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Reciprocating wear tests of Al–Si/SiC$_p$ composites: A study of the effect of stroke length

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Abstract

The aim of the work described here was to find evidence for the influence of stroke length on the reciprocating wear of aluminium matrix composites. For this purpose, two kinds of tests were performed: reciprocating ball-on-plane geometry experiments to apply stroke in the millimetre range, and fretting tests to study the strokes in the micrometer scale. The relationships between the dissipated energy and the wear volume were established to compare these two different scale tests. The results are discussed in terms of energy approach and of the comparison of the wear mechanisms observed on the wear scars resulting from both tests.

Keywords: Wear; Fretting; Aluminium matrix composites

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1. Introduction

Metal matrix composites are materials into which a reinforcement, typically a ceramic-based material, is added with the purpose of improving the material's properties. Of the various ceramic materials that can be used as reinforcements, silicon carbide (SiC) and aluminium oxide (Al_2O_3) are the two that have seen the widest use, due to their favourable combination of density, price and property improvement potential. Reinforcements also come in a variety of forms: continuous fibres, whiskers and particulates. When these reinforcements are combined with an aluminium matrix the resulting material exhibits significant increases in its elastic modulus (stiffness), and in some cases, strength, fatigue and wear resistance.

Practical applications include the automotive and aerospace industry, in particular composite brake components. The expected lowering of the cost of the aluminium composite materials, as well as more efficient processing and increased design experience, will expand the application of these kinds of materials.

Functionally graded materials are a class of advanced engineering materials that are characterized by continuous or gradual variations in composition and microstructure across the material's thickness. Because of their specific mechanical properties, aluminium matrix composites reinforced with ceramic particles have received increasing attention as engineering materials. An optimised combination of surface and bulk mechanical properties can be achieved if these composites are processed with a controlled gradient of reinforcing particles. This means that the functionally graded composites may be a promising solution for tribological applications. Although some wear evaluation studies have been conducted by various authors on continuous sliding conditions [1–7], the real effect of the reinforced particle content on the improvement of wear behaviour is not yet clear.

This experimental study was designed to determine the effect of stroke length in reciprocating tests of steel against functionally graded Al–Si/SiC$_p$ composites.

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2. Experimental procedures

2.1. Materials

A SiC particulate reinforced aluminium matrix composite (Duralcan F3S-20S) was melted in a high frequency induction centrifugal casting furnace, equipped with a vacuum system. The melt was centrifugally poured at 850 °C, at a maximum applied acceleration of $24.5 \times g$. As a consequence, a cylindrical dowel (Fig. 1a) was produced, with the SiC content varying along its axis. Plates for tribological tests were machined from this dowel. For the tribological characterisation, three cross-sections were considered, located, respectively, at the outer edge (considering the positive direction of the centrifugal force), and at 5 and 20 mm from the outer dowel edge (Fig. 1a). The Al–Si/SiC$_p$ composite specimens have three different particle volume fractions thus: 25.8%, 30.5% and 33.4%. Fig. 1b shows the typical appearance of the tested specimens' surface. An AISI 52100 steel ball bearing was used as the counterface.

2.2. Tribological tests

The tribological tests were carried out using the ball-on-plane contact according to the principle and geometry schematically shown in Fig. 2.

The effect of the amplitude of the reciprocating movement on the tribological behaviour was studied experimentally using two types of tribometers: a prototype fretting test apparatus and a PLINT TE 67/R tribometer with a reciprocating plate adapter. The fretting test apparatus, which allows the direct measurement of the relative displacement of the specimens is described in detail elsewhere [8]. In the fretting test apparatus, the normal load is applied to the spherical counterbody against the flat sample by means of a compressed spring, while in the reciprocating test tribometer the load is applied to the pin by adding calibrated masses to the loading pan. Both tests used flat Al–Si/SiC$_p$ composite samples against steel balls, and the relative oscillation is found by applying horizontal sinusoidal waves.

Before the tests, the specimens were ultrasonically cleaned in ethyl alcohol, followed by warm air-drying. In the fretting tests, the wear scars were assessed at the end of each test using 2-D and 3-D profilometry to evaluate the removed volume. The wear volume of the removed material was calculated according to a procedure described elsewhere [9]. In the reciprocating tests, 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. Optical and scanning electron microscopes were used to examine the morphology of the wear surfaces.

