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Fretting behaviour of glass-fibre-reinforced polypropylene composite against 2024 Al alloy

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Abstract

Composite materials, mainly fibre type ones, are used to respond to crucial demands in engineering applications. Various limitations mean that it is usually impossible to produce structures without mechanical joints. Fretting is an important failure mode for such joints, especially for dynamic loads. This paper sets out to assess the influence of this failure mode—fretting—in association with the effect of displacement, surface treatment with aluminium (anodisation) and the effect of environment, temperature and relative humidity. A series of experiments was carried out, changing each of the variables. To analyse the influence of each parameter, tangential force and displacement were used to establish the fretting cycles for every condition tested. Variations in the shape of the cycles revealed three regimes typical of fretting: stick, slip and partial slip, but the most effective way to characterize the transition between regimes was based on energy dissipation by friction. Surface treatment by anodisation leads to lower wear values, for small amplitude displacements, while for higher displacement amplitudes the wear volume was larger, for the case of room temperature and humidity. Increased temperature resulted in a rise in wear volumes, especially for non-anodised aluminium. Variation in humidity did not greatly influence the behaviour of the specimens studied.

Keywords: Fretting; Fretting map; Wear; Polypropylene composites; Aluminium alloy; Anodisation; Temperature; Relative humidity

1. Introduction

The development of composite materials, their design and manufacturing technologies are among the most important advances in the history of material science. Composites are multifunctional materials, which are characterised by excellent mechanical and physical properties, and which can also be produced to meet special requirements for a particular application.

The class of composite materials most widely used today is the Polymeric Matrix Composite (PMC). In the last decade there has been a considerable increase in their usage in a great variety of fields. In some applications these materials are frequently subjected to vibration, where fretting can be a possible failure mechanism.

Composite materials, particularly fibre-type ones, are used to overcome various solicitations in engineering applications. Several limitations usually mean, that it is impossible to produce composite and mixed structures without joints. Mechanically fastened joints, principally riveted or bolted, are commonly used in joining processes. Joints of this kind produce stress distribution that is characterised by high stress gradients near the bolts or the rivets, associated with relative displacements between the joined elements, and, in the particular case of dynamic loads, fretting is necessarily an important failure mode. The two materials, polypropylene-glass-fibre/aluminium alloy, have one special application in riveted joints, particularly in aeronautical construction.

The fretting behaviour of PMC against aluminium alloys has not been studied in depth, and this is especially true for the case of small displacement amplitudes. There are virtually no fretting studies on aluminium alloys/PMC material pair, and, to the best of our knowledge, the effect

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Table 1
Chemical composition and main mechanical properties of the aluminium 2024-T6 [1,2]

Elements	Si	Mg	Mn	Fe	Cr	Zn	Cu	Ti	Other
% wt	0.5	0.5	3.8–4.9	0.3–0.9	1.2–1.8	0.1	0.25	0.15	0.05

Ultimate strength (MPa)	Yield strength (MPa)	Rupture strain (l_0=50 mm), ε_f	Hardness (HV)	Young's modulus (GPa)
427	345	5	142	72.4

of relative humidity and temperature have never been properly studied in fretting tests, although they are recognized as important environment factors. The most widespread surface treatment of aluminium alloys is anodisation, but there are no technical papers where its influence in fretting situations is described.

The aim of this paper is to characterise the fretting behaviour of an aluminium alloy 2024-T6, with and without anodisation treatment, against a polypropylene composite reinforced with E-glass fibre. In this work, particular attention was given to the effect of: relative amplitude displacement; temperature; relative humidity, and surface treatment by anodisation of the aluminium alloy.

2. Materials and experimental procedures

The two materials studied in this work were the aluminium alloy 2024-T6, very commonly used in the aeronautic industries, which was tested, against the polypropylene (PP) reinforced with E-type fibreglass.

The Al alloy was chosen because it is a very attractive alloy for structural applications, with high specific resistance. The chemical composition and the main mechanical properties of the Al 2024-T6 are presented in Table 1 [1,2].

Two types of aluminium alloy specimens were used in this study, one after surface treatment by anodisation and the other without. The key objectives of the oxide layer formed by anodisation are to protect against atmospheric corrosion, increase surface hardness, improve abrasive resistance and to modify the electrical properties. Here, sulphuric anodisation was used to treat the surface of the 2024-T6 aluminium specimens. Fig. 1 shows the layer originate by oxidation; it is between 8 and 13 μm thick. The treated surface layer has a micro hardness value of $HV_{15}=390$ (kgf/mm^2), while the substrate value is $HV_{1000}=130$ (kgf/mm^2).

The polymer composite studied was Twintex T PP reinforced with a bi-directional cloth, composed of fibres of polypropylene and E-glass, which cross perpendicularly. The test specimens were machined from plates with seven layers of cloth, all of them oriented at 0° relative to the sliding direction. The PMC test composite had a 33.8% volumetric fraction of fibreglass and its most important mechanical properties are described elsewhere [3], and are presented in Table 2.

To assess the influence of these parameters, the fretting tribometer used allowed the varying, controlling and monitoring of each of the factors focused on in the study. This equipment was developed in the Department of Mechanical Engineering of the University of Coimbra [4].

The tribometer comprises three fundamental units: control, test and acquisition/processing. The purpose of the control unit is to define the variables imposed to the test unit. Thus, the Proportional Integral Differential (PID) controller guarantees the amplitude of displacement between the specimens. The frequency of the alternative displacement can be selected and adjusted on a function generator.

The test unit, Fig. 2, has three major components, a module for applying movement, a component for applying a normal load and a system to measure friction force. The first component consists of an electromagnetically actuated movable specimen carrier, to which the semi-spherical ended aluminium specimen is attached, which it is equipped with an accelerometer. The acquisition of signals from the accelerometer and from an LVDT on the shaft of the actuator allows the precise difference between the effective and the imposed displacements to be identified. The lower specimen holder is stationary and has the composite specimen connected to it. This specimen is under tension to ensure rigidity of the contact; the static traction force is imposed by a spring. The friction force is measured by a piezoelectric load cell, which measures the tangential force applied to the contact in the stopped specimen carrier, as the equilibrium force of the stationary specimen carrier.

A vertical spindle compressing an attached helical spring constitutes the system that applies the normal load to the specimens. This system is sustained on two bases, which are

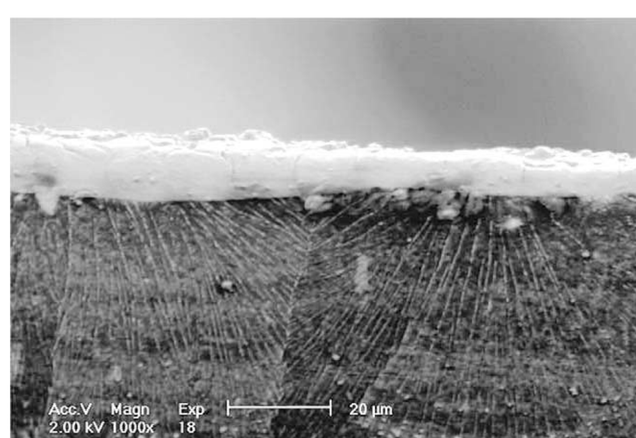

Fig. 1. Picture of the anodisation layer of one specimen of aluminium alloy 2024-T6.

Table 2
Main mechanical properties of the PMC

Ultimate strength (MPa)	Rupture strain ($l_0=50$ mm), ε_f (%)	Young's modulus (GPa)
438	3.42	15.9

supported by four columns, the spring guarantees the compression force applied to the contact during the test. The compression force applied to the contact is measured by means of a load cell incorporated in the loading system.

Among the several variables that affect the fretting phenomena [5–7], the present study evaluates the influence of the stroke and environmental conditions, air temperature and humidity on the fretting behaviour of PP PMC tested against 2024-T6-aluminium alloy, with and without anodisation treatment.

An acrylic chamber isolates the air near the specimens from the laboratory conditions, thus allowing a tight control of environment conditions. An electric heater is used to control the temperature environment of the specimens. In order to study the influence of the relative humidity on fretting the chamber and its control allowed the relative humidity to vary between 5 and 90%. The humidity was controlled by software to command a Programmable Logic Controller (PLC). A humidity sensor monitored humidity in the test chamber. Besides the test chamber there were two more chambers: one that had saturated air, and another containing dry air. With respect to the humidity levels, air pumps were provided to circulate the air in order to obtain the desired percentage of humidity.

In the experiments was used a contact geometry ball-plane, and it was to change each variable independently. Aluminium alloy pins with a hemispherical tip and a contact radius of 5 mm slip against flat composite specimens were used. Fig. 3 shows the geometry and relative position of the specimens tested. To analyse the influence of each

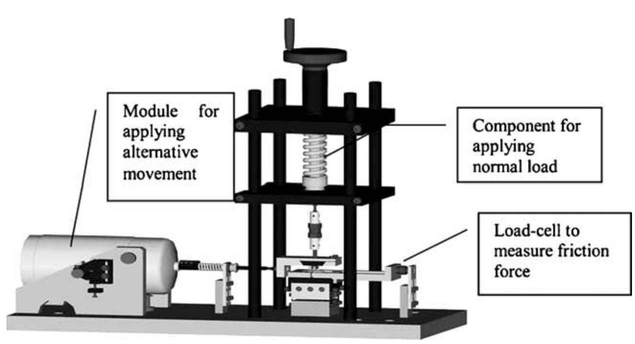

Fig. 2. Test unit of the fretting apparatus and identification of the three main components. The module that insures the alternative movement, a piezoelectric force transducer, a component used for the application of normal force and the system to measure the friction force, an accelerometer.

