The effects of dry grinding processing parameters on the electromagnetic and geometrical properties of Nd2Fe14B permanent magnets

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Abstract. The automotive industry has grown increasingly interested in electric propulsion over the past few years, which has led to an increase in engine and battery efficiency improvements. The study of rare earth permanent magnets has recently become essential for the development and improvement of electric engines because rotors are constructed of permanent magnets that interact with the stator windings. Due to its strong remanence and coercive field, neodymium magnet is the most frequent rare earth employed in electric motors. Nd2Fe14B magnets are made by sintering in the simple geometries of prismatic, cubic, and cylindrical, and they typically require machining to achieve the final shape necessary for the construction and assembly of the rotor. However, prismatic Nd2Fe14B row materials that have just been sintered are extremely brittle and challenging to produce; as a result, they are typically finished through grinding with a CBN grinding wheel. This study's objective is to evaluate the effects of a dry grinding process with a wet traditional one through an experimental campaign. Process parameters such as cutting speed and feed rate were varied and surface roughness and morphology were compared, together with the magnetic field loss due to the increment of the temperature occurring during the processes. Due to the large number of electric motors that are anticipated to be manufactured in the upcoming years, dry grinding could represent the turning point in terms of eco-sustainability of the process.

Introduction

Rare earth elements (REEs), or “rare earth metals”, are a group of seventeen elements which consists of fifteen lanthanides, as well as scandium and yttrium. These REEs have similar properties and are often found together in geologic deposits. Most of them are used in wind turbines, electric vehicles, and solar panels, the main function for which these materials are used is that of permanent magnets [2]. Due to the electrification of the automotive industry, rare earth magnet applications surged by more than 56% between 2010 and 2015; this trend seems destined to continue in the upcoming years [3]. In this study we will focus on Neodymium magnets that are characterized by very high flows and the highest energy products among all state-of-the-art magnets. We will focus on the effects induced on magnetism by the grinding process after having studied and fixed the chemical composition of examined magnets. Initially the Neodymium could resist up to 120 ° C, after which the material tended to demagnetize. This greatly reduced the fields of application, but today new technologies have raised this limit up to 230 °C. This temperature limit can be reached in two main moments: during the on-site application in the machine and in the vehicles or in the production cycle of the components that include magnets like rotors in our case. The main goal of this work is to understand the consequences that grinding induces on the magnetic field generated from the rotors. In the contact area between the grinding wheel and the workpiece heat is generated but it was hard in our situation to detect the trend of the temperature during the process. We therefore decided to investigate the degradation through the measurement of the magnetism pre and post process correlating it to the parameters of the process itself. Another aim is to do this process in a sustainable way and to reach this result, one of the main factors is to eliminate the lubro-refrigerant fluid. A single grinding machine normally requires 2000–4000 L of oil to fill it, of which 100–200 L must be changed each month [4], having an especially negative impact on the environment and the workers. Oil is used to reduce grinding forces, absorb heat created during the process, and make it easier to remove grinding swarf and wheel debris from the cutting zone [5]. The tool used to carry out the test plan is a CBN grinding wheel that we describe in the following chapter. The work done by Lin et al. [6] enables to state that using CBN wheels is better to keep temperature low than using aluminum oxide wheels, in this study they also demonstrate that the differences between the temperatures for dry and wet grinding with CBN wheel appeared to be small [7]. Considering these statements, it should be possible to work magnetic material without the use of coolant liquids, provided that the component's magnetic properties are not compromised. In this work, authors find the optimized parameters to carry out the process by reducing the environmental impact while maintaining the performance of the material.

Materials and methods

Before starting with the removal process on the magnet and with the definition of the processing parameters, a study of the raw material was carried out. This study includes the analysis of the material composition, the surface morphology and the distribution of the punctual phases. After understanding the characteristics of the material, will be described the type of tools used and the parameters on which attention will be paid in the test plan.