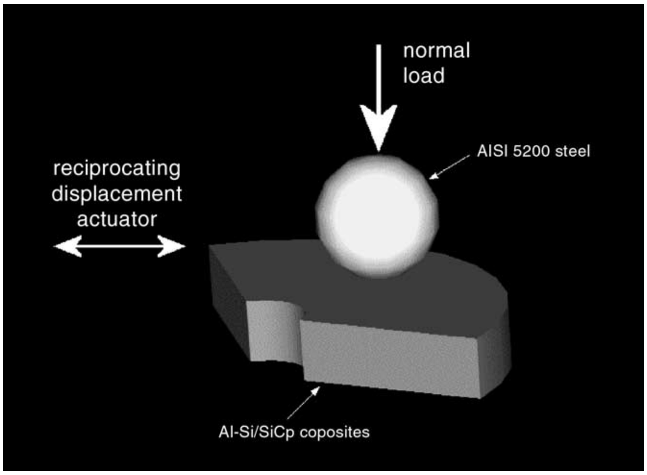

Fig. 2. Schematic diagram of the reciprocating tests' geometry and principles.

Table 1
Experimental test conditions

	Fretting tests	Reciprocating tests
Normal load (N)	10	10
Stroke (peak to peak)	0.25–0.75 μm	2–6 mm
Frequency (Hz)	30	1
Test duration (cycles)	1.5×10^5	–
Temperature (°C)	25 ± 1	25 ± 1
Atmosphere	Laboratory air	Laboratory air
Relative humidity (%)	55 ± 5	55 ± 5

In order to analyse the effect of the displacement amplitude, tests were carried out on the three materials described above using the two different test set-ups. The normal load remains constant for all the tests, having a value of 10 N. The test duration of the fretting tests was 150,000 cycles while for the reciprocating tests the duration was varied to maintain a constant value of 43 m for the sliding distance. Table 1 summarises the main test conditions.

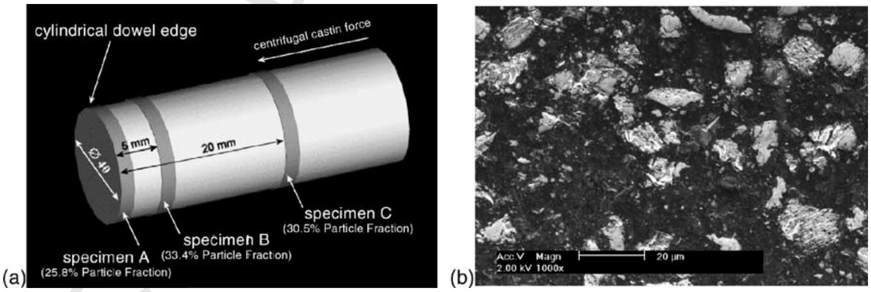

Fig. 1. Functionally graded composite specimens used in this study. (a) Schematic representation. (b) Typical surface morphology.

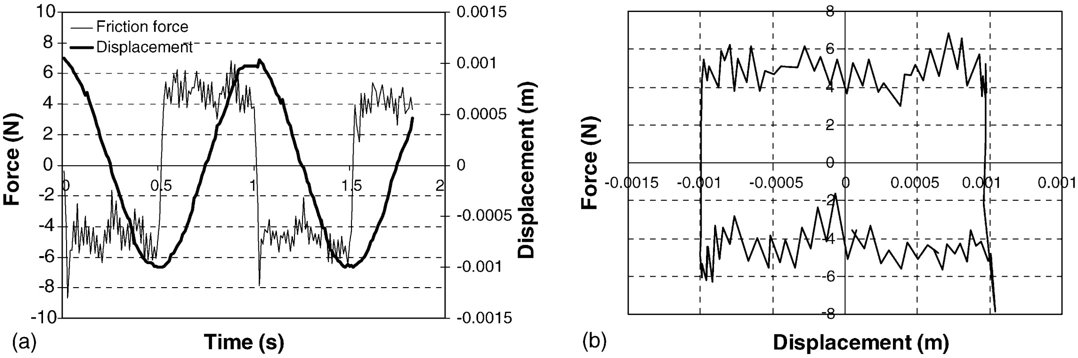

Fig. 3. (a) Friction force and displacement variation during a reciprocating test. (b) Friction force–displacement loop for the signals of the graph (a).

