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EVALUATION OF THE WEAR MECHANISMS OF THE CONTACT TIP IN FLUX CORED ARC WELDING PROCESS THROUGH A PIN-ON-DISC TEST

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Abstract. *In welding processes in which the wire is fed continuously, electrical current is transferred from the welding source to the wire electrode through a contact tip, commercially made of copper alloys. The contact tip also has the function of guiding the wire to the molten pool. During the process, the contact tip wears out rapidly, in extreme cases it must be replaced within hours. The present work aims to investigate the wear mechanisms shortening the contact tip's life. Experiments were carried out using a pin-on-disc type tribometer. The pins were made of low carbon steel and the disc made of electrolytic copper. It was noted a relation between friction coefficient and test parameters. Higher sliding velocities and higher normal loads result in higher friction coefficient. It was observed continuous rising in friction coefficient due to adhesion between the two metals. Optical microscopy techniques and scanning electron microscopy were employed to analyze the wear tracks. It was shown adhered particles in both pin and disc surfaces.*

Keywords: *Wear mechanisms; Contact tip; Copper – steel sliding.*

1. INTRODUCTION

Welding processes which employ continuously fed wire/electrode make possible higher deposition rates compared to other process, once the welding arc can be established for longer periods with no interruptions. During the process, wire is fed continuously to the welding torch by an automatic wire feeder. Among these processes, the most used in industry are GMAW, FCAW, SAW and TIG welding (Villani et.al.; 2011).

Electrical current is transferred to the welding wire through a sliding electrical contact, called contact tip, which is assembled at the end of the welding torch. The contact tip has a cylindrical body, 20 to 45mm length, outer diameter of about 12mm and a center hole which the wire passes through. The center hole diameter is 200 μ m bigger than the wire diameter, in order to promote good electrical contact as the wire passes through (Shimizu et.al.; 2006). The contact tip also has the function of guiding the electrode to the molten pool. Due to electrical properties and fabrication costs, the contact tip is commercially made of Copper alloys (Dietrick and Prayner, 1984).

As the welding process takes place, it is required to the contact tip to operate under severe conditions, wearing out rapidly. Due to the proximity to the welding arc, the tip is subject to high temperatures. Oxidation, gases generated in the process and condensation of metallic vapor can cause deposition in its surface (Manning and Hampton, 1985). The higher wire feed speeds can accelerate the wear process. As the copper is a relatively ductile metal, it is subject to accelerated abrasive wear, enlarging the center hole. Consequently, the current transfer is impaired, reducing the process stability. The wire, also, is deviated from its ideal position in the base metal (Hidaka and Tsuki-Gun, 2000; Walters, 2008; Yoshinaka et.al., 2008).

The real contact between the wire and the contact tip happens in a few points. Due to its storage in coils, the wire has a radius of curvature that expands as a result of the elastic deformation caused when the wire passes through the contact tip. At the end of the tip, the wire tends to return to its initial coil condition, causing the contact tip to wear in this region (Shimizu et.al.; 2006), as shown in Fig. 1. As the wire is fed, the effective contact occurs at the peaks of asperities. The real contact area is the sum of the individual contact area of each asperity. Due to deformation of the material, the contact area is directly proportional to the normal load (Hutchings, 1992). This causes the contact tip to wear at the end of the sliding length.

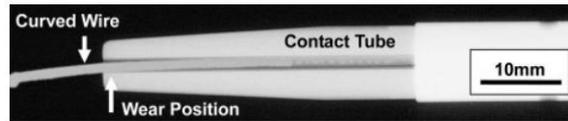


Figure 1: Curved wire inside the contact tip.
 Source: Shimizu et. Al., 2006.

The solid wires continuously fed in semi-automatic welding process are coated with a thin Copper layer. This layer is deposited through immersion and has the function of protecting the wire metal from oxidation and improving the electrical contact between the wire and the contact tip (Bothma et.al., 2011). In the welding process with tubular wire, the electrode consists of a bended low carbon strip with the flux deposited inside. The electrode is not coated, since that the molten Copper would penetrate inside the wire. Due to its condition, the welding current is transferred from the Copper alloy surface of the contact tip to the steel surface of the tubular wire.