Microstructural analysis

A standard metallographic preparation was used to examine the material's structure: the sample was prepared by hot mounting in a phenolic resin and then polished with a metallographic machine by using SiC abrasive papers with decreasing grain size from 80 to 2500. The last two polishing stages instead were performed with the use of two different diamond suspensions with respective granulometry of six and one micron. The ultrasonic washing concludes each polishing stage of the sample to avoid contamination of the process with the subsequent decreasing granulometry. Vilella's reagent (5 ml HCl, 1 g picric acid, and 100 ml ethanol) was finally used to etch the polished surface for 10 to 15 seconds before cleaning it with ethanol and drying it with hot air [8]. A Zeiss Axio optical microscope (OM) was used to observe the sample thus prepared and chemically etched. Following OM, the samples were analyzed with scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS, X-Act/INCA,10mm^2 SDD Oxford Instruments) to identify the distribution of different elements and phases in the center of the grains and in their borders. This first analysis of the material was conducted to learn more about the chemistry inside the magnets and understand how it affects magnetism. The dissolution of the magnetic material in acids (nitric and hydrochloric) was used as part of the analysis to study the material; using this method, it is possible to precisely determine the compositional percentages by weight of the elements inside the magnet. The analysis took place through an analytical instrument capable of measuring the light (optical emission) produced by a liquid sample when introduced into an inductively coupled argon gas plasma. Through this mechanism it is possible to quantify the metals contained in the sample by measuring, for each one, the intensity of the light emitted with a specific optical bench. The intensity of the light emitted allowed us to quantify the presence of each element. The instrument used to perform this type of analysis is the MP-AES following the standard procedures of the ICP-OES analysis. (UNI EN ISO 17072-1).

Characterization of the magnet: roughness, hardness, and magnetism

The base material was observed with a non-contact optical profiler (Taylor Hobson CCI MP-L) after the sintering process and prior the grinding test plan. With the same instrument the roughness of the samples after machining was measured to appreciate the differences induced by the variation of the machining parameters. To find out the hardness of the material that composes the permanent magnets, a Rockwell hardness tester ERGOTEST COMP 25 from the Officine Galileo was used. The magnetism was tested before and after the grinding process to check if it was influenced by the grinding process. The 18 samples were measured with a gaussmeter (PCE Instruments, PCE-MFM 3000) prior to machining to identify the magnetic field generated in the unprocessed state for each component in order to comprehend the entity of the magnetic degradation brought on by the grinding. The gaussmeter probe was installed on a centesimal motion system with three degrees of freedom (x,y,z); the precision of the handling system is essential to maintain the constant air gap between the probe and the sample being measured. This air gap has been set at 0.1 mm from the material and it must be respected when measuring the magnetic field of the raw and machined material.

Magnets grinding

In the traditional production process of the rotors, the parallelepiped-shaped magnets (Fig. 1(a)) are glued together and grounded simultaneously on a cylindrical grinding machine. In this case the samples will be subjected to a tangential grinding machine on a single magnetic element of the rotor at a time to simplify the test plan and to have a greater number of samples. The post-process surface integrity and the corresponding magnetic degradation were evaluated by working on a single magnet stick [9]. The CBN grinding wheel is composed of cubic-shaped grains with a CBN concentration of 40% and a porosity of 37%. The hardness of the binder is low and the porosity is chemically induced. The grinding machine (Rettifica Delta, model TP 1200 x 500) on which the 18 samples have been dry ground is made up of a grey cast iron frame which supports a workpiece table equipped with a permanent magnet table for anchoring the components to be machined. The table runs along "V" guides with recirculating ball bearings and oil scraper lubricated by an intermittent control. Longitudinal and transversal motions of the table, as well as the vertical motion of the wheel spindle, are manually controlled by handwheels. As shown in Table 1, the cutting speed and feed rate were varied on three and two levels, respectively, with three repetitions being carried out for each parameter combination.

Table 1 Grinding test plan.