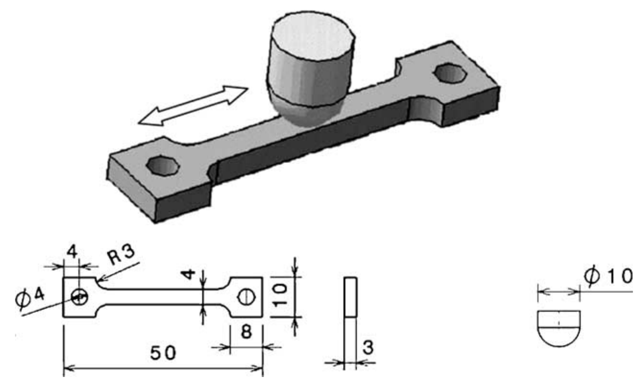

Fig. 3. Geometry and relative position of the specimens, the arrow indicates the sliding direction.

parameter, tangential force and displacement were acquired during the test and used to build the fretting cycles for each condition tested.

The surfaces were observed with both optical and scanning electron microscopes, to identify the surface morphology and characterize the main wear mechanisms. The material response and running conditions were the criteria used to identify and evaluate the different fretting regimes, i.e. stick, slip and partial slip [8].

3. Results and discussion

To determine the influence of the specified parameters (relative displacement amplitude, temperature, humidity and surface treatment) on fretting behaviour, Table 3 shows the range of variation of each factor. The other test conditions, which were kept constant, were: normal load (20 N), frequency (190 Hz), traction force applied to the composite specimen (320 N$\cong$27 MPa), contact geometry, ball-plane and test duration (1.368×10^6 cycles).

The friction force and displacement were acquired in a regular number of cycle intervals, 1.14×10^5 cycles, throughout the test. As a result of the force imposed by the oscillator, the type of motion law is nominally harmonic.

The variation of the friction force with the displacement corresponds to a closed cycle, where the area A of the close cycle represents the work produced by the friction force in

Table 3
Test conditions for the present study

Temperature (°C)						
22±3		50			70	
Relative humidity (%)						
5		50±5			90	
Amplitude displacement (μm)						
5	10	20	40	60	100	200

each cycle (1):

$$A = \oint_s F(s)\,\mathrm{d}s \tag{1}$$

where $F(s)$ represents the friction force as a function of the displacement s. This energy parameter is coming to be used by a growing number of investigators to characterize the fretting behaviour of materials [9–12].

The data acquired enabled the total energy dissipated by friction to be determined. Considering tribological contact as a thermodynamic system, the dissipation of friction energy constitutes the major portion of energy entering the system, and consequently leads to a rise in: the contact temperature, the removal of material, and in some cases the initiation and propagation of cracks in the contact surfaces. Summing the friction force work produced along the test gives the total energy dissipated by friction in each test. The value of the work produced by friction, calculated for every acquisition, has been considered representative of the interval between acquisitions.

This energy parameter was related to the wear volume of the aluminium specimens. In spite of some attempts to measure the volume of the composite material removed, it was not possible to guarantee a precise value, even using a laser profilometer. In relation to the pin surface, the diameters of the flat circular area produce by wear were measured to determine the wear volume using Eq. (2)

$$\Delta V = \frac{\pi}{3}[h^2(3r - h)] \tag{2}$$

where $h = r - \sqrt{r^2 - a^2}$, with r being the radius of the round-ended specimen and a the radius of the wear scar. The radius a of each specimen was measured by a scanning electron microscope (SEM). Fig. 4 illustrates the parameters used to determine the wear volume. As mentioned above, this energetic approach can relate the volume of material removed by wear to the total energy dissipated by friction. Many research works have corroborated this approach for several materials [11,12].

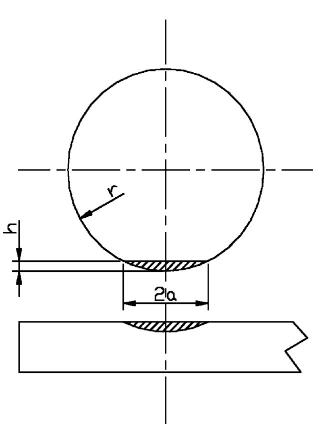

Fig. 4. Schematic diagram of the variables used in the determination of the wear volume for the aluminium pins.

3.1. Effect of amplitude displacement

First, the results for laboratory conditions of temperature 22±3 °C and relative humidity 50±5%, are given, and the effect of displacement amplitude and surface treatment discussed. Table 4 shows the values for the material removed, total dissipated energy, and effective and imposed displacement amplitude, for the two types of aluminium alloy pins tested.

The values of imposed displacement amplitude chosen for the two pairs of materials were 20, 40, 60 and 100 μm, but, due to the fact that the composite/anodised aluminium alloy pair did not exhibit the stick regime in this displacement amplitude range, it was necessary to select smaller amplitudes, namely, 5 and 10 μm. A test of 200 μm was done to verify that once the fretting regime of slip was attained there was no change in the regime.

Vingsbo and Söderberg [8] and Waterhouse [13], according to Mindlin's model, confirmed the existence of three fretting regimes, stick, slip and partial slip. In the stick regime, the imposed displacement is accommodated by elastic deformation of the material in contact; the friction force varies almost linearly with the displacement. This implies that the fretting cycles are almost closed and the amount of energy dissipated by friction is very small. In the slip regime, the displacement gives rise to slip in all of the contact area, thus leading to very open fretting cycles, implying very large values of energy dissipation. The third regime is the partial slip, and this is characterised by slipping at the contact's borders with no relative displacement in the centre of the contact. The cycles of this regime are elliptical and have intermediate energy dissipation values.

In fretting tests, the influence of the system's compliance [14] is very important, especially in small amplitude displacement. The present work overcame this problem by

Table 4
Values of the volume of material removed from the aluminium alloy tested pins, total dissipated energy, effective and imposed displacement amplitudes

Test number	Imposed displacement (μm)	Effective displacement (μm)	Wear volume (mm^3)	Total energy dissipated (J)
Non-anodised aluminium alloy, laboratory conditions				
1	20	15	0.0035	91.2
2	40	24	0.0078	1585
3	60	28	0.0085	2337.3
4	100	78	0.1338	5112
Anodised aluminium alloy, laboratory conditions				
5	5	6	0.0026	5.3
6	10	9	–[a]	128
7	20	22	0.0031	605.4
8	40	36	0.0136	1418
9	60	47	0.0176	2240.4
10	100	79	0.1787	6331
11	200	141	0.0392	8559

[a] Wear scar impossible to measure.

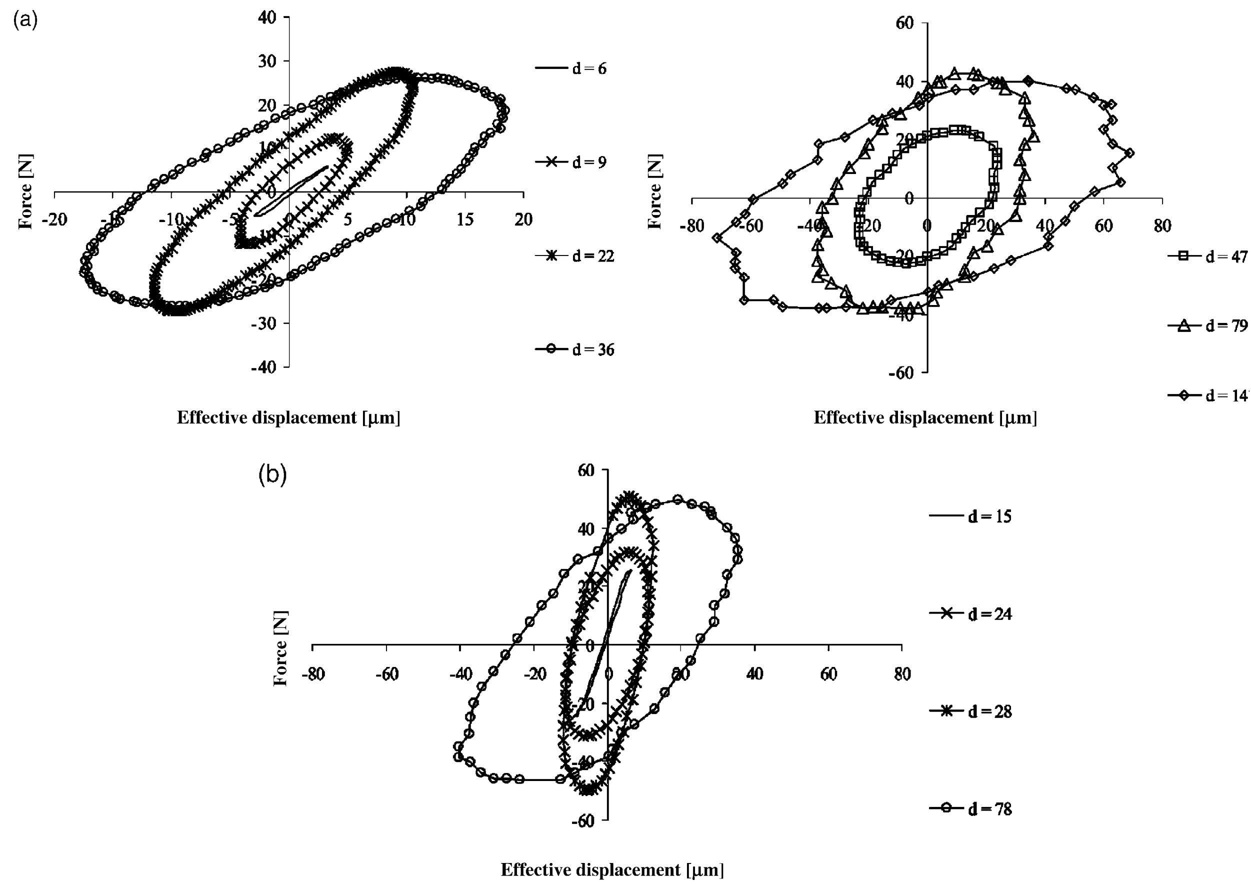

Fig. 5. (a) Fretting cycles, composite/anodised aluminium alloy, for all amplitude displacements tested; (b) the same as (a) but for composite/non-anodised aluminium alloy pair.

putting an accelerometer directly in the mobile specimen-holder, thereby measuring the effective, and not the imposed, displacement amplitude. The values of the friction force acquired can be affected by dynamic response on its amplitude and phase angle. These influences were evaluated by means of a model developed by Ramalho [15].

