25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-XXXX
DEVELOPMENT OF A FRETTING FATIGUE DEVICE TO TEST ALUMINUM WIRES

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Abstract. *The aim of this work was to develop and to manufacture a fretting fatigue device to test aluminum wires that operate through a Material Testing Machine (MTS). The device was capable of inducing fretting fatigue in test wires, as occurs in the wires of a conductor within the suspension clamp. In order to design a device to meet all the needs for fretting to occur in wires, a study on the phenomenon of fretting fatigue was conducted. For the same purpose, a specification was also written that collects all the requirements and conditions that the device must meet. In conclusion, the device developed in this work can accomplish successfully the fretting fatigue test of two contacting wires.*

Keywords: *fatigue, fretting, cable conductors, wire, aluminum alloy.*

1. INTRODUCTION

It is known that in the energy sector fretting fatigue is the main cause of failure in overhead conductors. With the wind generating vibration loads, the failures and ruptures arise where the aluminum wires of the cable are in contact with the suspension clamp (Azevedo et al., 2009; Abreu et al., 2010, Fadel, 2010). Aluminum wire failure may impose a strong reduction in the transmission line life (Zhou et al., 1995). Thus, it would be useful to study single wire fretting fatigue behavior in order to correlate with complete conductor results (Zhou et al., 1994).

The suspension clamp is composed of a body, a keeper, and two U-type bolt and nuts (Figure 1). Failures in cables mostly arise at the contact between the cable and the body or keeper of the clamp. According to the design of the clamp, visual inspection or the use of sensors are particularly complex (Azevedo et al., 2009; U.S. Department of Energy, 2010).

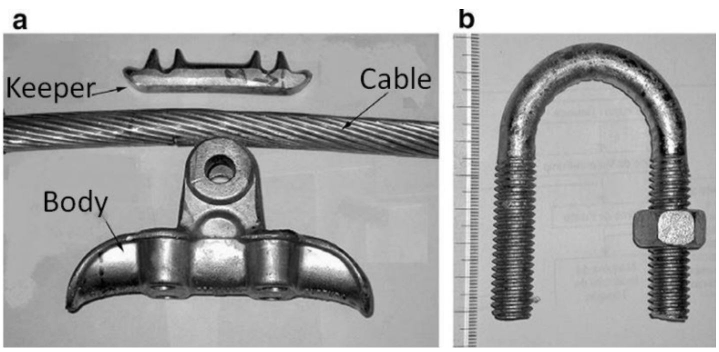

Figure 1. (a) Suspension clamp. (b) U-type screw (Azevedo et al., 2009).

The tightening torque of screws varies between 50 and 60 N.m, depending on the manufacturer. The various types of conductor cables are constituted of tiers of wires laid at different angles. Figure 2(a) presents an example of how the layers of aluminum wires are arranged in a conductor cable with a steel core. In this example, the external layers are composed of pure aluminum wires and the internal ones are steel wires. The diameters of the wires vary according to the model and manufacturer.

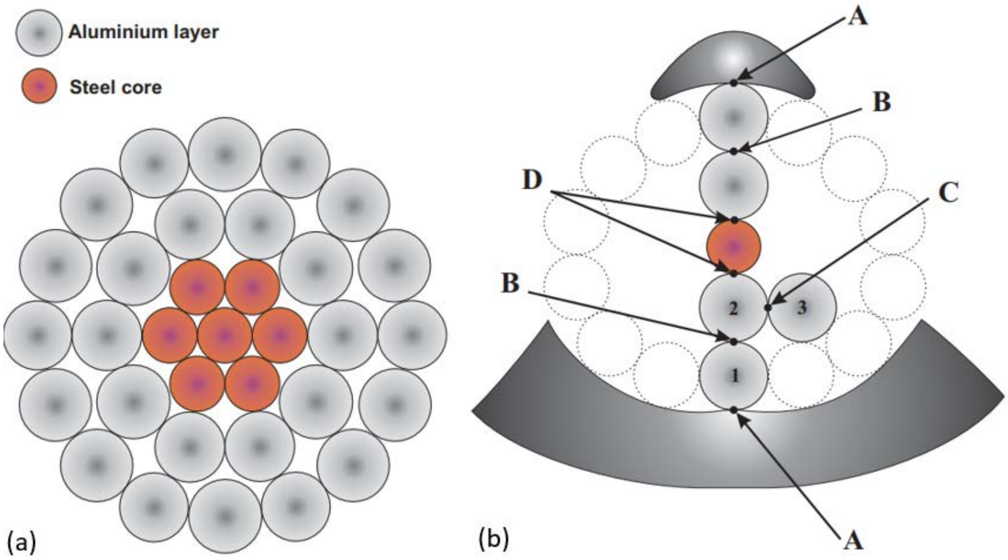

Figure 2. Arrangement of layers of aluminum wires and steel wires (a). Points of contact where fretting fatigue can occur in this example of an aluminum conductor cable with a steel core (b).

Fretting fatigue normally occurs between the aluminum wires that form the different layers of a conductor cable, especially in the region of the suspension clamp. Point B in Figure 2(b) indicates the contact between wires from different layers. Wires from the same layer are in contact at point C. Fretting fatigue can also occur at the points of contact between the wires from the external layer and the clamp itself (A in Figure 2b) and between the internal layer of aluminum and the layers of steel wires of the core (point D).