The present work aims to investigate the wear mechanisms of the contact tip due to the sliding against the tubular wire during the welding process. The tests were conducted in a pin-on-disc type tribometer.

2. MATERIALS AND METHODS

The experiments were conducted according to specifications of ASTM G99-05 – Standard Test Method of Wear Testing with a Pin-on-Disc Apparatus. The pin is kept steady and is pressed against the disc fixed on a turntable. A constant force is applied to the pin by means of weights fixed along its longitudinal axe. The experimental configuration is shown in Fig. 2 (a). The initial contact between the pin and disc is shown in Fig. 2 (b). Due to the radius at the tip of the pin, the initial contact occurs in a small concentrated area. Figure 2 (c) shows the tribometer used in the experiments.

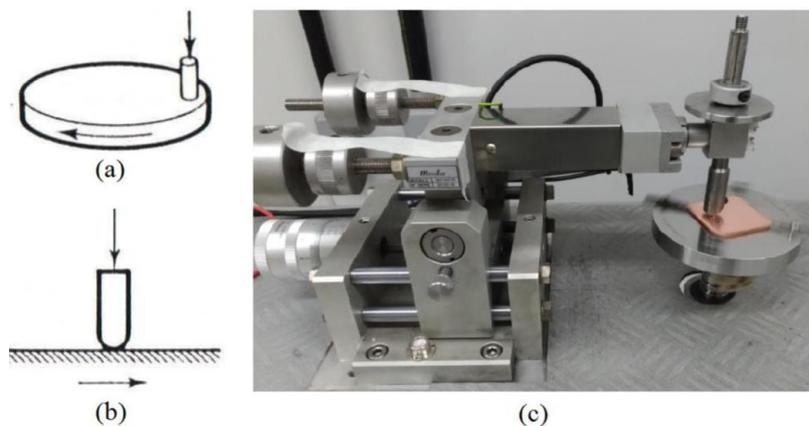


Figure 2: (a) geometric configuration of the tribometer; (b) initial geometry of contact; (c) tribometer used in experiments.

The pin was fabricated in a low carbon steel ABNT 1020. The disc was fabricated in Copper alloy C110, commercially known as pure Copper. The mechanical properties and dimensions of the samples are shown in Table 1.

Table 1: Samples dimensions and mechanical properties.

Pin – ABTN 1020 Steel						
Length	Diameter	Contact Radius	Surface Finish	Microhardness HV	Yield Point	Tensile Strength
15mm	6mm	3mm	Polished	162	350MPa	420MPa
Disc – Copper Allow C110						
Thickness	Surface Roughness	Microhardness HV	Yield Point	Tensile Strength	Specific Mass	
3,17mm	0,08Ra	116	55MPa	220MPa	8,89g/cm ³	

The parameters used in the experimental procedure were set with the objective of reproducing the real sliding conditions that occur between the electrode and the contact tip in welding processes. The parameters are shown in Table 2. Experiments were carried out at three different sliding speeds, within the values used in real FCAW and GMAW welding conditions, as reported by Manning & Hampton, 1985.

Table 2: Experimental Parameters

Test Number	Normal Load [N]	Sliding Speed [m/min]	Sliding Radius [mm]	Revolutions per minute
1	1	5	10	79,62
2	1	5	12	66,35
3	1	20	14	227,48
4	1	12,5	16	124,40
5	2	20	8	398,09

In real welding conditions, the load applied on contact tip internal surface is a result of elastic deformation of the wire as it passes through the contact tip hole. Loads of 1 and 2N were selected as an attempt of reproducing the real loads. Due to the short experimentation time of each run and the small amount of wear noticed in the disc surface, all runs were carried out on a disc sample, setting different sliding radius to each run.