Fig. 5(a) and (b) shows the fretting cycles for the two pairs of materials. The three fretting regimes can be seen, although the transition between regimes, in terms of displacement, is different for each pair of materials tested. In general, a steady state regime has been reached after the first cycles and the fretting loops remain constant during the test. The loops represented as typical correspond to the mid duration test cycle.

For the composite/anodised aluminium alloy pair, analysis of the shape of the cycles reveals the existence of the stick regime for an effective amplitude displacement, d, of 6 μm. The slip regime is observed for effective displacement amplitudes greater than, or equal to, 36 μm. The partial slip regime is detected for the effective amplitudes of 9 and 22 μm.

In the case of the composite/non-anodised aluminium alloy pair, the partial slip regime was not identified. The stick regime can be observed for the amplitude of 15 μm. Finally, the slip regime is attained for effective displacement amplitudes equal to, or greater than, 24 μm.

Combining the findings of the fretting cycles and the values of wear volume for the aluminium pins and dissipated energy from Table 4, the graph shown in Fig. 6(a) was built up. This graph displays the wear volume of the aluminium alloy pins, anodised and non-anodised, relative to the total dissipated energy. The regions I, II and III identify the fretting regimes. The previous analyses conducted in terms of the shape of the fretting cycles for the two pairs of materials can be confirmed.

In region I, corresponding to the stick regime, the upper limit of dissipated energy is 100 J. Two points can be observed in this region, which correspond to anodised aluminium, with 6 μm of effective displacement amplitude, and to the non-anodised aluminium with a displacement amplitude of 15 μm. Region II, corresponding to the partial slip regime, represents the tests aluminium for displacement amplitudes of 22 and 36 μm; this region is limited, in terms of energy, from 100 to 1500 J. In this region there are no points representing non-anodised aluminium.

Region III is characterized by the slip regime and has a lower limit of 1500 J. In this region, the tests with larger

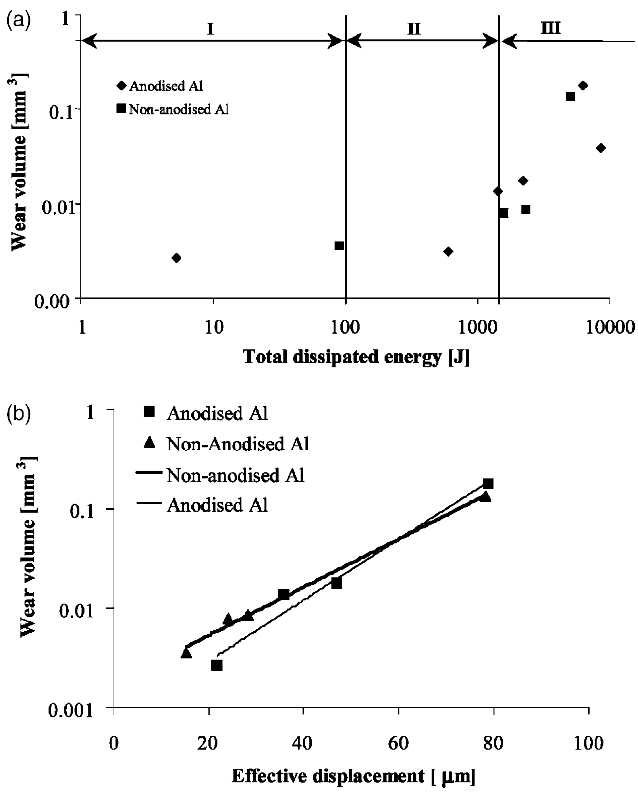

Fig. 6. (a) Wear volume of the anodised and non-anodised aluminium alloy pins, as a function of the total dissipated energy; (b) wear volume versus effective displacement amplitude for anodised and non-anodised aluminium alloy.

displacement amplitudes are represented, thus leading to greater wear volumes.

The limits between the different fretting regimes can be established both as a function of the running conditions (RCFM, running conditions fretting maps) and the type and extension of the damaged produced on the contact surfaces (MRFM, material response fretting maps). In the present study the criteria used to establish the limits of energy for each regime, Fig. 6, are based on the study of evolution of the wear volume with the dissipated energy. That evolution is characterized by two periods, the first one shows a small increase of wear volume with the dissipated energy, followed by a second period where a rise of the wear volume takes place. The value of the dissipated energy corresponding to that transition has been assumed to distinguish between the partial slip and slip regimes.

Fig. 6(b) represents the wear volume as a function of the displacement amplitude for both pairs, aluminium alloy with and without anodisation. It is possible to observe that for the two pairs of materials the low values of displacement amplitude correspond to low values of energy dissipation. In these cases, revealed by SEM observation, the degradation of the composite surface was limited only to a polishing of the composite's matrix, and the fibres were not affected. For higher values of displacement amplitude, the wear of the pins was greater and the composite presented rupture of its fibres. This kind of failure was also observed for unidirectional carbon-fibre-reinforced glass matrix composite against SiC paper [16].

Although surface treatment by anodisation smoothes the transition between regimes, it does not greatly reduce the material removed by wear. Thus, it can be concluded that applying surface treatment is not of great benefit to the fretting behaviour of the aluminium alloy 2024-T6 against a polypropylene matrix reinforced with glass fibre, for room temperature and relative humidity conditions.

To assess the morphological changes associated with the variations in displacement amplitude, for the environment condition and small displacement amplitudes, the aluminium alloy pins without anodisation are characterised by reduced wear and the transfer to them of large quantities of polypropylene debris, Fig. 7(a). Meanwhile, the contact surface of the polypropylene specimen is very polished and there are no ruptured fibres. At the contact boundary, in the slide direction, there are considerable amounts of adherent polypropylene, Fig. 7(b). With increased amplitude displacement, the areas of wear increase, with significant plastic deformation in the pins, demonstrating typical abrasion morphology, and large quantities of polypropylene still visible, Fig. 7(c). Fig. 7(d) shows a detail where no adhesion in the interface fibre–matrix can be seen, and there are also broken fibres.

With increasing displacement amplitude the composite shows a rise in surface degradation through wear of the matrix, expressed in broken fibres and appreciable quantities of aluminium adhering to its surface, Fig. 7(e).

With regard to the anodised aluminium pins, there is hardly any change in the morphology of the contact surfaces. The anodised layer is effective for small displacement amplitudes, but for the case of medium and large amplitude displacements, the layer is completely destroyed, which means that the wear volume for the pins with anodisation is higher than the wear volumes occurred for the non-anodised ones.

3.2. Effect of relative humidity

In order to evaluate the influence of relative humidity on the fretting behaviour of the composite/aluminium alloy, with and without anodisation, pairs, relative humidity values of 5, 90 and $50 \pm 5\%$ were chosen, the latter already presented. For the current tests, the remaining conditions were the same, normal load, frequency, traction force applied to the polypropylene specimen, contact geometry and test duration.

The tests were carried out in a similar manner as those described above, with regular acquisition intervals of the friction force and displacement. The reason why different displacement amplitudes were selected for the two pairs of materials was because, in the case of

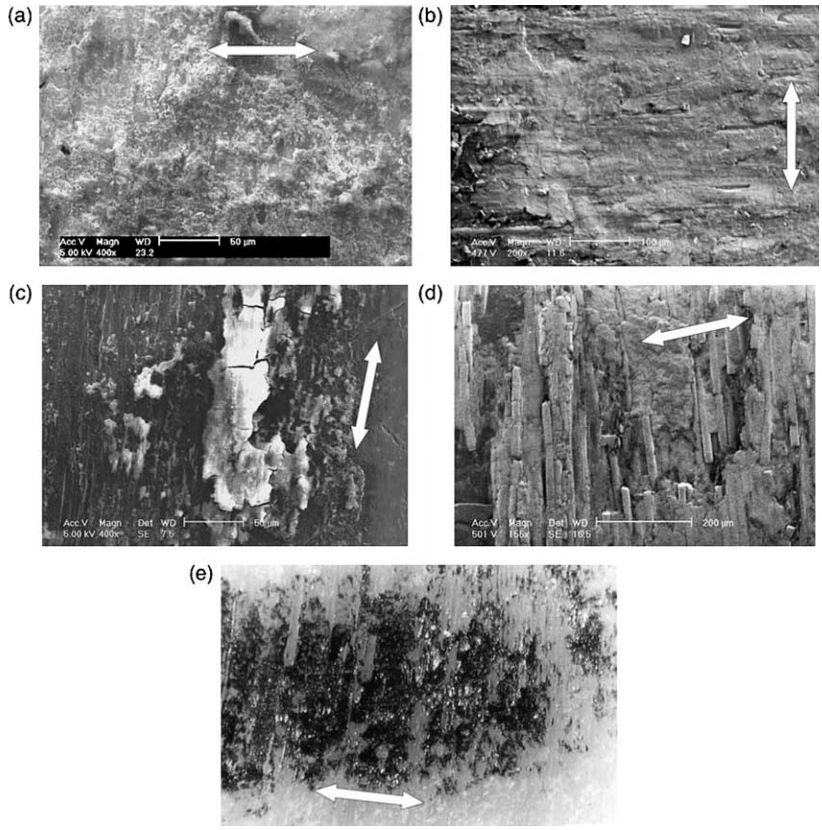

Fig. 7. Wear surface morphology of the non-anodised aluminium alloy/polypropylene composite pair for environment condition: (a) detail of contact area of an aluminium alloy pin, for effective displacement amplitude of 36 μm; (b) polished composite specimen, for a test with 36 μm effective amplitude displacement; (c) composite layer transferred to the aluminium alloy pins, for a 47 μm imposed displacement amplitude; (d) composite showing rupture of its fibres for a 47 μm effective displacement amplitude; (e) optical microscope image revealing large amounts of aluminium stuck to the surface of the polypropylene composite, for an imposed displacement of 79 μm. The arrows indicate the sliding direction for each picture.

the polypropylene/anodised aluminium alloy pair, the value of energy dissipation was much lower than for the other pair. Thus, the smaller displacement value selected was 10 μm instead of the 20 μm for the case of anodised aluminium alloy.

