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MANUFACTURING OF MICRO-SCALE Nd-Fe-B MAGNETS BY DIAMOND WIRE SAWING AND ELECTROPOLISHING PROCESSES

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Abstract. *Nd-Fe-B based permanent magnets play a very important role for a wide range of industrial, military and consumer devices. Among the various processes applied for the production of permanent magnets are included the machining processes that are responsible for ensuring dimensional and shape accuracy, surface integrity quality, and ensuring tight tolerances. However, in the scientific literature there is still a lack of information about the machining processes of Nd-Fe-B magnets and the phenomena involved in the formation of the machined surface, such as the diamond wire cutting process. Thus, the objective of this study was to evaluate the surface integrity and magnetic properties resulting from diamond wire cutting of Nd-Fe-B based magnets. Cutting experiments of Nd-Fe-B magnets were carried out. The cutting speed (v_c) was of 10 m/s, feed rate (v_f) of 1 mm/min and final thickness of the samples of 500 µm. The results obtained showed that the hardness of the machined surface with diamond wire sawing and electropolished were lower than the faces just polished, which can be attributed to the presence of residual stress. Despite the brittle nature of the material, it was observed the presence of microcutting over the machined surface when used diamond wire sawing. However, due to the brittleness of the Nd-Fe-B, the machined surface also presented pittitng and craters. Regarding to the surface roughness, it was observed that the increase of the outer diameter and the size of diamond grain of the cutting tool resulted in the increased the R_a, R_q and R_t values. This behavior is attributed to the higher penetration depth of the diamond grains on the surface of the workpiece, favoring the formation of craters. The phases analysis via X-RD revealed just presence of hard magnetic phase ($Nd_2Fe_{14}B_1$ grain), with some peaks related to the oxides phases. For the magnetic property, it was possible to observe that the H_{cj} presented closed values when varying the diamond wire. Thus, the diamond wire sawing and electropolishing are potential processes to be applied to manufacturing of Nd-Fe-B micro-magnets.*

Keywords: NdFeB, diamond wire, surface integrity, magnetic properties, micromachining.

1. INTRODUCTION

1.1. Rare Earths

Rare earths (TR) are a group of chemical elements that present a variety of magnetic, electronic, optical and catalytic properties that allows the formation of several alloys and compounds and they are mainly manufactured into magnets, with emphasis on the ternary compound Nd-Fe-B. These magnets are essential for a wide range of industrial and electronic devices due to their excellent performance in applications that require, for example, larger coercivity (H_{cj}) and high energy stored per volume ($(BH)_{max}$), which are important characteristics for component miniaturization (MOHAPATRA and LIU, 2018). Employed in many applications, among them vibrating motors for cell phones, hybrid and electric vehicles, electronic devices such as high-capacity hard drives, wind power generators, and various others high technology products (CONSTANTINIDES, 2016).

Currently, China dominates the mining, enrichment, and metallurgy processes and technologies employed in the manufacturing of TR permanent magnets, which leads to a dependence on countries that do not have reserves in their territory or cannot meet the domestic demands for the production process involved in the manufacturing of TRs. In fact, the future demand for TR elements should exceed the supply level, making the worldwide exploration efforts are being directed towards the implementation of a TR supply chain with foundations outside China (HATCH, 2012; CHARALAMPIDES et al., 2015). A potential supplier is the Brazil that is considered the country with the second largest reserve of TR elements in the world, possessing about 22 million tons of exploitable TR elements, remaining only behind China that has approximately 44 million tons of TR in its territory (ANDRADE, 2013).

Regarding to the Nd-Fe-B based magnets, these ternary compound exhibits high saturation polarization (J_s), high coercivity (H_{cj}) and excellent energy stored per volume ($(BH)_{max}$). However, the Nd-Fe-B exhibits a mechanical behavior of brittle-hard behavior, which make it as a material of low machinability when applied conventional machining processes, being commonly employed the electrical discharge machining process (KLOCKE, 2008; LI et al., 2015).