3. Results and discussion

3.1. Friction

The values of the friction force and the relative displacement were acquired periodically during the tests. Fig. 3a illustrates the typical variation of the displacement and of the friction force during the course of a reciprocating test. The energy dissipated in the contact can be calculated as the work of the friction force. Thus, the area of one friction force–displacement loop is the energy dissipated in the corresponding cycle [10,11]. Fig. 3b shows the loop corresponding to the friction and displacement signals represented in Fig. 3a.

The energy dissipated during one cycle depends on the shape and magnitude of the friction force–displacement loop, and also on the stroke and the friction force values. With respect to the test parameters, if the normal load remains constant the dissipated energy depends mainly on the displacement amplitude (Fig. 4a). The maximum value of the friction force is in fact more or less the same for all the tested displacement amplitudes. Even if compared with the fretting tests, Fig. 4b, the maximum values of the friction force are similar, in spite of the significant variation in the stroke. Therefore, the height of the loops remains more or less constant, whereas their width is proportional to the displacement amplitude (Fig. 4a).

The total energy dissipated throughout a reciprocating experiment is obtained by adding the energy per cycle in all the successive cycles. The total energy dissipated can be considered as a measure of the input energy in the system during the performed test. Fig. 5 shows the evolution of the total energy dissipated in the performed fretting tests (Fig. 5a) and in the reciprocating tests (Fig. 5b). As we can see, in both cases the larger displacement strokes lead to higher values of dissipated energy.

3.2. Wear

The Al–Si/SiC$_p$ composites are reinforced with small ceramic reinforcement particles. Different test specimens yielded various fractions of reinforcement particles, but the average particle size remained similar. Fig. 6 shows that, even for the fretting tests, the contact size is much larger than the average size of reinforcement particles; therefore, in all different performed tests, a significant set of particles was always included inside the contact.

The morphology of the wear scar resulting from the fretting tests (performed on specimen A) is shown in Fig. 7, using two and three-dimensional assessments. The 2-D cross-

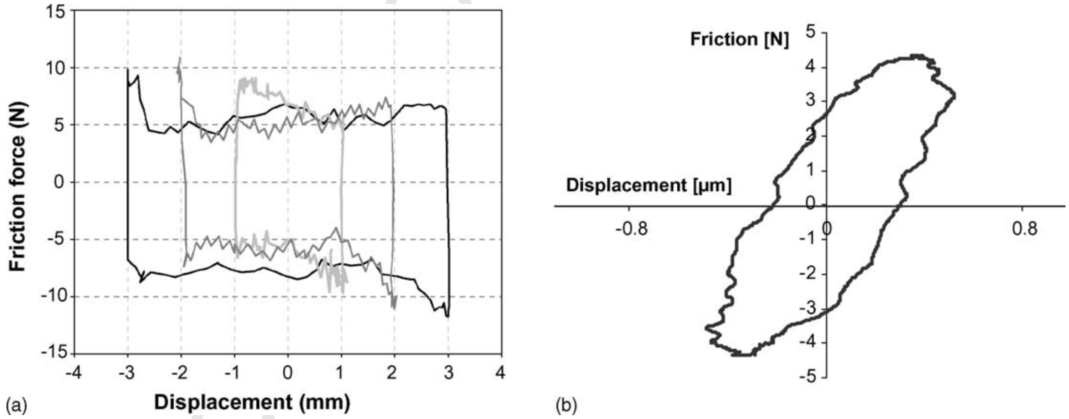

Fig. 4. (a) Loops for reciprocating tests with stroke values of 2, 4 and 6 mm, specimen C. (b) Fretting loop for a 0.75 μm stroke, specimen A.