As happened for the case of environment conditions, it was not possible to determine the precise amount of the polypropylene composite removed by wear. Relative to the aluminium pins, the wear was measured in the same way as before, measuring the planar circular area and using expression (2). Tables 5 and 6 give the wear volumes of the two types of aluminium alloy pins for the conditions of relative humidity of 5 and 90%.

Fig. 8 displays the typical fretting cycles of the tests of non-anodised aluminium alloy pins for the three humidity conditions considered. For Hr = 5%, the corresponding tests are numbers 12, 13 and 14. The first two tests have effective

Table 5
Values of the volume of material removed from the non-anodised aluminium alloy pins in humidity conditions of 5 and 90%, total dissipated energy, effective and imposed displacement amplitudes

Test number	Imposed displacement (μm)	Effective displacement (μm)	Wear volume (mm^3)	Total energy dissipated (J)
Non-anodised aluminium alloy, Hr = 5%				
12	20	12	–[a]	223
13	40	24	0.0116	431
14	100	71	0.0737	6481.1
Non-anodised aluminium alloy, Hr = 90%				
15	20	22	0.0032	282.3
16	40	36	0.0166	731.4
17	100	76	0.0852	9316.1

[a] Wear scar impossible to identify.

Table 6
Values of the volume of material removed from the anodised aluminium alloy pins in humidity conditions of 90 and 5%, total dissipated energy, effective and imposed displacement amplitudes

Test number	Imposed displacement (μm)	Effective displacement (μm)	Wear volume (mm^3)	Total energy dissipated (J)
Anodised aluminium alloy, Hr = 90%				
18	10	11	0.00368	5.3
19	40	25	0.0176	1433
20	100	69	0.0670	7011
Anodised aluminium alloy, Hr = 5%				
21	10	17	0.0059	71.3
22	40	28	0.0112	1159.1
23	100	74	0.0591	4498.2

displacement amplitude of 12 and 24 μm, respectively, and considering the shape of the cycles, an elliptical one, while the fretting regime can be classed as partial slip. For test number 14, with effective displacement amplitude of 71 μm, the shape of the cycles clearly indicates a fretting regime of slip, displaying very open cycles. For the same pair of materials, although environment conditions made it impossible to identify the partial slip regime, the stick regime was identified for test 1. There was effective displacement of 15 μm, with the rest of the test having a displacement larger then 24 μm, characterized by slip regime. Finally, for 90% humidity, tests 15 and 16, with effective displacement of 22 and 36 μm, respectively, are characterised by a partial slip regime. Meanwhile, for test

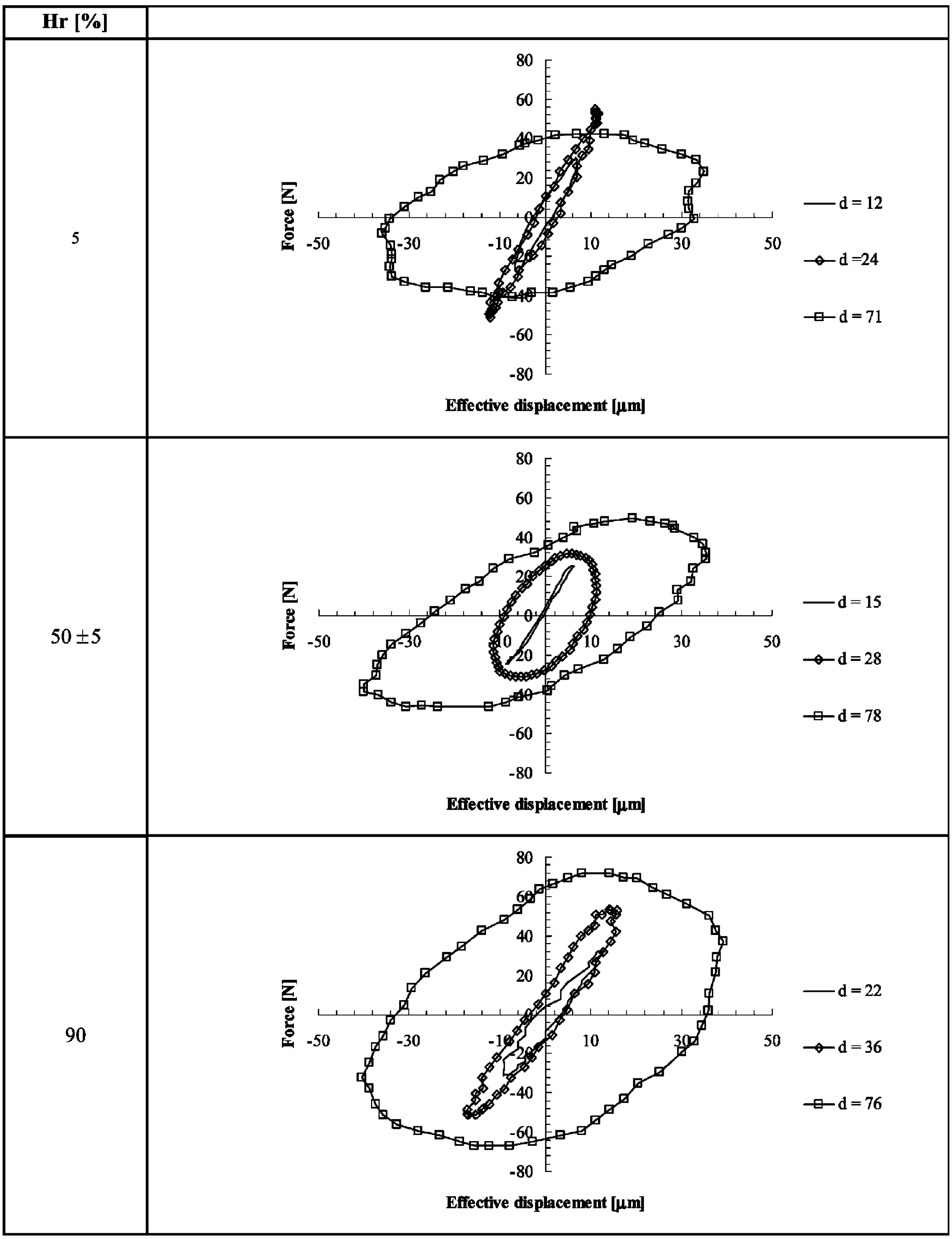

Fig. 8. Plot of the typical fretting cycles of the tests for the polypropylene composite/non-anodised aluminium alloy pair, for relative humidity conditions of 5, 90 and 50±5%.

17, with effective displacement of 76 μm, and very open cycles, the typical regime is one of slip. For this humidity value it was not possible to identify the stick regime, since none of the tests achieved a small value of effective displacement.

For the ease of the pair composite/anodised aluminium alloy, in Fig. 9 the typical fretting cycles of the tests are presented for various values of displacement amplitude as well as for different values of relative humidity.

With respect to the condition of 5% humidity, the three fretting regimes can be identified for the correspondent tests, 21, 22 and 23, with effective displacement of, respectively, 17, 28 and 74 μm. Test 21 is characterized by a closed cycle, stick regime, whereas test 22, has