However, due to the high heat input of the process, there is the formation of white layer, micro cracks and pores as well as re-melted and re-solidified material on the eroded surface. Moreover, the eroded surface presents high values of surface roughness and larger damage on the surface integrity, which requires the application of many steps as post-processing, increasing production time as well as adding cost to the final price of the magnet as a marketable component. In view of this, different machining processes can be investigated to analyze their potential application in the machining stage of magnets. Among these, the endless diamond wire sawing can be highlighted, as it allows the manufacturing of magnets with fine thickness in the micro-scale order, with good productivity and geometric tolerance guarantee within the project requirements, allowing a better quality of the machined surface of magnets (COSTA et al., 2022a; COSTA et al., 2023).

1.2. Diamond Wire Sawing

The diamond wire sawing process is a variant of Multi-Wire Sawing (MWS) that has rapidly gained industrial attention due to its potential for two to three times higher productivity and the potential for kerf recycling (WU, 2016). The cutting tool used is based on an abrasive-fixed wire with diamond grits randomly attached via electroplating, brazing or resin bonding, on the surface of a steel wire, promoting greater holding force and higher wear resistance of the diamond wire (COSTA et al., 2022b). Both water and emulsion can be used as cutting fluid in the sawing process. This machining technique is widely used for the fabrication of wafers (micrometer-thick blades) of silicon crystal, sapphire, silicon carbide, and other semiconductor materials (KLOCKE, 2008).

Since the diamond wire sawing is based on an abrasive-fixed wire, the main material removal mechanism is governed primarily by the two-body-wear due the direct interaction of the diamond grits with the workpiece surface through the penetration of the grits cutting edge into the surface to be machined. In the manufacturing environment, this technique led to increased productivity and a significant improvement of the quality of machined surface, as well as enabling chip recycling due to the low contamination of the water-based cutting fluid that is used and less chip degradation (COSTA et al., 2018).

1.3. Electropolishing

Electropolishing is the electrochemical process to remove metallic material from the workpiece to obtain a smoother surface. It is used in many engineering applications as well as in fields regard the food, medical, pharmaceutical, and semiconductor industries. It refers to the electrochemical process dedicated to remove material from a metal part to polish, passivate, and deburr metal parts. It is also known as electrochemical polishing or electrolytic polishing. Regarding to the chemical phenomena, it is a specific type of electrolysis that involves a direct electric current passing through an electrolyte in an electrolytic cell. The metal part to be electropolished act as the anode and is connected to a positive terminal of a direct current (DC) power supply, with the negative terminal connected to the cathode. The part is then immersed in a bath consisting of a specially formulated electrolyte solution. Activation of the power supply produces an electric current that passes from the anode to the cathode, resulting in oxidation of the metal surface and removal of surface impurities and irregularities, which dissolve in the electrolyte and diffuse through the film to the cathode. Typically, current and time are the two main variables that can be controlled to achieve high quality of the surface finish (YANG, 2016).

Although the diamond wire sawing process is growing in the industrial sector, currently, not much information regarding the micro and macro cinematic aspects/phenomena when slicing Nd-Fe-B is subjected to the diamond wire sawing technique is found in the scientific literature. For this reason, it is essential to study the influence of the diamond wire sawing and electrochemical polishing processes on the machined surface quality and magnetic properties of Nd-Fe-B based permanent magnets.

2. MATERIALS AND METHODS

2.1. Machine-Tool

As machine tool was used an endless wire saw machine that is composed of aerostatic bearing and slides mounted with a pair of aligned pulleys coupled with spindle. This machine allows an endless wire cutting movement by a single welded diamond wire wrapped around pulleys, as described by Costa et al. (2022b). The spindle has a maximum drive power of 370 W allowing it to achieve a maximum wire cutting speed (v_c) of up to 26 m/s. The workpiece feed system allows setting a feed speed (v_f) with a minimum of 0.08 mm/min. The cooling lubrication system employs atmospheric pressure and emulsiable oil-based fluids are used, which have additives that prevent oxidation of the workpiece and improve cooling and lubrication of the cutting zone.

2.2. Cutting tool and permanent magnets workpiece

Two types of diamond wire were used as cutting tools, the first being diamond wire with a nominal outer diameter of $Ø_{ext}$ = 450 μm (INSOLL Tools Technology). This diamond wire, unlike industrial diamond wires, is pre-machined in loops on a laboratory scale, and there is no need to weld the ends to do it into a loop. It is composed of a core of steel wires interwoven with diamond grits attached to a Ni-Cr alloy as bonding layer. The unused wire surface and the diamond grits are totally or partially covered with this bond. According to the manufacturer, this tool has a diamond grits density of approximately 30%. The micrograph obtained via scanning electron microscopy (SEM) presented in Fig. 1a shows the surface of the laboratory diamond wire.