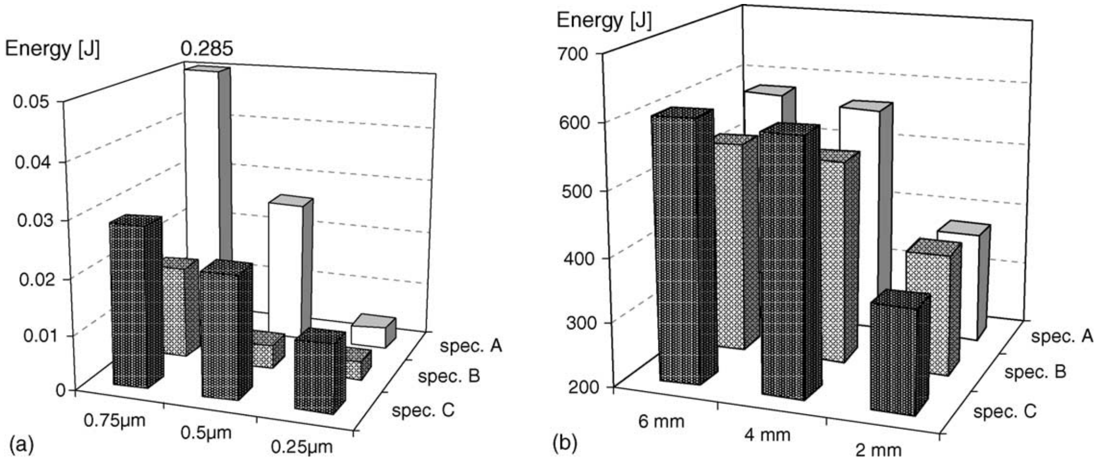

Fig. 5. Dissipated energy during tests against specimens A–C. (a) Fretting tests. (b) Reciprocating tests.

section, corresponding to the central profile of the wear track, illustrates how the fretting scars' section evolves as the stroke increases and the 3-D assessment shows the global topography of the fretting scar. It can be seen on both types of topographical assessments that the wear severity increased with the rise of the fretting stroke.

After tested against Al–Si/SiC$_p$ composites, the steel ball tips revealed a significant amount of transferred material and the original surfaces showed almost no apparent wear.

Fig. 8 shows the profiles of the wear scars produced by reciprocating tests of composite A using 2-D and 3-D assessment. A marked increase in wear occurs when the stroke rises from 2 to 4 mm.

Fig. 9 illustrates the wear volume of scars for each test performed, for both fretting and reciprocating wear. It can be seen that for each composite material increasing the stroke leads to higher values of wear volume.

4. Discussion

Both fretting and reciprocating wear tests lead to a rise in the energy dissipated by friction with the increase of the stroke (Fig. 5). Both the energy and the wear volume show a similar evolution to the test parameters. Numerous fretting studies have demonstrated, for several materials, that in fact a relationship could be established between the energy dissipated by friction and the volume of material removed by wear [12–14]. Some works reveal that similar relationships could also be derived from sliding tests [15,16]. If the wear

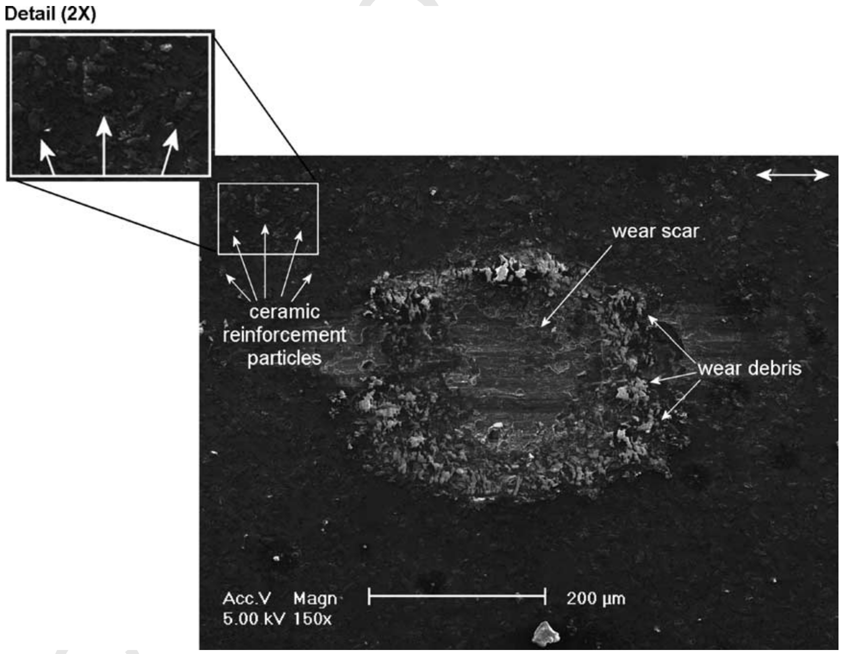

Fig. 6. SEM observation of the specimen A wear scar of the 10 N normal load and 0.75 µm stroke fretting test.

