

PROCESSING AND CHARACTERIZATION OF PM DIAMOND BEADS

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Abstract: *The cutting operations for non-metallic materials, such as ceramics, rock, concrete, requires the use of diamond tools. These tools are produced by the techniques of powder metallurgy, comprised by diamond crystals embedded into a metal matrix. This work studies the microstructural characterization of diamond composites processed according to industrial powder metallurgical route: sintering by hot pressing at 800°C/35MPa/ 3 minutes. For such, commercial ferritic alloy DIABASE-V21 and diamond crystals with average grain 425µm were used. X-ray energy spectroscopy (EDX), X-ray diffraction (XRD), energy dispersive spectrometry (EDS) and scanning electron microscopy (SEM) were performed aiming to evaluate the structure and microstructure resulting from the sintering process. The results showed that this alloy presented a favoring formation of solid solutions, which enabled a adhesion improvement of diamonds in the metal matrix. Wear tests were performed using a physical simulator, comparing results with a commercial bead.*

Key-words: diamond beads, hot pressing, ferritic alloy, microstructure, wear.

1. INTRODUCTION

The diamond tools are characterized by presenting as main part of the cutting elements, manufactured based in metal composite and diamond. Diamonds are impregnated in the metal matrix, where the connection between the matrix and the diamonds must be strong enough for high performance while cutting rocks and concrete (Del Villar et al, 2001; Oliveira et al, 2007; Artini et al, 2011).

The diamond wire beads are annular segments with external diameter of 10 to 12 mm, mounted with spacing approximately 25 mm on a stainless steel multifilament rope, on which diamond beads are placed (metal matrix + diamond), separated by rubber rings and / or springs. This set makes up the diamond wire, which are cutting tools applied to the processing of ornamental rocks. The diamond beads are the most important parts of the tool, because they are responsible for the cutting action (Oliveira et al, 2007; Filgueira and Pinatti, 2003).

Usually, most diamond tools are produced by hot pressing, which may be terminated by metal infiltration in some cases, but some of these tools are produced by cold pressing and sintering. During the process, the diamond particles are bonded to the metal matrix by a chemical and physical combination of interactions and a tight control of processing parameters is required (temperature and pressure) to prevent attack, dissolution and / or diamond graphitization that can affect the tools' cutting performance (Oliveira et al, 2007; Filgueira and Pinatti, 2003; Yamaguchi et al, 1997).

The choice of a suitable metal matrix for the diamond tool manufacturing is a challenging issue, because this choice depends upon the abrasiveness of the material to be cut. To achieve good tools' performance, the metal binder must have good chemical and mechanical compatibility with the diamond, being able to hold it during the cutting (Konstanty, 2005). Normally, is used tungsten (W) for cutting extremely hard materials, such as concrete. Cobalt (Co), W-Co alloys for high hardness materials such as granites. Cobalt Co-bronze, iron(Fe)-Co, Fe-bronze are binders employed in the cutting of moderate hardness materials such as marbles (Przyklenk, 1999; Oliveira et al, 2009).

For many years, Co has been used in the processing of diamond tools because it has perfect chemical compatibility with diamond at the processing temperatures, an adequate retention of diamond crystals and excellent

wear resistance during the cutting operations of non-metallic materials. However, it is highly toxic and is subject to large price fluctuations in the market (Barbosa et al, 2010).

Due to this fact, researchers have developed new alternative alloys that can be used as a binder matrix, to substitute or reduce the cobalt content in diamond tools (Webber and Weiss, 2005; Kamphuis and Serneels, 2004).

When the diamond composite is sintered by powder metallurgy, a filling layer may be used in order to reduce porosity. This is a phase of low melting point, generally consists of copper base alloy which melts during the sintering and fills the pores. As this phase decreases the hardness of the matrix, its use is particularly suitable for less aggressive cutting conditions and their amount should be reduced as much as possible during the cutting of very hard materials (Artini et al, 2011).

The diamond crystals used in the processing of some diamond tools, *i.e.*, diamond beads, must present high thermal conductivity, toughness and hardness. The size of the diamond particles is approximately 40/50 mesh at concentrations of 30-50, which correspond respectively 0.26 and 0.44 g per cm³ of the diamond composite (diamond crystals + metal matrix) (Oliveira et al, 2012; Oliveira et al, 2007; Filgueira and Pinatti, 2003).