The contacts between wires can be summarized in two types, as shown in Figure 3 (Raoof, 1990).

- The contact B in Figure 3 occurs between wires from different layers. At this point, the wires cross and the contact is elliptical.
- The points A in Figure 3 show contact between wires from the same layer. In this case, the contact is linear.

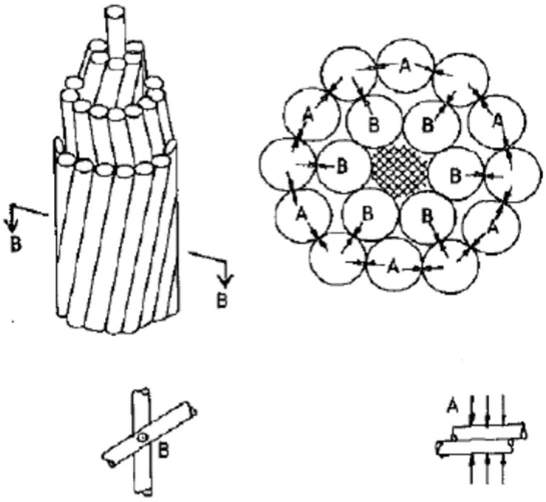

Figure 3. Type of contact between wires from different layers or same layer (Raoof, 1990).

Despite the occurrence of fatigue failure in conductor cables being one of the main problems in a transmission line project, the scientific research in this area is still in its infancy (Raoof, 1990; Cruzado et al., 2010). Full-scale tests have already produced useful data for evaluating fatigue resistance in cables (Raoof, 1990). However, fatigue tests in conductor cables are relatively costly, require large physical spaces, and take long periods to execute.

Therefore, this study developed an innovative device for fretting fatigue tests, seeking to evaluate the influence of tension concentrations on the fatigue life of the individual wires that compose a conductor cable. The results obtained will serve as intermediate stages for the elaboration of lower cost experimental methodologies and validation of new models for fatigue life prediction in conductor cables used in transmission lines.

The device developed in this study was attached to a universal MTS testing machine. One of the aluminum wires removed from one of the layers of cable was subjected to a remote fatigue load applied by the MTS. A second wire and a bearing attached to the testing device acted as load contact pads, used in the fretting test, as according to the description of the device presented as follows.

2. DESCRIPTION OF THE DEVICE

The device meets the two primary needs for fretting, that is, the cyclic movement of slip between the two surfaces in contact and the force of contact between them (Figure 4). The MTS machine allows the shear load, *Q(t)*, and the remote fatigue load, *B(t)*, to be applied and controlled. The device designed allows the application of load *P*, with normal compression between the wires, so that fretting takes place.

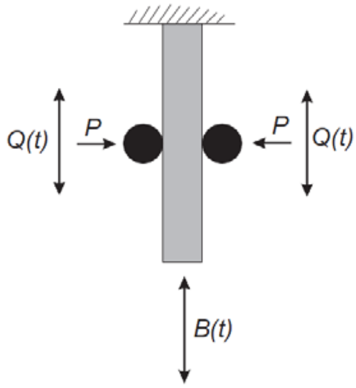

Figure 4. Schematic diagram of the fretting fatigue apparatus.

In the proposed configuration, one of the wires acts in the role of the test specimen, being fixed in the grips of the universal MTS machine and subjected to a fatigue load. Another wire is placed in contact with the first, on one side of the device, acting as one of the pads of the fretting test. This device can simulate various crossing angle options observed in transmission line cables (Raoof, 1990; Cruzado et al., 2011). On the other side of the device, a bearing was placed that acts as a pad on the opposite side, in the fretting. Figure 5 presents the proposed configuration.

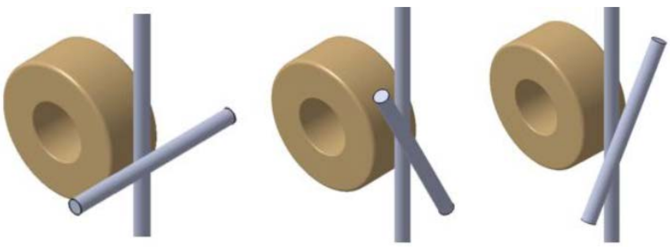

Figure 5. Schematic design of possible configurations of the positioning of the wires in the test machine device, at the different contact angle options, observing the bearing acting as one of the pads and a wire as the other pad.

Figure 6(a) presents a schematic diagram of the universal MTS testing machine with two independent actuators used in this work. The upper actuator is the fretting actuator and the lower one is the fatigue actuator.

The lower actuator applies the remote fatigue load *B(t)* and the upper one applies the shear load *Q(t)* (Figure 6b).

The frequencies of the two loads can be altered, if necessary. In fretting fatigue devices that use a single actuator, the *B(t)* and *Q(t)* loads are synchronized (Martins, 2008).