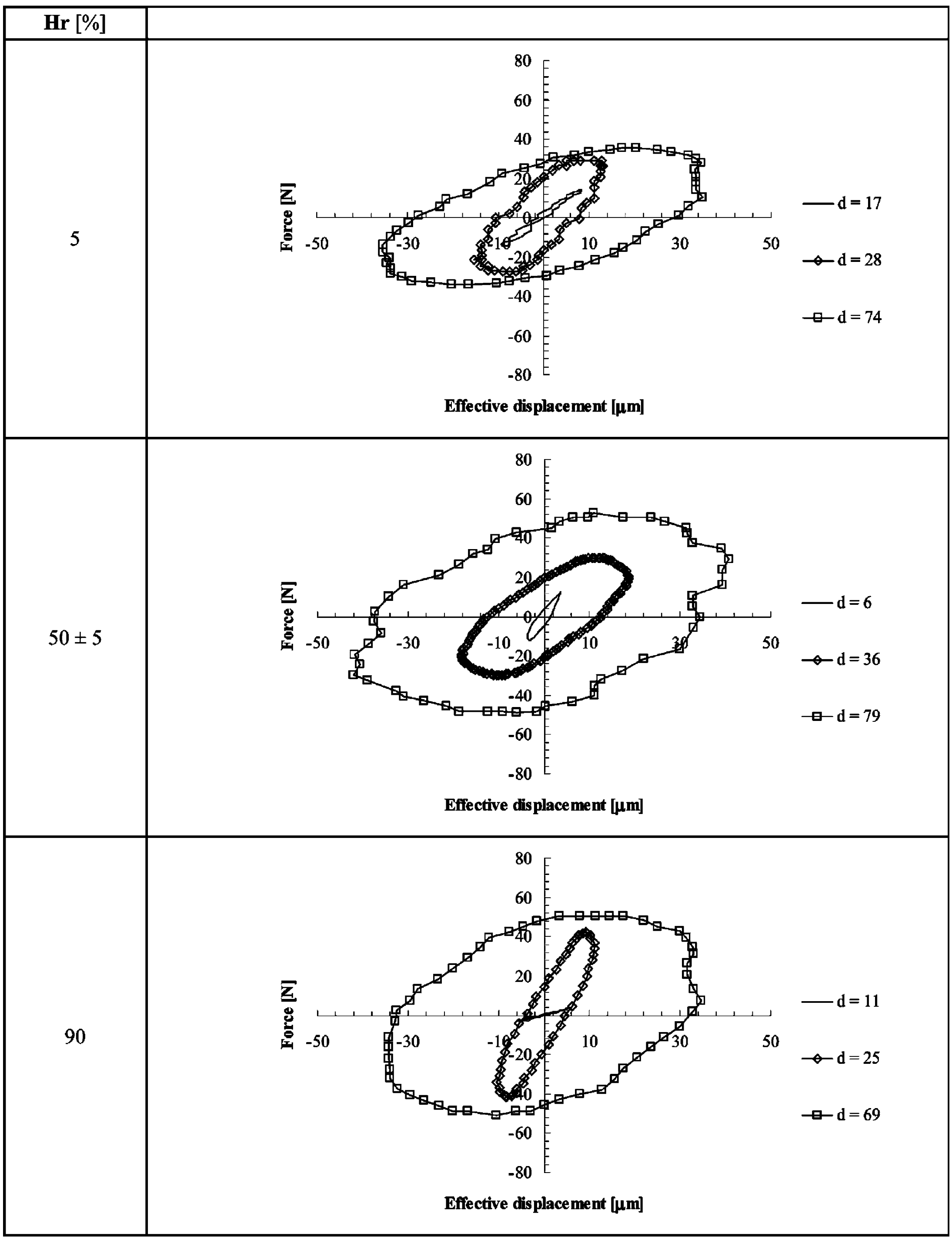

Fig. 9. Plot of the typical fretting cycles of the tests for the polypropylene composite/anodised aluminium alloy pair, for relative humidity conditions of 5, 90 and 50 ± 5%.

an elliptical cycle, with a partial slip regime, and the last test has a very open cycle, slip regime.

For the case of environment conditions, tests 6 and 8 were characterised by a partial slip regime, with effective displacement amplitude of 9 and 36 μm, respectively. Test number 10, with effective displacement of 79 μm, and very open fretting cycles, was in a slip regime.

The three fretting regimes were confirmed for the 90% humidity condition. Test 18, with effective displacement of 11 μm, was characterised by the stick regime, while test 19, with effective displacement of 25 μm, registered the partial slip regime, and the slip regime was recorded for test 20, with effective displacement of 69 μm. Analysis of the shape of the fretting regimes for the polypropylene composite/anodised aluminium alloy pair, and for the conditions of 5 and 90%, showed that the transition from the stick regime to the partial slip regime occurred in a higher range of displacement amplitudes than the range of values registered for the humidity environment.

As explained earlier, in order to identify the fretting regimes, graphs of the wear volume as a function of the total dissipated energy were constructed for each pair of materials and all the three humidity conditions. Thus, Fig. 10(a) was created with the values from Tables 4 and 5, and corresponds to the polypropylene composite/non-anodised aluminium alloy pair.

An examination of Fig. 10(a) confirms the evaluation made from the shape of the cycles, with three distinct regions that correspond to the three fretting regimes being

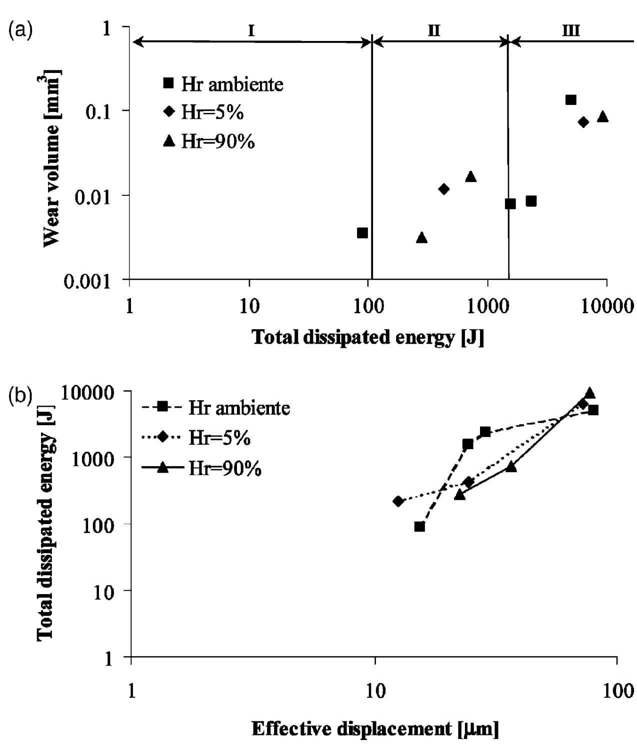

Fig. 10. Polypropylene composite/non-anodised aluminium alloy pair for all humidity conditions: (a) total energy dissipated versus wear volume; (b) effective displacement amplitude versus total dissipated energy.

identified: stick, partial slip and slip. Hence, the in region I, representing the stick regime and characterized by small values of dissipated energy, only test 1 can be found, which corresponds to effective displacement of 15 μm and a humidity environment with a value of dissipated energy of 91 J. Region II lies between the values of dissipated energy of 100 and 1500 J. This is a partial slip regime, and tests 13, 15 and 16 can be identified, which have effective displacement amplitudes of 24, 22 and 36, respectively. Test 13 corresponds to a humidity condition of 5%, while tests 15 and 16 were conducted for a 90% saturation environment.

In region III, the tests present are 2, 3, 4, 14 and 17. The first three tests correspond to effective displacement amplitudes larger then 24 μm, for environment conditions; test 14, with a displacement amplitude of 71 μm, for 5% humidity, while test 17, with displacement of 76 μm and environment saturation of 90%. Values of dissipated energy higher than 1500 J characterize all these tests. This analysis is consistent with the one made based on the shape of the cycles.

This analysis is again confirmed by Fig. 10(b), which gives the plot for the polypropylene composite/non-anodised aluminium alloy pair, the effective displacement versus the total dissipated energy for all humidity conditions. The figure also shows that the behaviour for the extreme humidity values is different from the one shown for environment, once the cycles of Hr 5 and 90% are more open, for intermediate amplitude displacements. This different behaviour is probably caused by the existence of a third body that, due to the different values of humidity, constitutes distinct oxides. It may thus be concluded that the variation in humidity can affect the behaviour of the polypropylene composite/non-anodised aluminium pair in fretting solicitations. McNicol et al. [17] observed identical behaviour for polyethylene.

Computing the values of total dissipated energy, wear volume and effective displacement amplitude, from Tables 4 and 6, which relate to anodised aluminium alloy pins, enabled the graph shown in Fig. 11(a) to be constructed. This graph shows the variation of wear volume of the pins versus energy dissipation. As before, three regions, which correspond to fretting regimes, can be found, and once again the classification of the shape of the cycles corresponds to the energy approach used. Therefore, in the region that corresponds to stick regime, region I, are represented the tests number 5, 18 and 21, which correspond to a displacement of 9, 11 and 17 μm for values of humidity environment, 90 and 5%, respectively. In region II, where the limiting values of energy dissipation are 100 and 1500 J, tests number 6, 7, 19 and 22 are plotted. The two first tests relate to a humidity environment, the third to 90% saturation and the fourth to 5% humidity. Region III has its lower limit in the value of 1500 J; the tests that fit into that region are numbers 8, 10, 20 and 23. Test numbers 8 and 10 were carried out in a humid environment and are characterized by effective displacement amplitudes of 36 and 79 μm.

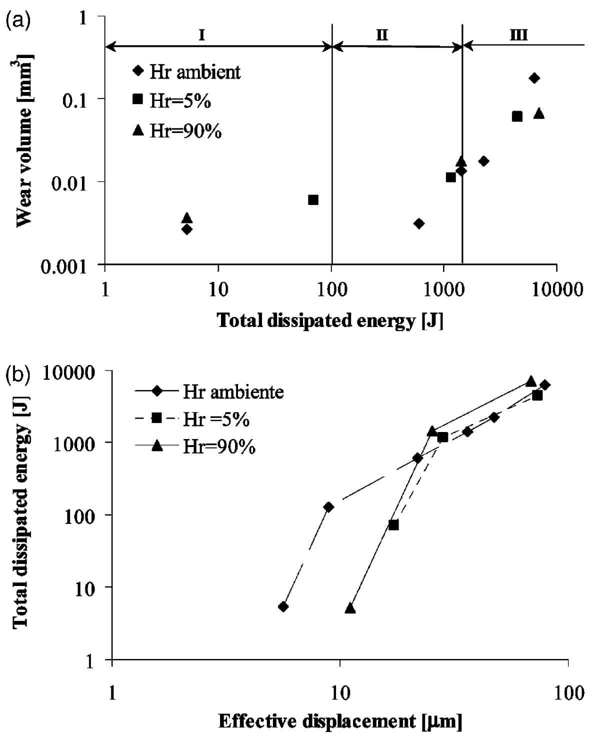

Fig. 11. Polypropylene composite/anodised aluminium alloy pair, for all humidity conditions and the three fretting regions: (a) total dissipated energy versus wear volume; (b) effective displacement amplitude versus total dissipated energy, for the polypropylene composite/anodised aluminium alloy pair, for all humidity conditions.