Diamond beads are produced by powders mixtures (diamond crystals + metal matrix), followed by cold pressing at 100 to 350MPa, followed by free sintering or by hot pressing. After that, the sintered diamond composites are brazed outside carbon steel rings (Moreira Jr, 2013).

This work aims to process diamond beads by hot pressing in a single step - eliminating further cold pressing and brazing steps. Structural and microstructural features of the sintered (hot pressed) bodies were investigated by XRD and SEM/EDS. Wear tests were also conducted, and they pointed out for the possibility of producing diamond beads with satisfactory properties, when compared to a commercial diamond bead. This is an important achievement, once two processing steps were eliminated.

2. EXPERIMENTAL

The metal matrix used to adhere diamonds was the commercial ferritic powder alloy Diabase-V21 (62wt%Fe-22wt%Cu-13wt%Co-3wt%Sn) from the company Dr. Fritsch, presenting an average particle size of 27.59µm. This powder was chemically pre-alloyed by atomization.

The diamonds used were purchased from Diamond Innovations (Trademark of General Electric Company (USA), type MBS960SI2 - high toughness and impact strength - with coating of silicon carbide (SiC) to improve diamond adhesion into the metal matrix. These diamonds presented crystal size of 400µm - what is the industrial standard for diamond beads.

The Diabase-V21 powder was weighed and mixed with the diamonds using an industrial mixer by Pyramid, during 30 minutes. The diamond content in the beads was 4% by weight, which corresponds to 50 concentration usually used in processing of diamond beads, as predicted by Oliveira et al (2012).

The diamond composites (beads) were produced by using an industrial hot press - Pyramid [details in Moreira Jr (2013)]. This step was performed under the following parameters: 800°C/35MPa/3 min., since these are commonly used in industry, in the processing of diamond beads, according to Konstanty (2005). No previous cold pressing was used. Carbon steel tube was mounted directly inside the graphite mould, in such a manner that the powders mixture were poured directly around the tube, inside the mould orifices. Hot pressing promoted the chemical bonding between powders and steel tubes, eliminating further welding step.

Scanning electron microscope (SEM) by Shimadzu was used for the microstructural analyses. Energy dispersive X-ray spectroscopy (EDS) coupled to the SEM, was used for chemical analysis of the beads. To analyze the structural aspects of the diamond beads, a Shimadzu XRD diffractometer was used, using CuK α radiation ($\lambda = 1.54\text{\AA}$) and a Ni filter, 2θ ranging from 30 to 100°, at a velocity of 0,2°/sec. A XRF spectrometer by Shimadzu was employed to quantitatively determine the chemical elements present in the diamond beads - processed by this work, and a commercial one.

Table 1. Dimensional data diamond wire bead.

Data	Diamond composite	Metallic Tube
\varnothing_e (external diameter)	11 mm	8 mm
\varnothing_i (internal diameter)	8 mm	5 mm
Length	6 mm	12 mm

Wear tests were conducted in a physical simulator - modified AMSLER wear tester - by CONTENCO - Model AB800-E. The cut material was a gray granite disc, with oriented structure, with coarse grains, ranging from 4 to 20 mm, and medium hardness. The samples (diamond beads) were mounted vertically on the granite disc, which was installed horizontally on the simulator table, by a fixed support. Wear tests used the following parameters: granite disc rotation 20RPM, vertical load on diamond beads 2 kgf, during cumulative times of 2-6-12 min. - standard condition to wear tests in diamond beads, as described by Oliveira et al (2007). After each time of wear test samples were subjected to analysis of the microstructure by SEM. Moreover, the beads were weighed on a digital balance by Mars, with resolution 0.0001g - before and after each wear test, to calculate the percent mass loss (ΔM), according to

Equation 1 - where m_i is the initial mass (before the wear test) and m_f is the final mass (after wear test) for further wear resistance calculation (WR) according to Equation 2. Same wear tests were performed for a commercial diamond bead, as a matter of comparison. Table 1 shows the dimensions of the diamond beads produced by this work.

$$\Delta M = [(m_i - m_f)/m_i] \times 100 \quad (1)$$

$$WR = 1/\Delta M \quad (2)$$

3. RESULTS AND DISCUSSION

Figure 1 shows an overview of the diamond wire beads produced by this work. Diamond composites beads were sintered directly into the metal tube. In this way, the welding of the diamond composite on the metal support was not necessary, reducing the manufacturing time of this kind of the cutting tool.



