SURFACE QUALITY BY EDM OF HARDENED AISI P20 STEEL

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Abstract. *The Electrical Discharge Machining (EDM) is a process widely used in machining of hardened materials, mainly to obtain complex geometries. However, due to its principle of material removal, in which high frequency electrical discharges cause melting and vaporization of material, the machined surface is subjected to high thermal loads. Therefore, the control over the surface quality of parts produced by the EDM process is very important. The influence of this process on the generated surface is quite characteristic, forming layers with different metallurgical properties in surface and subsurface of the part. This work presents a study of surface quality of cavities obtained by EDM process using copper and graphite electrodes. Metallographic analyses were performed to identify metallurgical changes, and also were carried out analysis of chemical composition of the surface layer. It was observed that the affected layer is affected by the depth of the machined hole.*

Keywords*: machining, electrical discharge machining, metallurgical changes.*

1. INTRODUCTION

EDM is a widely used manufacturing technology. Its unique abilities to deal with complex geometries with high-accuracy level regardless the materials hardness impelled its consistent use in the precision and micro-machining applications of several manufacturing sectors. In particular, the EDM technology has one of major application fields in the moulds and dies manufacturing sector (Peças and Henriques, 2008). Today, typical process plans for mould components (e.g. cavity shape) consist of milling operations (roughing and finishing) followed by a number of EDM operations. Typically, sinking EDM is applied for detailed feature geometries such as deep and narrow regions (Lauwers et al., 2010). In the area of precision engineering, many components for the manufacturing, telecommunications and information industries can be fabricated with high precision using EDM (Mahardika et al., 2008).

In this electro-thermal process, material is mainly removed by a series of carefully controlled discrete sparks (electrical discharges) generated between the tool electrode and work piece both of which are submerged in a dielectric. The high temperature of the discharges melts and evaporates the work piece material locally and leaves overlapped craters on the surface. Since there is no mechanical contact between the two electrodes, the process is able to machine any conductive component into accurate and complex shapes (Clijsters et al., 2010).

The material removal is dependent on several EDM parameters such as applied current, pulse duration, gap voltage, frequency of discharge, type of electrode and work material, dielectric flushing condition, etc. (Khanra et al., 2007). In EDM, commonly cupper and graphite tools are used as electrodes. Graphite is widely used due to its good electrical and thermal properties, along with its machinability (Muttamara et al., 2009).

High thermal effects generated during the material removal by EDM induce mechanical, metallurgical and chemical modifications under the machined surfaces. These layers are characterized by high work hardening, high tensile residual stresses and wide thermal crack networks that have detrimental effects on the fatigue life of the machined components (Ghanem et al., 2010). The spattered EDM surface layer is created when expelled molten metal and small amounts of electrode material form spheres and spatter the surface of the work piece. This spattered material is easily detached. The next layer is the recast layer (white). The action of EDM has actually altered the metallurgical structure and characteristics in the recast layer. This layer is formed by the un-expelled molten metal solidifying in the crater. The molten metal is rapidly quenched by the dielectric. Micro-cracks can form in this very hard, brittle layer. If this layer is too thick or is not reduced or removed by polishing, the effects of this layer can cause premature failure of the part in some applications. The last layer is the heat-affected zone (HAZ) or annealed layer, which has only been heated, not melted. The depth of the recast layer and the heat-affected zone is determined by the heat sinking ability of the material and the power used for the cut (Kumar et al., 2009).

The recast layer increases surface roughness, makes the surface become hard and brittle, and decreases the fatigue strength due to the presence of micro-cracks and micro-voids. The composition of dielectric has an important influence on the characteristics of the recast layer since the discharge gap is partially filled by the dielectric during the EDM process which is also a chemical process (Zhang et al., 2010). The cracking behavior of the machined surface is determined by the amount of thermal energy created and the conductivity of the work piece. Cracks formed due to thermal stresses in a single discharge tend to follow the pitting arrangements created in the surface by EDM. They normally form closed loops, instead of crossing the material's surface (Ekmekci et al., 2005).

As pointed by the literature, EDM is a complex process and the machined surface can present characteristics which are detrimental to the performance of the work piece service. Therefore, it is very important the understanding and the control over the surface changes in electrical discharge machined parts. This work presents a study of surface quality of cavities obtained by EDM process using copper and graphite electrodes in order to identify metallurgical, mechanical and chemical changes under the surface layers, phase transformation, hardening of the layers and diffused material electrode material, respectively.

