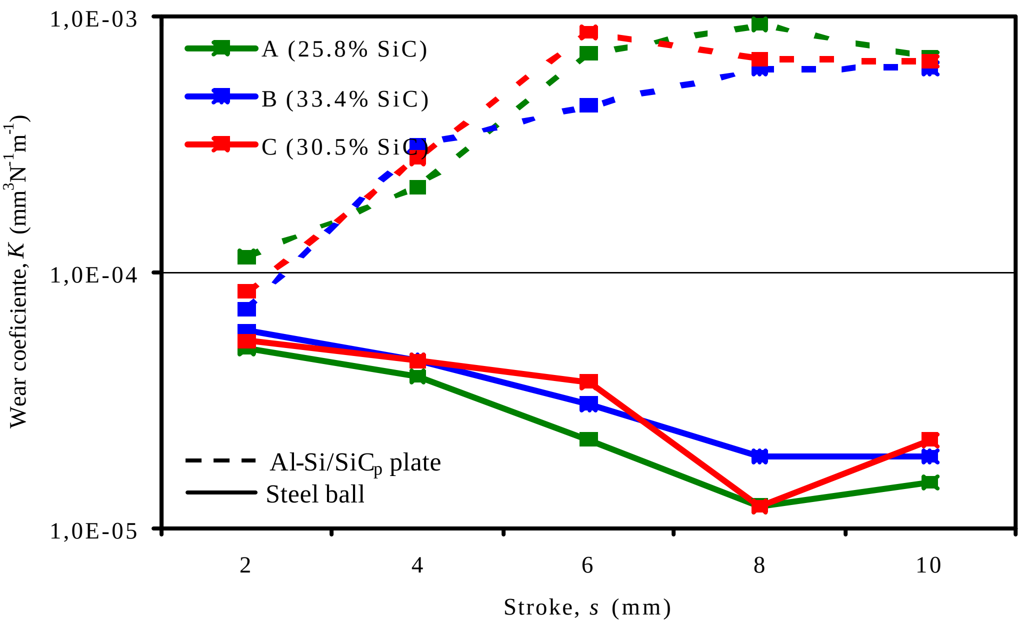
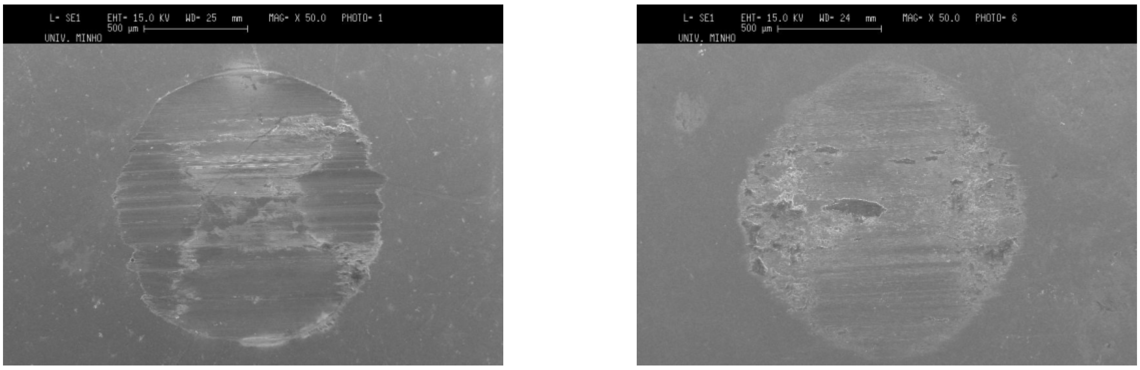


Figure 3. Wear coefficient of AISI 52100 steel balls and Al-Si/SiC$_p$ composite plates for different stokes (W=10 N, f=1 Hz, x=40 m).

Figure 4 presents the typical appearance of the overall wear scars on the steel balls after reciprocating sliding for low stroke (Fig. 4(a)) and high stroke (Fig. 4(b)). As can be seen in these micrographs, the morphological features of the ball wear scars changed with the stroke length. Thus, for low strokes, the ball wear scar is almost circumferential (Fig. 4(a)), whereas for high strokes the ball worn area tends to be elliptical (Fig. 4(b)). These geometrical features correlate with the wear depth on the mating Al-Si/SiC_p plate, as the wear of composites significantly increased for higher strokes (Fig. 3).



