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3D Printing of NdFeB Rare Earth Permanent Magnet

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Abstract: NdFeB (Neodymium magnets) rare earth permanent magnet is an advanced magnetic material characterized by a high energy product and excellent magnetic performance, which has broad application prospects. With the rapid development of 3D printing technology, its application in the research and fabrication of rare earth permanent magnet materials has become a research hotspot. This paper reviews the latest research developments of rare earth permanent magnet NdFeB materials in 3D printing. It introduces the basic properties and applications of rare earth permanent magnet materials and highlights the main challenge these materials faced, which is how do we improve their solid content. Additionally, the advantages and challenges of 3D printing technology in preparing rare earth permanent materials are analyzed in this paper. By comparing the variations in magnet properties of ferrite and rare permanent magnet materials with increasing temperature, it is found that the latter have relatively poor magnetic stability at high temperatures. Based on these points, the paper summarizes optimization methods of the current 3D printing process for rare earth permanent magnet materials. Finally, the paper discusses the development prospects of rare earth permanent magnet materials in 3D printing, as well as problems need to be solved and future research directions.

***Keywords*:** rare earth permanent magnet, NdFeB, 3D printing, ferrite, temperature

1. Introduction

3D printing is one of the rapid prototyping manufacturing technologies that allows for the direct production of products with complex structures. This makes it particularly suitable for the production of customized products, significantly improving the production cycle and reducing costs for many products. This is especially beneficial for some rare precious metals to maximize their potential. Consequently, 3D printing technology has been widely applied in industrial design, automotive manufacturing, aerospace engineering, medical engineering, etc [1-2]. In addition, 3D printing technology can achieve near-net shape forming for products with complex shapes, eliminating the need for subsequent mold manufacturing and mechanical processing, thus providing feasibility and theoretical support for 3D printing of magnetic materials. Moreover, 3D printing technology has greatly simplified the manufacturing of net-shaped bonded magnets, streamlined the prototyping of new-phase magnets, and enabled efficient utilization of precious rare earth elements. Among these, Al-Ni-Co alloys, hard ferrite magnets, and rare earth permanent magnet NdFeB are the main focuses of 3D-printed permanent magnet materials [3-4].

NdFeB magnetic material is a typical permanent magnet material characterized by a high energy product,

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remanence, and coercivity. Due to its high magnetic performance, NdFeB enables the efficiency, miniaturization, and lightweighting of magnetic devices in high-tech industries. This material has been widely used in national defense and military sectors such as aviation, aerospace, maritime, and weaponry, as well as in civilian and military fields like instrumentation, energy transportation, medical equipment, and electronic communications [5]. Furthermore, since NdFeB contains strategic rare earth elements such as Nd, Dy, and Tb, directly utilizing 3D printing to form NdFeB products can achieve near-net shape forming without the need for subsequent machining, thereby avoiding the waste of rare earth resources [6-7].

Based on the latest research, this paper mainly summarizes existing technologies in 3D printing of NdFeB permanent magnet materials, ferrites, non-rare-earth permanent magnet materials, and amorphous alloys, focusing on their performance and limitations, as well as the relationship between the microstructure and properties during the printing process.

2. Properties and applications of NdFeB magnet

Currently, NdFeB permanent magnet materials are produced through two processes: microcrystalline powder grinding and liquid phase sintering. Generally, the microstructure of NdFeB permanent magnets consists of single crystals, primarily the NdFeB phase, separated by non-magnetic thin layers. The toughness of sintered polycrystalline $Nd_2Fe_{14}B$ is limited by various internal defects, crystal grain size, and grain boundaries. The industrial sintering process of NdFeB permanent magnet consists of 8 main stages, as shown in Figure 1(a). In Figure 1(a), the alloy used for producing NdFeB permanent magnets is obtained through a rapid solidification technique known as "thin strip continuous casting"; however, the slow cooling rate limits the alloy's solidification into the necessary components. This alloy is decomposed using hydrogen, crushed, and ground into powder. The powder is then shaped by extruding single crystal NdFeB particles (5-10 μm), arranged into the desired shape within a magnetic field. Finally, the green billet undergoes sintering and annealing at a lower temperature, with a coating applied to preserve the physical and chemical properties of the NdFeB permanent magnet material and protest it from corrosion. During the sintering process of NdFeB permanent magnet, as temperature increases, the magnets achieve single-phase magnetic properties with high stability and corrosion resistance due to heat treatment, resulting in uniformly distributed fine grain bands after arc melting.