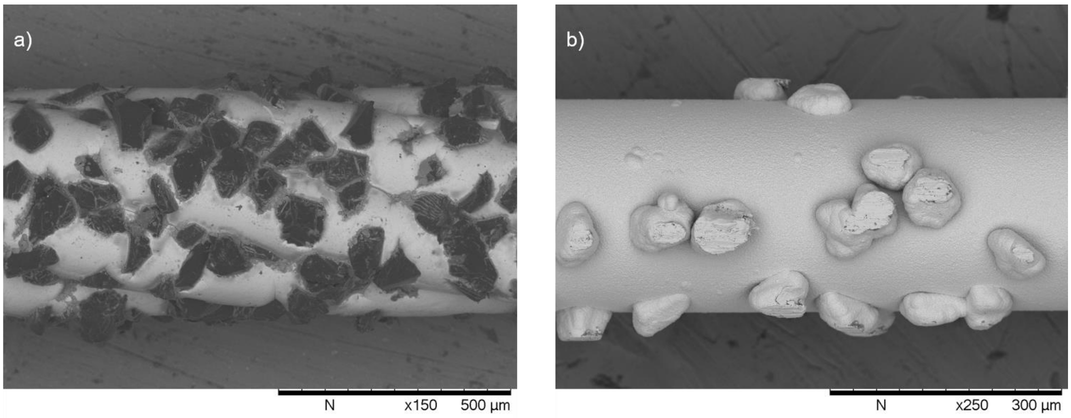

Figure 1. Micrograph of the diamond wires: a) laboratory wire; b) industrial wire.

The other cutting tool used was an industrial diamond wire with a nominal outer diameter of $Ø_{ext}$ = 350 μm, supplied by Saint-Gobain Abrasives Brazil. This tool has diamond grits, with a grit size in range of 30-45 μm, randomly electrodeposited on the core surface of a 0.8% steel wire using Ni as the bonding. Micrographs obtained via SEM presented in Fig. 1b shows the surface of the diamond wire.

As workpiece was used a sintered Nd-Fe-B permanent magnet (magnetic properties of $BH_{(max)}$ = 335 kJ/m^3 and J_s = 1.23 T) in a demagnetized state, widely employed in wide turbine generator and servomotors. The workpiece had a parallelepiped geometry with dimensions of 30 mm x 7 mm x 10 mm. All the micro-magnet specimens were sliced with a thickness of 500 μm.

2.3. Experimental procedure

The process parameters of wire cutting speed (v_c) and feed rate (v_f) were of v_c = 10 m/s and v_f = 1mm/min. To produce a single and continuous diamond wire into a loop, a segment of wire was submitted to the butt-welding process, according the following steps: (i) the ends of a short length of a commercial diamond wire were prepared with sands to provide flatness, parallelism, and smoothness of abutting surfaces; (ii) the wire was fixed on clamping die to ensure alignment of the abutting surfaces; (iii) an electrical source was used to apply a current (A) with time controlled and then butt-welding and subsequent heat treatment of the welded joint; (iv) the welded joint was sanded to remove the burr (COSTA et al., 2022b). After the continuous diamond wire was manufactured, it was wrapped in pulleys on the wire saw machine. The workpiece was positioned and fed in perpendicular direction against the wire cutting movement.

The sawing experiments were conducted under application of a Motor's Soluble 100 lubricating cutting fluid of the emulsifiable type at 5% dissolution. This fluid has additives that protect the workpiece from oxidation and improve cooling and lubrication at the interface between the cutting tool and the workpiece. The application method was of the conventional intermittent jet type. At the end of the test, the parts were submitted to ultrasonic cleaning using absolute ethyl alcohol PA.

2.4. Electropolishing

The electrolytic polishing procedure was performed at an electrolytic tank (see Fig. 2) suitable for the size of the small samples after machining with diamond wire sawing process. This tank is based on INOX sheet, the electrode employed is of tungsten and the solution used is formed by 50% sulfuric acid and 50% phosphoric acid. The procedure was performed on Nd-Fe-B micro-magnet samples obtained with two different diamond wires shown in the Fig. 1. The parameters used are presented in Table 1.