The disc wear rate was estimated through Eq. 1, as a function of the sliding diameter (D), the area of removed material (A) identified by perfilometry, the Copper alloy specific mass (ρ_{Cu}) and the total sliding time (t).

$$Wear\ rate = \frac{\pi * D * A * \rho_{Cu}}{t} \quad (1)$$

All runs were set to a maximum sliding time of 5 minutes and were conducted at open air. All samples were clean with acetone. Images of the produced tracks at disc surface were obtained with optical through microscopy and scanning electron microscopy.

3. RESULTS AND DISCUSSION

During the tests, all runs were interrupted before reaching the total time due to the high value of friction coefficient. The tribometer used in experimentation is set to stop a test whenever the measured friction coefficient is equal or higher than 3. Figure 3 shows the friction coefficient as a function of sliding distance for all five conducted tests. The values were treated with filter 40, in order to show the mean values with no interference of peaks and valleys generated during real time measurement.

Tests 1 and 2 were conducted at the same load and sliding speed. It is shown a linear increase of the friction coefficient. This initial behavior can be related to oxide layers removal and the transition of friction static dynamic. It can also be seen that the total distance of test 2 was longer than test 1. This can be explained by the intensity of deformation generated at the copper surface at each revolution. The larger sliding radius of test 2 required smaller rotation to keep the same velocity, consequently the pin passed on the same surface point in smaller frequency and longer time was necessary to promote the same amount of plastic deformation in the more ductile material, in this case, the Copper alloy.

It can be seen, in all runs, a continuous increase in friction coefficient until a maximum value. This behavior is related to wear mechanisms that occur at the experiments. Metallic surfaces, under dry sliding condition, are susceptible to adhesion and abrasion wear. Others wear mechanisms can happen, however, with smaller effect. As the pin slides through the disc surface, the initial mechanisms involve adhesion, hardening and fracture. Also, the loose debris lead to abrasion wear (Wibberley and Eyre, 1969; Rigney, 1988).

Tests 3 and 5 were conducted at sliding speed of 20m/min. Figure 3 (c) and (e) shows that friction coefficient for these runs were higher than those for the remaining runs, reaching values higher than 0,6. This observation indicates that friction coefficient increases at higher sliding speeds. More heat is generated in the contact of peaks of the rough surfaces and creates condition to higher adhesive forces act in the contact, due to micro welds, causing plastic deformation and hardening of the material, as observed by Chowdhury et.al., (2014), resulting in higher friction coefficient.