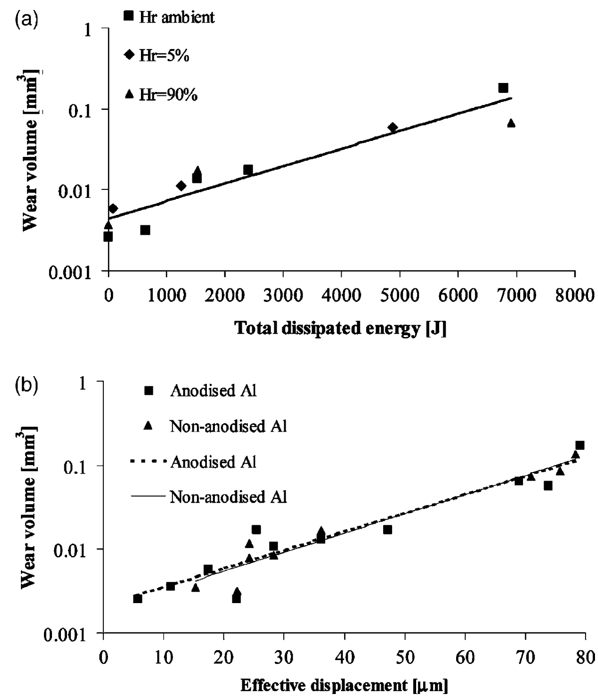

Fig. 12. (a) Total dissipated energy versus wear volume of anodised aluminium alloy pins, for all humidity conditions; (b) effective displacement amplitude versus wear volume, for both pairs of materials and all humidity conditions.

Tests 20 and 23 were performed for imposed displacement amplitudes of 100 μm and relative humidity of 90 and 5%.

Another important conclusion, that was pointed out in the analyses of the shape of the fretting cycles, which can also be observed in Fig. 11(a), is the transition from the stick to partial slip regime, which occurs sooner for the humidity environment than for the other two conditions. The next graph, Fig. 11(b) shows the effective displacement versus the dissipated energy for the polypropylene composite/anodised aluminium alloy pair in all humidity values tested.

In Fig. 11(b), the marked tests with lower displacement were performed in a humidity environment and are characterized by 6 μm and 5.3 J (test 5) and test 6 with 9 μm and 128 J. Thus, in accordance with the energy analyses, the first test is in region I, the stick regime, and the second test is characterized by a partial slip regime, which has its limits between 100 and 1500 J. In the same graph, test number 18, 90% humidity and effective displacement amplitude of 11 μm, is characterized by a value of dissipated energy of 5.3 J. Apart from this small difference there is no change in the tendency of the curves that represent the energy dissipation as a function of the effective displacement amplitude. From the analysis of the graph in Fig. 12(a) one can conclude that the humidity does not greatly affect the behaviour of the polypropylene composite/anodised aluminium alloy pair in fretting solicitation. In fact, the variation in relative humidity does not change the manner how the function of the wear volume vary with energy dissipation, as this function is exponential, as shown in Fig. 12(a), a linear variation in a semi-logarithmic representation.

As Fig. 12(b) shows, surface treatment by anodisation does not affect the way the function of the wear volume varies with the effective displacement when the values of relative humidity vary. Thus, the effect of the variation of humidity values only influences the values of energy dissipation.

The study of the effect of the relative humidity in the morphology of the contacting surfaces again confirms the energetic approach, i.e. a weak influence of the saturation values in the fretting behaviour. For the aluminium pins with anodisation, and for high displacement amplitude values, almost total wear of the anodised layer occurred, Fig. 13(a). With respect to the polypropylene surface, only a few rupture in the fibres occurred, Fig. 13(b). There were no other alterations in morphology, because of the effect of humidity.

3.3. Effect of temperature

In order to assess the influence of temperature on the fretting behaviour, tests were done in a controlled atmosphere at constant temperature. To study its influence, three values of temperature were chosen, 22 ± 3 °C (environment temperature), 50 and 70 °C. For the composite polypropylene/anodised aluminium alloy pair, the values of imposed displacement amplitude were 10, 40 and 100 μm, and for the case of the composite polypropylene/non-anodised

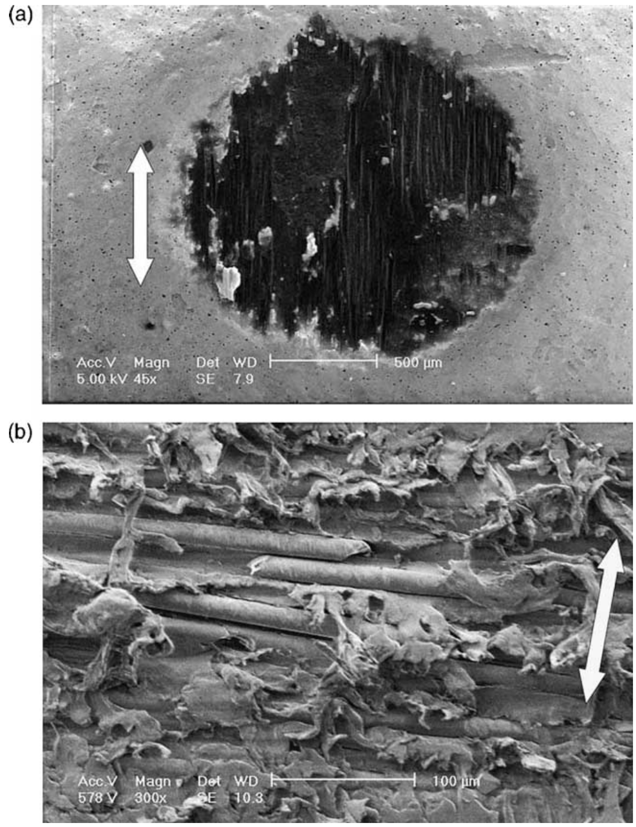

Fig. 13. (a) Detail of an anodised aluminium pin where the anodised layer has been destroyed; (b) composite showing rupture of its fibres for a 40 μm imposed displacement amplitude displacement against anodised aluminium alloy pins for Hr = 90%. The arrows indicate the sliding direction for each picture.

aluminium alloy pair the amplitudes used were of 20, 40 and 100 μm. All the other conditions were kept constant, the same as before.

Each of the procedures described above was executed in exactly the same way as for the study of the other parameters.

In addition to Tables 7 and 8, which present the results for tests at 50 and 70 °C for both sort of pins, Table 4, which contains the values corresponding to environment temperature, must also be considered.

As with the study of the effect of humidity, first the shape of the fretting cycles for the two types of aluminium alloy pins tested will be examined, and afterwards, the energetic approach will be used to confirm the analysis, also for all the tests.

Fig. 14 shows the typical fretting cycles for aluminium alloy pins without anodisation for all temperature conditions. The first temperature condition, environment temperature, was studied in the previous analysis. Test condition of 50 °C, test 24, with effective displacement amplitude of 17 μm, corresponds to a regime of partial slip, because the typical shape of the test is approximately elliptical. For this temperature condition, test numbers 25 and 26, with effective displacements of 25 and 68 μm, respectively, are characterized by very open cycles, which correspond to the a slip regime. With regard to a condition of 70 °C, the situation is identical to the case of 50 °C, because test 27, with 20 μm displacement amplitude, is in a partial slip regime, and tests 28 and 29, with effective displacement of 42 and 75 μm, are in the slip regime.

Fig. 15 shows the results obtained for the same analysis for the polypropylene composite/anodised aluminium alloy pair, and summarised in Table 8. The environment condition was as mentioned in the preceding point. With respect to the 50 °C condition, it was possible to identify only two fretting regimes. Thus, test 30, with an effective displacement of 11 μm, is in a stick regime; test 31, with effective displacement amplitude equal to 40 μm, and given the very open shape of its cycle, is obviously in the slip regime. The same type of cycle characterises test 32, for effective displacement amplitude of 63 μm.

The absence of a partial slip regime is perhaps due to the fact that there is a large discrepancy in the values of amplitude between tests number 30 and 31, since the first is 11 μm and the other 40 μm. If a test with an intermediate displacement amplitude value were run, a partial slip regime would perhaps occur. The same thing occurs at 70 °C.

Table 7
Values of the volume of material removed from the non-anodised aluminium alloy pins in temperature conditions of 50 and 70 °C, total dissipated energy, effective and imposed displacement amplitudes

Test number	Imposed displacement (μm)	Effective displacement (μm)	Wear volume (mm^3)	Total energy dissipated (J)
Non-anodised aluminium alloy, T = 50 °C				
24	20	17	–[a]	340
25	40	25	0.0575	1777
26	100	68	0.1585	6140
Non-anodised aluminium alloy, T = 70 °C				
27	20	20	0.0708	465
28	40	42	0.0979	2935.4
29	100	75	0.436	6309

[a] Wear scar impossible to identify.

Table 8
Values of the volume of material removed from the anodised aluminium alloy pins in temperature conditions of 50 and 70 °C, total dissipated energy, effective and imposed displacement amplitudes

Test number	Imposed displacement (μm)	Effective displacement (μm)	Wear volume (mm^3)	Total energy dissipated (J)
Non-anodised aluminium alloy, T = 50 °C				
30	10	11	0.0062	21
31	40	40	0.0643	3201.1
32	100	63	0.0106	5143.2
Non-anodised aluminium alloy, T = 70 °C				
33	10	8	–[a]	73.34
34	40	43	0.0955	3387.2
35	100	69	0.1292	4161

[a] Wear scar impossible to identify.