2. METHODOLOGY

The experiments were carried out on an Engemaq machine, EDM 440 NC model, and the dielectric fluid was the Microcorte 102-A, produced by Micro Química Ltda. The machined material was an AISI P20 steel with hardness between 36 and 38 HR_c, and dimensions of 70 x 60 mm. The tools were made in copper and graphite electrodes, used in the machining of square cavities with dimensions of 10 x 10 mm, and depths of 3 and 9 mm. Initially, a roughing operation was performed on all cavities, leaving an excess metal layer of 0.3 mm, because preliminary tests showed an affected layer by roughing of approximately 0.1 mm. Before removing the excess metal layer of each cavity, the electrode was machined in order to minimize the influence of electrode wear on the test results. For each test condition was carried out an experiment and a replica.

It was performed roughing tests, applying the values of technological parameters showed in Tab. 1.

Table 1. Parameters used in the experiments.

Machining condition	TS	TON (µs)	DT (%)	GAP (V)
Roughing	6	300	75	4

The process occurred in cycles of 3 seconds of intermittent erosion, with a retreat of 1 mm per cycle and full retreat out of the cavity every 10 complete cycles. For the graphite electrode, due to the severe condition and poor cooling effect, erosion cycle time was reduced to 1 second, and the full retreat after 5 cycles

For metallographic analysis was used a Nikon optical microscope and microhardness measurements were performed with a Shimadzu hardness tester, HMV-2 model. The metallographic samples were etched with a Nital 2% solution, and an average value of the maximum affected layer was measured in five points. Microhardness measurements were carried out using a Vickers indenter, load of 0.025 kg and distance of 20 µm between indentations. SEM and EDS analysis were also performed, using a Shimadzu Scanning Electron Microscope, SSX-550 model. The surface integrity analysis was carried out in the bottom of the cavities.

3. RESULTS AND DISCUSSION

Due to the higher thermal severity presented by the EDM process in comparison to other conventional machining process, it is necessary to evaluate changes occurred after the machining, to better understand the material removing phenomenon during electro discharge machining. Figure 1 shows the thickness of the affected layer after machining with a copper electrode.

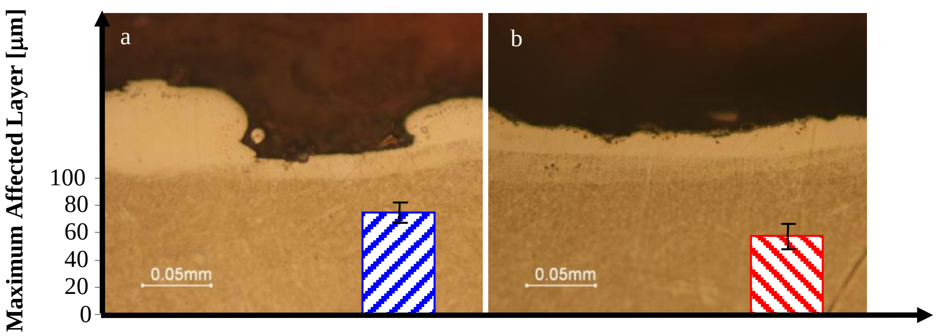

Figure 1. Affected layer and micrograph images for copper electrode: (a) depth of 3 mm; (b) depth of 9 mm.

The typical machined surface can be observed, presented by the white layer, followed by the heat affected zone, composing a heat affected layer. As can be observed, deeper machined cavity generated lesser affected layer. This behavior could be associated to the dielectric fluid flow condition into the cavity. For the 3 mm deep cavity, was observed an average of approximately 75 µm, as for the depth of 9 mm, approximately 60 µm. The deeper condition presented a more uniform white layer structure, when compared with the condition of depth 3 mm, which presented peaks of recast layer.

The presence of microcrack is, according to Wong et al. (1995), related to the white layer thickness. A thicker white layer and consequently, thicker affected layer, presents a higher concentration of microcrack as shown in Fig. 2.

