FRETTING BEHAVIOUR OF GLASS-FIBRE-REINFORCED POLYPROPYLENE COMPOSITE AGAINST 2024 AL ALLOY

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SUMMARY
Composite materials, mainly fibre type ones, overcome very important solicitations in engineering applications. Due to different types of limitations it is usually impossible to produce structures without mechanical joints. For these types of joints the fretting must be an important failure mode mainly for dynamic loads. In order to access the influence of this failure mode – fretting – in association with the effect of displacement and surface treatment in aluminium (anodisation), the experiments where carried out changing each one of the variables. To analyse the influence of each parameter, tangential force and displacement were used to build the fretting cycles for every condition tested. The variation of the shape of the cycles allows identifying the three regimes typical of fretting; stick, slip and stick-slip, but the most effective way to characterize the transition between regimes was based in the dissipated energy by friction. The surface treatment of anodisation lead to smaller values of wear to amplitude displacement minor then 60 µm, meanwhile to bigger displacement amplitudes the wear volume was larger.

Keywords: fretting, wear, polypropylene composites, aluminium alloy, anodisation.

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

These materials, as well as their production processes, are well adapted for their application in large and complex structures reducing manufacturing costs.

The composite materials are widely used, not only in the aerospace industry but also in a large and increasing number of commercial mechanical engineering applications.

Nowadays the class of composite materials more widely used is the Polymeric Matrix one's (PMC). In the last decade there has been an important increase in their utilisation in a great variety of fields, in which these materials are frequently subjected to vibrations, where fretting can be a possible failure mechanism.

Composite materials, mainly fibre-type ones, overcome very important engineering applications. Due to different types of limitations it is usually impossible to produce structures without joints. Mechanically fastened joints, mainly riveted or bolted, are widely used in joining processes. This type of joints lead to a stress distribution characterised by high gradients of stresses near the bolts or the rivets, relating to relative displacements between the joined elements, and in the particular case of dynamic loads the fretting must be an important failure mode. One of the typical applications of the pair polypropylene/glass fibre and aluminium alloys is the riveted joint, namely in the aeronautic construction.

The fretting behaviour of PMC against aluminium alloys is not a very well studied subject, especially for the case of small displacement amplitudes. There aren't almost any fretting studies of aluminium alloys/PMC material pairs. The most widespread surface treatment of aluminium alloys is the anodisation, and in our knowledge there are no technical papers where its influence in fretting situations is studied.

The aim of this paper is the characterisation of the fretting behaviour of an Al alloy 2024-T6, with and without anodisation, against a polypropylene composite reinforced with E-type fibreglass. The parameters studied where relative amplitude displacement and surface treatment of the aluminium, i.e. anodisation.

2 MATERIALS AND EXPERIMENTAL PROCEDURES
The material's pair studied in the present work was the aluminium alloy 2024-T6, very common in the aeronautic industries, against the polypropylene (PMC) reinforced with E-type fibreglass.

The choice of the Al alloy was due to the fact that it is a very attractive alloy in structural applications, with high specific resistance, and also due to the fact that there are few studies in fretting solicitations. The chemical composition and the main mechanical properties of the Al 2024 are presented in table 1.
Table 1: Chemical composition and main mechanical properties of the Al – 2024 [1,2].

<table>
<thead>
<tr>
<th>Elements</th>
<th>Si</th>
<th>Mg</th>
<th>Mn</th>
<th>Fe</th>
<th>Cr</th>
<th>Zn</th>
<th>Cu</th>
<th>Ti</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Wt</td>
<td>0.5</td>
<td>0.5</td>
<td>3.8- 4.9</td>
<td>0.3- 0.9</td>
<td>1.2- 1.8</td>
<td>0.1</td>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Rupture strain ((l_0=50 \text{ mm}), \varepsilon_f)</th>
<th>Hardness [HV]</th>
<th>Young’s Modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>427</td>
<td>345</td>
<td>5</td>
<td>142</td>
<td>72.4</td>
</tr>
</tbody>
</table>

The surface treatment of anodisation gives rise to an oxide layer, which main objectives are the protection against atmospheric corrosion, increasing of superficial hardness, better abrasive resistance and modification of the electrical properties. In the present work, the sulphuric anodisation has been used to treat the specimens of Al 2024-T6. The treated surface layer has a value of hardness of \(HV_{15} = 390 \text{ [Kgf/mm}^2]\), while the substrate value has \(HV_{1000} = 130 \text{ [Kgf/mm}^2]\).

The polymeric composite studied in this work was the Twintex T PP reinforced with a bi-directional cloth, composed with fibres of polypropylene and E-glass, which cross perpendicularly. The orientation of the seven layers of cloth is 0º, relative to the sliding direction, and the volumetric fraction of fibreglass is 33.8%.

The main mechanical properties of the PP are presented in table 2.

Table 2: Main mechanical properties of the PP [3].

