Scripta Materialia xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat

Viewpoint article

Additive manufacturing of near-net-shape bonded magnets: Prospects and challenges

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A R T I C L E   I N F O

Article history:
Received 21 September 2016
Received in revised form 27 December 2016
Accepted 28 December 2016
Available online xxxx

Keywords:
3D printing
NdFeB
Bonded magnets
Binder jetting
Big Area Additive Manufacturing

A B S T R A C T

Additive manufacturing (AM) or 3D printing is well known for producing arbitrary shaped parts without any tooling required, offering a promising alternative to the conventional injection molding method to fabricate near-net-shaped magnets. In this viewpoint, we compare two 3D printing technologies, namely binder jetting and material extrusion, to determine their applicability in the fabrication of Nd-Fe-B bonded magnets. Prospects and challenges of these state-of-the-art technologies for large-scale industrial applications will be discussed.

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1. Introduction

Permanent magnets (PM) refer to materials with a broad hysteresis loop; they are widely used in areas in which an energy conversion, usually from electrical to mechanical energy, is required, such as in motors and hard disk drives [1]. Another fact about permanent magnet is that they consist of a large amount of rare-earth (RE) elements such as Nd, Dy and Tb, majority of which are mined and separated in China, and US is experiencing a "rare earth crisis". As the strongest PM, $Nd_2Fe_{14}B$ based magnets occupy 2/3 of the PM market even though they cost 25 times as that of the hard ferrites ($BaFe_{12}O_{19}$). In response to address this RE criticality, considerable research efforts have been made to develop heavy RE free and/or reduced RE permanent magnets [2–4]. However, this approach involves screening tremendous number of compositions resulting in slow progress.

One of the alternative strategies to diversify the critical materials supply and lower the PM cost is to reduce the material waste associated with the manufacturing (*e.g.*, cutting, machining, *etc.*) which cannot be readily re-used. The state-of-the-art technology additive manufacturing (AM) is well-suited to fabricate magnets which frequently involve the expensive and critical RE elements. As opposed to conventional subtractive manufacturing, AM produces complex shaped objects through joining materials in a layer-upon-layer fashion based on a computer-aided-design (CAD). Owing to this unique fabrication method, AM exhibits significant advantages such as reduced materials waste and energy consumption, no machining/tooling required and low labor cost, *etc.* To date, the majority of the additive efforts have been focused on structural materials such as fiber-reinforced composites [5] and alloys [6–8], *etc.*, whereas AM of functional materials such as magnets is still in its infancy. Laser metal printing has been utilized to rapidly synthesize Fe-Co magnets with varying compositions, enabling fast assessment of magnetic properties of this binary system [9]. Nevertheless, metal printing of NdFeB magnets is more challenging owing to the high melting temperature, different evaporation rates of each elements and the complexity in the ternary phase diagram. Very recently, extrusion printing of NdFeB bonded magnets have been explored [10,11]. Huber *et al.*, reported the fabrication of Nylon bonded NdFeB magnet with a commercial 3D printer [10]. The magnetic powder loading fraction is 54 vol.%, and the density of the printed magnet is 3.6 g/cm^3, which is lower than that of the injection molded samples, indicating a higher level of porosity in the 3D printed samples [10]. Compton *et al.* fabricated NdFeB bonded magnets with a direct-write 3D-printer *via* an epoxy-based thermoset ink composed of 40 vol.% anisotropic MQA powder and 60 vol.% epoxy [11]. ASTM F42 committee classified AM into seven categories including directed energy deposition, powder bed fusion, binder jetting, and material extrusion, *etc.* [12]. In this viewpoint, we compare the feasibility of two of these technologies, namely binder jetting and material extrusion, for fabricating near-net-shape NdFeB bonded magnets. In particular, we demonstrate that the material extrusion method using the Big Area Additive Manufacturing (BAAM) system is superior in fabricating bonded magnets with magnetic and mechanical

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http://dx.doi.org/10.1016/j.scriptamat.2016.12.035
1359-6462/Published by Elsevier Ltd. on behalf of Acta Materialia Inc.

properties comparable to those produced by conventional injection molding method. The prospects and challenges of permanent magnets AM being adopted for industrial production will be evaluated.

