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ADDITIVE MANUFACTURING OF RARE EARTH PERMANENT MAGNETS: A REVIEW ON LASER POWDER BED FUSION (LPBF)

Röhrig, M.;

melissa.rohrig@posgrad.ufsc.br

Fim, R.G.T.

Mechanical Engineering Department, Federal University of Santa Catarina, UFSC, Florianopolis, SC, 88040-001, Brazil
rafael.gitti@posgrad.ufsc.br;

Faria, R.N.

Metallurgy Department, Nuclear and Energy Research Institute, IPEN-CNEN, São Paulo, SP, 05508-900, Brazil
rfaria@ipen.br

Landgraf, F.J.G.

Department of Metallurgical and Materials Engineering, Polytechnic School of the University of São Paulo, EPUSP, São Paulo, SP, 05508-030, Brazil
f.landgraf@usp.br

Pla Cid, C.C.

Mechanical Engineering Department, Federal University of Santa Catarina, Florianopolis, SC, 88040-001, Brazil
cristiani.campos@ufsc.br

Ahrens, C.H.

Mechanical Engineering Department, Federal University of Santa Catarina, Florianopolis, SC, 88040-001, Brazil
carlos.ahrens@ufsc.br

Wendhausen, P.A.P.

Mechanical Engineering Department, Federal University of Santa Catarina, Florianopolis, SC, 88040-001, Brazil
paulo.wendhausen@ufsc.br

Abstract. Additive Manufacturing (AM) emerges as an alternative technique to fabricate rare earth (RE) based bonded magnets, as reported by several authors, overcoming the challenges faced by conventional techniques in terms of geometrical limitations and possibly magnetic flux configuration. In the case of the Laser Powder Bed Fusion (LPBF) technique, one important challenge is to increase the magnetic flux density levels up to the commercially available injection molded ones, which stand out as a benchmark. This enhancement in magnetic performance can be attained by increasing magnetic properties such as remanence (B_r) and consequently the energy stored per unit volume ($(BH)_{max}$). Since B_r values are proportional either to the density and magnetic texture level of the magnet, a practical approach is to increase both values once the current literature reports the obtention of highly porous and magnetically isotropic components. On Powder-based AM systems, for example, the porosity level of the as-printed magnetic samples is very sensitive to both powder characteristics and processing parameters. In the case of Nd-Fe-B bonded magnets, the main target is to increase the magnetic texture values once magnetically anisotropic powders are commercially available. On the other hand, for the Sm-Fe-N magnetic system, the goal is adequate powder morphology, which is mostly found as flake particles, not suitable for AM processes. In this work, the influence of processing parameters and technological properties of the raw materials employed on the final magnetic properties of the as-printed components obtained via LPBF are discussed. Densification of Nd-Fe-B bonded magnets has been reported by the feedstock composition adequation, tuning the fraction of binder. This approach allowed the obtention of bonded magnets with only 5% porosity using spherical particles. Concerning texturization methods, there are promising alternatives but still needs further investigation. In the case of Sm-Fe-N bonded magnets, adjustments on both particle morphology and feedstock composition emerge as future alternatives to reduce the current elevated porosity degree of the as-printed magnetic samples.

Keywords: Additive manufacturing, Laser Powder Bed Fusion, permanent magnets, Nd-Fe-B bonded magnets, Sm-Fe-N bonded magnets.

1. INTRODUCTION

Rare earth (RE) based magnetic materials have been widely used in many industrial applications, primarily applied to energy harvesting and automotive sectors for electric and hybrid vehicles production. In this decade, the increasing demand for this class of materials has attracted attention to develop alternative manufacturing processes and applications (Goodenough et al., 2018). Industrially, this material can be produced in two forms: sintered or polymer matrix bonded. The first one is obtained in form of sintered blanks and is submitted to post-processing steps to adequate its geometry for a determined application. Depending on the desirable geometry, raw material waste from machining/cutting operations can be as high as 70% of the sintered magnet mass, not readily reused or recovered (Matsuura *et al.*, 2006; Miura *et al.*, 2008; Machida *et al.*, 2003).

An alternative to sintered ones is the bonded permanent magnet, which comprises the compression or injection of a mixture of polymeric binder and magnetic powder into matrices, molds, or cavities. These manufacturing processes allow obtaining bonded magnets with elevated geometrical complexity with the minimization of waste generation, i.e., near-net-shape. Yet, depending on the level of geometrical complexity demanded, costs associated with matrix/mold manufacturing can make it infeasible.