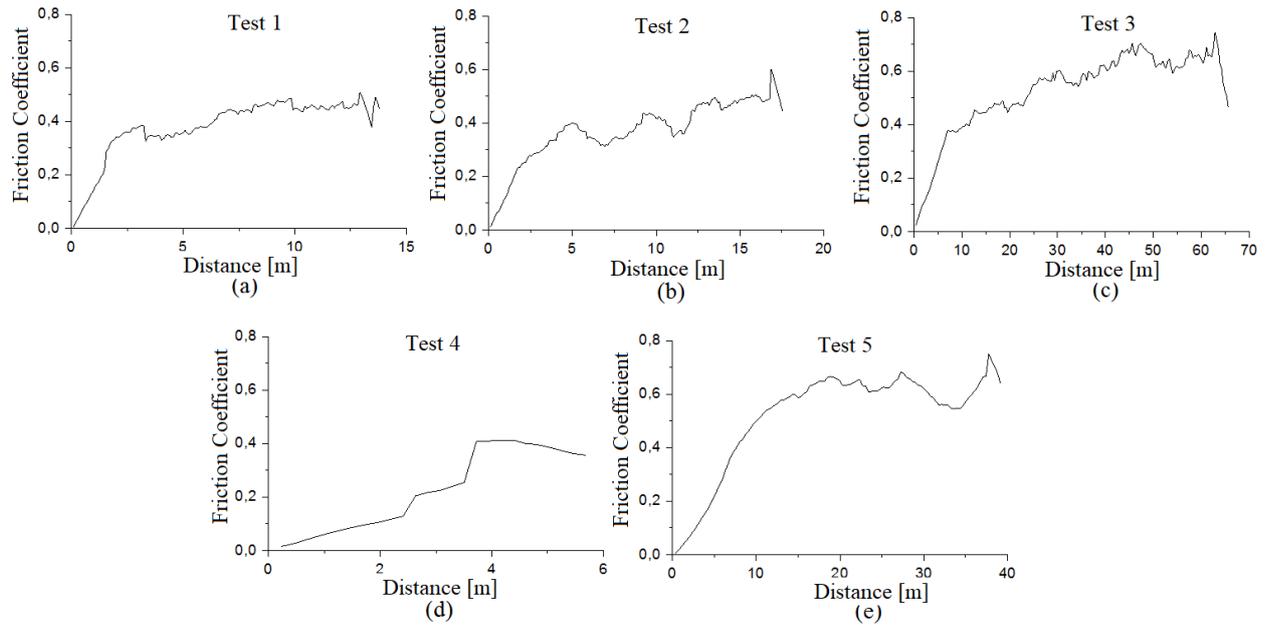


Figure 3: Friction Coefficient versus Sliding Distance for runs (a) 1, (b) 2, (c) 3, (d) 4 e (e) 5.

Figure 4 shows the tracks produced at the disc and pins surfaces during the experiments. The images were obtained by optical microscopy. Lines of plastic deformation formed parallel to the sliding direction. In Fig. 4 (a), it is possible to observe lighter particles, coming probably from the pin material, present at the disc surface, as indicated by the yellow arrows. As Copper is the more ductile material, the debris penetrated in its surface leaving tracks produced by plastic deformation, once they act as abrasive particles in the softer material. Small cracks are present perpendicular to sliding direction, as a result of localized rupture on the surface due to localized tension. Figure 4 (b) shows material coming from disc surface adhered at the pin surface.

