The Experimental Approach on the Tribological Behavior of Al-12wt%Si and Al-20wt%Sn Alloys submitted to Ball-on-Flat Microabrasive Wear Test Under Dry Sliding Conditions.

Kleber Agustin Sabat da Cruz

Engineering and Geosciences Institute - Federal University of the Western Pará – Vera Paz st., P.O box: 68040-255

kleber.cruz@ufopa.edu.br

Abstract. *The wear behavior of light alloys can be evaluated by parameters such as wear volume (V) or wear rate (Q). According to previous studies, the wear rate is dependent of the applied load during the test used to analyze the wear resistance. In other research, experimental laws correlating dendrite arm spacings and wear volume were obtained for Al-Sn, Al-Bi, Al-Sn-Si alloys similar to the Hall-Petch relation for mechanical properties. This study seeks the experimental analysis with the objective to research the relationship between wear rate (Q) and the test time (t) during the ball-on-flat microabrasive wear test, for samples made of pure aluminum, pure tin and the alloys Al-12wt%Si and Al-20wt%Sn. These materials were chosen due to their wide tribological applications, particularly as bearing materials. The tests were performed for five different test times (2, 5, 15, 20 and 40 min) under dry sliding conditions, with a hard spherical ball made of bearing steel (AISI 52100) used as a counter-body. The experimental data were processed by the linear regression, and the experimental laws to describe the evolution of the wear rate (Q) as a function of the test time (t) were obtained by the polynomial regression analysis with least squares method to verify the quality of fitting (R-squared). The results presented that the alloys were more wear resistant than the pure elements (Sn and Al), and the characterization of the wear crater produced in the wear test were performed by optical microscopy. The diameter of each crater was measured five times and the average value and standard deviation were calculated to obtain accuracy. The wear rate (Q) was calculated by the equation based on the geometry of the crater, and tended to increase with the test time, which agrees with Archard's law because the test time is proportional to the sliding distance, and the wear rate is proportional to the wear volume. The worn surface was characterized by electron microscopy to analyze the wear mechanism that acted during the test*

Keywords: *Tribology, wear, light alloys, Aluminum.*

1. INTRODUCTION

The mechanical and tribological properties of metallic alloys used in journal bearings are affected by the microstructure of the part, which constitutes mechanical systems. Experimental laws, which describe the correlation between dendrite arm spacings (λ_1 and λ_2), mechanical and wear resistances, have been obtained to predict the mechanical behavior of alloys used for tribological applications (Cruz et al, 2008), similar to the well-known Hall-Petch's law, which presents the tensile strength as a function of grain size (Petch,1953).

The interdendritic phase plays an important role in the mechanical wear resistance of aluminum alloys (binary or ternary). For Al-Sn, the phase in the interdendritic spacing act as a solid lubricant, which increases the wear resistance (Cruz *et al*, 2010). The lubricant action was also observed in Al-Sn alloys modified with Si and Cu (Bertelli *et al*, 2017). The change in the microstructure caused by the precipitation hardening also affects the wear resistance of Al-Si alloys during the heat treatment of artificial ageing (Shah *et al*, 2007 and Tripathy *et al*, 2007).

Corrosion resistance, high specific strength and stiffness, and high conductivity are some of the desired mechanical properties that make aluminum and its alloys promising materials in weight-critical aerospace and automotive applications. Due to superior mechanical properties and commercial aspects, they have been extensively investigated for their potential use in tribological applications. Moderate wear rate, less friction, limited material removal, and less temperature raise during sliding contacts are some of the requirements in such applications. However, a high wear rate and friction, tendency to seize, and extensive plastic deformation are some limitations in the tribological performance of aluminum alloys (Hasan *et al*, 2021).

Similar to the study carried out by Cruz *et al* (2010) for Al-Sn alloys, the tribological performances of aluminum alloys while retaining their desired mechanical properties, were studied by the incorporation of graphite particles as solid lubricants into the aluminum matrix for manufacturing aluminum matrix metal composites (MMC) (Deaquino-Lara *et al*, 2015). In the literature, there are many studies about the performance of the tribological system formed by aluminum-based alloys and steels, Zhang *et al* (2021) studied the torsional fretting properties of the 7075 aluminum alloys against 42CrMo4 steels. The friction torques, wear volumes and wear mechanisms at different lubrication conditions were comparatively analyzed. In another study, biomimetics 6082 aluminum alloys was tested by using a 37Mn5 casing steel

as a counter-body. This study simulates the morphology of non-flat surface similar to a tidal shell produced by laser surface remelting bionics to verify the wear resistance performance of 6082 alloy (Zhao *et al*, 2022).