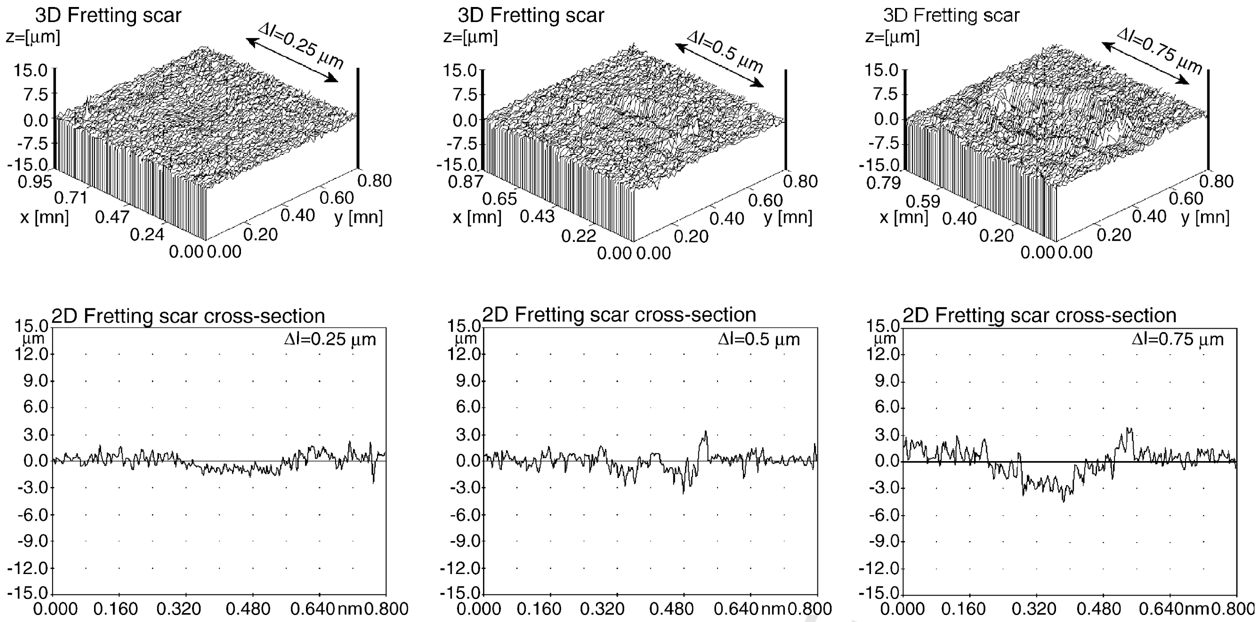

Fig. 7. 2-D and 3-D assessments of the wear scars resulting from the fretting tests performed on specimen A.

volume is represented against the energy, a tendency for the wear volume to increase with the dissipated energy is evident for all the composites tested, for the fretting tests and the reciprocating tests alike (Fig. 10). While fretting reveals linear evolutions of wear volume with the dissipated energy, the reciprocating tests also show an increase of the wear with the dissipated energy, although this effect is more pronounced for the tests with strokes of 4 and 6 mm (Fig. 10).

From Figs. 5, 9 and 10 it can be concluded that both the wear and the dissipated energy have different orders of mag-