(a) (b)

Figure 4. Wear scars on steel balls after reciprocating sliding against composite B (33.4% SiC):
(a) s=4 mm; (b) s=10 mm (W=10 N, f=1 Hz, x=40 m).

Depending on the stroke length, distinct morphological features can be observed on the central region of ball wear scars and on the two lateral zones corresponding to the contact with the composite plate at the two ends of the stroke. Thus, for lower strokes, the presence of grooves along the sliding direction confirms that the abrasive action by SiC particles in the composite counterface is particularly effective, both at the central region and at the lateral zones of the contact (Fig. 4(a)). In addition, no transfer of material from the Al-based counterface was detected by EDS analysis. However, for the higher strokes, the central area of ball wear scars is characterised by a flat appearance with some marks of adherent material and almost no ploughing grooves (Fig. 4(b)). Also, the main feature disclosed by the lateral contact zones is the presence of large amounts of adherent material. EDS analysis reveals that this adherent material is composed by Al and Si transferred from the composite matrix, this result being corroborated by the backscattered image presented in Fig. 5.

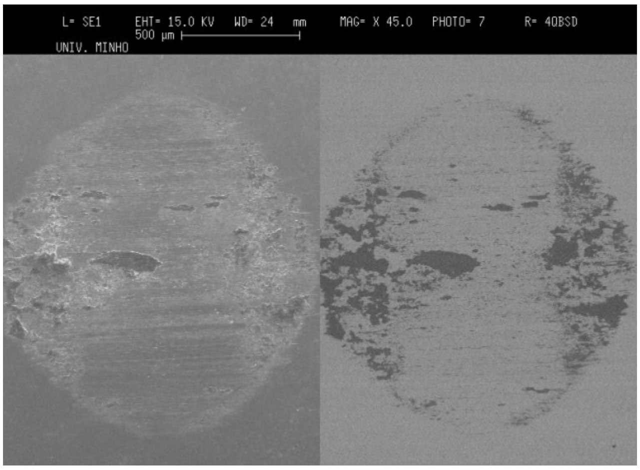
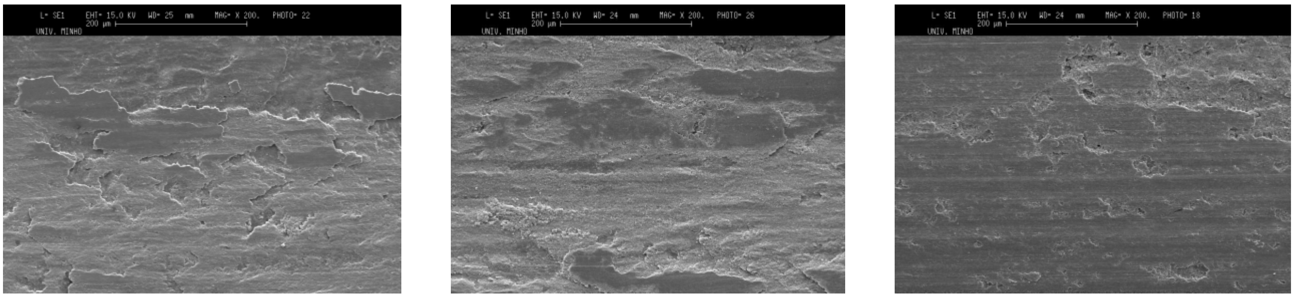


Figure 5. Wear scar on the steel ball after reciprocating sliding against composite B (33.4% SiC) with stroke of 10 mm:
SEM/SE (left) and SEM/BS (right) (W=10 N, f=1 Hz, x=40 m).

The adherent Al-Si tribolayers transferred to the steel surface after sliding with higher strokes protect this triboelement against wear. This effect is determinant to the decrease of wear values measured on steel balls and, at the same time, contributes to the increase of wear losses on the mating composite plates (Fig. 3). Therefore, with higher strokes, the sliding contact is established between the Al-based composite and a steel surface partially covered by Al-based material. So, in a certain extent, the tribological interaction tends to occur under self-mated conditions, which increases the adhesion component of friction. As a consequence, the average friction coefficient values increased with the rise of stroke length (Fig. 1).