N °samples	Wheel speed [RPM]	Cutting speed [m/s]	Depth [mm]	Feed rate [mm/s]
1-3	1400	14,6	3 x 0.01	90
4-6				132
7-9	1900	19,9		90
10-12				132
13-15	2400	25,1		90
16-18				132

Result and discussion

Chip formation depends on the grit size of the grinding wheel and the peripheral speed with which it works. With the same wheel selected for a process, chip size can be changed by changing the grinding parameters. The cutting speed greatly affects the size of the chip; at high peripheral speeds, the chip is smaller, generating less force on the grain and applying less stress on the wheel. At the same time, small chips and high cutting speeds increase the amount of heat dissipated, increasing the risks of the wheel wearing. When grains and binder break, other new sharp elements will be made available, and the removal capacity will increase [10]. Theoretically, wheels with soft behavior generate less heat because they always have new cutting edges which facilitate removal. Wheels with hard behavior have a longer life but if the chips are too small, they can cause clogging and overheating of the piece. The most influential parameter on the volume of the chip formed is the feed rate, the substantial difference between these two parameters is that the cutting speed does not affect the cycle time. Increasing the feed rate is possible to reduce the production time but it must be taken into consideration that the mechanical stresses on the grinding wheel will increase and the precision of the machining will decrease.

Metallurgical characterization

Starting from metallographic images captured by OM and following ISO 4499-2:2020 standard, the mean grain dimension was measured and the final results is 8 microns. Another aspect of such results shows the presence of a sintering binder. The binder is used by the manufacturers of rare earth magnets to perform the sintering operations of the components, usually this process takes place by placing powders and binders in the matrices subjecting them to high temperatures and high pressures [10]. The Fig. 1(a) shows the sample before grinding and Fig. 1(b) represents the microscopic characteristics of the base material.

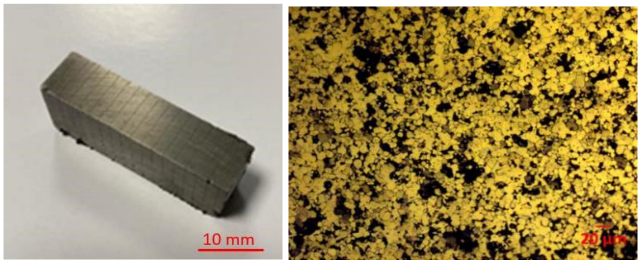


Fig. 1 (a) stick magnet (b) Metallographic structure

Chemical composition

The results obtained with EDS analysis are shown in Table 2.

Table 2 Result from the dissolution analysis

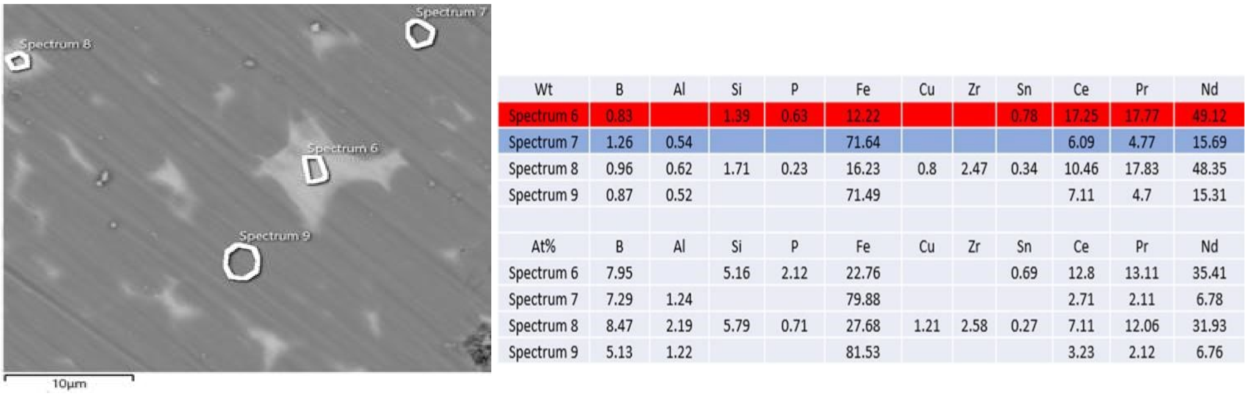
	Fe	Nd	B	Pr	Dy
Wt %	65	27	0.77	<LdR	3.3
S. Dev.	3	1	0.04		0.1

The Nd2Fe14B material's stoichiometric composition is confirmed by this test, along with one additional finding: the presence of dysprosium. According to Brown's et al. [4] research, the presence of dysprosium alters magnetic properties of permanents components. Dysprosium could increase the modulus of the coercivity which in practice corresponds to the increase in resistance to demagnetization, on the other hand this alloying causes a reduction in the magnetic remanence [11]. When using these types of magnets, temperatures tend to rise, and the dysprosium helps maintain a significant resistance. In Brown's et al. [4] study dysprosium and praseodymium were analyzed and an amount of 0% and 10% of dysprosium was measured. In this condition, the magnetic coercivity decrease with the grow of the temperature in both materials but in the material where more dysprosium was measured, the temperature starts to decrease after reaching a higher value [4]. It can be concluded that materials rich in dysprosium have higher magnetic coercivity at the same operating temperature and, as a result, are more resistant to demagnetization.