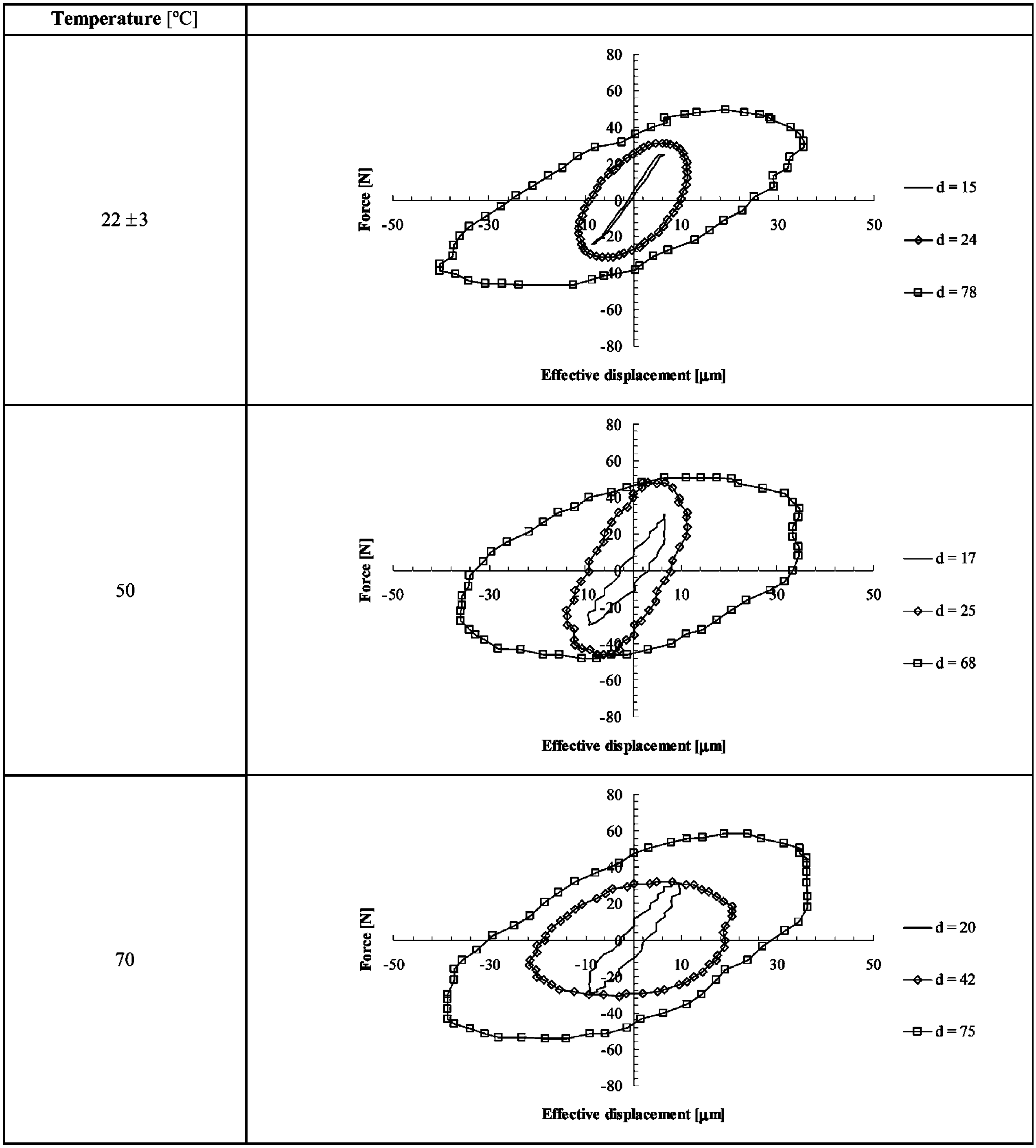

Fig. 14. Plot of the typical fretting cycles of the tests for the polypropylene composite/non-anodised aluminium alloy pair, for temperatures of 22 ± 3, 50 and 70 °C.

In order to identify the fretting regimes for each pair of materials at all temperature conditions, graphs of the total dissipated energy in function of the wear volume were constructed. Thus, Fig. 16(a) was created using the values from Tables 4 and 7, and corresponds to the polypropylene composite/non-anodised aluminium pair. The plot confirms the evaluation done on the basis of the typical shape of the fretting cycles.

The graph in Fig. 16(b) was created using the values from Tables 4 and 8 for the polypropylene composite/anodised aluminium pair. The plotted graph confirms the evaluation done on the basis of the typical shape of the fretting cycles, considering the three fretting regions.

The graph in Fig. 17(a) shows the total dissipated energy as a function of the effective displacement for the material polypropylene composite/non-anodised aluminium alloy

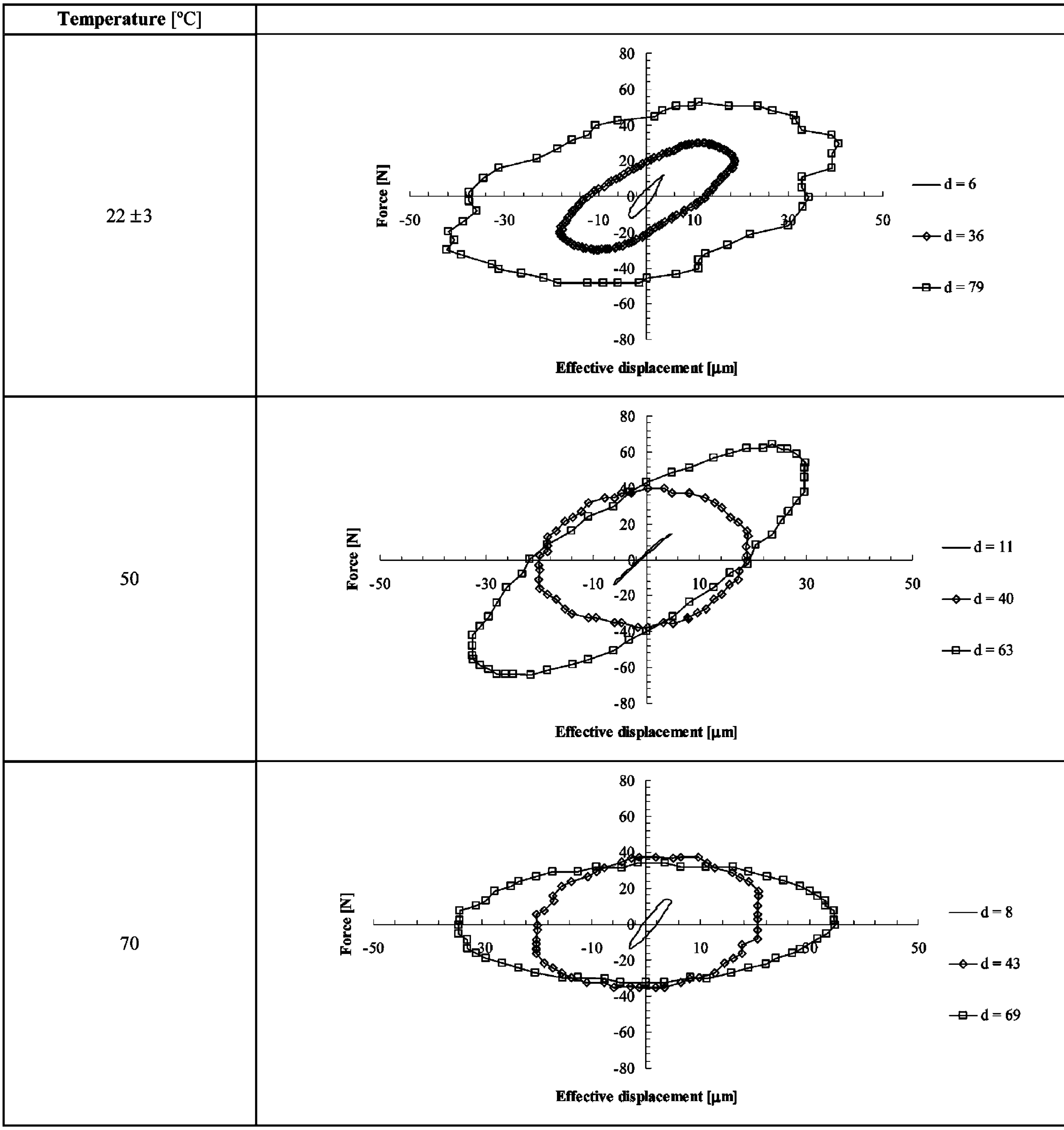

Fig. 15. Plot of the typical fretting cycles of the tests for the polypropylene composite/anodised aluminium alloy pair, for temperatures of 22 ± 3, 50 and 70 °C.

pair, for all tests at all temperature conditions. No difference can be seen between the fretting behaviour for the three temperatures, since the variation in the dissipated energy with increased effective displacement is the same for all. With respect to the other pair of materials, and observing the graph in Fig. 17(b) an identical situation occurs, although, for the temperature of 50 °C and effective displacement of 11 µm, the amount of dissipated energy is smaller when compared with the other temperature values. In spite of that, the evolution of the dissipated energy with the amplitude displacement is identical for all temperature conditions.

In order to observe the influence of the temperature on the fretting behaviour of each pair tested, Fig. 18(a) and (b) shows plots of the wear volume as a function of the total energy dissipation. Fig. 18(a) gives the results for the composite/non-anodised aluminium alloy pair. It shows that for the test at low temperature, these small energy values cause the aluminium alloy pins to exhibit smaller wear volumes than the same pair does at higher temperatures. This fact is due to the increased exposure of the glass fibres with increased temperature, which produces an alteration in the rheologic properties of the material's polymeric matrix.

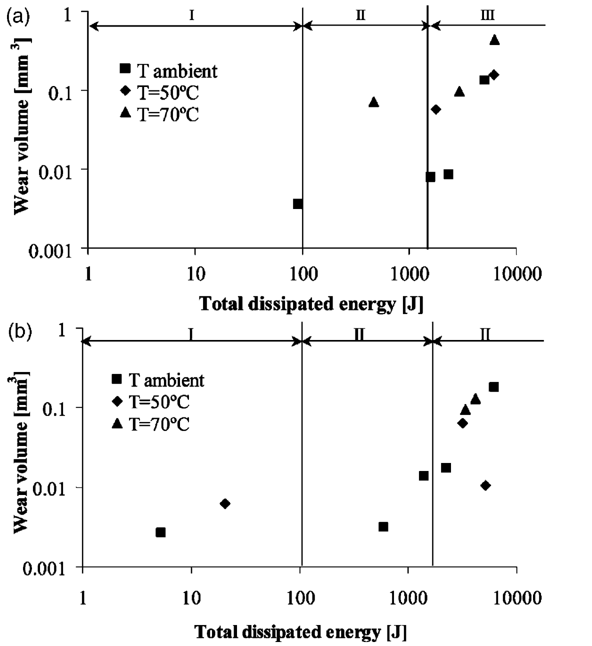

Fig. 16. Total dissipated energy versus wear volume for all the temperature conditions: (a) polypropylene composite/non-anodised aluminium alloy pair; (b) polypropylene composite/anodised aluminium alloy pair.