The fact that the MTS has two independent actuators is of great interest, since it enables synchronous or asynchronous load programs to be applied, in phase, out of phase, and variable (Bellecave, 2015). For the fretting fatigue test, one of the wires (test specimen) is subjected to a fatigue load *B(t)*. In the device developed in this study, only one contact wire was used acting as one of the pads in the fretting test, in order to generate a normal contact load *P*. The second wire, which acts as a second pad, was substituted for a bearing, as presented in Figure 6(b).

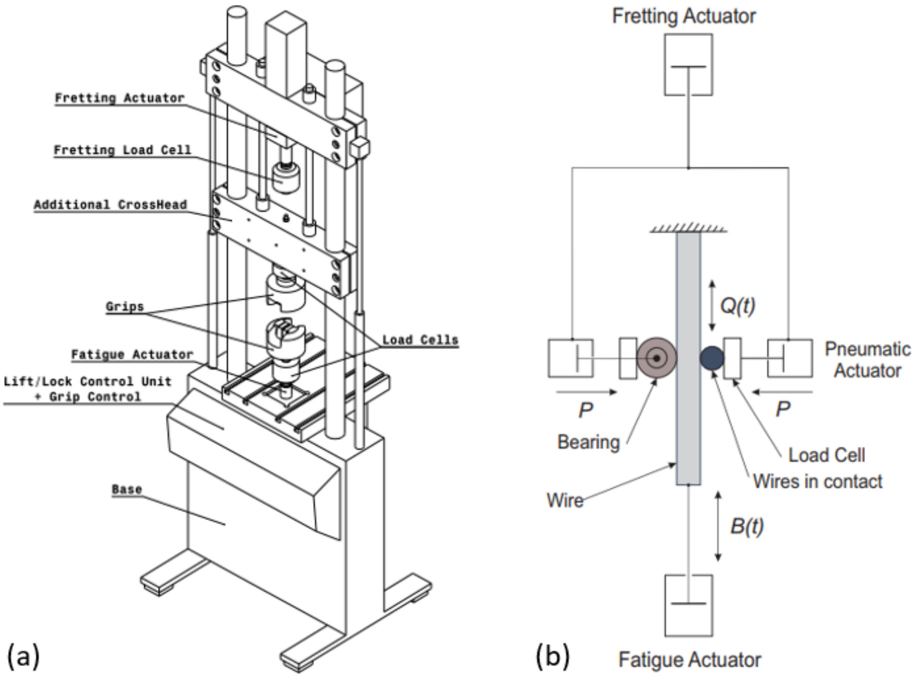

Figure 6. Diagram of the MTS machine adapted for inclusion of the fretting fatigue device (a). Schematic diagram of the device for testing fretting in wires (b).

It is important to highlight that the tangential load *Q(t)* can be controlled in the test, but it can also be produced in the reaction of the pad (wire in contact) with the remote load *B(t)*.

Previous studies obtained 2.81 kN as the maximum tightening load for obtaining similar surface deformations to those observed in wires of aluminum conductor cables (Nunes Filho, 2016). To conceive the device developed in this study, the design foresees the possibility of applying tightening loads of between 0.1 and 2.81 kN.

A previous study (Martins, 2008) presented a device for testing fretting fatigue with flat test bodies, using cylindrical pads for contact. In this case, it was observed that for a high number of cycles, the wear of the sample during the fretting test causes a loss of material at the contact zone. With this, the pads tend to be displaced in the direction of the test specimen, which causes a loss of load in the hydraulic circuit. With the aim of compensating for this loss of load, the design of the device developed in this study included a load cell inserted between the wire in contact and the actuator responsible for the application of the normal load (Figure 8). The signal emitted by the load cell was used to monitor and control the existing force in the set of wires. The small variations in force perceived by the load cell are sent to controllers that readjust the loads according to need.

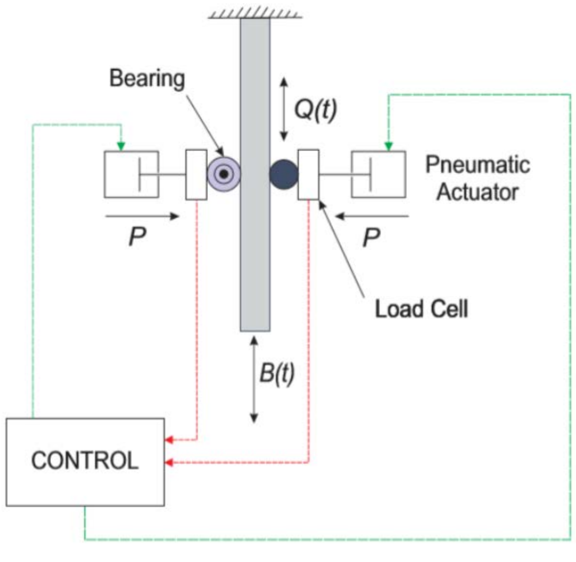

Figure 8. Diagram of the control of the loads *P* through the actuation of pneumatic actuators controlled by the load cells.

The aim of the load cell in the device is to monitor and control the existing load in the set of wires. This load cell should perceive small variations in load and send the electric signals to a controller. Due to the conception of the device, priority was given to load cell models that work in compression and that can measure forces in the order or magnitude of 3000 N.