2. Bonded magnets

Bonded magnets are fabricated by mixing the magnet powder with a polymer binder (*e.g.* nylon, epoxy, *etc.*), then molded into desired shapes *via*, conventionally, injection molding, compression molding, extrusion *etc.* [13]. The volume fraction of magnetic powder in injection and compression molding is typically 65% and 80%, respectively [13]. Compared to sintered magnets, bonded magnets have enhanced freedom in terms of geometry, and are more cost effective but at the expense of reduced energy product BH_{max} due to the incorporation of the non-ferromagnetic polymer binder [14]. In terms of mechanical properties, bonded magnets present a better ductility while lower tensile strength. The shape flexibility of bonded magnets enables innovative designs for motor magnets, which can potentially increase the torque output.

3. Binder jetting with ExOne X1-Lab

Binder jetting involves a liquid binder which is selectively deposited into a powder bed to bind materials to form complex shaped parts. It is suited to print magnets as it does not employ heat during the build process. Upon printing completion, the printed magnet is then placed in an oven at 100–150 °C to cure the thermoset binder. A detailed description of the set up and working principle of the ExOne X1-Lab printer is available in Ref. [15,16]. This AM technique has been shown to fabricate various metals [17], ceramics [18,19], and functional solid oxide fuel cells [16], *etc.* In this work, we printed NdFeB bonded magnets using two kinds of magnet powders - isotropic MQP-B-20173-070 (Magnequench) and anisotropic magfine powder MF18P (Aichi Steel), respectively. Fig. 1(a) shows some images of the printed magnets with a horseshoe, square, and ring shape. Fig. 1(b) presents the demagnetization curves of the parts printed with the isotropic powder MQP-B. The printing process did not degrade the intrinsic coercivity H_{ci} at all.

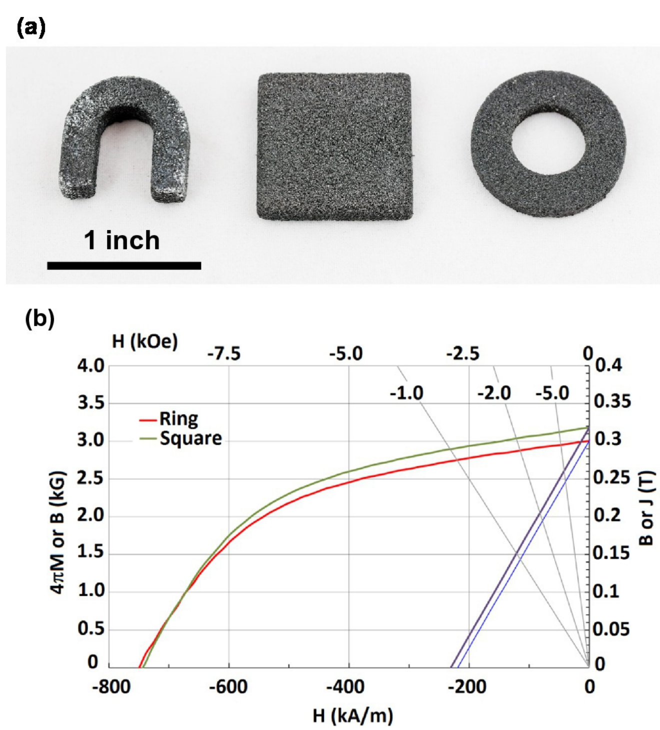

Fig. 1. (a) Images of the binder jet printed NdFeB magnets with different shapes; (b) magnetic properties of the binder jet printed NdFeB magnets using MQP-B powder. (reprinted with permission from Ref. [15]).