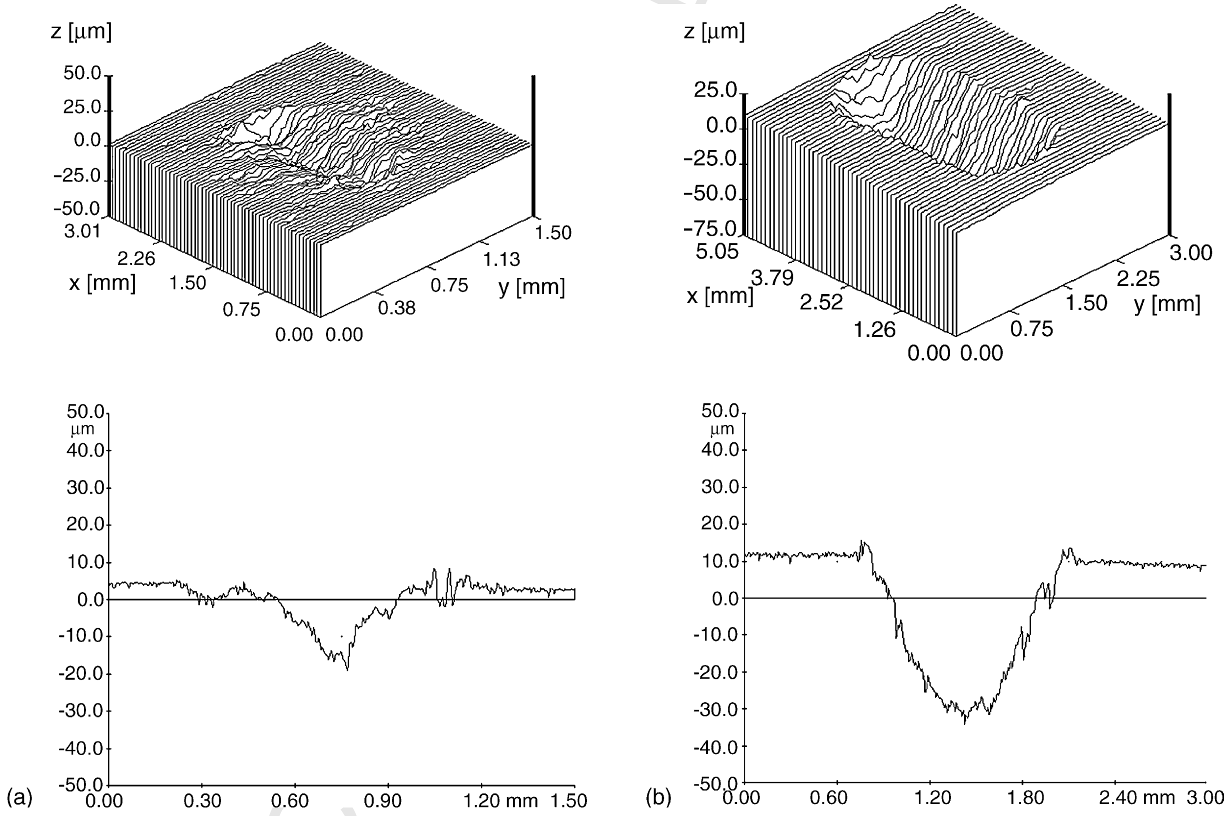

Fig. 8. 2-D and 3-D assessments of the wear scars resulting from the reciprocating tests performed on specimen A. (a) Stroke 2 mm. (b) Stroke 4 mm.

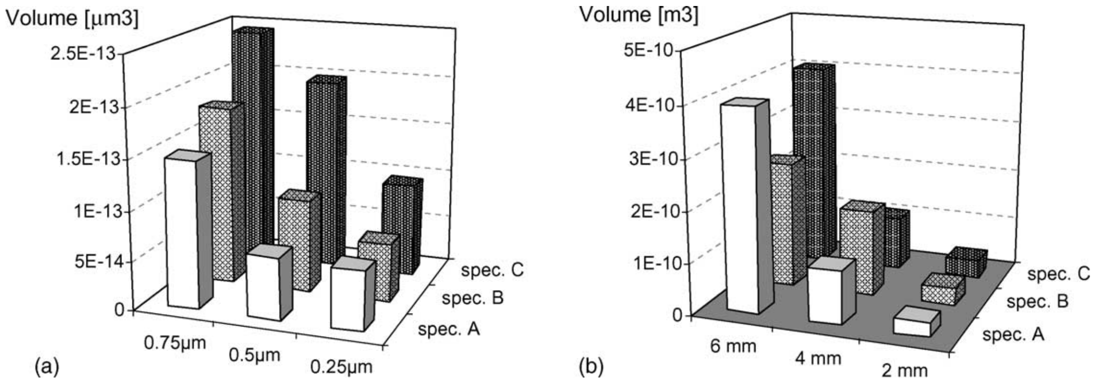

Fig. 9. Wear volume for tests performed on specimens A–C. (a) Fretting tests. (b) Reciprocating tests.