Additive Manufacturing (AM) technologies emerge as promising routes to produce RE-based bonded magnets, overcoming many limitations that traditional manufacturing processes present. As a result of the principle of layer-by-layer construction, net-shape magnets can be obtained with no support structures and post-processing steps for geometrical corrections, such as cutting and machining, reducing or eliminating waste generation, ready for its application. The versatility of AM processes allows the rapid prototyping and development of customized parts in a brief period, giving rise to obtaining permanent magnets with unthinkable functionalities, such as functionally graded components and magnetic lines field manipulation (Paranthaman *et al.*, 2016).

Among the AM techniques used to obtain RE-based permanent bonded magnets, the main three are Extrusion-based, Binder Jetting, and Powder-based, each one with its particular benefits and challenges. The last one has attracted attention and will be discussed in more detail. This process is based on the successive consolidation of individual layers of loose powder (metallic, polymeric, ceramic, or composite), melting completely or selectively this layer, where the energy is delivered by a laser source or electron beam (Kruth *et al.*, 2005).

There are several reports on the obtention of RE-based bonded magnets via Powder-based AM, specifically the Laser Powder Bed Fusion (LPBF) technique. Not only the Nd-Fe-B bonded magnets are produced via this technique, but other emerging magnetic systems such as the Sm-Fe-N.

In the state-of-art, the major challenge on this subject is to increase the overall magnetic performance of the as-printed bonded magnets up to the level of the commercially available ones, which stands out as a benchmark. A practical approach to overcome this limitation is to increase both density and magnetic texture values of the printed magnets, since the majority reported are porous and isotropic. This work will discuss the challenges of RE-based bonded magnets AM, discussing the particular obstacles for each hard magnetic system.

2. LASER POWDER BED FUSION OF RARE EARTH BONDED PERMANENT MAGNETS

According to Gibson et al. (2021), on Powder-based AM, the Powder-based AM processing parameters can be divided into four categories: laser-related, scan-related, powder-related, and temperature-related parameters. These parameters mutually interact and are interdependent, influencing directly the consolidation process of the additively manufactured components. Detailed information is available in Table 1.

Table 1: Powder-based AM processing parameters.

Category	Parameters
Laser-related	laser power, spot size, pulse frequency, and duration
Scan-related	scan speed, spacing, and pattern
Powder-related	particle morphology, size, size distribution, intrinsic properties, and layer thickness
Temperature-related	powder bed temperature, feeder temperature, temperature homogeneity.

The investigation of these classes of parameters is an essential step to define the most suitable processing conditions for each material. The processing parameters are defined as a function of raw materials features, such as technological properties (apparent density and flowability index) and intrinsic properties (thermal, optical, and rheological, for example).

In the case of RE-bonded magnets, the combination of these parameters must be designed to result in the adequate sintering of polymeric particles while magnetic particles remain unaltered, forming a defect-free microstructure. The following sections will review the state-of-art will presenting these correlations for RE-based bonded magnets.

2.1 Isotropic Nd-Fe-B Bonded Magnets

In order to compensate for the absence of magnetic texture on the as-printed magnet, it is desirable to employ the highest magnetic powder fraction on the feedstock and eliminate porosity to the minimum achievable. Baldissera *et al.* (2017) reported the obtention of Nd-Fe-B bonded magnets via Selective Laser Sintering (SLS) technique, evaluating the influence of layer thickness (LT), hatch spacing (HS) and laser power (LP) on the porosity level of the as-printed magnetic samples. In their work, a mixture of spherical isotropic Nd-Fe-B powder (MQP-S-9-8, 66% vol.) grade and polyamide-12 (PA-12) powder (Innov'PA 1550 XS, 34% vol.) was laser processed into bonded magnets using a CO₂ laser ($\lambda = 10.6 \mu\text{m}$) as an energy source.

The combination between the maximum LP (62 W) and HS (0.3 mm) with the minimum LT (0.05 mm) resulted in bonded magnets with a mean geometrical density of $\rho = 3.6 \text{ g/cm}^3$. This value is the maximum achieved in this work, which represents a porosity level of around 30%. The obtained samples presented remanence (B_r) and maximum energy product ($(\text{BH})_{\text{max}}$) values of $B_r = 300 \text{ mT}$ and $(\text{BH})_{\text{max}} = 15.3 \text{ kJ/m}^3$. For a dense composite magnet obtained with the employed fractions, the calculated geometrical density is $\rho = 5.14 \text{ g/cm}^3$. The discrepancy between the manufactured sample and its theoretical limit is due to a poor consolidation level.