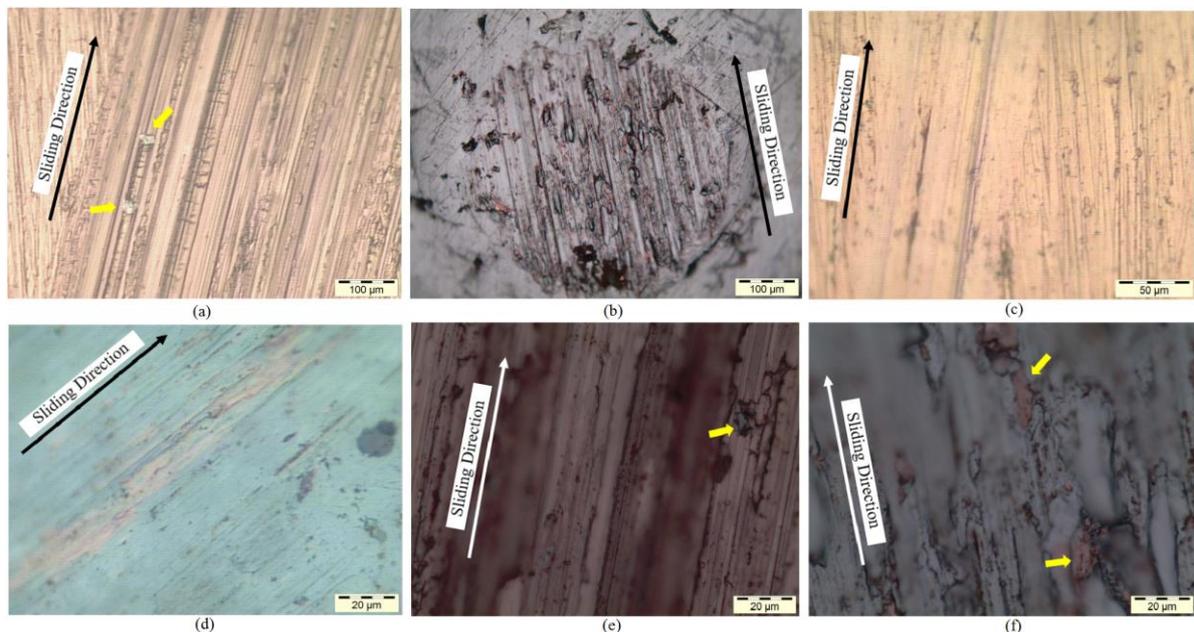


Figure 4: Tracks produced at samples surfaces: (a) disc – Test 5 – amplification 200x; (b) pin – Test 5 – amplification 200x; (c) disc – Test 4 – amplification 500x; (d) pin – Test 4 – amplification 1000x; (e) disc – Test 5 – amplification 1000x; (f) pin – Test 5 – amplification 1000x.

The presence of steel particles on disc surface, and Copper particles on the pin surface indicates that adhesion wear occur during sliding. Due to the ductility of the materials used, plastic deformation takes places on wear mechanisms. According to Hutchings (1992), adhesion occurs on the contact between asperities, leading to small mass transfer to the

opposite surface. As the surfaces slide against each other, more debris are set loose, as shown in Fig. 4 (b). When a larger particle constituted of hardened material detaches, it acts as an abrasive particle. As shown in Fig. 4 (a), the steel debris causes abrasive wear at Copper surface, as a result of mechanical resistance.

Material transfer due to adhesion occurs at the beginning of sliding process. As reported by Heilmann (1983), at the initial contact between asperities, small amounts of material are transferred to the opposite surface. Test 4 was the one with the smallest sliding distance, 5,7 meters, as shown in Fig. 3 (d). Tracks produced on pin and disc surfaces in test 4 are shown in Fig. 4 (c) e (d), respectively. At the disc surface, it is possible to observe an initial plastic deformation with no visible steel particles. In Fig. 4 (d), it can be noted the presence of material from the disc adhered at the pin surface. Adhesion occurred in a small sliding distance due to the higher ductility of the Copper alloy. In sliding combinations such as Copper against low Carbon steel, it is rapidly seen adhered particles in the opposite surface. These initial adhered particles continue the material transfer due to cooperative effect (Rabinowicz, 1995).

Figure 4 (e) and (f) show the tracks produced at test 5, magnified 1000 times through optical microscopy focused on asperities peaks. As observed in all produced tracks, there is possible to note adhered particles in both surfaces of pin and disc. The tracks irregular shape indicated severe wear behavior, as described by Rabinowicz (1995).

The track produced at the disc surface in test 5 is shown in Fig. 5 (a), magnified 1300 times. At the top right it can be seen cavities originated due the removal of material adhered at the pin surface. At the bottom of Fig. 5 (a), a relatively large particle is adhered at the disc surface. Figure 5 (b) and (c) show the compositional map of the area shown in Fig 5 (a), to the elements Fe and Cu, respectively. The particle adhered at the bottom shows high quantity of Fe (b) and is shown as area with small concentration of Copper (c), indicating that the particle was removed from the pin during sliding, proving the adhesion of Fe, in this case, low Carbon steel, on Copper surface.