Additionally, it has been observed that the magnetism of the same material obtained using different manufacturing processes can vary significantly. Sintering processes produce magnets that have a higher magnetic remanence at the expense of coercivity. The starting magnet conditions studied in the paper, with 3.3% of dysprosium and the use of sintering process, have probably mitigated the effects on magnetism that ultimately result.

SEM characterization

Analysing the composition at the centre of the grain, the stoichiometric constitution of the material occurs (spectrum 7) in Fig. 2 (a). At the grain boundaries it was noticed instead that the elements in these areas differ widely from the standard ones (spectrum 6) Fig. 2 (b), mainly because praseodymium and neodymium are there concentrated. The presence of praseodymium was particularly studied by H. Sepehri-Amin and explains the growing of the magnetic coercivity from these intergranular phases [12]. Traces of C,O,Al,Si,Cl were identified by SEM analysis, as shown in Fig. 2(b). This could be due to the sample preparation steps that require the use of SiC abrasive papers and a lot of water to perform the cold polishing. The presence of copper could indicate that some of the elements used to form the sintering powder may have come from recycled sources, usually these magnets work near the stator windings which are made from copper which is likely to contaminate the finished product. Sometimes zirconium is used as a binder in the constriction of powders, so it is not difficult to find it at the grain boundaries.



Wt	B	Al	Si	P	Fe	Cu	Zr	Sn	Ce	Pr	Nd
Spectrum 6	0.83		1.39	0.63	12.22			0.78	17.25	17.77	49.12
Spectrum 7	1.26	0.54			71.64				6.09	4.77	15.69
Spectrum 8	0.96	0.62	1.71	0.23	16.23	0.8	2.47	0.34	10.46	17.83	48.35
Spectrum 9	0.87	0.52			71.49				7.11	4.7	15.31
At%	B	Al	Si	P	Fe	Cu	Zr	Sn	Ce	Pr	Nd
Spectrum 6	7.95		5.16	2.12	22.76			0.69	12.8	13.11	35.41
Spectrum 7	7.29	1.24			79.88				2.71	2.11	6.78
Spectrum 8	8.47	2.19	5.79	0.71	27.68	1.21	2.58	0.27	7.11	12.06	31.93
Spectrum 9	5.13	1.22			81.53				3.23	2.12	6.76

(a) (b)

Fig. 2 SEM image (a) and element concentration (wt% and at%) measured on the selected areas (b)

Hardness and roughness characterization

The average hardness measured in each of the 18 samples is about 50 ±2 HRC, this high value combined with the high brittleness of the sintered material, making the magnets difficult to machine. The roughness measured with non-contact optical profiler (Taylor Hobson CCI MP-L) on the sintered component before grinding is very low (Ra = 0.27 μm) and subsequent cutting operation negatively affects this value. In Fig. 3 the correlation between grinding parameters and roughness can be seen. The roughness decreases as the cutting speed increases and therefore the rotation speed of the grinding wheel increases.

It is interesting to observe that rare earth-based materials follow the same trend that iron alloys and steel would have if subjected to the same process. Although feed rate has a negative impact on surface finish, which should remain below 0.42 μm to allow for proper assembly of rotor parts, increasing the feed rate enables to shorten production cycle times. Trough non-contact optical profiler (Taylor Hobson CCI MP-L) the surface of the worked magnets was scanned and collected; here the worst and the best results (respectively sample number 5 and 16). Fig. 4 (a) shows the 2-D of the surface with the highest roughness value among all (0,51 μm). On the other hand, Fig. 4

(d) shows proper cutting that allowed for the best roughness value (0,33 µm), highlighting that the tool effectively cut the material's surface while leaving clean lines on the same layer. Fig. 4 (b) and Fig. 4 (e) are useful to understand the profile that the instrument reads to produce the average value of respective roughness.