The Tribological behavior of Al-Cu-Mg alloy was analyzed by the Pin-On-Disc test. The disc was made of hardened steel (EN-310) and the rotation of the disc was monitored by a reduction gearbox (Seikh *et al*, 2021). Hardness and wear resistance was studied. Aluminum alloys submitted to friction stir welding process were studied through pin-on-disc test by Umasankar *et al*. (2020). The tribological couple was formed by aluminum alloy samples and the rotating disc made of 62 EN32 steel, showing important results about the wear resistance of Al-Mg-Si alloys.

2. EXPERIMENTAL DETAILS

2.1 Preparation of the samples

Initially, the casting parts (Al, Sn, Al-12wt%Si and Al-20wt%Sn) were produced by directional solidification experiments performed in an experimental apparatus that promoted the vertical and upwards directional solidification with a water-cooled system at the bottom of the casting chill. This apparatus is a furnace with electric resistances used as heaters (Cruz, 2008). The temperature was monitored by thermocouples and data-logger. After the obtention of the ingots, they were sectioned in the midplane, and the cross-section samples were cut and machined according to the methodology presented in Figure 2.1.
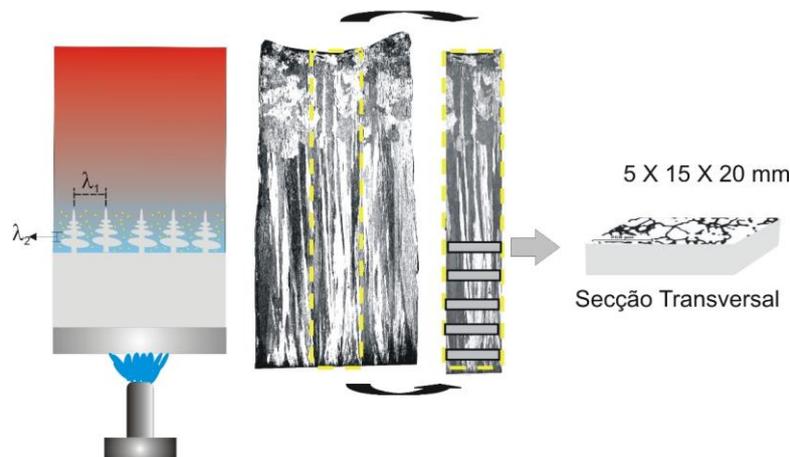

Figure 2.1- Sketch of the sequence of the preparation of the samples for the wear tests.

It was produced three samples for each material studied. The samples were ground and polished with 400, 600, and 1200 grit abrasive paper, and cleaned ultrasonically in acetone and ethanol for 15min. The face characterized was perpendicular to the direction of the heat extraction to visualize the as-cast solidification microstructures of the two alloys Al-12wt%Si and Al-20wt%Sn. The characterization was performed both optical and scanning electron microscopes

2.2 The wear resistance evaluation

The tribological performance was verified by the ball cratering (ball-on-flat) microabrasive wear test (**surface engineering laboratory EESC-USP**). This test was carried out by a rotating ball placed into contact with flat sample. This test can be performed under dry or lubricated conditions. In this study the tests were performed under dry sliding conditions but drops of water were dropped in the sample-conterbody interface with the aim of preventing the local heating and remelting (Cruz,2008).
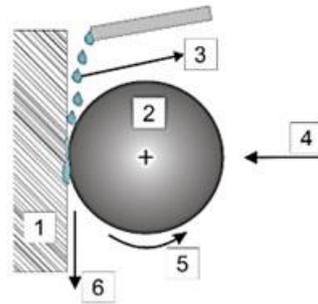
Figure 2.2 – Schematic Representation of the type of wear test developed in this study: (1) Sample;(2) sphere
(counter-body); (3) Abrasive Solution; (4) Normal Force; (5) rotation of the sphere

After the test, the rotating ball printed a crater on the surface of the sample. The diameter of the crater was measured and by the equation 01 the wear volume is calculated, and then, by the equation 02, the wear rate was calculated (Pinto, 2004, Colaço,2001).
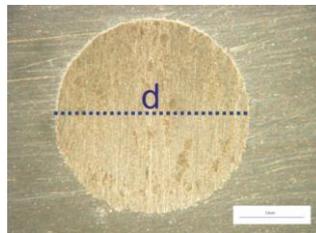