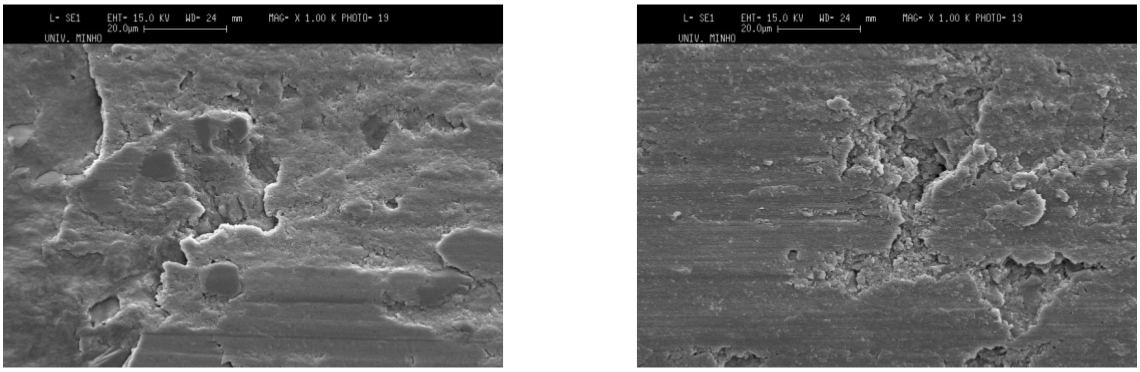
The typical morphology of the wear tracks on Al-Si/SiC_p composite plates is shown in Fig. 6 for different strokes. In all cases the contact surfaces present high level of plastic deformation along the sliding direction. For lower and intermediate strokes, the composite worn tracks revealed the presence of adherent iron-rich tribolayers as confirmed by EDS analysis. However, for higher strokes (*s*=8mm and *s*=10 mm), the composite surfaces were clean, without signs of chemical constituents from the opposing surface. Also, abrasive grooves are absent from the composite surfaces tested with low stroke (Fig. 6(a)), but can be observed after sliding with the highest stroke (Fig. 6(c)). In this contact situation the wear coefficient for the composite material is high (Fig. 3), the abrasive grooves on the plate surface being promoted by SiC loose wear particles.



(a) (b) (c)

Figure 6. Wear tracks on Al-Si/SiC_p plates of composite B (33.4% SiC) after reciprocating sliding against AISI 52100 steel with different strokes: (a) *s*=2 mm; (b) *s*=6 mm; (c) *s*=10 mm (*W*=10 N, *f*=1 Hz, *x*=40 m).

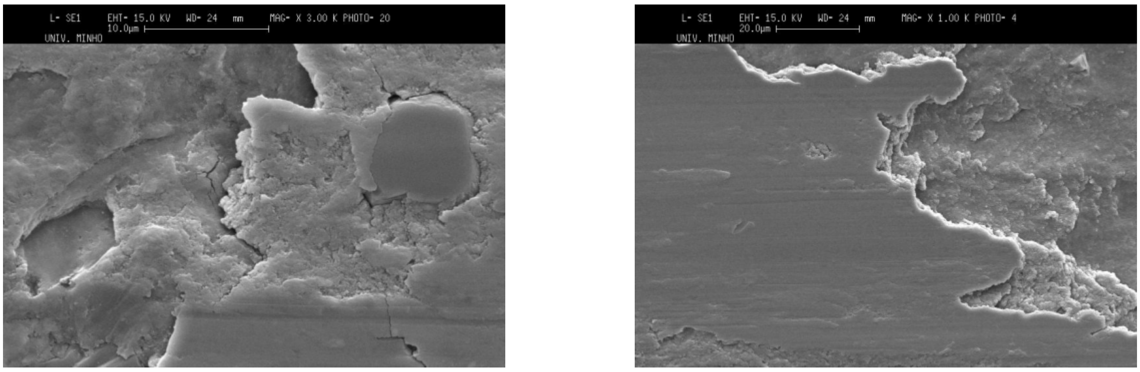
As the presence of adherent iron-rich tribolayers was detected only for lower strokes, this means that their generation occurs at particular sliding conditions. In fact, for reciprocating motion, the maximum sliding speed is attained at the central point of the wear track with a maximum value that is proportional to stroke length. Thus, for lower strokes (*s*<6 mm), the maximum sliding speed is relatively low and the energy dissipated by friction is not enough to significantly increase the temperature at the contact interface. Under these conditions, the mechanical properties of the composite matrix are preserved as well as their ability to retain reinforcing ceramic particles. Therefore, abrasion on the steel counterface by protruding SiC particles assumes particular importance and the removed material is partially transferred to the composite wear track. In a different way, for higher strokes (*s*=6 mm), the maximum sliding speed is higher, the energy dissipated in the tribocontact increases (Gomes *et al*. (2005)) and the temperature at the contact interface rises. As a consequence, the mechanical properties of the composite matrix deteriorates, the ability to retain SiC particles fall and the adhesion of Al-Si matrix to the harder steel counterface is promoted. According to these phenomena, the worn surfaces of composites after sliding with low stroke revealed protruding SiC particles well supported by the Al-Si matrix acting as anchoring points for retention of transferred iron-rich tribolayers (Fig. 7(a)). On the other hand, for sliding with high stroke, the worn surfaces of composites are characterised by the absence of protruding SiC particles and indicate a high level of surface damage (Fig. 7(b)).