Figure 1. Processed diamond beads. Red arrow points to the sintered diamond composite. Dashed red arrow points to the inner carbon steel tube.

3.1- EDX Analyses

The table 2 shows the results of chemical analyses by EDX, that allowed the determination of the chemical composition of the binders (metal matrix) from the diamond composites of the beads.

The binders from the beads produced in this work presented major quantities of Fe and Cu elements - and they form a solid solution. Sn is a liquid phase former to improve sintering bonding, and Co is far the most used binder for diamond's adhesion, and it promotes solid solution and/or precipitation strengthening of both Fe and Cu (Araújo, 2018).

As to the commercial bead's binder, it was found a large iron content, about 72% wt, predominantly a ferritic matrix. According to the phase diagram in the system Cu-Fe (ASM, 1979), there is a high solubility of copper in iron, thus providing solid solution formation. Sn and Zn form a liquid phase during sintering and some precipitates (mainly with Cu), and Ni is a well known solid solution and precipitation hardener for Fe (Araújo, 2018).

Table 2. Results of chemical analysis of the binder matrix of diamond beads obtained via X-ray spectroscopy (EDX).

Diamond Wire Beads	Binder Elements [wt%]					
	Fe	Cu	Co	Sn	Ni	Zn
Commercial	72.85	8.12	-	3.50	10.66	4.87
This Work	62.00	22.00	13.00	3.00	-	-

3.2- Structural Analyses

The diffractogram of the diamond composite produced with commercial beads ferritic-Diabase alloy V21 (Fe-Co-Cu-Sn) are shown in Figure 2, showing predominant presence of solid solution CoFe, and Co₃Fe₄, Fe₄Cu₃ and Cu₁₀Sn₃ precipitates.

The formed precipitates are responsible for the hardness and abrasion resistance of the alloy, and its formation was, probably, facilitated by the presence of the liquid phase of Sn, which contributes to atomic diffusion of Fe, Cu and Co elements during sintering - see Curiotto et al (2007), Del Villar et al. (2001) and Barbosa et al. (2010). The iron and cobalt have their respective melting points higher than the sintering temperature used in this work. However, there is affinity between the elements and their mutual solubilities under sintering conditions is high enough to form the observed solid solution CoFe and the precipitate Co₃Fe₄ - see phase diagram (ASM, 1979).

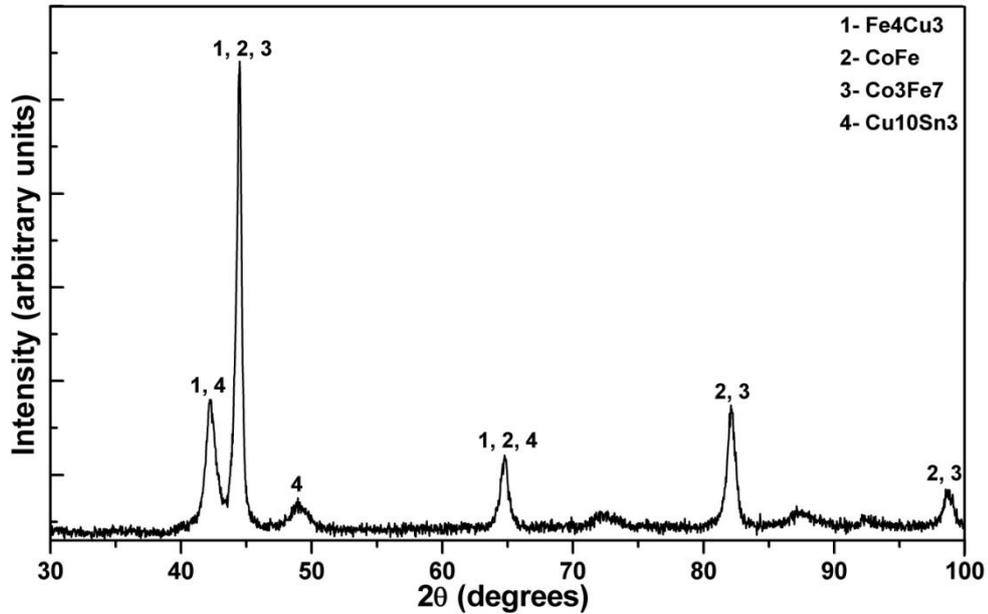


Figure 2. XRD pattern of the processed diamond bead.