The fretting device was fixed to the upper actuator of the universal MTS machine, using a metallic plate with four screws, in accordance with the design shown in Figure 9. This enables the vertical displacement of this device due to the action of the upper actuator. The lower actuator of this machine applies uniaxial cyclic tension in the central wire. The complete device attached to the MTS machine is positioned between the two actuators, as shown in Figure 9.

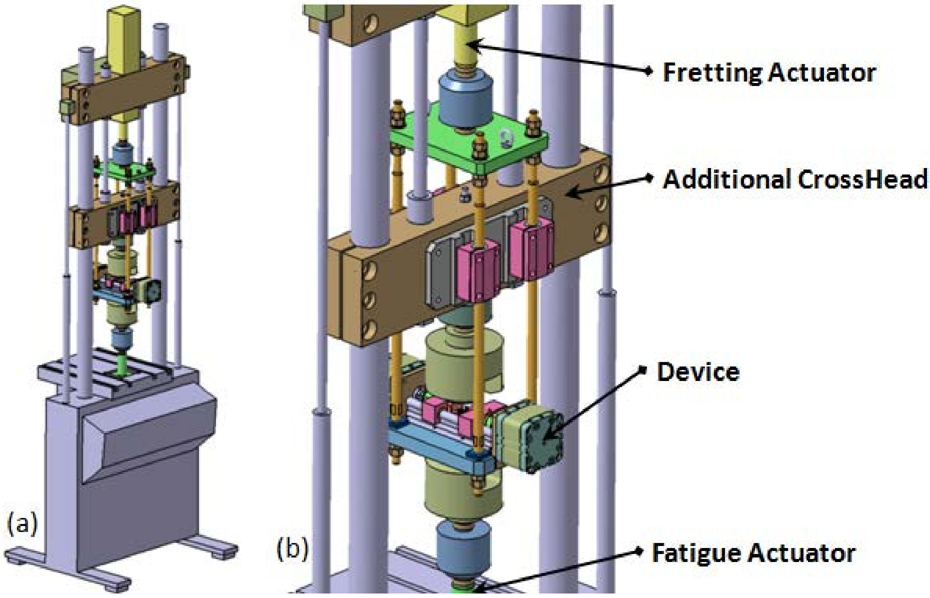

Figure 9. Design of the device attached to the MTS machine (a). Magnified view of the device (b).

The aluminum wires of conductor cables are rolled up helicoidally in various layers. The device developed in this study simulates this torsion angle and enables fretting to be tested at different angles. These angles are the result of the wire-stringing step during the cable's manufacture. Thus, the device was designed to enable fretting tests at the possible angles formed between the wires, with a centering pin and holes positioned at the 13°, 16°, 20°, 29°, and 90° angles (Figure 10a). The perpendicular positioning does not correspond to any type of contact of a conductor cable, but it is of considerable interest in terms of fretting fatigue. With the 90° angle, the device enables a comparison of the test results with other studies that have chosen perpendicular crossing (Cruzado et al., 2010; Zhang et al., 2013; Zhou et al., 1994).

Figure 10(b) presents in detail the region of contact between the bearing and the wires tested. The support for fixing the contact wires (pads) enables pads of different diameters to be tested.

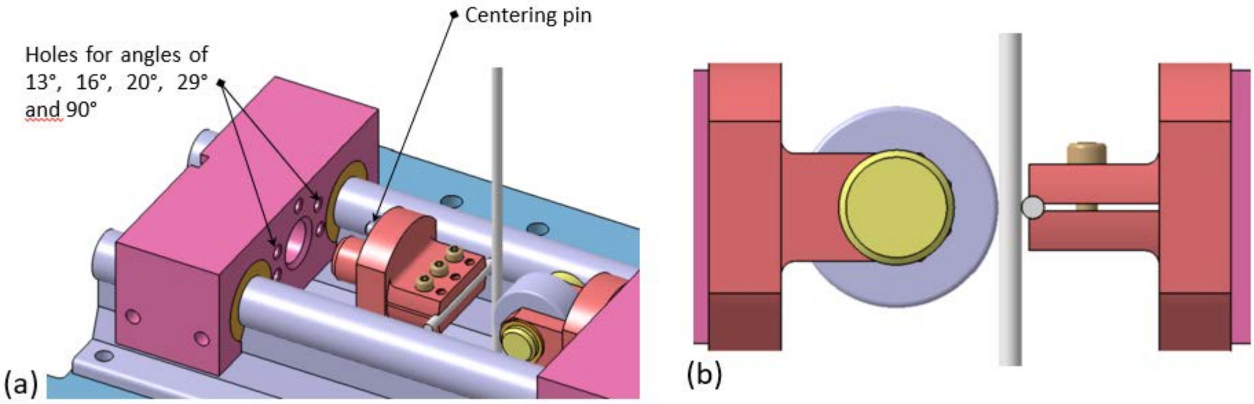

Figure 10. Detail of the conception of the support wire, with holes for fixation at different angles (a). Schematic diagram of the support for fixing the contact wires (pads), enabling the use of pads of different diameters (b).

The pneumatic actuator was chosen with the aim of guaranteeing the normal maximum load *P* foreseen in the device design. Figure 11 shows a longitudinal section of the final version of the device, with the main items.