(a) b)

Figure 7. Wear tracks on Al-Si/SiC_p plates of composite B (33.4% SiC) after reciprocating sliding against AISI 52100 steel with: (a) low stroke, *s*=2 mm; (b) high stroke, *s*=10 mm (*W*=10 N, *f*=1 Hz, *x*=40 m).

The retention of an iron-rich tribolayer by the anchoring effect of a protruding SiC particle is well documented in the high magnification micrograph presented in Fig. 8(a). These adherent tribolayers tend to be particularly extensive for sliding conditions with lower stroke (*s*=2 mm) and are characterised by a flat and smooth appearance Fig. 8(b). Several important effects can arise from the presence of a tribolayer at the contact interface. In fact, it modifies the contact pressure distribution, tends to spread the contact area and diminish the contact pressure (Sharma *et al*., 1997). Thus, for sliding with lower strokes, the presence of a protective tribolayer on the contact surface of composites was decisive for the observed reduction of wear values (Fig. 3).



(a) b)

Figure 8. Wear track of Al-Si/SiC$_p$ composite B (33.4% SiC) after reciprocating sliding against AISI 52100 steel with low stroke, *s*=2 mm: (a) retention of an iron-rich tribolayers by the anchoring effect of a protruding SiC particle; (b) extensive adherent tribolayer with a flat and smooth appearance (*W*=10 N, *f*=1 Hz, *x*=40 m).

The wear surfaces of Al-Si/SiC$_p$ composite plates after sliding with higher strokes (s=6 mm) revealed the existence of cracks perpendicularly oriented to the sliding direction (Fig. 9). This morphological feature allows us to conclude that a surface damage mechanism by fatigue on composite materials is active in these test conditions. In fact, the reciprocating sliding determines a tangential loading situation particularly severe, which was intensified by the higher friction coefficient values obtained with higher strokes (Fig. 1). Thus, surface fatigue together with the absence of protective iron-rich tribolayers contributed to the aggravation of composite wear losses for higher strokes.

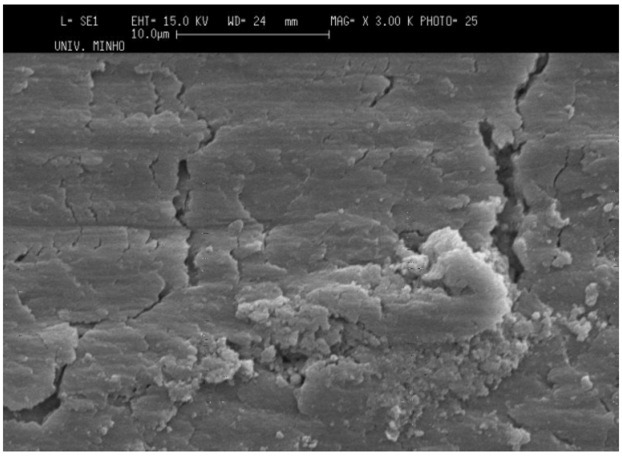


Figure 9. Wear surface of Al-Si/SiC$_p$ composite C (30.5% SiC) after reciprocating sliding against AISI 52100 steel with high stroke, *s*=10 mm (*W*=10 N, *f*=1 Hz, *x*=40 m).