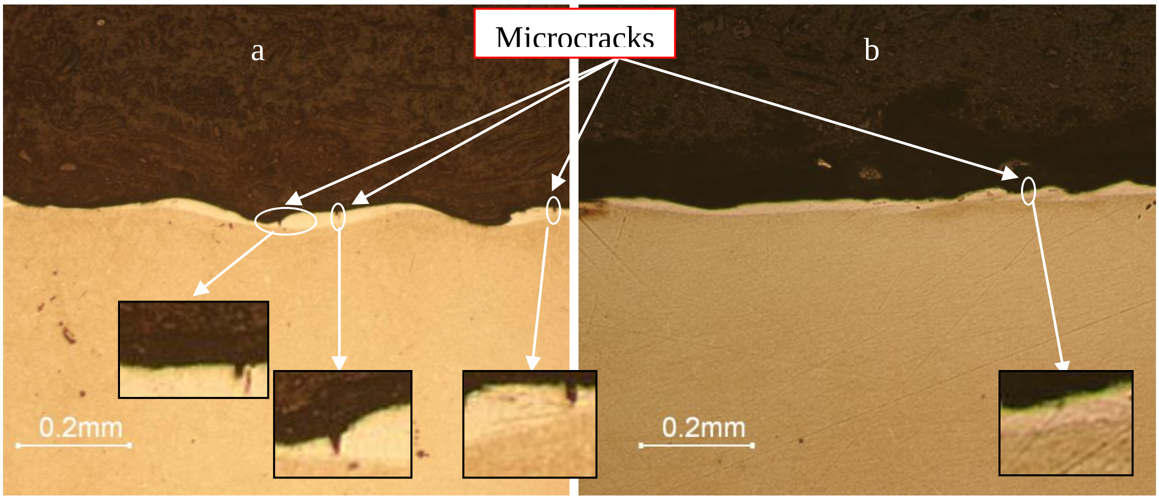

Figure 2. Metallographic image of microcracks: (a) depth of 3 mm; (b) depth of 9 mm.

As observed, in a total of 1 mm of evaluate length, it was noticed presence of 3 microcracks for the depth of 3 mm. For the depth of 9 mm, it was found only 1 microcrack, in the evaluated length of 1 mm. This result is in agreement with the hypothesis presented previously.

In order to characterize the affected layer, microhardness measurements were performed, evaluating its behavior along the machined surface, as can be seen in Fig. 3.

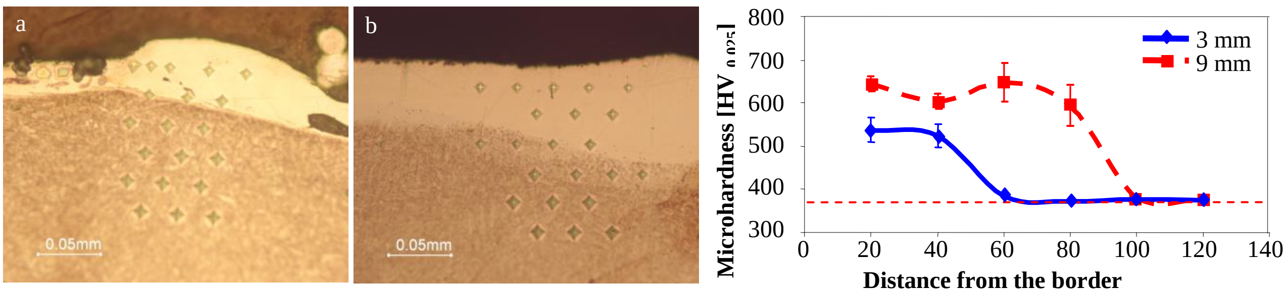

Figure 3. Microhardness behavior for the copper electrode condition: (a) depth of 3 mm; (b) depth of 9 mm.

The graph show the typical microhardness behavior found for the EDM process, where the hardness was evaluated from an initial distance of 20 µm, according to the measurements rule. As observed, the hardness presents an increase, due to the layer change, from white layer to heat affected layer, illustrated in the micrographic images. It is shown that the microhardness tends to decrease, from the affected surface to the bulk material.

One of the phenomenon which modifies the hardness on the surface, is the carbon enrichment; a physical phenomena which occur at the time of the flashing operation like the thermal distortions or the modification of volume accompanying the phases transformations. The dielectric interacts with material of the part and that of the electrode under the conditions of heat flux reigning at the time of the machining operation (Boujelbene et al., 2009).