Figure 2.3 – Crater printed by the ball cratering microabrasive wear test

The measurement of the diameter was performed five times to obtain the statistic parameters (average and standard deviation), and then the least squares method was used to obtain the best data fitting to derive experimental laws for the relationship between the wear rate (Q) as a function of the test time (t). The measurements of the diameters of the printed craters (Figure 2.3) were carried out by using optical microscopy (**surface engineering laboratory EESC-USP).** The sphere used in the test was made of 52100 steel with hardness equal to 850 HV. The normal load used was 0.6N, the rotation was 260 RPM. The sliding distances were 41, 103, 311, 414 and 829 m, and the time tests were equal to 2, 5, 15, 20 and 40 min.

$$V = \frac{\pi d^4}{64R} \qquad\qquad (1)$$

$$Q = \frac{V}{L} \qquad\qquad (2)$$

$$L = 2.\pi.rot.t \qquad\qquad (3)$$

Where: R- Radius of the sphere
Q – wear rate
d – diameter of the crater printed over the initially flat sample
L -sliding distance
V – wear volume
F_N – Normal Load of the test
t – test time
rot – rotation

2.3 The Data Fitting Procedure

The experimental data were treated by least squares method to get the experimental laws obtaining the relationship between the wear rate and the test time. The least squares method is the more efficient mathematical tool for data fitting especially for exponential, potential or polynomial functions that are able to be converted in linear form by means of logarithmic transformation (Palm, 2013). The criteria of least squares used in this study is based on the calculation of the sum of the squares of the residuals (J).

$$J = \sum_{i=1}^{m}[f(x_i) - y_i]^2 \tag{4}$$

The J parameter was used to compare the fitting quality for different mathematical functions used to describe the same data set. The parameter S was calculated by equation 05 that is the sum of the square of the difference between the average value of the wear rate and the experimental data.

$$S = \sum_{i=1}^{m}[y_i - \bar{y}]^2 \tag{5}$$

The equation 05 is used to calculate the main parameter to indicate the fitting quality that is the R-squared value (R^2).

$$R^2 = 1 - \frac{J}{S} \tag{6}$$

The J/S ratio is the evaluation of the data set that are neglected by the model. Therefore, the fitting quality is going to be more efficient if the R^2 is near 1.

3. RESULTS AND DISCUSSIONS

3.1 Characterization of the Wear Crater

Figure 3.1 presents the optical micrographs of the wear craters obtained by the ball-on-flat micro-abrasive wear test under dry sliding conditions, for test time equal to 15 minutes, with a rotating ball of steel 52100 (25.4mm diameter) (Oliveira *et al*,2006). The craters for pure Al and Sn were bigger (longer diameters) than the craters printed on the samples of Al-12wt%Si and Al-20wt%Sn. The micrographs indicates that the effect of the alloy elements must have caused an important role during the friction process, making the wear resistance increase, therefore the alloys presented a higher wear resistance. These results are in agreements with other studies in the literature (Cruz,2010 and Bertelli,2017).
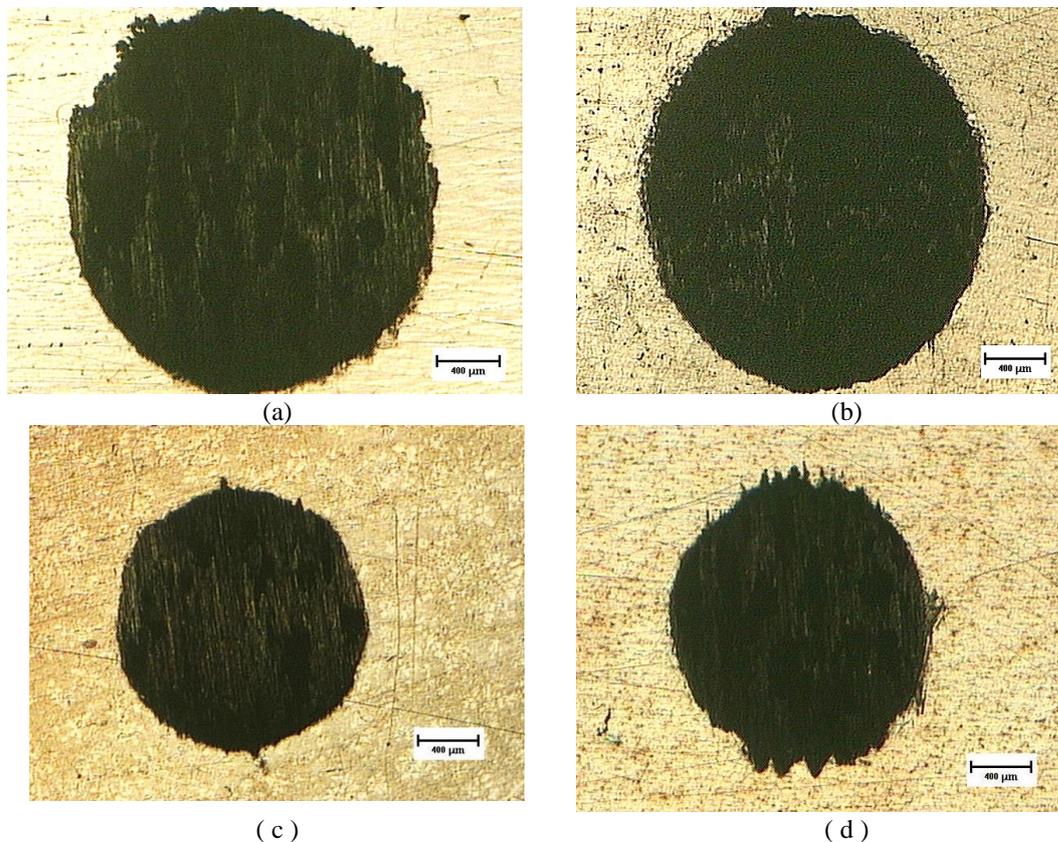

