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Prospects of additive manufacturing of rare-earth and non-rare-earth permanent magnets

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Abstract

Additive manufacturing (AM) or 3D-printing started as a prototyping technique in plastic has succeeded in metals for life safety applications as airspace and medical implants production. Today having advantages in fabricating products of desired shape, geometry, lightweight structures and required mechanical properties, 3D-printing faces a new challenge – AM of permanent magnets (PM). 3D-printing significantly simplifies manufacturing of net-shape bonded magnets, simplifies the new phase magnets prototyping, and also enables efficient use of rare earth (RE) elements [1]. The major development nowadays is performed by AM of bonded Nd-Fe-B using different binders/polymers [1, 2]. 3D printing technologies of non-RE magnets are not so widely represented [3]. The AM of RE-free PM, such as Al-Ni-Co [4] and MnAl(C) [5], is also developed, because of their great benefit of being non-RE, presenting advantages of AM technology and sufficient magnetic properties.
This work presents the state-of-the-art of 3D-printing of PM, including RE and RE-free, bonded and non-bonded magnets.
Prospects of electron beam melting (EBM) of non-rare-earth MnAl(C) are shown.

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Keywords: 3D-Printing; addititve manufacturing; permanent magnets; rare-earth magnets

1. Introduction

This paper gives an overview the state-of-the-art in the field of additive manufacturing of hard magnetic materials with and without rare-earth (RE) elements.

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Though the additive manufacturing of magnetic materials has just recently begun, it can already be said that this new fabrication method makes manufacturing of net-shape easier and use of critical RE materials more efficient.

The development of new magnetic materials is essential and indispensable for improving the efficiency and performance of devices in electric power generation, conditioning, conversion, transportation, and other energy-use sectors of economy. Functional magnetic materials, such as advanced hard and soft magnets, magnetic refrigerants, magnetic MEMS (microelectromechanical systems), magnetic shape memory alloys, and magnetorheological fluids and elastomers, substantially impact all contemporary energy-saving technologies. Among these classes of materials, advanced permanent magnets play an important role providing high efficiency and reliability and compact, low cost, and low maintenance solutions for renewable energy technologies, including wind turbines, hydroelectric power generators, and wave power buoys. The main attempts of permanent magnets printing are held with NdFeB magnets, because of its outstanding magnetic characteristics.

The industrial powder metallurgy process of permanent magnets made of NdFeB can be divided in 7 steps (Fig. 1a) concluding three basic stages: preparation of the powder, fabrication and post-processing

The functional magnetic properties of permanent magnets are extrinsic in nature, depending on the particular microstructure developed during magnet processing. The magnetization reversal in NdFeB sintered magnets is known to start at the surface of main phase grains, and that is why the microstructure optimization in NdFeB-based sintered magnets involving grain size reduction and grain boundary engineering has been extensively investigated in the last few years. To counteract the magnetic reversal, a special microstructure has been developed (Fig. 1b). It consists of single crystalline $Nd_2Fe_{14}B$ (grey on Fig. 1b) grains a size of 3-10 µm, surrounded by a continuous layer of amorphous Nd - rich phase (white regions on Fig. 1 b) with a thickness of only a few nm and larger Nd - rich phases in the grain junctions. Each grain acts as an independent small magnet. The thin grain boundary smoothers the grain surfaces and eliminates to some extent the number of structural defects, which decreases the probability of nucleation of reversed domains. Furthermore, the grain boundary phase (GBP) magnetically decouples the grains, which prevents reversal “avalanches” within the magnet. The GBP is generally believed to be paramagnetic.

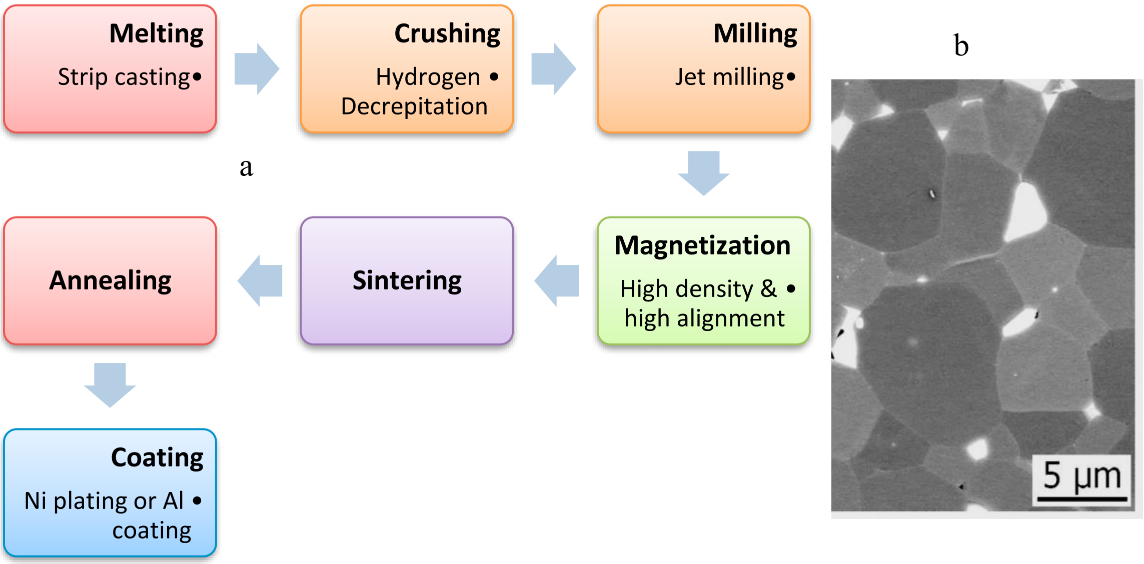

Fig 1. (a) Production route of NdFeB sintered permanent magnets [6]. **(b)** SEM image of a typical microstructure of a sintered NdFeB permanent magnet. The faint bright contrast between the grains stems from the nanometer-sized grain boundary phase.

The NdFeB magnets are currently produced at the industrial scale by the powder metallurgy route starting from micro-crystalline powders and involving liquid phase sintering step. Basically, the microstructure is made of individual crystallites, mainly of the $Nd_2Fe_{14}B$ phase, and separated by nonmagnetic thin layers [7]. Nowadays it is believed that various kinds of internal defects, as well as the grain size and grain boundary dimensions, govern the