When comparing the different depths, it is possible to notice a difference on the microhardness profile, where the depth of 9 mm machining condition generated deeper microhardness behavior (100 µm), compared to the 3 mm depth, which produced a shallow microhardness profile (60 µm). This behavior could be related to the difficult of assessment of the dielectric fluid in deeper cavities and thus, not providing the necessary cooling and cleaning, generating an increase of the molten material depth. As for lower depths, the dielectric fluid could easily assess, conceding a quicker cooling and consequently, a shallower microhardness profile.

The appearance of microcracks within the white layer, due to the relatively high fragility, is an undesirable phenomenon, which can affect the part mechanical properties, leading to a premature fail of the component. Therefore,

Fig. 4 shows SEM images of the samples were performed, aiming to verify the presence of microcracks, as well as to better characterize the different layers, generated after machining with copper electrode.

Figure 4. SEM images after machining with copper electrode: (a) depth 3 mm; (b) depth 9 mm; (c) perspective of the microcrack.

A typical microcrack can be seen, from the surface to the affected layer, within the white layer. According to Lee and Tai (2003), crack formation can be attributed to the presence of thermal stress and tensile stress in the machined component. Thermal stress is produced when the electrode discharges bombard the surface of the sample during the machining process. It is though not apparent the different regions observed through the metallographic analysis, due to the similar contrast they present.

In order to evaluate the presence of diffused copper, arising from the electrode, in the affected layers, EDS analysis was applied, as can be seen in figure Fig. 5.

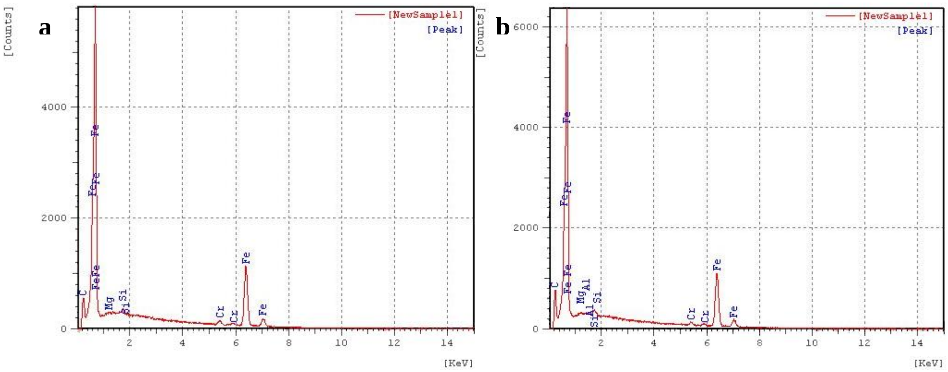

Figure 5. EDS analysis for the 9 mm depth sample: (a) white layer; (b) Heat Affected Layer.

As can be seen, the copper peak of energy, around 8 KeV, is not present on the white layer. Different results were found when machining a Fe-Mn-Al alloy using finishing parameters, where the electrode material, Cu, diffused into the machined surface (Guu, 2007).

In means to compare different materials effects on the surface integrity, experimental tests were performed with graphite tools. Figure 6 presents the affected layer values found when machining in different depths, 3 and 9 mm.

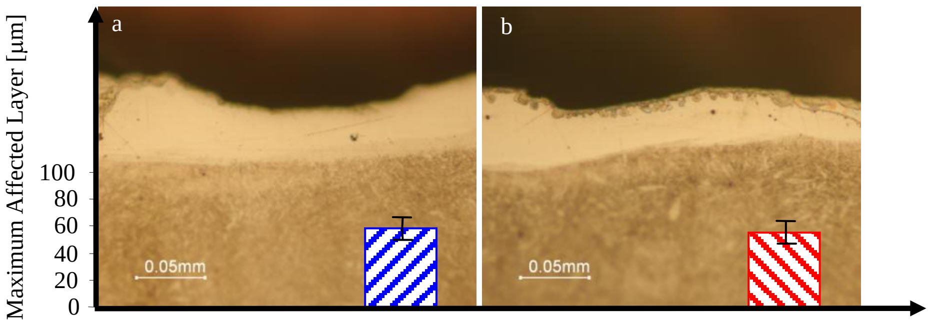

Figure 6. Affected layer for the surface machined with graphite electrode: (a) depth of 3 mm; (b) depth of 9 mm.