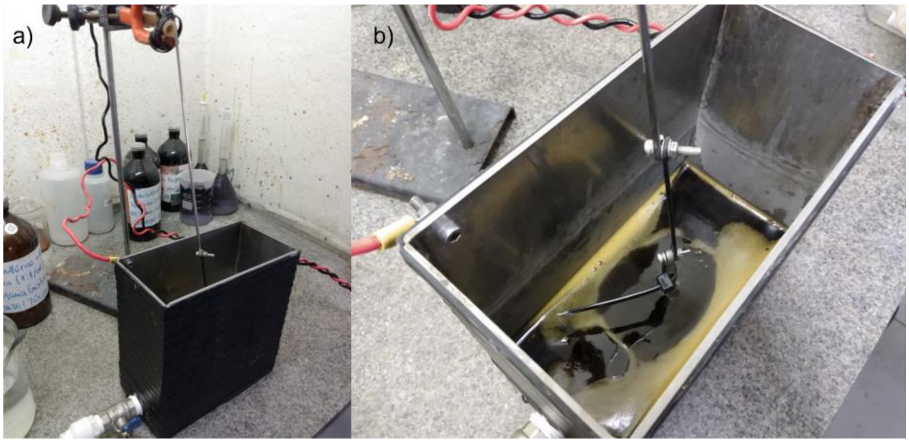

Figure 2. Electrolytic tank electropolishing

Tabel 1. Electropolishing parameters

Electric Current (A)	Voltage (V)	Time (min)
10	14	3

3. RESULTS AND DISCUSSION

3.1. Analysis of hardness of the machined surface

Indentation tests applying different loads were performed on the faces of the Nd-Fe-B samples sawed with two different diamond wires and after electropolished them. As shown in Fig. 3, it was possible to observe that the hardness Vickers averages were lower than the hardness of bulk that is about 676 HV. From the samples sawed by both diamond wires, the hardness values present variability and they were slight higher than those electropolished. After performing the hardness tests, when compared to the average hardness of the material just polished and without having undergone stress (value of 676 HV), it is possible to note that the sample machined with the laboratory wire had a loss of property. This can be attributed to the presence of residual stresses, since the wire has a larger diameter and a larger contact area. On the other hand, on the surface machined with the industrial wire there was not much difference between the hardness in comparison to the polished material.

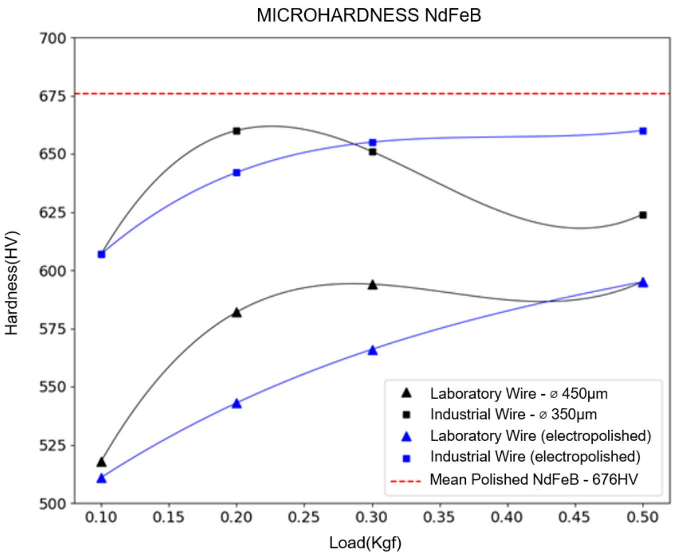

Figure 3. Hardness (HV) versus cutting tool variation for Nd-Fe-B.

3.2. Analysis of surface morphology

Analysis of the machined surface was performed in order to analyze the surface formation characteristics as well as the material removal mechanisms. This step was important to determine the characteristics of the damage caused by the contact between the diamond wire and the workpiece. Overall, it was possible to observe that the variation in cutting tools resulted in the formation of machined surfaces with both material removal regimes (brittle and ductile). Figure 4 shows the three-dimensional surfaces of the samples obtained via laboratory and industrial diamond wire cutting.