<table>
<thead>
<tr>
<th>Ultimate strength [MPa]</th>
<th>Rupture strain ((l_0=50 \text{ mm}), \varepsilon_f)</th>
<th>Young’s Modulus [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>438</td>
<td>3.42</td>
<td>15.9</td>
</tr>
</tbody>
</table>

The fretting tribometer used in this experimental work was developed in the Department of Mechanical Engineering of the University of Coimbra [4].

Some authors [5, 6] refer a great number of variables that affect the fretting phenomena. Bill [7] classifies these factors in three groups: i) contact conditions, ii) environment and iii) material properties. In what concerns the contact conditions, the fretting tests include factors like displacement amplitude, loading frequency, normal force applied to the specimens, contact geometry and the duration of the tests.

In order to access the influence of this failure mode - fretting- in association with the effect of displacement and surface treatment in aluminium (anodisation), the tested contact geometry was a sphere-plane type one. With this type of contact, the experiments where carried out changing each one of the variables. In order to analyse the influence of each parameter, tangential force and displacement were used to build the fretting logs for every condition tested.

The surfaces were analysed in both optical and scanning electron microscopes, in order to observe the main wear mechanisms. With the purpose of identify and evaluate the three different fretting regimes, i.e. stick, slip and the mixed stick-slip, the material response and running conditions were used as criteria [8].

3 RESULTS AND DISCUSSIONS

In order to access the influence of the relative displacement amplitude in the behaviour of the two material pairs, it was varied from 5 to 200 \(\mu\text{m}\), keeping constant the rest of the variables. The testing conditions were: normal load (20 N), relative humidity (50 to 55%), temperature (18 to 25ºC), frequency load (190 Hz), contact geometry (sphere-plane) and duration test \((1.368 \times 10^6 \text{ cycles})\).

During the entire test the signals of the friction force and displacement were acquired in a regular number of cycles intervals - \(1.14 \times 10^5 \text{ cycles}\). In result of the imposed force by the oscillator the type of movement law is sensibly harmonic.

The variation of the friction force with the displacement corresponds to a closed cycle - \(\log\) -, where the area \(A\) of the close cycle represents the work produced by the friction force (1) in each cycle:

\[
\int S F(S) \, ds
\]

Where \(F(S)\) represents the friction force in function of the displacement \(S\). Recently these energetic parameter is being used by a growing number of investigators, in order to characterize the fretting behaviour of materials [9, 10].

From the acquired data it was possible to attain the total energy dissipated by friction. Considering the trybological contact as a thermodynamical system, the dissipation of friction energy constitutes the principal portion of energy entry in the system, and consequently, the rise in: the contact temperature, material removal, and in some cases the initiation and propagation of cracks in the surfaces of the contact. Adding the work of the friction force produced along the test can be obtained the total energy dissipation by friction force in each test. Every acquisition is considered the mean value of the work produced by friction force in the interval between acquisitions.
This energetic parameter was related with the wear volume of the aluminium specimens. This was due to the fact that the attempts to measure the volume of the removed composite material were impossible to guarantee a rigorous value, even using laser interferometry profilometer. Due to that fact it was measured in the pin surface the diameters of the flat circular area produce by wear, determining the wear volume of the aluminium pins using equation 2:

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

(2)

Where:

$$h = r \sqrt{r^2 - a^2}$$, being $r$ the radius of the spherical ended specimen and $a$ the radius of the wear mark. The radius $a$ of each specimens was measured in a Scanning Electronic Microscope (SEM).

As it was pointed out, in this energetic approach one can relate the volume of material removed by wear with the total energy dissipated by friction, this approach has been proved by many authors [9, 10], according to their experimental results for several materials. Hence, table 3, for the two types of aluminium pins tested, presents the values of material removed, total dissipated energy, displacement amplitude, effective and imposed and the corresponding number of the test.

<table>
<thead>
<tr>
<th>Teste Number</th>
<th>Imposed displacement [µm]</th>
<th>Effective displacement [µm]</th>
<th>Wear Volume [mm³]</th>
<th>Total energy dissipated [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>15</td>
<td>0.0035</td>
<td>91.2</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>24</td>
<td>0.0078</td>
<td>1585</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>28</td>
<td>0.0085</td>
<td>2337.3</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>78</td>
<td>0.1338</td>
<td>5112</td>
</tr>
<tr>
<td>Teste Number</td>
<td>Imposed displacement [µm]</td>
<td>Effective displacement [µm]</td>
<td>Wear Volume [mm³]</td>
<td>Energia total dissipada [J]</td>
</tr>
<tr>
<td>--------------</td>
<td>---------------------------</td>
<td>-----------------------------</td>
<td>-------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>6</td>
<td>0.0026</td>
<td>5.3</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>9</td>
<td>a)</td>
<td>128</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>22</td>
<td>0.0031</td>
<td>605.4</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>36</td>
<td>0.0136</td>
<td>1418</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>47</td>
<td>0.0176</td>
<td>2240.4</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>79</td>
<td>0.1787</td>
<td>6331</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>141</td>
<td>0.0392</td>
<td>8559</td>
</tr>
</tbody>
</table>

Table 3: Values of the volume of material removed from the aluminium pins tested, total dissipated energy, displacement amplitude, effective and imposed and the corresponding number of the test.