For higher values of energy dissipation, the wear volumes of the pins tested at environment temperature approach the values obtained at 50 and 70 °C. In fact, it seems that in this situation there is enough energy to remove the superficial layers of the matrix, exposing the fibreglass.

In relation to the anodised aluminium pins, the temperature effect is not demonstrated in the same manner

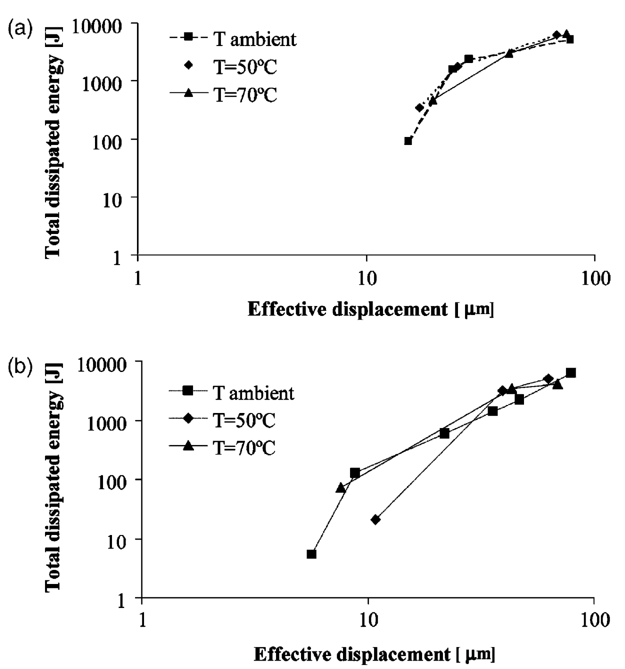

Fig. 17. (a) Total dissipated energy versus effective displacement of non-anodised aluminium alloy pins, for all temperature conditions; (b) the same as for (a) but for anodised aluminium alloy pins.

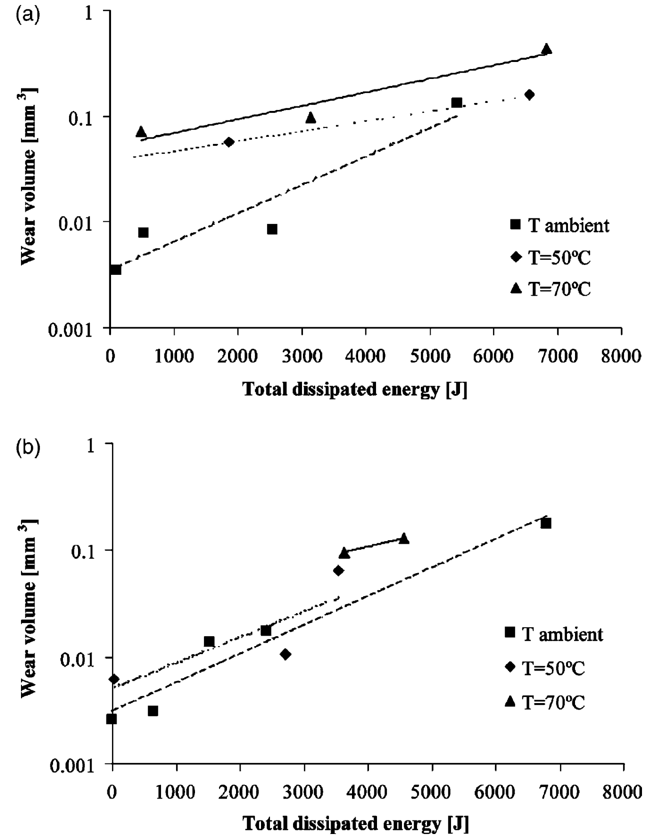

Fig. 18. Wear volume versus total dissipated energy for all temperature conditions for (a) non-anodised aluminium alloy pins; (b) anodised aluminium alloy pins.

as for the non-anodised pins, although the general tendency is identical. For elevated temperatures the wear volumes of the pins are higher, although the difference in the wear volume for the various temperature conditions is not very marked, Fig. 18(b). This behaviour is due to the transfer of polymeric material from the polypropylene specimen to the aluminium alloy pins, and the consequent formation of a third body. From this it can be concluded that for small values of energy dissipation and wear volume surface treatment by anodisation is effective for maintaining the fretting behaviour of the polypropylene composite/anodised aluminium alloy pair, almost independent of the tested temperatures, in the range of tested temperature.

In terms of morphology, the effect of temperature on the fretting behaviour of the pairs of materials considered was considerable. At higher temperatures, 50 and 70 °C, transfer of the matrix material to the pins' surface also occurred, Fig. 19(a). In addition, for the case of the non-anodised pins, fibres from the matrix of the composite ruptured and were removed, and these adhered to the pins' surface, acting as an abrasive third body, Fig. 19(b).

It was also possible to observe the separation of the fibres, although this was more frequent with the non-anodised aluminium pins, Fig. 19(c). At higher temperatures, the matrix was less viscous allowing greater adhesion

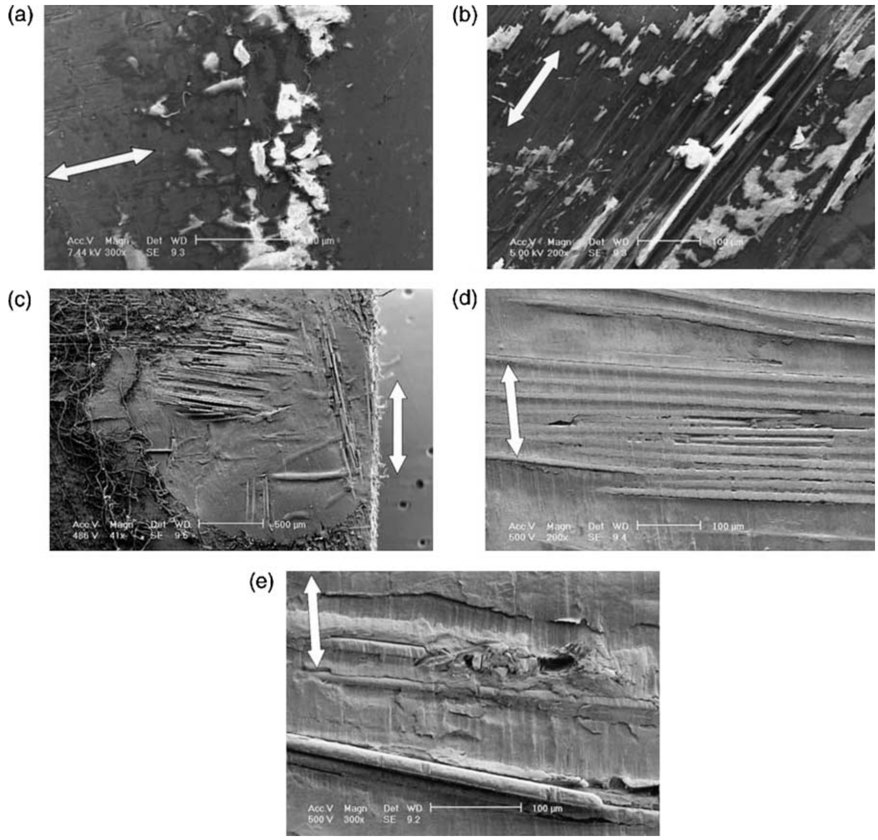

Fig. 19. (a) Illustration of the transfer of polymeric material to the non-anodised pins, for a condition of imposed displacement of 42 μm and temperature of 70 °C; (b) encrustation of fibreglass in non-anodised aluminium alloy pins for 68 μm and 50 °C temperature; (c) contact zone where the separation of the fibres can be identified for a test against non-anodised aluminium alloy pins with 68 μm and 50 °C; (d) material matrix involving the fibres; test against anodised aluminium alloy pins at 70 °C and imposed displacement of 69 μm; (e) abrasion of the matrix fibres by the small pieces attached to the aluminium pins; test against non-anodised aluminium alloy pins, 42 μm and 70 °C. The arrows indicate the sliding direction for each picture.

between the fibre–matrix interface, involve the fibres, which were prevented from becoming encrusted on the pins. This was observed especially for the anodised aluminium alloy pins, Fig. 19(d). In the case of the non-anodised pins, there was abrasion of the small pieces of fibres stuck to the pins, Fig. 19(e).

4. Conclusions

A comparative study of the fretting behaviour of glass-fibre-reinforced polypropylene composite and 2024-T6 aluminium alloy was conducted, enabling the following conclusions to be drawn.

Variation in the relative displacement amplitude implied a significant variation in the shape and area of the corresponding cycles, friction force versus amplitude displacement:

- The variation of the shape of the cycles enabled three typical fretting regimes to be identified: stick, slip and partial slip.
- The most effective way to characterize the transition between regimes was based on energy dissipation by friction.
- Surface treatment by anodisation led to smaller values of wear for small displacement amplitudes, whereas for higher displacement amplitudes the wear volume was larger.
- Variation in the relative humidity between 5 and 90% did not produce a significant change in the behaviour of the pairs of materials studied. Nevertheless, the effect of humidity was greater for the non-anodised pins.
- The behaviour of the pairs of materials was very much affected by temperature change. An increase in temperature implied greater wear volume, which affected the non-anodised alloy most.

In terms of morphology, and for the wear surfaces, the following were noted:

- For small values of displacement amplitude, only polishing of the polymeric matrix surface occurred, and the fibres were not affected. The pins did not exhibit very high wear volume. For larger values of displacement amplitude, the pins showed considerable wear volume, and the composite exhibited general rupture of fibres near the surface.

- In the test performed at high temperature, considerable amounts of composite matrix were transferred to the pin surface. This transfer involved not only matrix material but also small pieces of fibre, which attach themselves to the pins, acting as an abrasive.

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