Unlikely the presented results for copper condition, the EDM surface with graphite electrode presented similar affected layer thickness, for the two depths analyzed. This behavior could be related to the short erosion cycle used on this condition, 1 s erosion time and full retreat after 5 cycles, which granted a better cooling and flushing of the molten material and thus, presenting similar values, regardless of its depth. Aiming to evaluate the presence of metallographic alterations, the sample microhardness behavior was evaluated, as can be seen in Fig. 7.

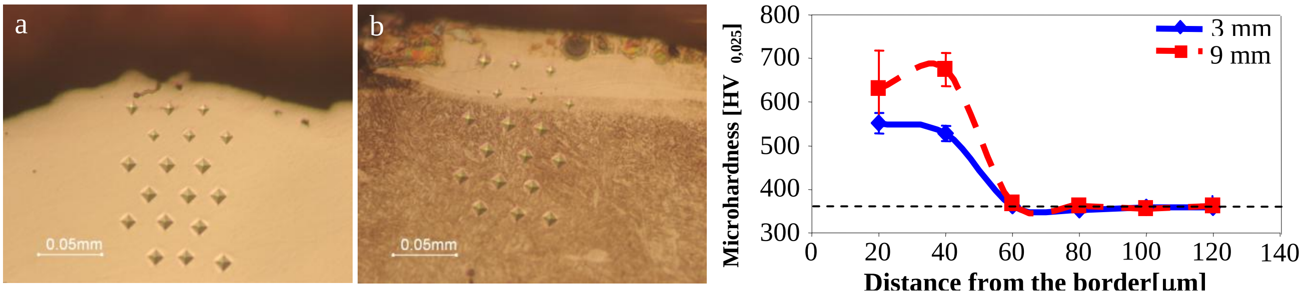

Figure 7. Microhardness behavior for the graphite electrode condition: (a) depth of 3 mm; (b) depth of 9 mm.

Due to the presence of the white layer, as well as the heat affect layer, the microhardness behavior changed along the surface to the bulk material. Higher machining depth produced lesser microhardness on the white layer, followed by a hardness increase in the heat affected layer and decrease as the distance from the border increased, reaching the bulk material hardness.

Deeper machined cavities, due to the difficulty of the fluid assess, produces an intense melting and consequently, solidified material. This solidified material may detach from the surface, causing the dielectric fluid to become saturated with impurities, causing a decrease of the removed material and affected layer. However, this phenomenon may induce a re-melting of the affected layer, causing a microhardness increase, observed in the above graphics.

Figure 8 shows SEM images of the samples were performed, aiming to verify the presence of microcracks, as well as to better characterize the different layers, generated after machining with graphite electrode.

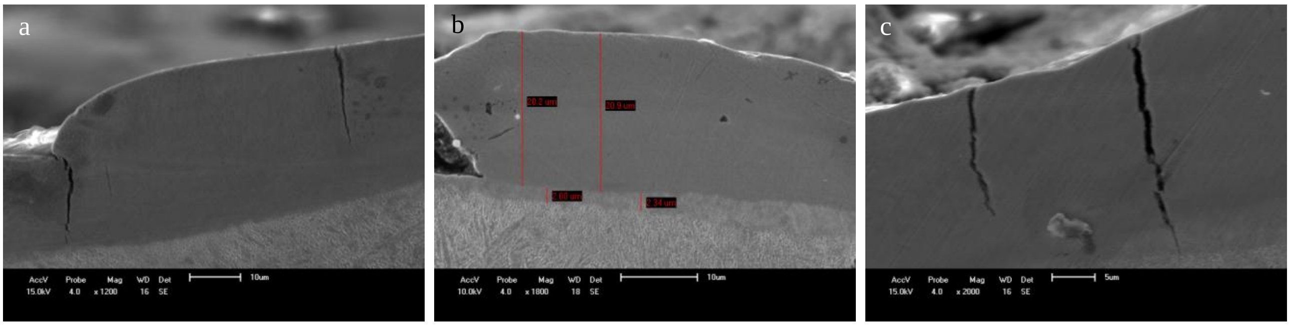

Figure 8. SEM images of the samples machined with the graphite electrode: (a) depth of 3 mm; (b) depth of 9mm; (c) microcrack for depth of 3 mm.