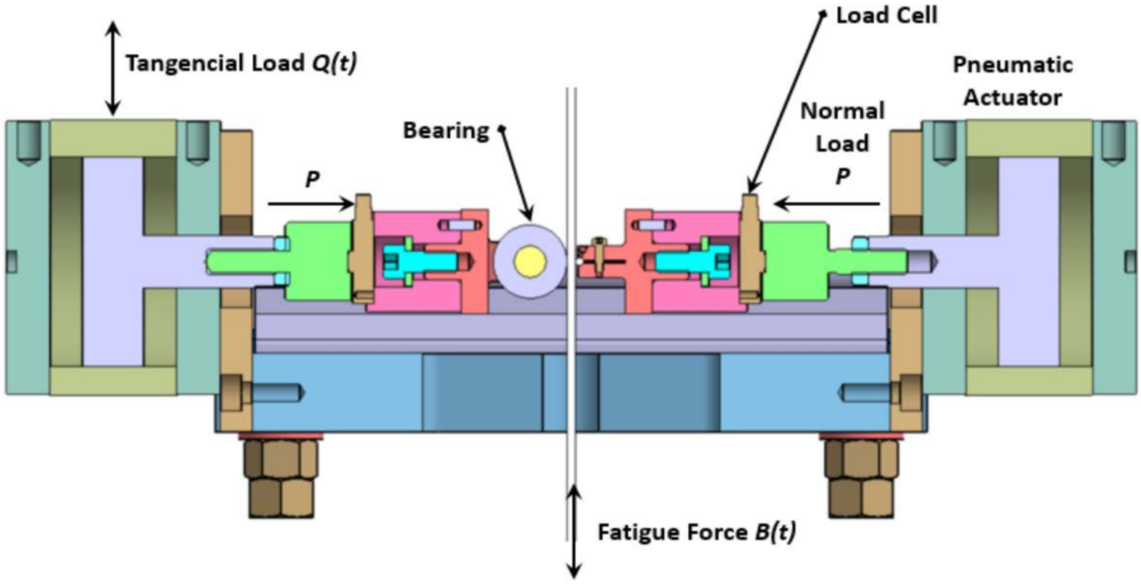

Figure 11. Longitudinal section of the wire fretting fatigue device.

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After its manufacture, the device was installed in the universal MTS testing machine, as shown in Figure 13.

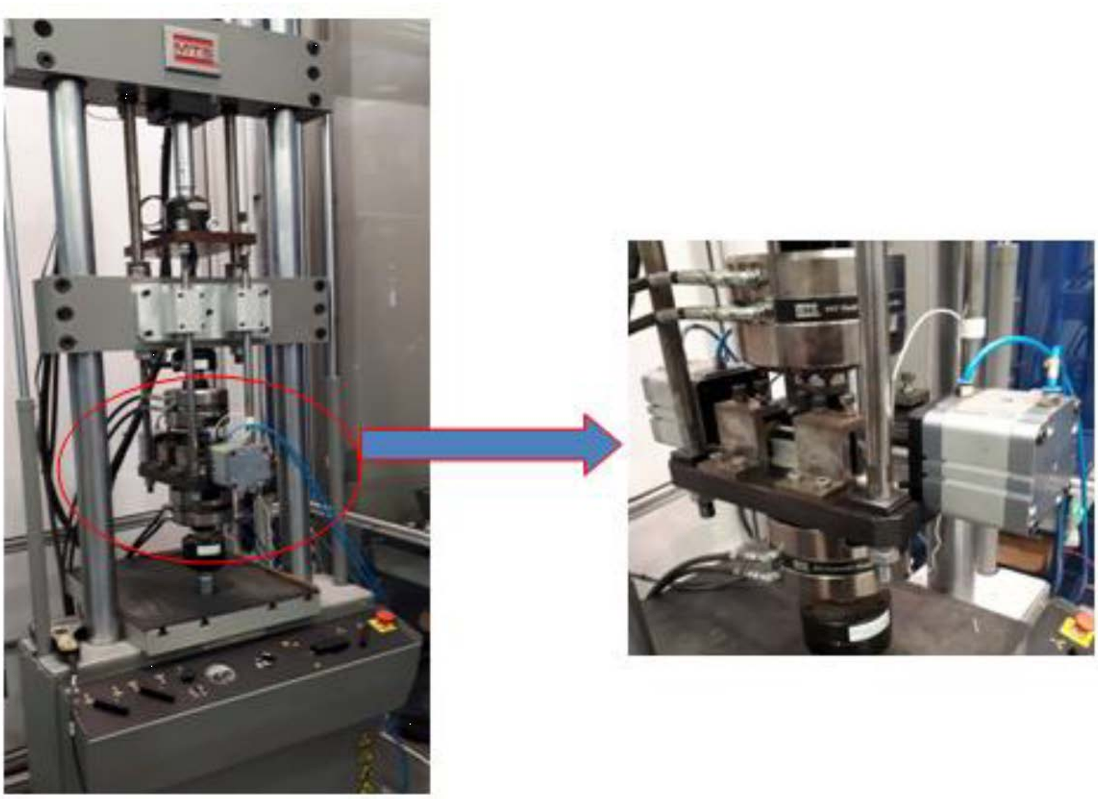

Figure 13. Device installed in the universal MTS testing machine. Detail of the positioning of the device.