Although the authors presented an optimized set of parameters, where it was possible to reduce porosity, a poor consolidation still is observed, indicating that other factors besides processing conditions are limiting the densification process. SEM images from the fracture surface of the as-printed samples revealed the absence of a continuous polymeric matrix, which reinforces the lack of binder on the feedstock. Insufficient binder fraction can lead to the formation of a partially consolidated microstructure, unable to reduce porosity.

In an analogous direction, Mapley *et al.*, (2019) investigated the SLS process of Nd-Fe-B bonded magnets using particles with distinct morphologies and their impact on the resultant microstructure and magnetic properties. Feedstocks composed of a mixture of PA-12 powder (40% vol.) with both spherical (MQP-S-11-9 grade) or flake-shaped (XCN1108A grade) particles were laser processed into magnetic samples using a solid-state laser diode ($\lambda = 450 \text{ nm}$) as an energy source. The LP values varied from 0.5 to 1.18 W, with HS = 0.23 mm and LT = 0.1 mm.

The produced as-printed samples presented maximum geometrical density values of $\rho = 3.8 \text{ g/cm}^3$ (spherical powder) and 3.2 g/cm^3 (flake powder) when LP values were maximum. Even increasing the fraction of PA-12 on the feedstock, the magnetic samples presented a porosity level ranging from 25% (flake powder) to 21% (spherical powder). The reported results suggested an optimization from those addressed by Baldissera, possibly due to an increase in binder fraction. However, this density enhancement was limited due to setup particularities.

In all conditions explored, it is possible to observe that the as-printed magnetic samples obtained from the flake powder were systematically porous than those obtained with the spherical powder. Since Powder-based AM consolidates individual layers from a loose powder bed mixture of the magnetic and polymeric binder powder, the final porosity on the printed part is proportional to the powder bed density, strongly influenced by the technological properties of the raw materials used as feedstock (apparent density and flowability). Both are intimately related to particle characteristics such as morphology, particle size, and size distribution (Gibson *et al.*, 2021).

Spherical particles acquire a more packed configuration in the loose state than non-spherical ones, reflected by their technological properties (White *et al.*, 1937). Powders with elevated apparent density values generate a less porous powder bed, contributing to obtain denser parts since there are fewer pores available to be filled by the binder (Gibson *et al.*, 2021; Kruth *et al.*, 2005). In this situation, it is possible to use less binder on the feedstock, increasing magnetic particles fraction, thus increasing the overall magnetic performance. Non-spherical particles such as flake-shaped particles present reduced apparent density and flowability index values, indicating a less packed configuration on the loose state, resulting in a more porous powder bed. To reduce this porosity level, an increase in binder volumetric fraction could be a practical approach, where consolidation is enhanced at the expense of magnetic powder volume.

Fim *et al.*, (2020) reported the influence of both laser scan speed (LS) parameter and binder volumetric fraction on the final porosity of bonded magnets obtained via SLS. In their work, a mixture of spherical Nd-Fe-B powder (MQP-S-9-8 grade) and PA-12 powder (Duraform PA2200) was employed as feedstock, where PA-12 fraction ranged from 36% to 45% vol. The SLS process was performed varying the LS values from 600 to 1400 mm/s, employing constant LP, LT, HS, and powder bed temperature values. For the feedstock composed of 36% vol. PA-12, the geometrical density values of the as-printed samples were maximum when LS = 600 mm/s ($\rho = 3.91 \text{ g/cm}^3$) and minimum for LS = 1400 mm/s ($\rho = 3.32 \text{ g/cm}^3$).

Using the optimum LS value (600 mm/s) and increasing the PA-12 fraction up to 45% vol., the geometrical density of the as-printed samples was further increased, from $\rho = 3.91 \text{ g/cm}^3$ to $\rho = 4.33 \text{ g/cm}^3$, in this order. The heat distribution over the scanned area is altered when LS is varied. Elevated LS values promote a rapid heat flow out of the scanned area, interrupting the sintering process of polymeric particles. Reducing LS values maintains the scanned area heated for a longer period, assisting the sintering process, as seen by the reported values (Hejmady *et al.*, 2019).