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 pair composite/Al anodised, in these range of displacement amplitude didn’t exhibit the stick regime it was necessary to select smaller amplitudes, namely 5 and 10 µm. A test of 200 µm was done to verify that once attained the fretting regime of slip there was no change in the regime.

Vingsbo and Vincent [8], based on Mindlin’s model, verified the existence of three fretting regimes; stick, slip and stick-slip. In the stick regime, the surfaces in contact don’t have relative displacement and the displacement imposed is accommodated by elastic deformation of the material in contact, the friction force varies in an almost linear way with the displacement. This implies that the fretting cycles are almost closed and the energy dissipated by friction is very small. In the slip regime, the displacement gives rise to slip in all of the contact area, thus resulting very open fretting cycles, implying very large values of energy dissipation. The third regime is the stick slip and is characterised by slipping in the contact’s borders and no relative displacement in the centre of the contact. The cycles of this regime are elliptical and have intermediate values of energy dissipation.

In fretting tests, the influence of the system’s compliance [11], especially in small amplitude displacement, in the connection between the actuator and the specimen’s holder is very important. In the present work by putting an accelerometer directly in the mobile specimen-holder and thus measuring the effective, and not the imposed displacement amplitude overcame this problem. The values of the friction force...
acquired are affected by dynamic response on it’s amplitude and phase angle, to correct these influence it was used a model by A. Ramalho [12], in the data treatment.

In figures 1 and 2, are represented the fretting logs, for the two pairs of materials. It can be observed the three fretting regimes, although the transition between regimes, in terms of displacement, is different for each pair of materials tested.

For the pair composite/Al anodised, analysing the shape of the cycles, can be observed the existence of stick regime for an effective amplitude displacement of 6 µm. The slip regime is observed for effective displacement amplitude greater or equal to 36 µm. The regime of stick-slip is detected for the effective amplitudes of 9 and 22 µm.

In the case of the pair, composite/Al non-anodised, the stick-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 or greater than 24 µm.

Combining the observation of the fretting logs and the values from table 3, wear volume of the aluminium pins and dissipated energy, it was built the graphic of figure 3.

In this graphic it is represented the wear volume of the pins of aluminium, anodised and non-anodised, in function of the total dissipated energy. The numbers 1, 2 and 3 identify the fretting regimes. It is possible to confirm the analyses done in terms of the shape of the fretting cycles for the two pairs of materials.

In region 1, corresponds to the stick regime, the upper limit of dissipated energy is 100 J. In this region can be observed to points, which correspond to Al anodised, with 6 µm of effective displacement amplitude, and to the Al non-anodised with a displacement amplitude of 15 µm. In region 2, corresponding to stick-slip regime, are represented the tests of Al anodised for amplitude displacements of 22 and 36 µm, this region is limited, in terms of energy, from 100 J to 1500 J. In this region there are no points representing Al non-anodised.

Region 3 is characterized by the slip regime and the lower limit is of 1500 J. In this region are represented the tests with larger displacement amplitudes, thus greater wear volumes.

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Region 3 is characterized by the slip regime and the lower limit is of 1500 J. In this region are represented the tests with larger displacement amplitudes, thus greater wear volumes.
Figure 4: Wear volume vs. effective displacement amplitude, showing that for aluminium with and without anodisation.

The graphic of figure 4, represents the wear volume in function of the displacement amplitude, showing that for both pairs, aluminium with anodisation and aluminium without anodisation, the law of variation between wear volume and effective displacement amplitude is the same, i.e. exponential. It is also possible to observe that for both pairs of materials the low values of displacement amplitude corresponds to low values of energy dissipation. In these cases and by observation in the SEM 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 amplitude displacement the wear of the pins was greater and the composite presented rupture of its fibres, figures 5 and 6, Lu et al. [13] also observed this kind of failures.

Although the surface treatment of anodisation smoothes the transition between regimes, until the value of 60 µm, its existence doesn’t reduce in a significant way the material removed by wear. One can say that the introduction of the surface treatment doesn’t have a big improvement in the fretting behaviour of the Aluminium alloy 2024-T6 against a polypropylene matrix reinforced with glass fibre.

4 CONCLUSIONS

It can be concluded that:

- The variation of the relative displacement amplitude implied a significant variation in the shape and area of the corresponding cycles.
- The variation of the shape of the cycles allows to identify three regimes typical of fretting: stick, slip and stick-slip.
- The most effective way to characterize the transition between regimes was based in the dissipated energy by friction.
- The surface treatment of anodisation lead to smaller values of wear to amplitude displacement minor then 60 µm, meanwhile to bigger displacement amplitudes the wear volume was larger.
- In terms of morphology, for small values of amplitude displacement occurred only a polishing of the polymeric matrix surface and the fibres were not affected, the pins didn’t exhibit very high wear volumes. For the bigger values of amplitude displacement the pins presented considerable wear volumes and generally the composite exhibit rupture of fibres near the surface.

5 REFERENCES