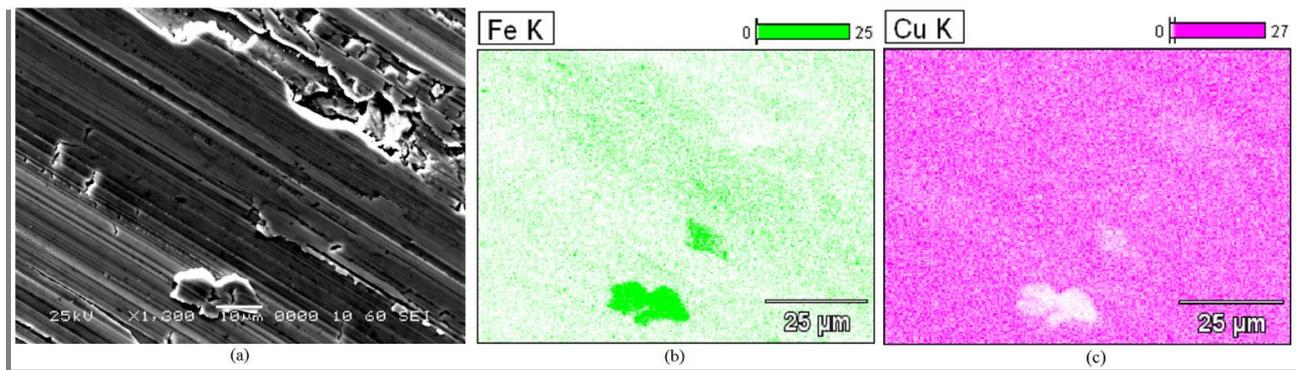


Figure 5: (a) Track produced on disc surface – Test 5 – Magnified 1300x by SEM; (b) Compositional map - Fe; (c) Compositional map – Cu.

The particle identified in Fig. 5 is shown in Fig. 6 (a) magnified 3000 times. It is possible to observe that the particle adhered on disc surface and participated on the sliding system, as indicated by the tracks produced on its surface parallel to sliding direction. Figure 6 (b) shows point A spectrogram, produced by EDS. The higher amount of Fe proves that the particle is originated from the pin steel. The presence of Copper on its surface indicates the adhesion of particles previously removed that adhered to the opposite surface during sliding. Figure 6 (c) shows the spectrogram of point B, produced by EDS. The amount of Fe adhered to the disc surface is much smaller.

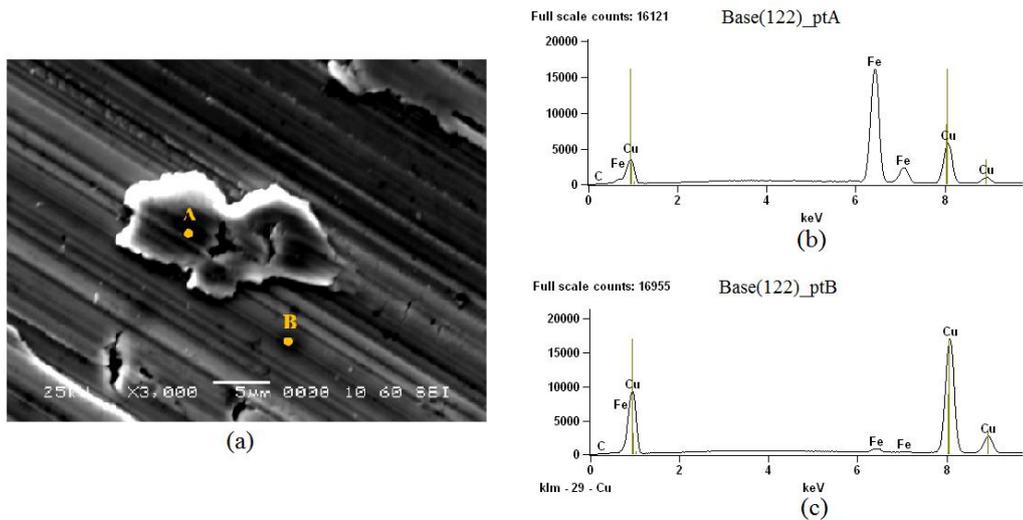


Figure 6: (a) Steel particle adhered to disc surface – Test 5 – magnified 3000 times – SEM; (b) Point A spectrogram produced by EDS; (c) Point B spectrogram produced by EDS.

The track produced on pin surface during Test 5 is shown in Fig. 7 (a), magnified 2000 times. The flat area formed due to pure sliding. Figure 7 (b) and (c) show compositional maps from Fig. 7 (a) to elements Fe and Cu, respectively. It can be observed areas formed by particles of Copper adhered on pin surface. The spectrograms shown in Fig. 7 (d) and (e), related to points A and B, respectively, indicate that surfaces subjected to pure sliding show no adhered particles. Point B spectrogram show Copper atoms adhered on steel. Due to its ductility, both materials, low Carbon steel and Copper alloy, are subjected to adhesive wear.