Analyzing the result of using the laboratory diamond wire (see Fig. 4a), a predominance of regions of material removal with the brittle regime was noted. Primarily brittle fractures in the form of craters were observed. To a lesser extent, removal in the ductile regime was also identified, being characterized by damage-free regions formed by the shallower penetration depth of the kinematic edges. With respect to the results obtained with the industrial diamond wire (see Fig. 4c), it is possible to observe a greater predominance of the ductile regime, since the presence of regions without brittle fractures become more evident.

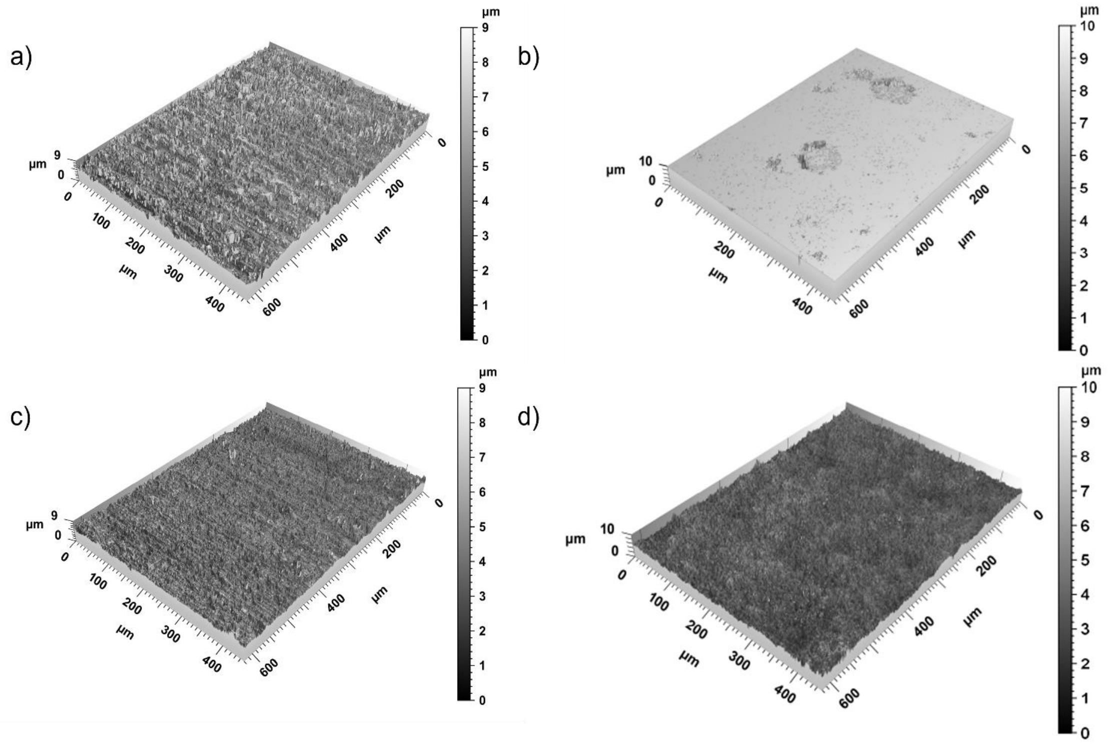

Figure 4. Morphology of Nd-Fe-B based magnet surface cut with diamond wire: a) surface machined with laboratory wire before electropolishing; b) surface machined with laboratory wire after electropolishing; c) industrial wire industrial wire before electropolishing; d) surface machined with industrial wire after electropolishing.

Comparing the two machined surfaces shown in Fig. 4a and 4c, it can be seen that there is a predominance of fractured regions for the surface machined with laboratory wire when compared to that obtained with industrial wire. This behavior can be attributed to the difference in sizes of the diamond grains present in the wires used (Costa et al., 2023). In this sense, it is expected that the kinematic cutting edges are submitted to a lower penetration depth the smaller the grain size. Further, is the larger nominal outer diameter of the laboratory wire, so that the working gap increases according to the diameter of the cutting tool and induces a higher propensity of material removal in the brittle regime.

Furthermore, during the experiments it was visually observed that during cutting a considerable vibration occurred on the side of the laboratory diamond wire when compared to the industrial wire, which may be one of the factors leading to crater formation. Thus, although Nd-Fe-B exhibits a hard and brittle mechanical behavior, material removal was considerably greater in the ductile mode.