(a)

(b)

(c)

(d)

Figure 3.1 – Wear Crater obtained from the wear test for the test time equal to 15 min, (a) pure aluminum [Al];(b) pure tin [Sn], (c)Al-12wt%Si, (d)Al-20wt%Sn

3.2 Data Fitting Results

In the chart presented in the Figure 3.4, it is seen that the alloys presented a better wear resistance than the wear behavior of the pure elements. The alloy elements (Sn and Si) gave a better tribological resistance to the aluminum, making the wear rate (Q) lower. According to the as-cast microstructures resulted from the directional solidification experiments, the Al-Si alloy revealed a dendritic microstructure and in the interdendritic phase, needle-like particles of Si were randomly distributed, playing an important role in the improving of the wear resistance.
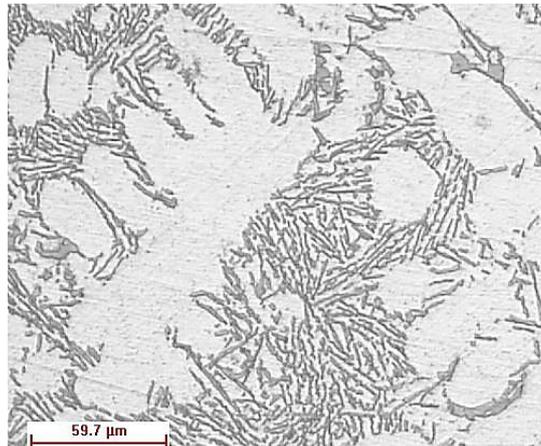

Figure 3.2 – Optical Micrograph for Al-12wt%Si presenting the hard needle-like particles in the interdendritic region.

Regarding the Al-20wt%Sn alloy, the as-cast microstructure is also dendritic, and the immiscibility of the Al-Sn system makes the most part of the Sn be rejected to the interdendritic region. The better wear behavior for Al-20wt%Sn must be due to the lubricant effect presented by the Sn-rich phase that is in the interdendritic regions. The Sn-rich phase works as a solid lubricant leading to the increase of the wear resistance. In the figure 3.3 is presented the electron micrography of the Al-20wt%Sn alloy with the color mapping to highlight the Sn segregation to interdendritic area and the Al-rich matrix.
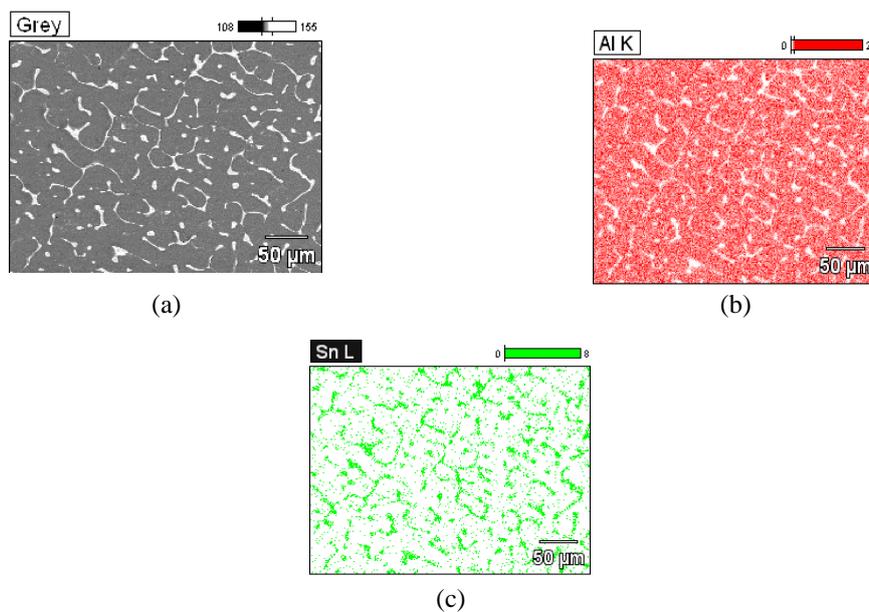