The representative morphology of loose wear debris produced during sliding with high stroke (*s*=10 mm) is shown in Fig. 10. The given example is for the contact involving composite C, but is characteristic of the wear debris resulting from the contact with the other two composites tested under the same conditions. It can be seen that fine particles (≈1 µm) predominate and that a large plate and a faceted particle are also present. EDS analysis revealed that loose wear debris are mainly composed by constituents from the composite as only a small trace of Fe was detected. This observation correlates with wear results, as for higher strokes the wear coefficient values were much higher for composites than for the steel ball (Fig. 3). EDS analysis also confirmed that Al and Si are the constituents of the large plate and that the faceted particle is SiC. Therefore, large plates were generated from matrix detachments due to crack propagation by surface fatigue and loose SiC particles resulted from the pull-out of reinforcing particles. These loose SiC particles generated after sliding with high stroke promoted three-body abrasion, which was particularly effective on the softer composite surface as evidenced by the presence of ploughing grooves parallel to the sliding direction (Fig. 6(c)).

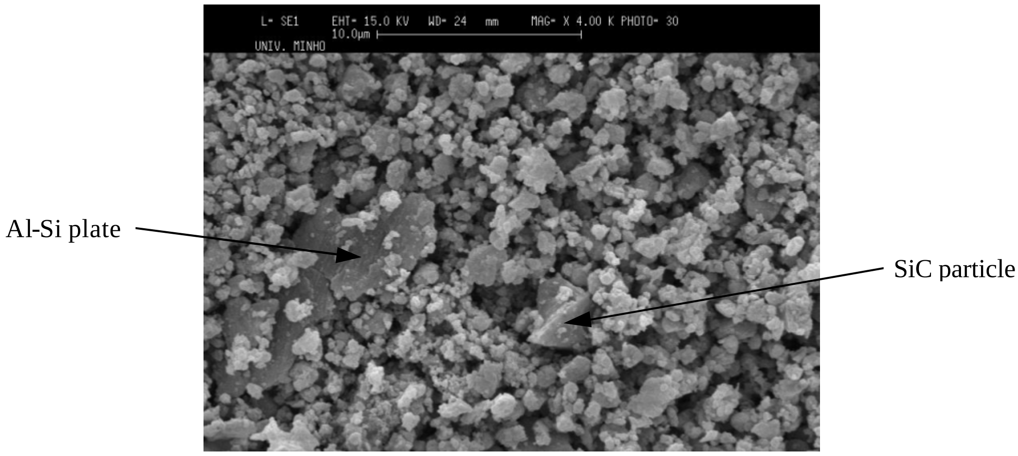


Figure 10. Morphology of wear debris resulting from Al-Si/SiC$_p$ composite C (30.5% SiC)/AISI 52100 steel contact with high stroke, s=10 mm (W=10 N, f=1 Hz, x=40 m).

The observations found in this work confirm that the transfer of material between the mating surfaces exerted a determinant effect on the tribological behaviour of the tribosystem and that the gradient of this transfer depends on the stroke length of the oscillating motion. Thus, for low stroke (s=2 mm), the transfer occurs only from the steel to the composite surface and therefore the wear coefficient increases for steel, but significantly decreases for the composites. In addition, if both the composites and steel counterface are considered, the best wear results were found precisely with the lower stroke length, particularly for the composite with the highest SiC content (33.4% SiC) (Fig. 3). In a different way, for high stroke (s=10 mm), the transfer occurs exclusively from the composite surface to the steel ball. However, although a decrease of wear on the steel surface, the wear performance of the tribosystem was poor due to excessive damage on the composites.

4. Conclusions

In the present work the friction and wear behaviour of Al-Si/SiC$_p$ composites in reciprocating sliding with different stroke lengths against AISI 52100 steel was characterised and the main conclusions may be listed as follows:

The stroke length of the reciprocating sliding had a strong effect on the tribological behaviour of both the AISI 52100 steel and Al-Si/SiC$_p$ composites, this effect being determined by the gradient of material transferred between the mating surfaces. For low stroke, the transfer occurs from steel to composite surface, which promotes the increasing of wear of steel and a notable decreasing of wear for the composites. For high stroke, the transfer is from the composite matrix to the steel counterface. In this case the wear of steel decreases but the wear of composites significantly increases.

The friction coefficient was between 0.50 and 0.65 and increased with the stroke length. The wear coefficient of composites was almost always in the order of 10^{-4} mm^{3}N^{-1}m^{-1}, one order of magnitude higher than for the steel balls, and slightly decreased with the increasing SiC content.

The dominant wear mechanisms were surface fatigue and abrasion, respectively for composites and steel, but adhesion was also effective with transfers of material between the mating surfaces.

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