Allying to these processing conditions, an adjustment on binder fraction promoted the elimination of the remaining porosity, ranging from 24% to only 5%. This enhancement on geometrical density values resulted in an increase in the overall magnetic properties, from $B_r = 363 \text{ mT}$ and $(\text{BH})_{\text{max}} = 21.4 \text{ kJ/m}^3$ (36% vol. PA-12) to $B_r = 385 \text{ mT}$ and $(\text{BH})_{\text{max}} = 24.1 \text{ kJ/m}^3$ (45% vol. PA-12). From the results reported by Fim *et al.* (2020) it can be concluded that employing

suitable processing conditions and tuning the feedstock composition is an effective method to increase the overall performance of the as-printed magnets.

2.2 Anisotropic Nd-Fe-B bonded magnets

Magnetic texture development is a vital step in permanent magnet manufacturing to increase magnetic performance (Herchenroeder *et al.*, 2002). Magnetic properties, such as B_r and $(BH)_{max}$, which are merit figures for a permanent magnet, are strongly related to magnetic texture. B_r can be described as Eq. (1):

$$B_r = \langle \cos\Theta \rangle f P J_s \quad (1)$$

where the alignment degree ($\langle \cos\Theta \rangle$) varies from 0.5 for an isotropic magnet and 1.0 for a perfectly oriented anisotropic magnet, the fraction of magnetic materials (f) varies from 0 to 1, P is the relationship between theoretical density and real density, and J_s is saturation polarization. The $(BH)_{max}$, which is energy stored per volume unit, can be expressed as a function of B_r values, as shown in Eq. 2. This presents that the energy stored in an anisotropic magnet is 4 times greater than an isotropic one, showing the importance of magnetic texture (Coe, 2020).

$$(BH)_{max} = B_r^2 / 4 \mu_0 \quad (2)$$

The compression/injection molding processes are carried out under an applied magnetic field, orientating the anisotropic particles parallel to the applied magnetic field, generating texture (Croat, 2018). In the case of the LPBF process, this step is still in the very beginning, with limited success so far. There are two approaches to induce magnetic texture: during the layer-by-layer construction (*in-situ*) or as a *post-printing* step. The first one comprises the application of a magnetic field (pulsed or continuous) on the loose powder bed previous to its consolidation via laser. By the successive consolidation of these oriented layers in a certain direction, it is feasible to induce magnetic texture. The second approach is to induce texture afterward the building process, by heating the as-printed magnets under a magnetic field. The heating softens the binder, giving freedom to the anisotropic particles to align parallel to the applied magnetic field. Further cooling step holds the particles in the desired direction, generating texture.

Gandha *et al.*, (2018) demonstrated the magnetic texture inducement process for Nd-Fe-B bonded magnets obtained via Extrusion-based AM. In their work, a commercial hybrid composite pellet composed of a mixture of 35% vol. PA-12 and 65% vol. anisotropic Nd-Fe-B powder (Magfine grade) + Sm-Fe-N based powder was used as raw material for Big Area Additive Manufacturing (BAAM). This work explored both *in-situ* and *post-printing* approaches: the *in-situ* alignment step was performed using permanent magnets (two 1-inch square Nd-Fe-B magnets) attached to the nozzle of the BAAM printer. The *post-printing* step was performed in a two-step way: first, the composite hybrid pellets were aligned in a Vibrating Sample Magnetometer (VSM) equipment, heating the samples to 257 °C for 15 minutes under applied magnetic field varying between 390 - 3900 kA/m. This step was carried out to determine the optimum alignment conditions (temperature and applied field H). Then, cubic magnetic samples were manufactured and post-aligned in a vertical furnace assembled between two electromagnets. In this step, the as-printed samples were heated to temperatures between 185 - 205 K for 15 minutes under a magnetic field of $H \approx 1190$ kA/m.

From the pellets alignment step, it was observed an expressive increase in B_r values up to $H \approx 1590$ kA/m, ranging from $B_r = 0.37$ T (starting isotropic pellet) to $B_r = 0.72$ T. On the range between 795 - 1590 kA/m, B_r values presented a discrete variation, and further increases beyond $H = 1590$ kA/m did not promote any increases on B_r values, indicating that the optimum applied field is between 795 - 1590 kA/m. Due to practical reasons, $H = 1190$ kA/m was adopted as an optimum value for further experimental procedures. Those results show the dependence between magnetic texture development and alignment conditions.

From the post-alignment step carried out using the as-printed samples, magnetic measurements revealed that for the same external applied field value ($H = 1190$ kA/m), the magnetic texture increases with the temperature as summarized in Table 2.