The MTS controller applies the loads or displacements through the servo valves attached to the MTS actuators and it receives and sends the information to the MTS data acquisition system. The computer of the universal testing machine can record the displacements, the tensions, the time, and the number of cycles.

3. FRETTING FATIGUE TESTS AND FAILURE ANALYSIS

3.1 Tests for fatigue under fretting conditions

The tests for fatigue under fretting conditions were carried out on 6201 aluminum wires, seeking an experimental evaluation of the device's performance. These tests were fundamental for validating the mechanical functioning of the device attached to the MTS machine, monitoring the effectiveness of the instrumentation, and verifying whether the device reproduces fretting fatigue conditions on the surface of the wires tested. The fretting test used 6201 aluminum alloy wires, used in electrical conductors, which in their production are subjected to T-81 thermomechanical treatments.

To evaluate the device, fretting fatigue tests were carried out with a tangential load *Q(t)* generated by the remote fatigue load *B(t)*; that is, the upper actuator of the MTS machine was disabled during the test.

The assembly option of the test chosen for the fretting fatigue test was wire-wire contact on one side of the test specimen and wire-bearing contact on the other, as presented in Figure 14. Load *P* was set at 250 N. The tests were carried out with a wire-crossing angle of 29°, which exists in some types of conductors. A tension ratio of R = 0.1 (traction-traction condition) and oscillation frequency of 20 Hz were used. The test conditions are similar to those of the cable used in transmission lines, where the remote load due to the traction preload generates no compression. Similarly, the frequency was chosen in accordance with the fatigue tests carried out in previous studies with CAL 900 cables (Kalombo et al., 2016), where the frequency range varied between 20 and 30 Hz. The lowest frequency was chosen to guarantee the stability of the tests and avoid excessive heating of the test body in the contact zone.

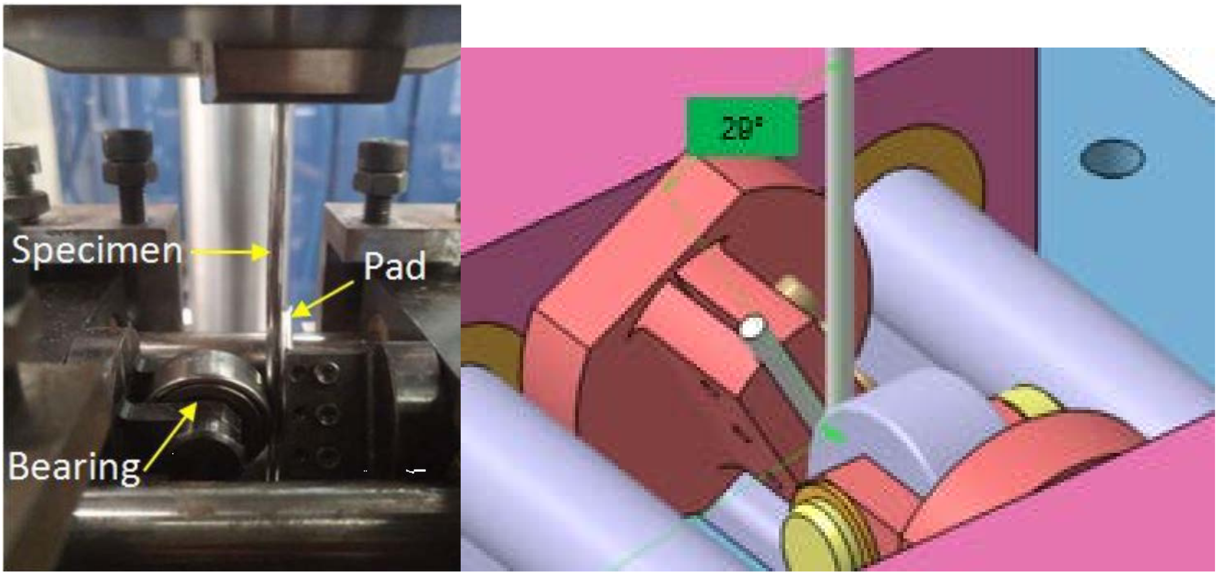

Figure 14. Device configured for the wire-bearing option, with the specimen, the bearing on one side of the specimen, and the pad on the other side (aluminum wire inclined at 29° in relation to the specimen).

3.2 Tests for fatigue under fretting conditions

The aluminum wires subjected to the fretting test were examined with scanning electron microscopy (SEM), using a JEOL SM-7100F field emission microscope with an energy dispersive spectrometer. The fracture surfaces were examined using SEM with the aim of establishing the possible points of initial failure and the propagation mechanisms involved. The analyses in the initial failure region, on the wire-wire contact surface, enabled the occurrence of fatigue under fretting conditions to be identified, characterized by the existence of adhesion zones and partial slip.

4. RESULTS AND DISCUSSION

4.1 Fatigue under fretting conditions

The S-N curve shown in Figure 15 presents the results obtained in the fatigue test under fretting conditions carried out in 6201 aluminum wires. The tests that reached the infinite life (run out) and the trendline are also indicated on the curve.