3.3. Analysis of surface roughness

In general, it was observed that the topographies of the samples machined with the industrial diamond wire provided a decrease in the values of R_t, R_a and R_q when compared to the conditions machined with the laboratory wire.

This roughness result is associated with wire wear as a function of the volume of material that was removed. The diamond grains in the unused wire are covered by a nickel layer. As the diamond grain comes into contact with the machined material, the outer nickel layer is removed to the side of the respective grain at the start of the cutting process and the diamond is exposed, thereby increasing the material removal efficiency due to direct contact of the kinematic grain cutting edges with the NdFeB.

The behavior can be attributed to the morphological aspect of the resulting machined surface, since the surface presents a greater predominance of brittle fractures, consequently, the increase in roughness values. With the increase of the granulometry, being that the laboratory wire has abrasive grains with higher values, there is a greater penetration of the cutting tool on the material favoring the removal in the brittle regime and, consequently, an increase in roughness. With the reduction of the grain size of these grains, less material is removed during the cutting process. Thus, there is a reduction of the defects generated by the diamond wire cutting process with smaller grain sizes, which resulted in a machined surface with lower roughness values (R_t, R_a and R_q).

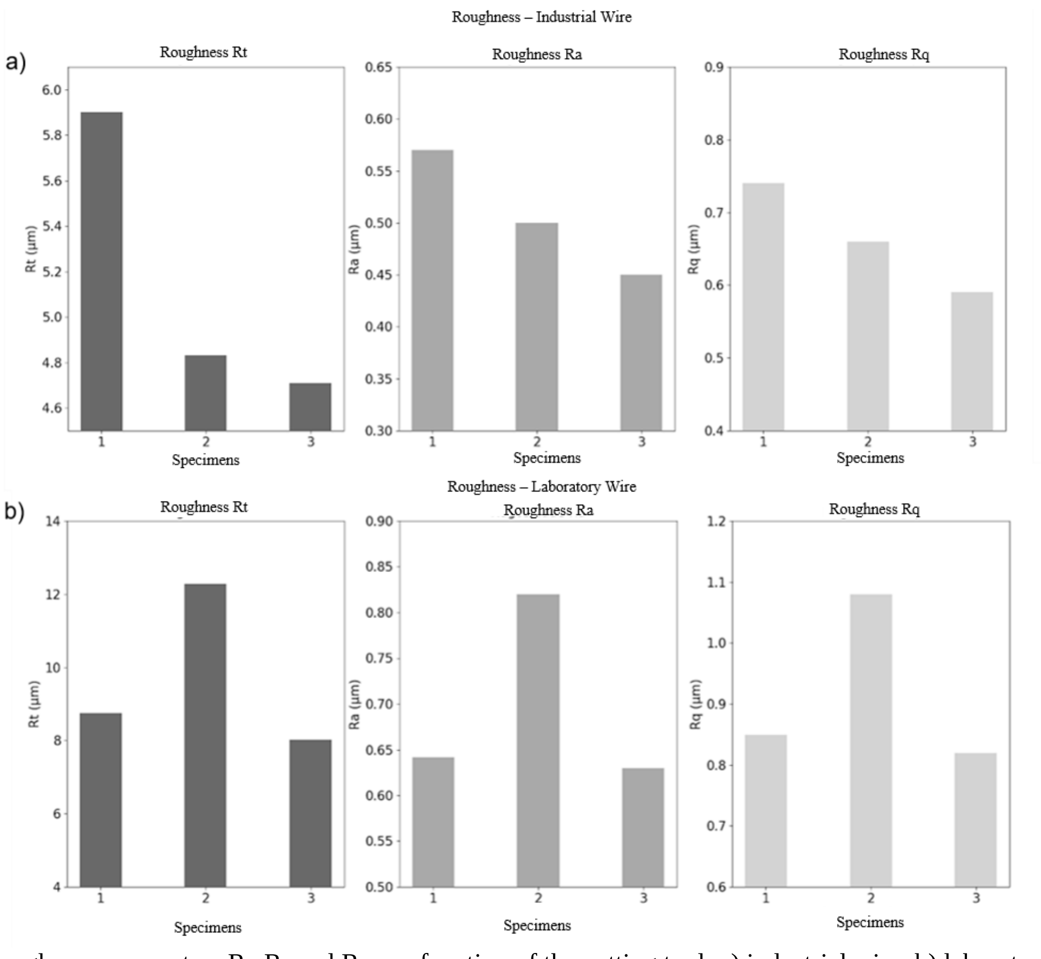

Figure 5. Roughness parameters R_t, R_a and R_q as a function of the cutting tool: a) industrial wire; b) laboratory wire.