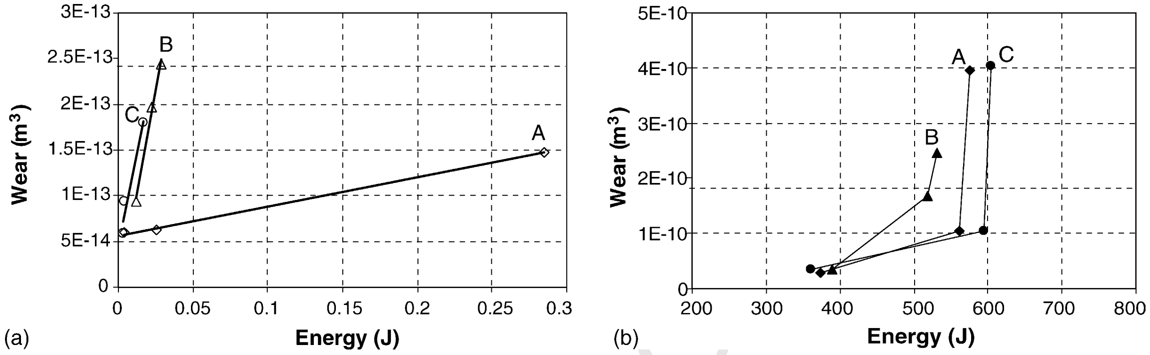

Fig. 10. Wear volume vs. accumulated dissipated energy. (a) Fretting tests. (b) Reciprocating tests.

nitude, depending on the type of test considered. It is therefore necessary to use bi-logarithmic scales to compare the results of the two types of tests (Fig. 11).

Analysing all the results shown in Fig. 11 leads to the identification of two different behaviours:

- the reciprocating tests with the lowest stroke value, 2 mm, agree well with the same wear/energy rate established for the fretting tests;
- if we consider the results of the reciprocating tests alone, the wear/energy rate is 125 times higher than the rate calculated for the fretting tests.

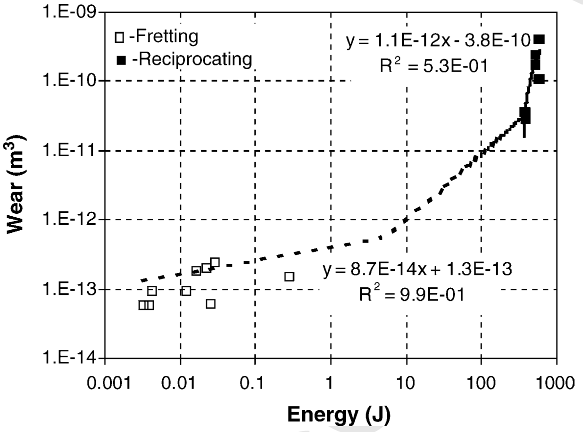

Fig. 11. Wear volume vs. accumulated dissipated energy for all the fretting and reciprocating tests' results.

Comparing Figs. 7 and 8 allows us to conclude that the reciprocating tests lead to wear scars significantly deeper than those produced by fretting. Scanning electron microscopy reveals that very different wear mechanisms also occur in each type of test. In fretting tests, the central area of wear scars exhibits a highly deformed metallic matrix, looking as though the reinforced particles have been extruded and eliminated to the borders (Fig. 12). The appearance of the wear scars produced by reciprocating tests is very different; in this case, the entire area appears to be covered by very adherent platelets (Fig. 13a). The pictures shown in Fig. 13 reveal that the wear mechanism of the reciprocating tests involves the following sequence:

(i) generation of the first wear debris involving matrix, reinforced particles and some steel from the counterface;
(ii) agglomeration of the debris by the action of the contact pressure. The agglomeration occurs mainly in the centre of the contact where the acceleration is low and therefore the ejection of the debris is difficult (Fig. 13b and c);
(iii) the formed platelets adhere readily to the wear surface of the composite. The reinforced particles seem to facilitate the process, acting as anchor points (Fig. 13d);