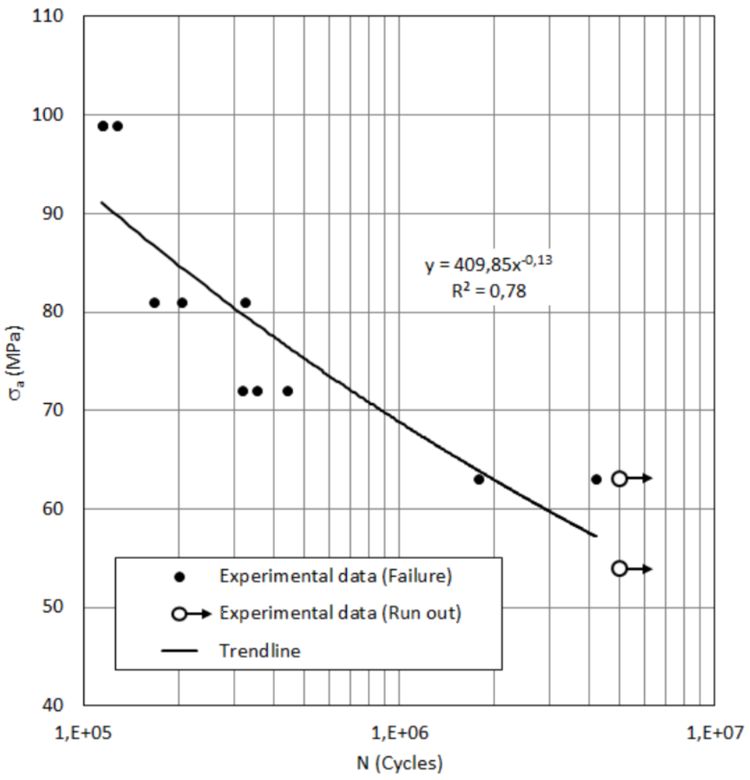

Figure 15. S-N curve of the fretting fatigue test in 6201 aluminum wires, using a load *P* of 250 N.

The correlation coefficient of the trendline ($R^2 = 0.78$) is significant, considering the dispersions observed in the fatigue life, obtained at the lowest tension levels.

4.2 Failure analysis using scanning electron microscopy

The evaluation of the device's performance included failure surface analysis using scanning electron microscopy, aiming to verify the characteristics of fracture due to fretting fatigue in the samples tested. The contact loads generated by the pads, associated with the oscillatory movements during the fatigue test, generated fretting marks on the wire-wire contact surface, which are responsible for the failure onset, as observed in Figure 16.

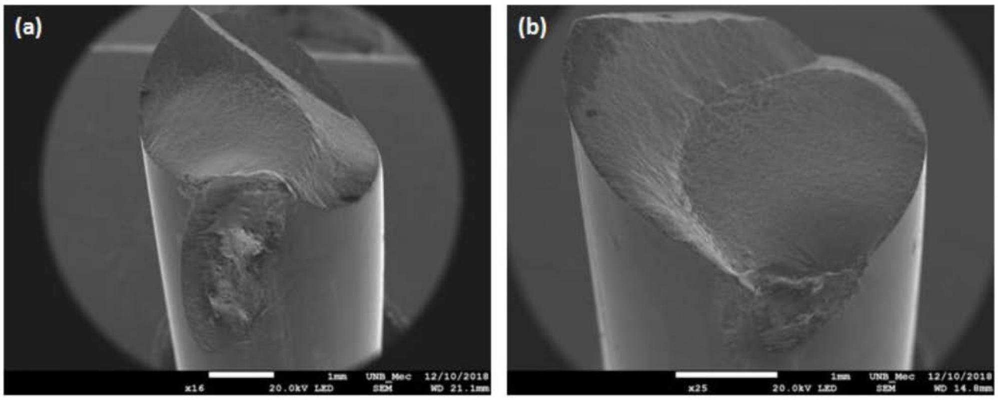

Figure 16. Mark of the failure onset due to fatigue under fretting conditions in the wire-wire contact, both in the lower (a) and in the upper (b) piece of the same aluminum wire tested.

Figure 17 presents the aspect of the wire fracture surface (a), dimple characteristics of the final ductile fracture (b), and area of the onset and propagation of the fracture (c).

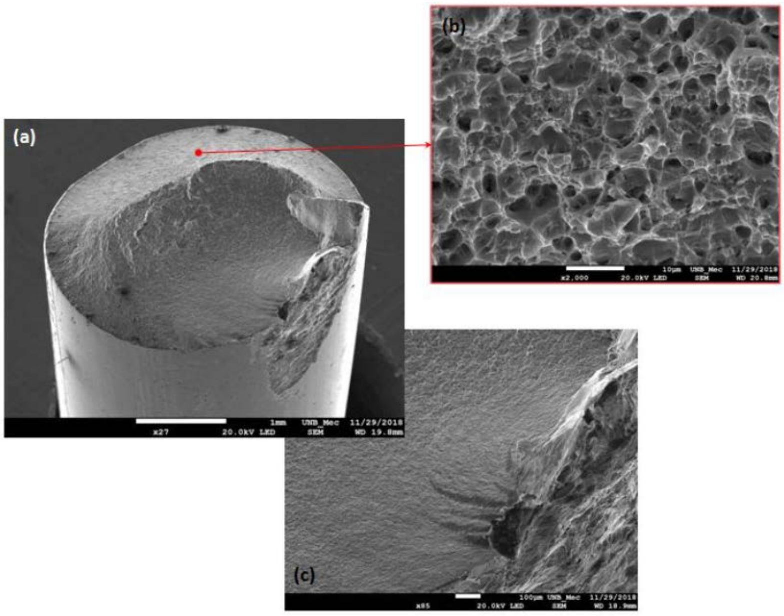

Figure 17. Surface of failure due to fretting fatigue (a), detail in the zone of the final ductile fracture (dimples) (b), and detail of the region of failure onset in the wire-wire contact zone (c).