The low difference between the roughness values for the laboratory wire and the industrial wire is due to the proximity of grain sizes and geometry of both. The change in predominance of the material removal mode from brittle to ductile regime, the surface morphology remains with the same characteristics, which is seen by the surface morphologies of the machined samples. The analysis of the machined surface topography indicated that it is influenced by the variation of the bead condition. This pattern of behavior may generate a higher average h_{cu}, as a result of the increased density of kinematic edges per contact that results in the decrease in the average load to which the diamond grains were subjected.

For the same specimens which were cited above, electropolishing tests were carried out and afterwards, roughness analyses were performed. As results, when compared to the results obtained in the roughness analyses before electropolishing, there was no significant change in the roughness values. The visual appearance of the samples after electrochemical polishing showed a surface with lower quality than expected, which would be a smooth and shiny surface, a result that may have been caused by the value of current or voltage used, or even the chemical solution that was used.

3.4. SEM and X-DR analysis

The quantification of the crystallographic texture by X-ray diffraction technique has been widely used in rare-earth permanent magnets in a satisfactory way. Analyzing the results extracted from X-RD after processing the data in Maud software present in Fig. 6a, it was possible to observe the presence of both $Nd_2Fe_{14}B_1$ and Nd-rich phases. It can be seen that the $Nd_2Fe_{14}B_1$ peaks (grains on different crystallographic planes) are more intense than Nd-rich peaks, which is in accordance with the amount of grains present in the microstructure (Costa et al., 2023). The peaks related to the planes (006), (105) and (004) can indicates the anisotropy of the Nd-Fe-B magnet due to the texture crystallographic induced by the alignment magnet.

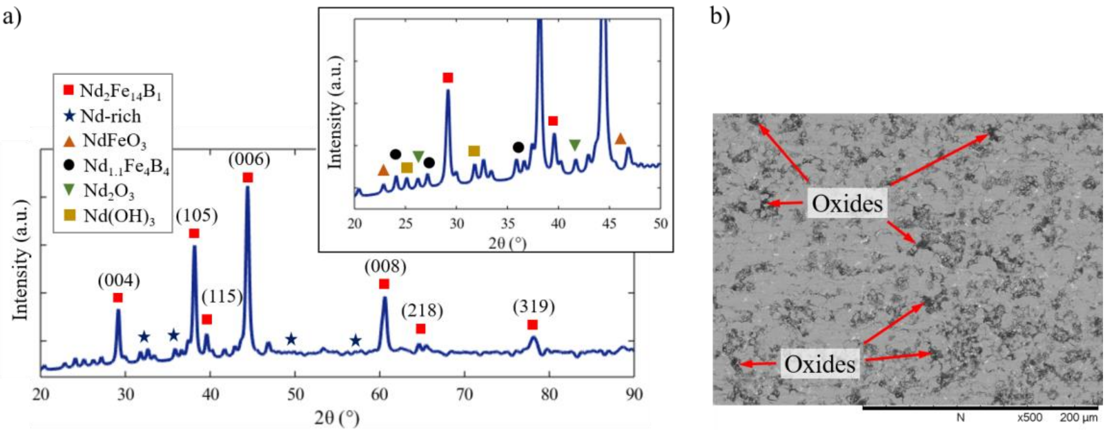

Figure 6. Machined Nd-Fe-B magnet: a) X-RD pattern; b) SEM image

However, it can be that secondary and oxide phases were also found in the diffractogram, as shown in the detail of the Fig. 6a. The formation of the $NdFeO_3$, Nd_2O_3 and $Nd(OH)_3$ phases were identified, which are in consonance with the water-based coolant lubricant fluid used during the diamond wire sawing. Additionally, the SEM image of the sawn surface of the micro-magnet was analyzed, as shown in the Fig. 6b. It was identified the some regions of oxides, which corroborate with the oxide phases peaks of the Fig. 6a. The minimum amounted of these secondary and oxide phases and no $Nd_2Fe_{14}B_1$ modification can indicate a low degradation of the magnet. This is an important indicative that the diamond wire sawing is a promissor machining process to micro-magnet manufacturing.