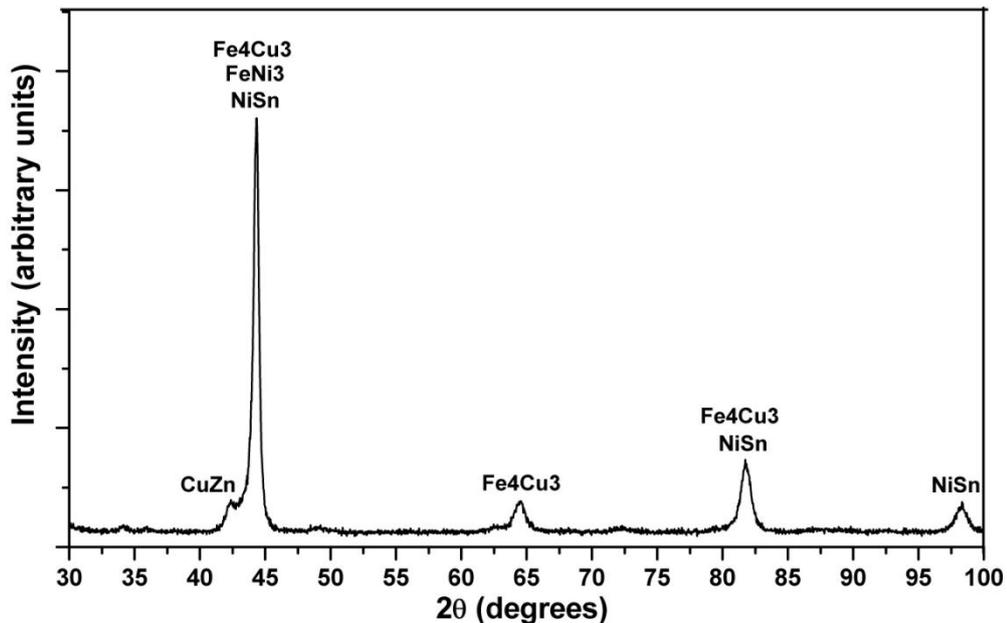


Figure 3. XRD pattern of the commercial diamond bead.

Figure 3 presents the XRD pattern for the commercial diamond bead. One can observe the intense formation of the Fe₄Cu₃, FeNi₃ and NiSn precipitates, and a slight brass (CuZn) formation. Therefore, solid solution and precipitation hardening there occurred, like the processed diamond bead.

In a general manner, solid solutions and precipitation hardening lead to improved wear resistance.

3.3- Wear Resistance of the Beads

Figure 4 shows the wear resistance results from both diamond beads in time intervals of 2, 6 and 12 minutes. According with Wensheng et al (2012), metallic alloys with higher copper content, provide better abrasion resistance results. Justified for the fact that during sintering, solid solution and Fe-Cu compounds formed. On the other hand, Ni additions to a ferritic matrix favour the formation of the hard FeNi₃ phase (Corrêa, 2018), which is very hard - therefore, wear resistant.

In view of the results shown in the Figure 4, the beads produced by this work presented satisfactory wear resistance comparable to the commercial bead. This is indicative of the technical feasibility for manufacturing of the diamond tools using the innovative methodology of this study, significant technological advance for the industry.