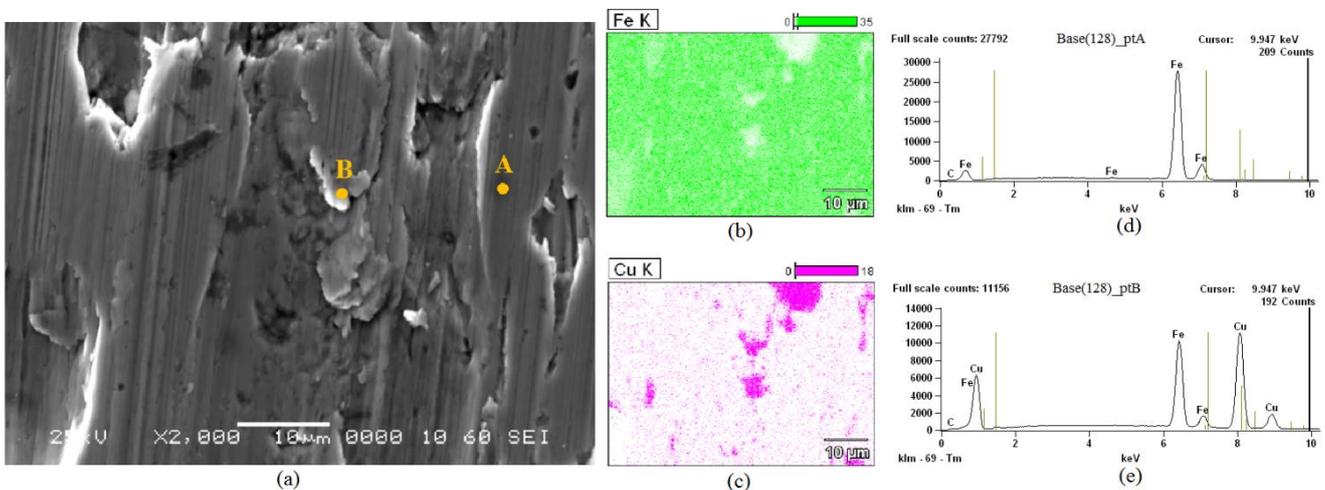


Figure 7: (a) Track produced on pin surface – Test 5 – magnified 2000x; (b) Compositional map – Fe; (c) Compositional map – Cu; (d) Point A spectrogram produced by EDS; (e) Point B spectrogram produced by EDS.

For all the tests, the disc wear rate was estimated through profilometry. Figure 8 shows the cross section of the tracks produced in Tests 1 (a) and 5 (b). The green areas above the Copper surface indicates plastically deformed material, due to the high ductility of the Copper alloy. The red areas indicate the removed material during sliding. The total removed area was calculated by the difference between the green and red areas.