X-ray diffraction (XRD) patterns from the as-printed samples show a strong texture obtained, represented by the (0 0 l) reflections, which correspond to the easy magnetization axis of the $Nd_2Fe_{14}B$ phase. This was an expected behavior since the binder viscosity decreases as the temperature increases, giving freedom to the anisotropic particles to align parallel to the external field. Despite the promising results, magnetic texture values increased at the expense of the geometrical features of the samples, especially at elevated temperatures where B_r was maximum ($T = 205$ K).

This temperature is superior to the PA-12 melting point ($T = 183^\circ\text{C}$) and it was not possible to retain the geometry of the samples. Although this work is not specifically from anisotropic bonded magnets obtained via LPBF, it showed great potential to be further explored. There is a similar work from the same authors about this specific subject (Gandha *et al.*, 2018).

Table 2: Magnetic properties of the post-aligned pellets as function of magnetic alignment step parameters.

Temperature (°C)	B _r (T)	(BH) _{max} (kJ/m ³)
27	0.37	22
185	0.47	36
195	0.69	81
205	0.72	87

Mapley *et al.* (2020) investigated the obtention of anisotropic Nd-Fe-B bonded magnet via LPBF using an *in-situ* alignment setup. The authors adapted a previous SLS setup assembling a Helmholtz coil ($\phi = 104$ mm) around the building plate. The Helmholtz coil was energized using a DC supply delivering $i = 22$ A, which resulted in an estimated magnetic field of $B = 20.4$ mT. For comparison purposes, the mixture was pre-magnetized prior to the SLS to enhance the texture inducement process. In this step, the powder was subjected to magnetic field values in the order of $B = 70$ mT (5% of the intrinsic coercivity value of the powder). This magnetic field value was elected as optimum due to the observation of powder agglomeration for higher B values.

In this investigation, a mixture of anisotropic Nd-Fe-B flake powder (MQA-38-14 grade) and PA-12 powder was employed as feedstock for anisotropic sample production. Each powder layer was deposited and subjected to the magnetic field for 250 milliseconds. Two other grades of Nd-Fe-B powder were also used in the samples preparation for comparison, both isotropic (spherical and flake).

Magnetic measurements from the as-printed magnetic samples on both parallel (easy axis) and perpendicular (hard axis) directions revealed a difference of 18% on B_r values, indicating a preferred alignment. This difference between B_r values was further increased up to 46% when the anisotropic powder was pre-magnetized before the manufacturing step. These results showed that the magnetic field supplied by the Helmholtz coil itself was not sufficient to align the powder bed completely. From XRD patterns, it was observed an increase in the intensity of (0 0 l) peaks of the as-printed magnetic samples subjected to the external magnetic field, reinforcing the magnetic texture inducement.

The limited performance of the obtained anisotropic samples can be attributed to several factors: the first one is the magnitude of the external magnetic field applied to the powder bed. As described, an agglomeration of the loose magnetic particles was observed when $B > 70$ mT. This value is two orders of magnitude smaller than those employed by Gandha *et al.* (2018) to align the same powder, limiting magnetic texture inducement. Few milli Tesla could only partially align the powder bed.

Another limiting factor is the porosity level of the printed samples, which was reported to be $\rho = 2.85$ g/cm³, which is the same as the apparent density values of the loose powder ($AD = 2.88$ g/cm³), indicating that no consolidation was achieved. The porosity is detrimental to the overall magnetic performance as discussed earlier, contributing to diminishing B_r values, making the magnetic texture development ineffective. This is evidenced when samples obtained using the spherical isotropic powder presented higher B_r values than the anisotropic ones, due to geometrical density differences ($\rho = 3.83$ g/cm³). The reported results present a potential that can be deeply investigated and further optimized to maximize the overall magnetic properties.

From the cited reports, it is possible to highlight many limitations regarding this topic, each approach with its particularities that need to be further investigated to increase the effectiveness of the magnetic texture inducement process. It was demonstrated that the *post-processing* approach can be very effective to induce magnetic texture only up to a certain level. The binder softening step to give the magnetic particles freedom to align according to the external magnetic field presents several risks, especially geometrical ones. When the binder viscosity is low, magnetic particles can be aligned, generating a strong magnetic texture in the component. However, heating the as-printed components near the melting point of the binder has the potential to distort the samples at the expense of elevated induced magnetic texture values, as reported by Gandha *et al.* (2018).

The *in-situ* method also revealed several challenges. Particle agglomeration and formation of clusters induced by the applied external magnetic field limit the magnitude of B, thus hindering particle alignment, as seen in Mapley *et al.* (2020).