Energy dispersive spectroscopy (EDS) analyses were carried out in this area of initial failure, in the region of the fretting mark observed on the surface of the fractured wire, presented at a higher magnification in Figure 18(a). The EDS mappings carried out in this region using scanning electron microscopy show the surface distribution of the main chemical elements existing in this fretting mark. Figure 18(b) presents the distribution of the aluminum, observing a concentration of this element in the adhesion region of the fretting (central green area).

Another EDS mapping on the same surface (Figure 18c) presents a region that is rich in oxygen in the area of partial slip. The oxygen in this region of partial slip originates from the aluminum oxide (Al_2O_3) particles generated by the wire-wire attrition during the test. Figures 18(d) and (e) present the distribution of the silicon and magnesium.

Figure 18(f) shows the assembly of the aluminum, oxygen, silicon and magnesium mappings. The adhesion zone, which is rich in aluminum, prevails in the central part of the fretting region (green dots in the center). In the partial slip region (blue dots around the green adhesion region), the presence of oxygen is predominant, which is the result of the formation of aluminum oxide (Al_2O_3) particles during this partial slip.

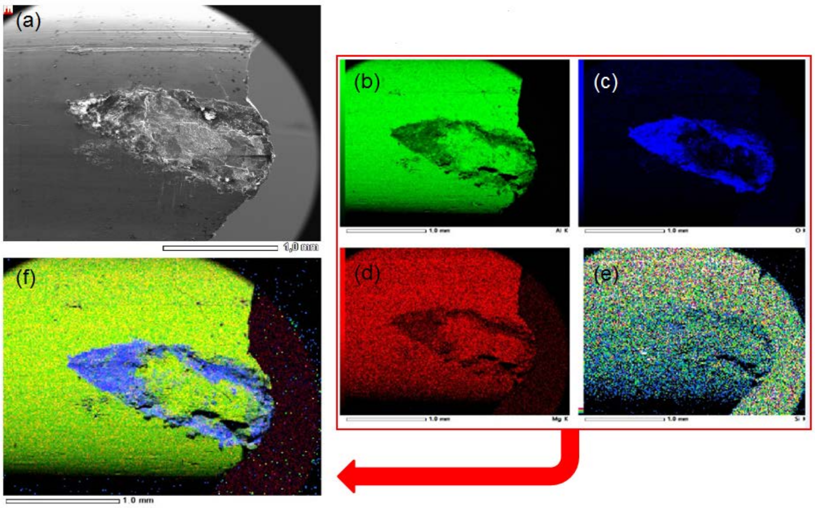

Figure 18. Energy-dispersive X-ray spectroscopy, a) photo of the fretting mark, b) EDS mapping of aluminum, c) EDS mapping of oxygen, d) EDS mapping of magnesium, e) EDS mapping of silicon, f) EDS mapping of the four elements.

Therefore, during the test an adhesion regime and another partial slip regime are observed in the fretting mark on the surface of the wire, which are characteristics of the fretting phenomenon, demonstrating that the device is able to reproduce a test for fatigue under fretting conditions in wires of conductor cables.

5. CONCLUSIONS

This study carried out the design, construction, and testing of an innovative device for evaluating the fatigue life of individual aluminum wires belonging to a conductor cable. The results obtained will serve as intermediate stages for elaborating lower cost experimental methodologies and validating new models for predicting the fatigue life of conductor cables used in transmission lines. Based on the results obtained, it is concluded that:

- The device developed is able to control and record the normal and tangential loads and the relative displacements produced by the fretting phenomenon.
- The data generated in the tests carried out with the device made it possible to build an S-N curve, thus allowing an evaluation of the fatigue life of the wires tested.
- The failure surface evaluations showed characteristics of rupture due to fretting fatigue, with almost planar propagation in an area cross-sectional to the longitudinal axis of the remote load application and a final rupture with a ductile appearance.
- The device is able to reproduce a fretting fatigue test in wires of energy conductor cables, inducing elliptical fretting marks comparable to the marks caused in the conductor cables when tested under fatigue at full scale.
- The EDS images and analyses obtained using scanning electron microscopy after the fatigue test demonstrate that the wire-wire marks generated by the device present, in the fracture region, all the characteristics found in internal layers of conductor cables of transmission lines fractured in use by fatigue under fretting conditions, such as clearly defined adhesion and partial slip zones and the presence of aluminum oxide where the partial slip regime prevailed.
- The failures arise mainly in the lower part of the fretting marks, that is, inside the slip zone, as observed in previous full-scale studies involving fatigue in conductor cables (Kalombo et al., 2016).

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7. RESPONSIBILITY NOTICE