(a)

(b)

(c)

Figure 3.3 – SEM presenting: (a) Al-20wt%Sn dendritic microstructure; (b) color mapping showing Al-rich dendritic matrix (reddish); (c) color mapping showing Sn-rich interdendritic regions (greenish).

The table 01 presents the coefficients calculated for the experimental laws for the best fitting for wear rate (Q) as a function of the test time (t). The type of regression analysis performed was the polynomial regression with the least squares method

Table 01 – Coefficients obtained for the linear fitting for each material analyzed

Coefficients - $y = m.x_1 + b$		
	m	b
Al	0,0000086	0,0002300
Sn	0,0000220	0,0001200
Al-12wt%Si	0,0000022	0,0000867
Al20wt%Sn	0,0000021	0,0001330

Figure 3.4 presents the graph that reveals the linear fitting applied to the experimental dataset obtained by the polynomial regression method generating Q=f(t) experimental laws. The wear behavior of the pure aluminum and pure tin is compared with two aluminum alloys: Al-12wt%Si and Al-20wt%Sn. In all cases, the wear rate (Q) increases with the increasing of the test time (t). When it comes to the effect of the material on the wear resistance, the alloys presented a better tribological performance compared to pure elements. Therefore, the alloys were more wear resistant than the pure tin and aluminum. The slope of the linear fitting for the alloys is smaller, revealing that, the sensitivity of the wear resistance of the materials to the test time is smaller for the alloys compared to the pure elements (Al and Sn).
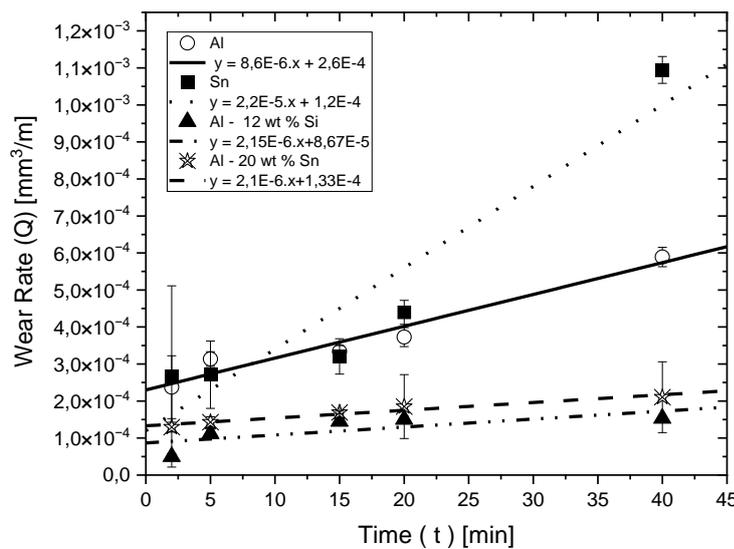

Figure 3.4 – The data fitting presenting the experimental laws relating the wear rate (Q) as a function of the test time (t) obtained by means of the polynomial regression with the least squares method applied on the experimental dataset.

4. CONCLUSIONS

In this study, the experimental analysis of the tribological behavior of two aluminum alloys (Al-12wt%Si and Al-20wt%Sn), which are widely used as bearing materials considering the test time of the ball-on-flat microabrasive wear test were undertaken. According to the results obtained, it was concluded:

1- The wear resistance increased for the alloys when they were compared to the pure elements (Sn and Al). The best performance was for Al-12wt%Si due to the Si-rich needle-like particles found in the interdendritic regions of its as-cast microstructure.
2- The polynomial regression with the least squares method from the first degree to the fourth-degree polynomial regression was the method used to calculate the experimental laws that describe the evolution of the wear rate (Q) as a function of the test time (t).

3- The sensitivity of the wear resistance of the materials to the test time is smaller for the alloys compared to the pure elements (Al and Sn).

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