Powder bed distortions can influence the densification process, generating porous components and reducing the B_r values, reducing the effectiveness of the texturization step. Besides, anisotropic Nd-Fe-B powders are commercially available only on flake morphology, due to their production method. The particle morphology also influences the final geometrical density values, as presented earlier. Using flake-shaped particles would lead to the need of feedstock adequation, adding more polymeric binder fraction to compensate for the lack of densification. Depending on the fraction of binder added, porosity would be eliminated at the expense of magnetic powder loading, also reducing the effectiveness of texturization methods. Particle morphology adequation aiming at the increase of technological properties of anisotropic

powders for LPBF applications can be an effective method to increase the overall magnetic performance of the as-printed anisotropic bonded magnets.

2.3 Sm-Fe-N bonded magnets

The Sm-Fe-N magnetic system emerged as a promising alternative to the Nd-Fe-B-based permanent magnets in certain application niches. The similarity between their intrinsic magnetic properties makes Sm-Fe-N-based magnets a potential to be explored. One major advantage of this system is the superior corrosion and aging resistance compared to the Nd-Fe-B-based materials. A particular drawback is its metastability at temperatures above 600°C, where conventional sintering processes are infeasible, making it a suitable candidate for bonded magnet manufacturing (Coey and Sun, 1990).

Sm-Fe-N-based powder presents a well-known inversely proportional relationship between particle size and intrinsic coercivity (H_{cj}). To develop high magnetic performance powders, it is essential to reduce the particle size to the sub-micrometer scale, achieving H_{cj} values between 1900 - 2100 kA/m (Okada *et al.*, 2017). Powders with these features are available from a few commercial sources. However, it is impracticable to employ submicrometric powders as raw materials for the LPBF process, since fine particles present very limited apparent density and flowability index, compromising the obtention of bonded magnets via Powder-based AM.

Rapidly solidified materials such as melt-spun ribbons can be employed as raw materials for bonded magnets AM as an alternative to very fine particles in this case. This production method generates ribbons with a refined microstructure (nanoscaled grains), which can be further powdered into coercive particles with hundreds of micrometers (Katter *et al.*, 1991). The result is a flake-shaped particle, and despite H_{cj} values being smaller than those cited ($H_{cj} \approx 750$ kA/m), they can be employed for AM purposes (Coey, 2019). Due to morphological characteristics, this flake-shaped powder presents limited apparent density and flowability index when compared to spherical particles, leading to limitations in the manufacturing of bonded magnets via LPBF.

Engerhoff *et al.* (2019) reported the obtention of isotropic Sm-Fe-N based bonded magnets via LPBF using flake-shaped particles as raw material for feedstock production. Following a similar experimental procedure as Baldissera *et al.* (2017), a mixture of 66% vol. of Sm-Fe-N melt-spun ribbons (Nitroquench-P grade) and 34% vol. of PA-12 powder (Innov'PA 1550 XS grade) was laser processed into bonded magnets via SLS. The melt-spun ribbons were comminuted to an average particle size between 35 - 50 μm before feedstock production. This work investigated the influence of LP and LT values on the densification process of the as-printed magnets, where LP = 32 - 42 W and LT = 70 - 100 μm , using a CO₂ laser ($\lambda = 10.6$ μm) as an energy source.

The as-printed magnetic samples presented geometrical density values varying from $\rho = 2.30 - 2.48$ g/cm³ for all the explored conditions. These values are very close to the apparent density values (AD) of the feedstock, which was reported to be AD = 2.33 g/cm³ and represents a porosity level of 57%. The obtained results showed that the selected parameters could not consolidate the powder. This poor consolidation resulted in magnetic samples with limited magnetic properties, where B_r values were ranging only between $B_r = 240 - 300$ mT. The intrinsic coercivity values varied between $H_{cj} = 616 - 642$ kA/m, which are considerably lower than the starting powder. Since this particular magnetic property is very sensitive to microstructural modifications, it was hypothesized the formation of soft magnetic phases such as α -Fe due to oxidation processes during the laser processing. However, XRD analysis presented that such phases were not formed, indicating that the microstructure was unaltered during the SLS process and the H_{cj} reduction would have another origin.

SEM analysis from the fracture surface of the obtained samples revealed the absence of a continuous polymeric matrix, with a heterogeneous distribution of PA-12 on the microstructure. The vast majority of the Sm-Fe-N particles were poorly adhered to the binder, reinforcing the geometrical density values and magnetic measurements. The absence of a continuous matrix encapsulating the magnetic particles and hindering their movement explains the reduction of H_{cj} values. Both B_r and H_{cj} increased after a cold isostatic pressing cycle of the as-printed samples, eliminating part of the remaining porosity, supporting the hypothesis.