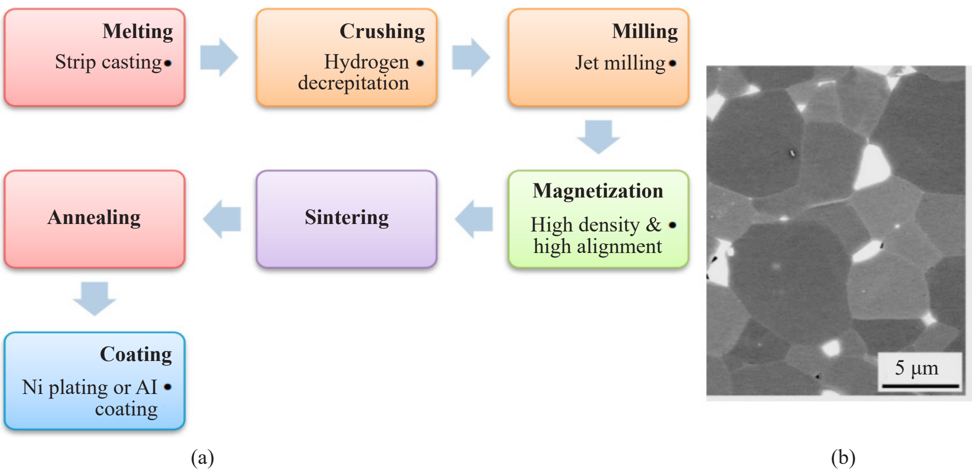

Figure 1. (a) The production process of NdFeB sintered permanent magnet. (b) SEM image of classical microstructure of sintered NdFeB permanent magnet

Figure 1 depicts a typical production process of sintered NdFeB permanent magnets and the microstructure of NdFeB magnets produced by this process. Although research on the additive manufacturing of magnetic materials is in its early stages, additive manufacturing simplifies near-net shape manufacturing and increases the efficiency of rare earth materials in utilization. Currently, the main methods of bonding NdFeB permanent magnet material are divided into four types: Injection molding, mold molding, calendering molding, and extrusion molding [3, 8]. With advancements in high technology and the strategic protection of rare earth, new bonding methods such as 3D printing become increasingly important. At present, the three most advanced 3D printing methods for NdFeB permanent magnet materials are three-dimensional printing (3DP), big-area additive manufacturing (BAAM) and direct-write 3D printing (direct-write 3DP) [9]. NdFeB products obtained through 3DP preserve their microstructure, maintaining coercivity without reduction in remanence compared to injection molding products, despite the lower solid content and thus resulting in a non-compact product. Therefore, how to improve the solid content in this method is a crucial future direction [10].

The magnetic and mechanical properties of NdFeB products obtained from large-area 3D printing are significantly superior to that from extrusion molding, making it suitable for large-scale industrial production. As for this technique, the future development trends primarily involve studying the effects of factors such as binder types, solid content, anisotropic powders, and molding temperatures on the magnetic and mechanical properties of molded products. NdFeB products obtained through direct-write 3DP exhibit good magnetic properties but have low solid content, prompting a development focus on improving solid content and stability, e.g. enhancing the capabilities of 3D printing to improve its stability [11-13].

3. 3D printing of rare earth permanent magnet materials

The powder bonding of NdFeB permanent magnet can be divided into three basic stages: powder grinding, equipment manufacturing and subsequent improvements. The properties of permanent magnet materials are mainly determined by the microstructure formed during the processing of magnets. The magnetic reversal of NdFeB bonded magnet starts from the surface of primary phase grains. In the current study, a special microstructure has been developed to counteract the internal magnetic reversal in NdFeB bonded magnets (Figure 1b). Here, single crystal grains NdFeb (gray in Figure 1b) with sizes ranging from 3-10 μm are surrounded by continuous amorphous thin layers (white regions in Figure 1b), with layer thicknesses of only a few nanometers. The intersecting Nd-rich phases within the NdFeB grains form a network, and the intersections of the Nd-rich phases are independently interconnected, smoothing the grain surfaces and reducing the number of structural defects at the boundaries of the thin layers, thereby lowering the reverse nucleation rate to some extent. In addition, the phase boundaries can magnetically separate the grain phases, preventing internal collapse within the magnet. As such, it can be concluded that the grain boundary phase is paramagnetic.