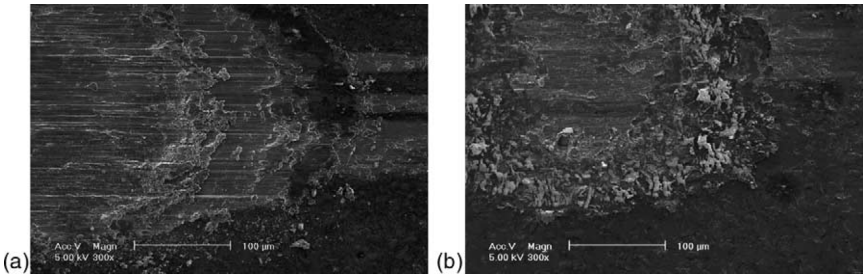

Fig. 12. Morphology of fretting wear scars.

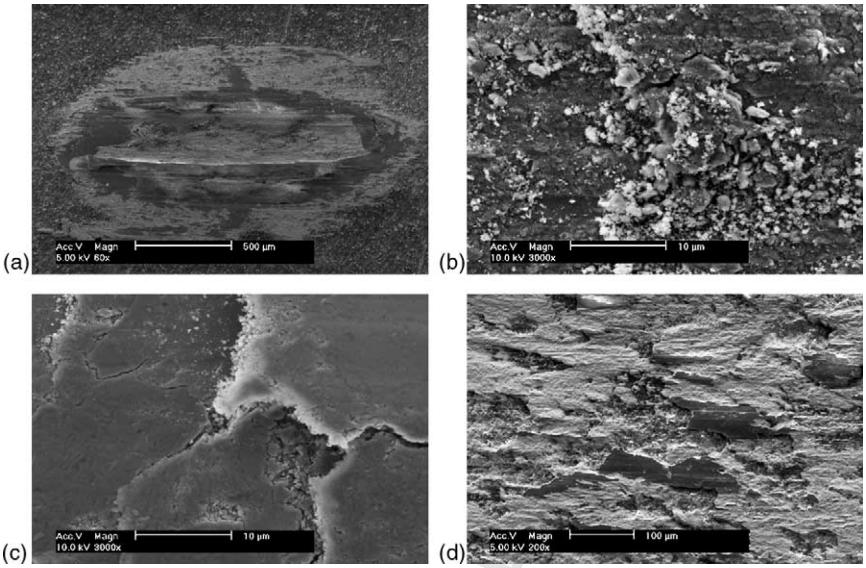

Fig. 13. Morphology of scars produced by reciprocating wear.

(iv) the wear process continues as a dynamic process of forming and removing of platelets inside the contact area.

The results and the wear mechanisms identified for the reciprocating tests agree very well with studies carried out for other composite materials [17,18]. In fact Diaz et al. [17] and Korkut [18] have observed that sliding wear is controlled by the formation of a mechanically mixed tribolayer formed by the agglomeration of wear products. Therefore, the effect of the reinforced particles is more or less a function of the behaviour of this adherent interlayer. If the tribolayer remains adherent the wear is mild and the reinforced particles improve wear resistance. But for aggressive contact conditions, the cracking of the tribolayer generates abrasive particles, thereby increasing the wear rate. In the present study, it seems that the abrasive action of the particles intensified for strokes higher than 4 mm.

5. Conclusions

In order to investigate the effect of stroke length on reciprocating wear, two types of tests have been performed: fretting tests to study the lowest displacements, and reciprocating sliding for the highest stroke values. The following conclusions can be drawn from this study:

(1) The content of SiC particles on the studied composites varies between 25.8 and 33.4% (volume). The wear results showed that the range seems to be too small to induce a significant variation in the wear behaviour.
(2) Within all the range of strokes analysed, from less than 1 µm to 6 mm, the energy dissipated by friction is a parameter suitable for correlation with wear volume. A single relation is not suitable, however, to characterize the full range of the tested values. The linear relation derived for fretting agrees with the reciprocating wear results for a stroke of 2 mm, but testing with a stroke of 4 and 6 mm resulted in a linear relationship with a higher wear/energy rate.
(3) The identified wear mechanisms differed for the two types of tests, thus:
    - Fretting: metallic matrix highly deformed; the contact area appears clean and the reinforced particles were extruded and eliminated to the borders.
    - Reciprocating: contact surfaces covered by adherent platelets formed by debris agglomeration.

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