The poor consolidation level reported in this work can be attributed to the lack of PA-12 employed on the feedstock, as discussed in section 2.1. Flake-shaped particles exhibit inferior technological properties when compared to spherical particles, for example. This leads to a situation where the low accommodation of the particles must be compensated by increasing the fraction of the binder. Mapley *et al.* (2019) reported this effect, increasing the PA-12 fraction up to 40% vol., resulting in as-printed samples with superior density values ($\rho = 3.2$ g/cm³).

The reported results reveal the influence of the particle morphology and magnetic powder technological properties on the consolidation process of bonded magnets via LPBF. Future works can explore in depth this relationship aiming the porosity reduction of Sm-Fe-N bonded magnets.

3. Outlook

Additive Manufacturing of rare-earth permanent bonded magnets presents a great potential for future developments and applications. Great efforts have been made to increase the overall magnetic performance of the printed magnetic components, concentrating on porosity reduction and magnetic texture inducement techniques.

Several methods have been described to reduce porosity in Nd-Fe-B bonded magnets AM with great potential to be further expanded. Isotropic spherical particles are the most suitable for LPBF processing, generating components with elevated density with minor corrections on feedstock composition and processing parameters adequation. The absence of magnetic anisotropy, in this case, can be overcome by using an anisotropic powder as a feedstock. Magnetic texturization can occur during or after the AM processing, as briefly discussed. Despite the exciting developments, this subject needs further investigation.

In the case of Sm-Fe-N-based bonded magnets, the efforts are directed towards particle morphology adequation for AM applications. Unlike the Nd-Fe-B system, there is a limited offer of suitable powders to be used on AM applications, mostly concentrated in rapidly solidified materials with flake-shaped particle morphology. In addition, texturization methods are not applicable since anisotropic Sm-Fe-N powders are obtained in a submicrometric scale, which is far from being suitable for LPBF purposes. Efforts are now concentrated on increasing magnetic performance via porosity elimination, where particle morphology adequation emerges as a potential candidate for future research.