4. 3D printed of magnetic ferrite

Although 3D printing enables near net shape manufacturing of complex products, reducing costs in production and minimizing waste of rare resources, there are many challenges for printing and molding NdFeB materials, such as how to use correct binders with corresponding amount and exploring appropriate powder compositions. Compared with traditional molding methods, 3D printing technology needs to focus on increasing the solid content of NdFeB magnetic powders. Similarly, hard ferrite magnets are another type of 3D printing material that requires enhancement of magnetic properties through improved powder formulation. Hard magnetic ferrites are manufactured using ceramic processing methods with raw materials such as Sr-O or Ba-O and iron(III) oxide, as presented in Figure 2. As a new type of magnetic material, hard magnetic ferrites not only function as magnetic field generators but also possess advantages such as high coercive force, high specific saturation magnetization, good mechanical hardness and chemical stability. With these advantages, they can be used in traditional permanent magnets, high density magnetic storage, and permanent magnetic visual recording, as well as microwave filters. Currently, barium strontium ferrite is the primary research direction among ferrite permanent magnet materials. It is a ferromagnetic oxide with a hexagonal crystal structure, exhibiting good chemical stability, corrosion resistance, high resistivity, and dielectric constant at high frequencies. Moreover, this material features high uniaxial magnetocrystalline anisotropy, with the easy magnetization axis parallel to the C axis, and a large perpendicular magnetic anisotropy constant. Compared with traditional methods of producing barium-strontium hard ferrite powder, 3D printing can create a perfectly networked hexagonal barium-strontium ferrite structure. Experimental results show that the networked barium-strontium ferrite exhibits saturation magnetization close to theoretical values after calcination, as indicated by the hysteresis loop. In addition, the coercive force of ferrite powder prepared by 3D printing is higher than that prepared by traditional ceramic technology, reaching a value of up to 4-6 koe.