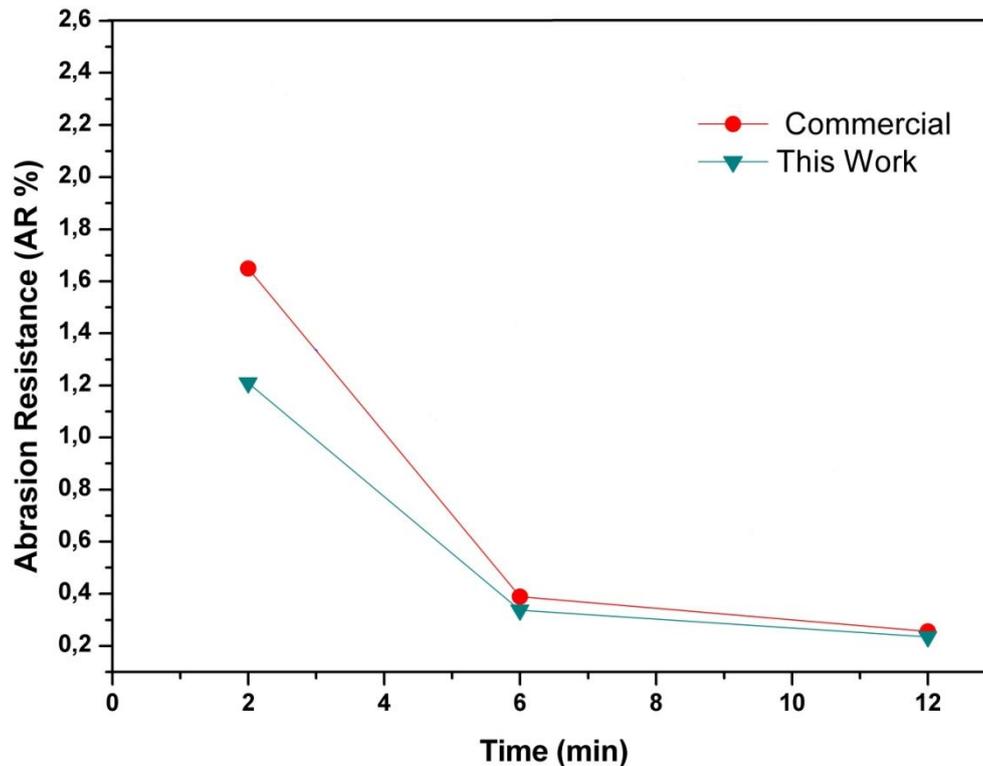


Figure 4. Wear (abrasion) resistance of the beads.

3.4- Microstructural analyses and wear mechanism

Figures 5 and 6 show the distribution of the diamond crystals in the binder matrix, as well as the behavior of some phenomena of diamond behavior composite during the wear test for the processed beads. It is worth informing that similar microstructures were found for the commercial beads.

In Figure 5 (a-b-c-d), there is an uniform distribution of diamond crystals in the metallic matrix, which contributes to retention of diamonds (Romanski, 2006). It can also be seen that, besides the good distribution of the crystals, they exhibit different heights of protrusion (height of the exposed diamond) - this feature is more remarkable as time increases. One can see that the diamonds had few defects, indicating the beginning of the cutting process. Furthermore, it can be seen good adhesion of the diamond crystals in the binder, which points to the satisfactory performance and lifetime of the diamond tool.

Figure 5(a) - 2 min. test, one can observe that almost all diamonds are emerged in the binder surface - some of them are cleaved - see the diamond in the center of the micrograph, and others are defect free crystals. The binder presents only a few scratches.

Figure 5(b) - 6 min. test, shows damaged crystals in a degraded binder, which presents scratches and grooves during the cutting work. One can also observe the presence of cracks in surface of the crystal, leading to cleavage and fragmentation. Despite of this, diamonds' retention by the binder is observed, so the metal matrix still is able to hold diamonds under load. The cleaved and self sharpened diamonds' surfaces continue the cutting process.

Figure 5(c and d) - 12 min. test, show diamonds with cracks and fragmentation. Half of the diamond crystals present worn surfaces (flatten), and also it is observed the presence of pull out in the metal matrix (see arrow). Both micrographs show some few diamond crystals at the end of their lifetime - severely damaged. Despite of this, some new diamond cutting faces just emerging from the binder are observed, indicating that the cutting process takes place in a continuous manner for a sintered diamond tool. It also indicates the successful choice of the binders, which promoted good adhesion to the diamond crystals, even to those with damages (Tonshoff, 2001; Rosa, 2004).