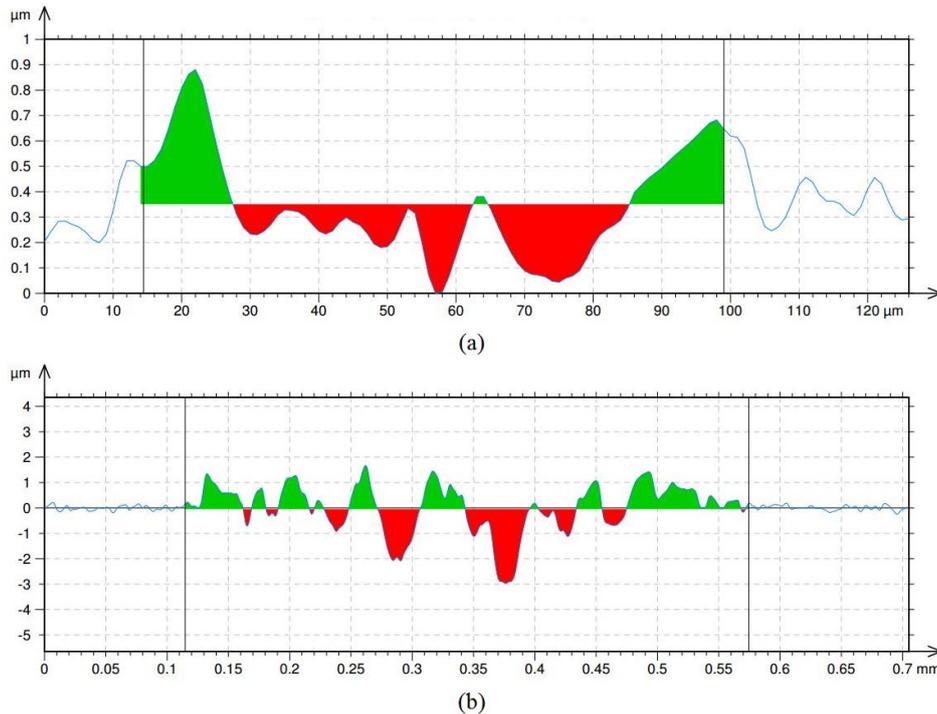


Figure 8: Tracks cross-sectional areas – Tests 1 (a) and 5 (b).

Wear rate for experiments 1 and 5, calculated through Eq. 1, was 0,36 and 0,68g/min, respectively. As indicated in Tab. 2, from experiment 1 to 5 was changed the sliding speed and the applied load. Increasing the sliding speed resulted in increase in wear rate. This can be explained by the increase on the local temperature in a few contact points, leading to reduction on hardness. As reported by AsadiKouhanjani et. al. (2009), the localized reduction in hardness leads to higher wear rate, according to Archard Equation.

The normal load was set to different levels in tests 1 and 5. The wear rate was higher in the tests carried out applying heavier loads. Increasing the normal load resulted in larger contact area between pin and disc as the pin is pressed against the disc surface. As reported by Chowdhury et. al. (2014) and AsadiKouhanjani et. al. (2009), higher loads increase the tangential force between sliding surfaces, accelerating abrasive and adhesive wear at the contact area, producing, also, higher friction coefficient as observed in Fig. 3.

4. CONCLUSION

The experiments carried out employing a pin on disc tribometer, using low Carbon steel pins and Copper disc, under different sliding conditions, made possible to draw the following conclusions:

- The total sliding distance was higher in larger sliding diameters, even operating at the same load and speed. Due to the higher diameter, it takes longer, or more revolutions of the disc, to promote equivalent amount of plastic deformation on disc surface.
- The metallic combination of low Carbon steel (ABNT 1020) and Copper 101 is subjected to adhesive and abrasive wear. Due to the high ductility of Copper, particles removed from the disc surface adhered to the pin at the beginning of the testes, leading to material transfer, increasing continuously the friction coefficient until the maximum value of 3. At this moment, sliding was happening under severe shear of Copper adhered on the pin surface.
- Friction coefficient is affected by both sliding speed and normal load. Under higher sliding speeds, the heat generated at the asperities produce higher adhesive loads on contact points, resulting in severe plastic deformation of the material. Higher loads produce larger contact areas, increasing the tangential force and accelerating abrasive and adhesive wear.
- The experiments shown the possible mechanisms acting in contact tip wear during FCAW welding process. Higher sliding speeds increase wear rate due to adhesion on contact points. Small variations on the tubular wire cross sectional area or longitudinal deformation can lead to higher load at contact points between the tubular wire and the contact tip, reducing its lifetime, once that the wear rate is accelerated by these conditions.

5. SUGGESTIONS FOR FUTURE INVESTIGATIONS

The authors suggest the following to future investigations:

- Carry the experiments using steel discs and Copper pins;
- Carry the experiments heating the sliding metals, considering that the contact tip is heated by Joule Effect in real welding processes.
- Carry the experiments forcing an electrical current on contact areas.

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8. RESPONSIBILITY NOTE

The authors are the only responsible for the printed material included in this paper.