As can be seen, the condition of deeper machining, presented less microcracks. According to Cusanelli et al. (2004), as a consequence of the rapid quenching process, micro and nanocracks are formed at the surface of the white layer. Thus, since the quicker cooling in the 3 mm condition samples, the occurrence of microcracks was more pronounced, associated to the thicker white layer and affected layer.

To evaluate the presence of electrode elements embedded in the affected layers, EDS analysis of the graphite electrode was carried out, as can be seen in Fig. 9.

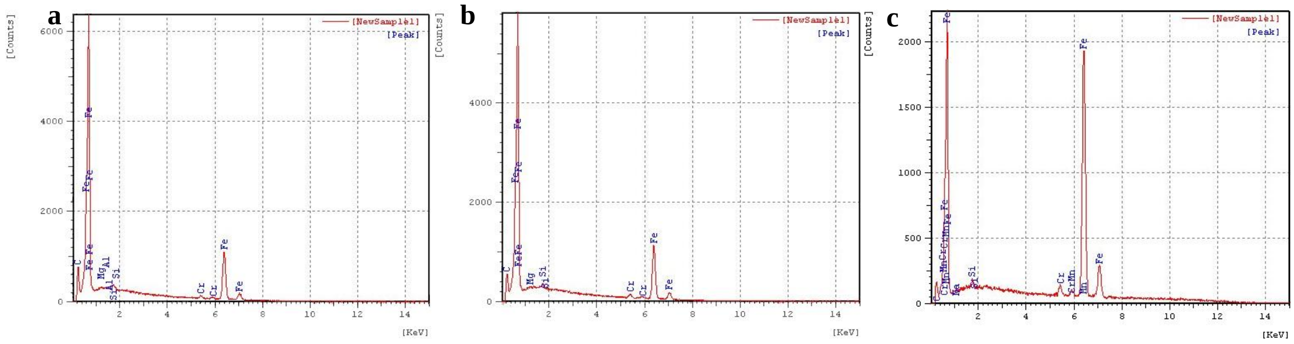

Figure 9. EDS analysis for: (a) white layer; (b) heat affected layer; (c) bulk material.

Observing the three EDS graphs, it is not possible to identify any significant variation regarding carbon count, and therefore, no graphite electrode elements, mainly carbon, was diffused in the affected layers.

Comparing the two different electrodes materials, with different properties, is important to evaluate the most suitable machining condition, for the evaluated environment. Figure 10 shows the comparison between copper and graphite electrodes.

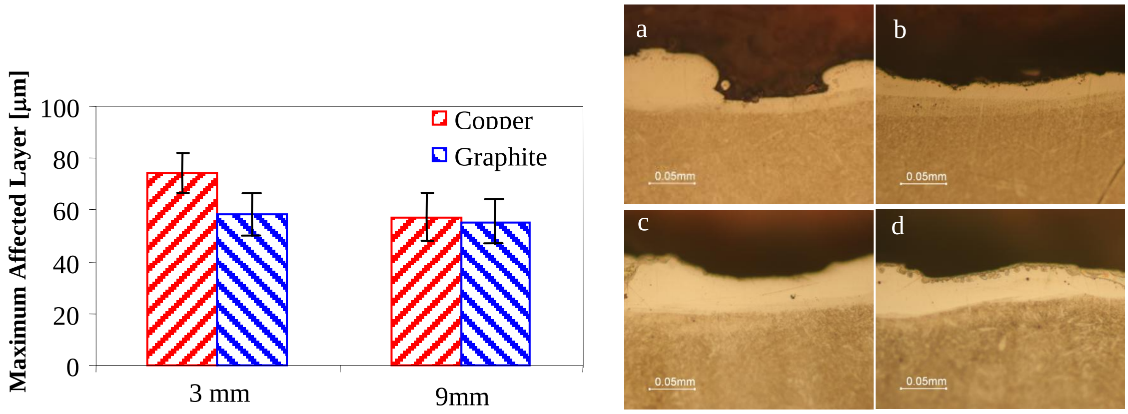

Figure 10. Affected layer and metallographic images for the copper electrode: (a) depth 3 mm, (b) depth 9 mm; and graphite electrode: (c) depth 3 mm, (d) depth 9 mm.