4. ACKNOWLEDGMENTS

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5. REFERENCES

- Baldissera, A. B., Pavez, P., Wendhausen, P. A. P., Ahrens, C. H. and Mascheroni, J. M. (2017) "Additive Manufacturing of Bonded Nd-Fe-B—Effect of Process Parameters on Magnetic Properties," *IEEE Transactions on Magnetics*, 53(11), pp. 1–4. doi: 10.1109/tmag.2017.2715722
- Coe, J. M. D. (2020) "Perspective and Prospects for Rare Earth Permanent Magnets," *Engineering*, 6(2), pp. 119–131. doi: 10.1016/j.eng.2018.11.034.
- Coe, J. M. D. and Sun, H. (1990) "Improved magnetic properties by treatment of iron-based rare earth intermetallic compounds in ammonia," *Journal of Magnetism and Magnetic Materials*, 87(3), pp. L251–L254. doi: 10.1016/0304-8853(90)90756-g.
- Croat, J. J. (2018) "Production and properties of bonded Nd magnets," in *Rapidly Solidified Neodymium-Iron-boron Permanent Magnets*. Elsevier, pp. 181–223. doi: 10.1016/b978-0-08-102225-2.00005-3.
- Engeroff, J. A. B., Baldissera, A. B., Magalhães, M. D., Lamarão, P. H., Wendhausen, P. A. P., Ahrens, C. H. and Mascheroni, J. M. (2019) "Additive manufacturing of Sm-Fe-N magnets," *Journal of Rare Earths*, 37(10), pp. 1078–1082. doi: 10.1016/j.jre.2019.04.012.
- Fim, R. G. T., Mascheroni, A. A., Antunes, L. F., Engeroff, J. B. E., Ahrens, C. H. and Wendhausen, P. A. P. (2020) "Increasing packing density of Additively Manufactured Nd-Fe-B bonded magnets," *Additive Manufacturing*, 35, p. 101353. doi: 10.1016/j.addma.2020.101353.
- Gandha, K., Li, L., Nlebedim, I. C., Post, B. K., Kunc, V., Sales, B. C., Bell, J. and Paranthaman, M. P. (2018) "Additive manufacturing of anisotropic hybrid NdFeB-SmFeN nylon composite bonded magnets," *Journal of Magnetism and Magnetic Materials*, 467, pp. 8–13. doi: 10.1016/j.jmmm.2018.07.021.
- Gandha, K., Nlebedim, I. C., Kunc, V., Lara-Curzio, E., Fredette, R. and Paranthaman, M. P. (2020) "Additive manufacturing of highly dense anisotropic Nd-Fe-B bonded magnets," *Scripta Materialia*, 183, pp. 91–95. doi: 10.1016/j.scriptamat.2020.03.012.
- Gibson, I., Rosen, D., Stucker, B. and Khorasani, M. (2021) *Additive Manufacturing Technologies*. Springer International Publishing
- Goodenough, K. M., Wall, F. and Merriman, D. (2017) "The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations," *Natural Resources Research*, 27(2), pp. 201–216. doi: 10.1007/s11053-017-9336-5.
- Hejmady, P., van Breemen, L. C. A., Anderson, P. D. and Cardinaels, R. (2019) "Laser sintering of polymer particle pairs studied by in situ visualization," *Soft Matter*, 15(6), pp. 1373–1387. doi: 10.1039/c8sm02081g.
- Katter, M., Wecker, J. and Schultz, L. (1991) "Structural and hard magnetic properties of rapidly solidified Sm-Fe-N," *Journal of Applied Physics*, 70(6), pp. 3188–3196. doi: 10.1063/1.349302.
- Kruth, J., Mercelis, P., Van Vaerenbergh, J., Froyen, L. and Rombouts, M. (2005) "Binding mechanisms in selective laser sintering and selective laser melting," *Rapid Prototyping Journal*, 11(1), pp. 26–36. doi: 10.1108/13552540510573365.
- Ma, B. M., Herchenroeder, J. W., Smith, B., Suda, M., Brown, D. N. and Chen, Z. (2002) "Recent development in bonded NdFeB magnets," *Journal of Magnetism and Magnetic Materials*, 239(1–3), pp. 418–423. doi: 10.1016/s0304-8853(01)00609-6.
- Machida, K., Masuda, M., Suzuki, S., Itoh, M. and Horikawa, T. (2003) "Effective Recovery of Nd-Fe-B Sintered Magnet Scrap Powders as Isotropic Bonded Magnets," *Chemistry Letters*, 32(7), pp. 628–629. doi: 10.1246/cl.2003.628.

- Mapley, M., Pauls, J. P., Tansley, G., Busch, A. and Gregory, S. D. (2019) "Selective laser sintering of bonded magnets from flake and spherical powders," *Scripta Materialia*, 172, pp. 154–158. doi: 10.1016/j.scriptamat.2019.07.029.
- Mapley, M. C., Tansley, G., Pauls, J. P., Gregory, S. D. and Busch, A. (2021) "Selective laser sintering of bonded anisotropic permanent magnets using an in-situ alignment fixture," *Rapid Prototyping Journal*, 27(4), pp. 735–740. doi: 10.1108/rpj-09-2020-0220.
- Matsuura, Y. (2006) "Recent development of Nd–Fe–B sintered magnets and their applications," *Journal of Magnetism and Magnetic Materials*, 303(2), pp. 344–347. doi: 10.1016/j.jmmm.2006.01.171.
- Miura, K., Itoh, M. and Machida, K.-I. (2008) "Extraction and recovery characteristics of Fe element from Nd–Fe–B sintered magnet powder scrap by carbonylation," *Journal of Alloys and Compounds*, 466(1–2), pp. 228–232. doi: 10.1016/j.jallcom.2007.11.013.
- Okada, S., Suzuki, K., Node, E., Takagi, K., Ozaki, K. and Enokido, Y. (2017) "Preparation of submicron-sized Sm₂Fe₁₇N₃ fine powder with high coercivity by reduction-diffusion process," *Journal of Alloys and Compounds*, 695, pp. 1617–1623. doi: 10.1016/j.jallcom.2016.10.306.
- Paranthaman, M. P., Shafer, C. S., Elliott, A. M., Siddel, D. H., McGuire, M. A., Springfield, R. M., Martin, J., Fredette, R. and Ormerod, J. (2016) "Binder Jetting: A Novel NdFeB Bonded Magnet Fabrication Process," *JOM*, 68(7), pp. 1978–1982. doi: 10.1007/s11837-016-1883-4.
- White, H. E. and Walton, S. F. (1937) "Particle Packing And Particle Shape," *Journal of the American Ceramic Society*, 20(1–12), pp. 155–166. doi: 10.1111/j.1151-2916.1937.tb19882.x.

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