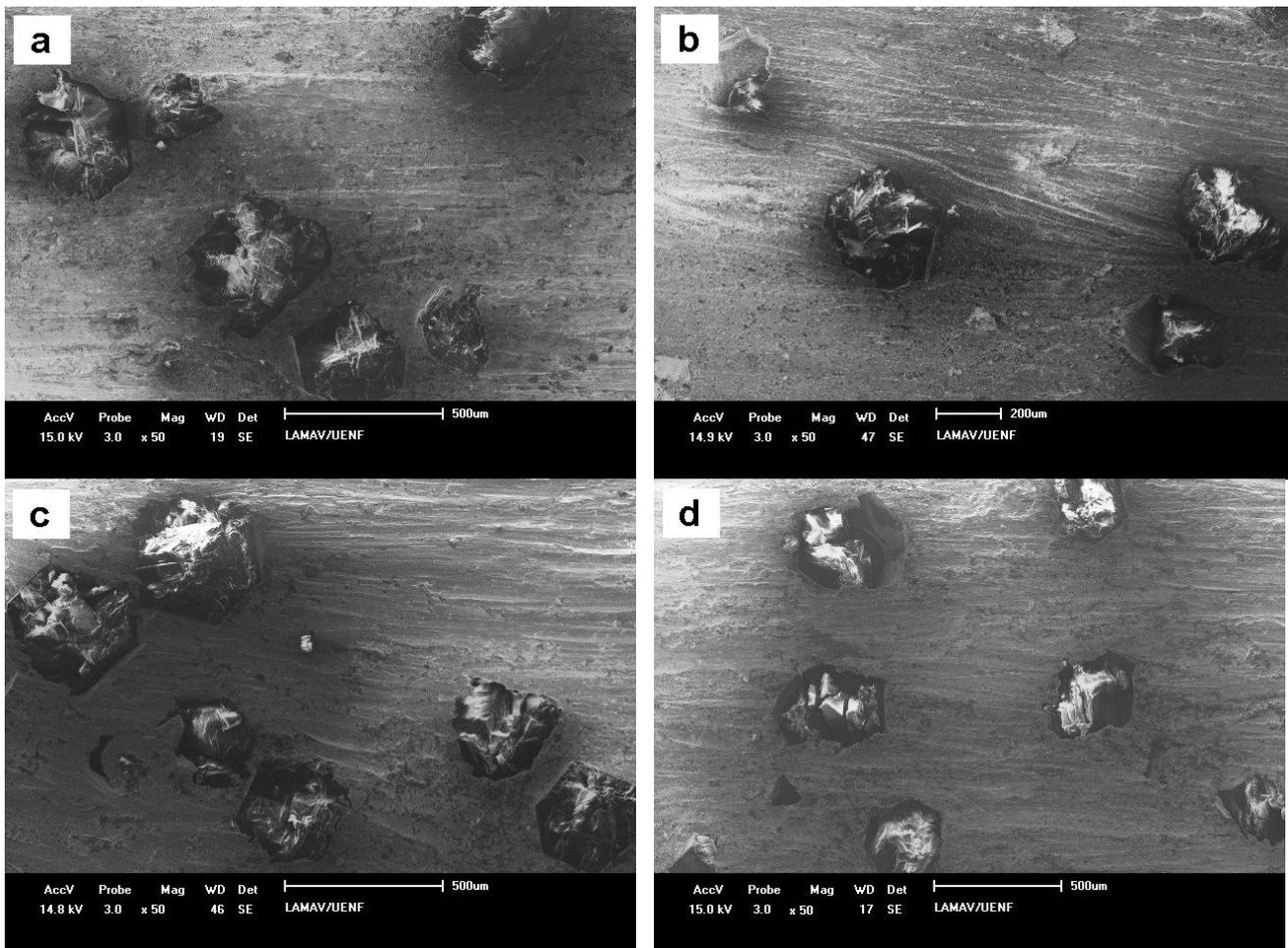


Figure 5. Wear test - microstructural progression for the processed diamond bead for the times of (a) 2 min., (b) 6 min., (c and d) 12 min. test.

4. CONCLUSIONS

This exploratory work showed that it is possible to process diamond beads without the pre-compacting of the diamond composite, prior to hot pressing, and welding of the hot pressed composite outside a carbon steel ring (tube). In this case, both steps occur during hot pressing - pressing aided sintering.

Structural study points to the formation of solid solutions and precipitates, which strengthened the binder. This is of great importance to the wear resistance improvement.

Microstructural evidences showed the continuous wear mechanism of diamond exposition on the binder, followed by binder abrasion - scratches and grooves, after that diamond grains cleavages and fragmentation was observed, in parallel with some new diamonds faces emerging from the binder surface.

Wear tests positively indicated that the processed beads presented the same wear resistance of the commercial one.

5. ACKNOWLEDGEMENTS

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