Density of the magnetic phase is essential to ensure magnet functionality as it determines how much magnetic flux the magnet can generate in a given space. Here, the measured density of the printed MQP-B magnet is 3.3 g/cm^3, which is nearly 43% dense compared to the theoretical magnet crystal density. The low density is related to the low volume fraction of the magnet powder as well as the inter layer and/or inter particle porosity. In fact, the commercially available thermoset binder from the ExOne company needs some improvement in terms of binding ability, and efforts are being made to apply stronger polymer binders to this 3D printing system.

Densification is a long-term challenge for binder jetting. Bimodal powders with varying particle sizes can be introduced during printing to improve the packing density. Furthermore, post-processing steps such as infiltration with nano-particles are frequently carried out to fill the voids and enhance mechanical strength [20]. For example, bronze was diffused into binder jetted stainless steel at 1050 °C to achieve full density. In the research community of permanent magnet, grain boundary diffusion process (GBDP) using low-melting point alloy (*e.g.*, Nd-Cu) is a well-known method to effectively enhance coercivity through modifying the intergranular phase between the magnetic $Nd_2Fe_{14}B$ grains [21]. Thus, it is of interest to apply this technique, optimally, with the application of expansion constraint to minimize the loss of remanence [22], to the binder jetted magnets to achieve densification, and meanwhile, improve coercivity.

With the downsizing of electronics, bonded magnets with higher energy product BH_{max} are strongly desirable. This can be achieved through magnetically aligning anisotropic powder during the manufacturing process to increase the remanence B_r as well as the density of the final part [23]. Dy free magfine powder MF18P with $H_{ci} = 14.2$ kOe was used to explore the feasibility of *in-situ* alignment during the printing process. However, *in-situ* alignment remains a major challenge for binder jetting as the distance between the print head and the powder bed is very small; once the powder is aligned, it interferes with the print head directly, which could damage the print head. Alternatively, in this study, alignment with a sintered NdFeB magnet which was placed at the bottom of the printed part was carried out during the post-curing stage in an oven at 100 °C. The magnetic field generated by the sintered magnet for the alignment is approximately 1 T. The density and magnetic characteristics of the printed magnets without and with alignment are summarized in Table 1. It can be seen that the alignment enhanced the density and remanence B_r, resulting in a BH_{max} enhancement from 2.4 to 3.8 MGOe. Further efforts are under way to realize *in-situ* alignment.

4. Material extrusion with the Big Area Additive Manufacturing (BAAM) system

BAAM is a system developed by a team of researchers from ORNL's Manufacturing Demonstration Facility and Cincinnati Inc. to fabricate large-scale parts *via* a material extrusion method [24]. BAAM deposits molten thermoplastics in a layer-upon-layer fashion – the materials are extruded from the nozzle and solidify rapidly [25]. Fig. 2 shows a schematic of the BAAM process for fabricating NdFeB bonded magnets. Magnequench isotropic MQP B+ powder (65 vol.%) was mixed uniformly with Nylon-12 (35 vol.%), and extruded first to obtain composite pellets, which were then used as feedstock materials in BAAM. Note that BAAM does not require pre-fabrication of filament. The temperature at the orifice exit of the extruder was approximately 270 °C, and the printed magnet was then polished and coated with a polyurethane polymer by TruDesign LLC.

Table 1
Characteristics of binder jetted NdFeB bonded magnets with anisotropic MF18P powder.

Sample	Density (g/cm^3)	H_{ci} (kOe)	B_r (kG)	BH_{max} (MGOe)
Without alignment	3.54	14.2	3.3	2.4
Aligned during curing	3.86	14.2	4.2	3.8

Please cite this article as: L. Li, et al., Additive manufacturing of near-net-shape bonded magnets: Prospects and challenges, Scripta Materialia (2016), http://dx.doi.org/10.1016/j.scriptamat.2016.12.035