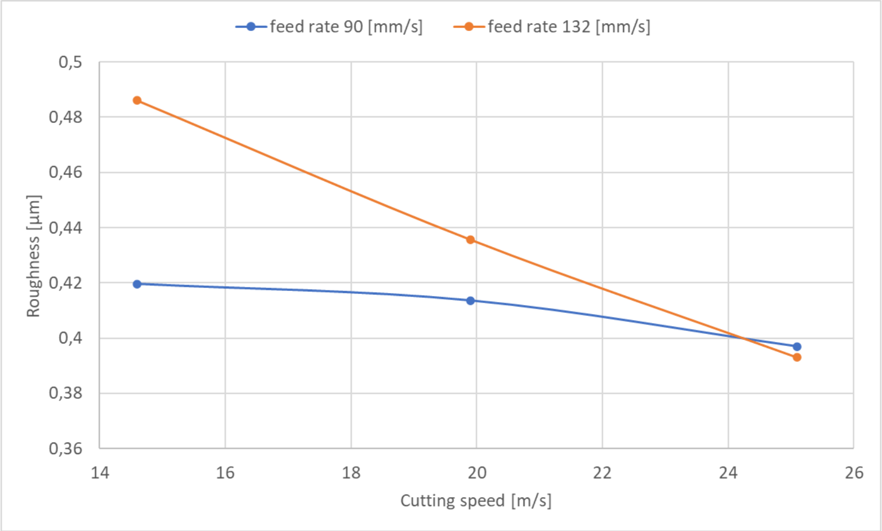


Fig 3: Effect of grinding process parameters on the roughness

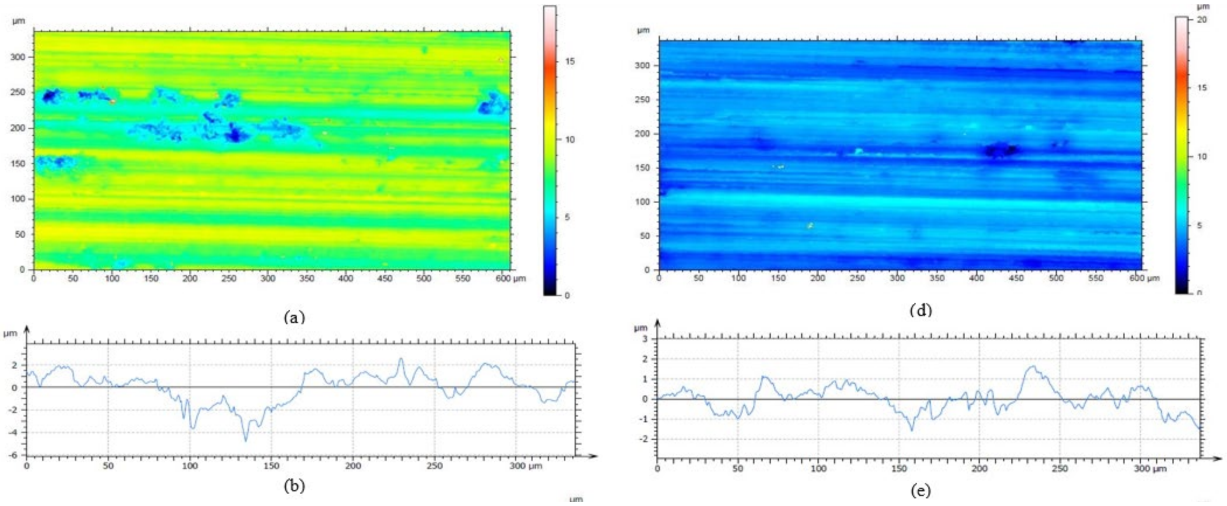

(a)
(d)
(b)
(e)

Fig. 4 Ra roughness measured on samples 5 (a,b) and 16 (d,e): (a,d) show 2-D reconstructions of samples surface and (b,e) represent a linear roughness acquisition through the grind marks.