3.4. Influence of the cutting tool on the coercivity of the Nd-Fe-B magnets

For the values of coercivity in relation to the variation of the cutting tool (see Fig. 7), analyzing the data, it was possible to observe that the value of intrinsic coercivity (H_{cj}) of the samples machined with the laboratory wire, whose final thickness was 500 µm, presented a value of 17.23 kOe. On the other hand, the sample machined with industrial wire with a thickness of 495 µm had a value of 17.33 kOe. Thus, it can be stated that there is no significant difference between the H_{cj} values of the samples obtained by different diamond wires, since the values are very close with the magnet before the machining. For the as etched sample, it was observed a slight reduction in H_{cj} values when comparing with the as sawed samples, as shown in the Fig. 7.

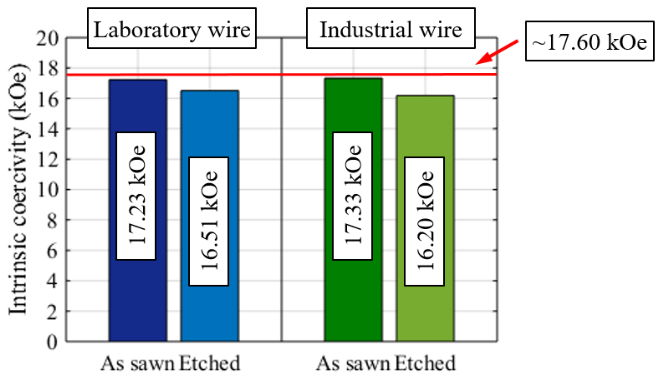

Figure 7. Intrinsic coercivity results

4. CONCLUSIONS

The present paper aimed to evaluate the surface integrity and magnetic properties resulting from diamond wire cutting of Nd-Fe-B based magnets in terms of machined surface morphology, roughness and intrinsic coercivity. For this purpose, the cutting tools were varied and the cutting speed was kept at v_c = 10 m/s and the feed speed at v_f = 1 mm/min with a tension of 20 N for the diamond wires. The tests were carried out under 5% dissolving emulsifiable fluid cooling. Firstly, the hardness of the material before and after cutting was analyzed. The morphology of the machined surface was analyzed and the surface roughness was quantified in terms of the parameters R_t, R_a and R_q. In order to verify the magnetic properties, the intrinsic coercivity was analyzed. Based on the results obtained, it can be concluded that:

- The hardness of the material in the samples sliced with the industrial wire and the laboratory wire had similar results, with averages of 547 and 633 HV, respectively. For the same samples after electropolishing, the values obtained were 555 and 641 HV, both before and after electropolishing the average hardness values agree with the values reported in the literature, between 500 and 700 HV for Nd-Fe-B based magnets.
- The cutting tool showed influence on the morphology of the machined surface, which presented regions with brittle and ductile removal regime. The samples machined with the laboratory wire suffered a greater removal in the brittle regime, compared to the samples machined with the industrial wire, which presented a predominance of ductile removal. Increasing the grain size of the wire increases the penetration depth of the tool may lead to the formation of a greater number of craters.
- The R_t, R_a and R_q values presented lower values with the industrial wire when compared to the laboratory wire, as a result of the smaller wire diameter the penetration is smaller and the removal of the kinematic edges favors the ductile removal. For the same samples, the average roughness values after electropolishing showed no significant change.
- For the quantification of the crystallographic texture, it was possible to observe that all the peaks found are from the $Nd_2Fe_{14}B$ and Nd-rich phases, which is a result of a more uniform surface without as much damage. Some secondary and oxides peaks were identified in the diffractogram that refer to the formation of oxides and/or impurities during the machining.
- The variation of the cutting tool did not show significant influence on the coercivity value of the Nd-Fe-B magnets. It was possible to observe that this property presented closed values for samples machined with the laboratory wire to those machined with industrial wire. There was a slight reduction of the coercivity for the etched samples.

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