As observed, the copper electrode generated a thicker affected layer, for both analyzed depths. Boujelbene (2009) stated that the white layer thickness almost does not vary according to the nature of material of the electrode. The big factors which influence the heat affected zone are the current, the discharge and pause duration and the inter-electrodes gap. Thus, due to the lower erosion time and greater cycle repeat, the condition machining with graphite electrode generated a thinner heat affected zone, when compared to the cooper condition. The objective of this analysis of the graphite and copper with the different cycles was to evaluate the behavior of the machined surface, not the comparison.

In these experiments, the graphite electrode generated a more uniform white layer, when compared to cooper, which presented zones of re-molten material.

Figure 11 shows the comparison between the two tested electrode materials.

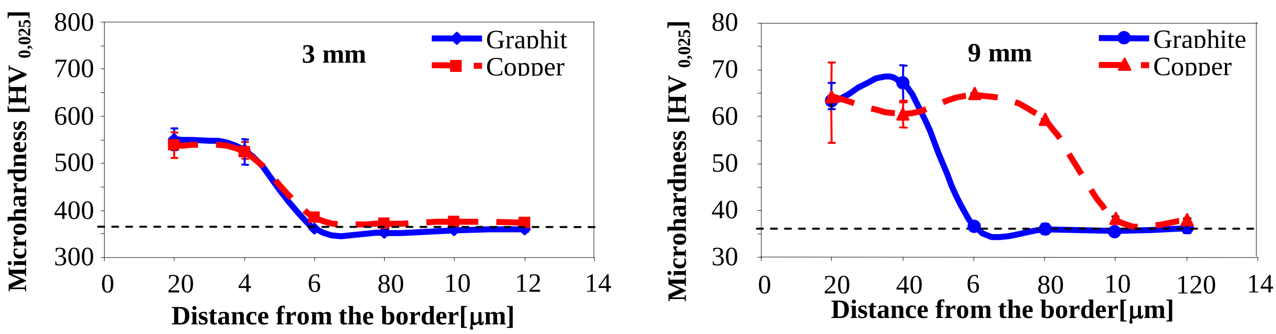

Figure 11. Microhardness behavior for the two different electrode tools and different depths.

For the depth of 3 mm, similar microhardness profile was obtained for the graphite and copper conditions. According to Boujelbene (2009), the heat affected zone hardness is higher for copper electrode than for graphite electrode, due to the copper presenting a better conductibility than graphite, the surface of the part quickly warms up at more raised temperatures and thus with the flow of dielectric at the time of the current cut, the speed of cooling increased. However, due to the reduced erosion time for the graphite condition (1 s) compared to the copper (3 s), and earlier full retreat (5 cycles), a quicker cooling and consequently hardness increase was observed.

However, as the cavity depth increased to 9 mm, both electrodes presented different behaviors. Since the easier assessment of the dielectric fluid for the graphite condition, the microhardness profile presented a quicker re-solidification and thus, shallower microhardness profile. As for the copper electrode, the difficult of assess of the dielectric fluid provided a deficient cooling and cleaning effect, generating a more intense and deeper melting, associated to a constant re-solidification, which granted a deeper microhardness profile.

4. CONCLUSION

The dielectric fluid flow had great influence on the resulted surface. The poor cooling and cleaning effect generated, for higher depths, generated deeper microhardness profile, associated to the constant and graduate re-solidification. The easier assessment of the dielectric fluid for the lower depths, the microhardness profile presented a quicker re-solidification and thus, shallower microhardness profile.

Another factor that influenced the results was the erosion time. The reduced erosion time, as well the quicker full retreat, granted a better cooling and cleaning effect, and thus, shallower microhardness profile.

Associated with the affected layer thickness, microcracks could be observed. It was noticed that, greater the amount of microcracks present, thicker the white layer, and consequently, the affected layer.

The EDS analysis for the surface machined with cooper electrode showed no Cu diffused on the evaluated white and heat affected layers. As for the graphite machined samples, no significant carbon count change in the white layer and heat affected layer was observed, for the graphite electrode condition.

Cavities with depth of 9 mm presented higher microhardness when compared with 3 mm depth cavities, associated to the decrease of material removal rate, caused by the concentration of impurities and thus, re-melting of the affected layer and consequently microhardness increase.

5. ACKNOWLEDGEMENTS

The authors would like to thanks the University of Caxias do Sul, for the support on the project Dry Drilling and financial support, and to the Prof. Gerson L. Nicola, for the help during the tests realization.

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