Sample characterization after grinding

Several studies have already analyzed the distribution of temperatures reached in the grinding area, in this work authors focus the experiments on process parameters that have relevant impact on heat generation. As we know increasing the cutting speed helps the removal of material and the obtaining of a better final surface, as reported before in the paragraph about the roughness, but at the same time the heat generated increases as well. According to the graph in Fig. 5 and Table 3, when feed rate around 90 mm/s was selected, both low (14,6 m/s) and high cutting speeds (25,1 m/s) do not lead to significant magnetism losses which are in the range of 10-15 mT. On the other hand, when the feed rate increases to 132 mm/s, the highest cutting speed (25,1 m/s) generates a substantial loss of magnetism of 25 mT. Until this last case the magnetism degradation is simply imputable to the volume reduction of the active material since a linear correlation between the volume of the magnet and the intensity of the magnetic field produced was highlighted. When the decrease in magnetism reaches more significant values, like twice the previous ones (20-25 mT) the heat becomes the main cause. The increase of the cutting speed, as demonstrated by the work of Lin et al. [6], causes the increase of the temperature and consequently is responsible for the magnetic degradation. With the introduction of lubro-refrigerants, it is possible to increase the feed rate and cutting speed but thereby compromising the environmental considerations. Before analyzing the correlation between the loss of magnetism and both the cutting speed and the feed rate it is necessary to keep in mind that the principal antagonist of this property is the high temperature. In the grinding process it is easy to generate heat in the contact zone between the piece and the grinding wheel especially if the parameters are not optimized.

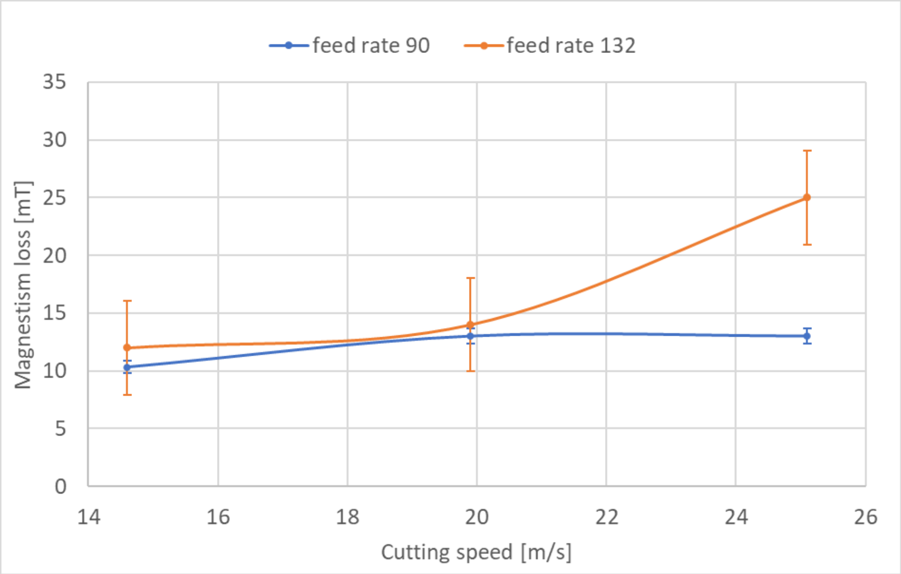


Fig. 5 Correlation between magnetism degradation and grinding parameters.

Conclusions

As the numerical results show, it is possible to grind permanent magnets without using any fluids, maintaining the magnetic field within an acceptable range. This can be considered a major achievement as these hard magnetic materials will surely be processed more frequently in the evolution of the manufacturing in the automotive sector. The rare earth permanent magnets machined with CBN wheels exhibit trends like those of conventional steels in terms of surface finish. Except for samples that are machined simultaneously at a high feed rate and high cutting speed, most of the time, the magnetic degradation brought on by the grinding process is negligible. The presence of 3.3% of Dysprosium increases the coercivity and consequently the resistance to the demagnetization at the same operating temperature making the application range of this material wider. The better roughness (Ra) obtained after grinding is around 0.4 µm and it has been reached with a cutting speed corresponding to 25,1 m/s and a feed rate of 132 mm/s. This corresponds to an overall productivity improvement of compared to the current practice. The only combination of parameters that involves a non-negligible magnetic degradation, which is around 5%, has a cutting speed of 25,1 m/s and a feed rate of 132 mm/s.

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