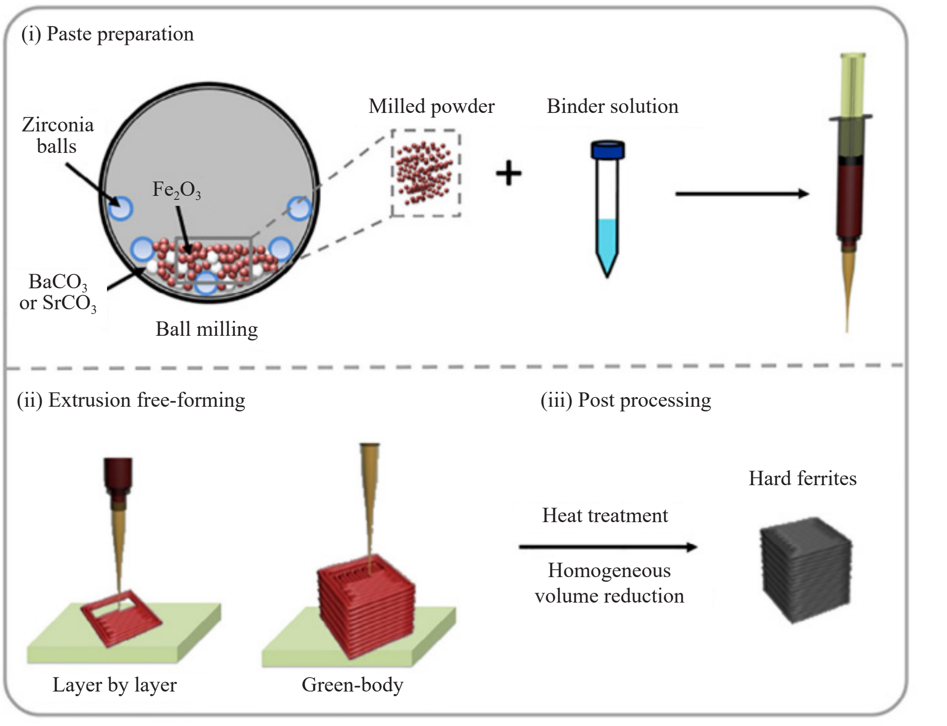

Figure 2. Schematic diagram of 3D printing production of hard

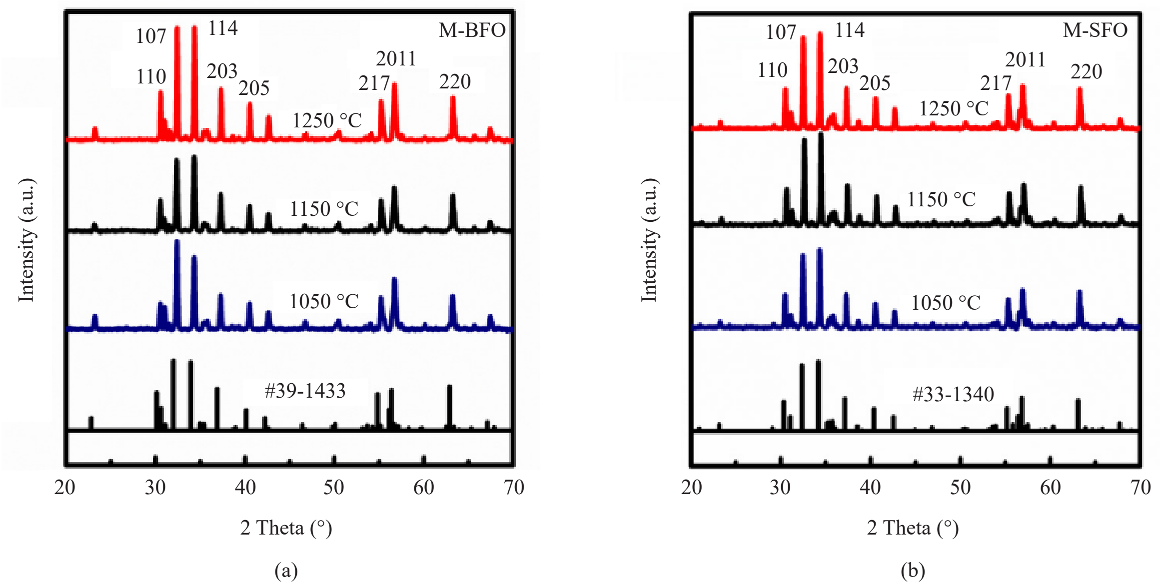

Figure 3. X-ray diffraction pattern of 3d-printed ferrite annealed at different temperatures. (a) barium ferrite (M-BFO) and (b) strontium ferrite

Figure 3 shows the X-ray diffraction patterns of printed ferrite annealed at different temperatures. All SRD peaks exhibit a strong correlation between the relative intensity and the temperature of annealing, indicating the hexagonal structure of m-type $BaFe_{12}O_{19}$ ferrite. The grain size of barium strontium ferrite increases with higher annealing temperatures. Therefore, in the 3D printing process of ferrite, controlling the heating temperature allows for precise control over grain crystallinity. By observing the grain size and microstructure of ferrite, it is revealed that as the grain size approaches the critical single domain limit, the impact of heat treatment on ferrite size becomes more pronounced. In comparison, NdFeB permanent magnet materials are generally unsuitable for high-temperature environments. For instance, when the temperature increases from 300 K to 315 K, a mere 15 K rise causes the magnetic flux density of NdFeB permanent magnet materials to decrease from 7.7 Tesla to 6.6 Tesla. Therefore, under high-temperature conditions, the magnetic properties of ferrites are superior to those of NdFeB [14].

5. Summary

As a direct prototyping technology, 3D printing can not only achieve near-net shaping of components with complex structures but also indirectly optimize the allocation of strategic resources. Due to magneto-electric reactions, magnetic materials are expected to play an increasingly important role in the era of rapid technology development. This paper introduces the application, advantages, and disadvantages of NdFeB permanent magnet materials in 3D printed magnetic materials. For instance, incorporating NdFeB materials in rare earth permanent magnet materials can reduce reverse nucleation rates. Meanwhile, compared to ferrite magnetic materials, NdFeB materials exhibit less stable magnetic properties at high temperatures.

Currently, the challenges of 3D printed magnetic materials mainly involve the shape, size, and composition of different magnetic powder materials, and their impacts on the magnetic properties of NdFeB permanent magnet materials. Therefore, key areas of research in the future would include studying how to increase the solid content of powder, selecting appropriate powder binders, and optimizing the laser beam scanning rate for powders.

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Conflict of interest

The authors declare no competing interest.

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