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The architecture of nanocomposite magnets

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ABSTARCT

Nanocomposite magnets based on magnetically hard and soft phases are considered as the next generation of permanent magnets with super high energy density. However, fabrication of bulk nanocomposite magnets with desired nanoscale morphology and magnetic anisotropy has been proved to be an engineering nightmare because traditional sintering and compaction techniques are ill suited to the processing of nanostructured materials with at least two phases. A breakthrough has been reported recently by a group at Yanshan University, Qinhuangdao, China.

From mobile phones to laptops, elevators and electric cars, applications of permanent magnets have become ubiquitous, and their impact on our society and daily lives is still growing at an accelerating pace. However, existing permanent magnets based on rare-earth compounds are quite expensive and the production also suffers from limited rare-earth supplies, impeding their further applications.[1-3] Recently, a group at the Yanshan University, China, led by Prof. Xiangyi Zhang, has made a breakthrough by devising a new type of strong permanent magnets that can be as twice strong as the current magnets while using much less amounts of rare-earth metals.[4]

The figure of merit of permanent-magnet materials is the energy product, $(BH)_{max}$. Achieving a large energy product requires high magnetization and high coercivity, where the latter one is the reverse-field strength needed to reduce the magnetization to zero. However, these two properties do not go hand in hand: there is a trade-off between the magnetization and the coercivity which constitutes inherent roadblocks for development of strong magnets.[5] Two decades ago, a novel nanostructuring strategy emerged that brought a hope for generating stronger but cheaper permanent magnets — the concept of exchange-coupled nanocomposite magnets[1,5-7] that combine a rare-earth hard-magnetic material with an abounding Fe-based soft-magnetic material. Such composite magnets have been predicted to be stronger than any of the existing pure rare-earth magnets (single-phase magnets) while being cheaper than any of the single-phase countparts.[1] However, to date the world-wide pursuit to this type of strong bulk composite magnets has been very challenging, owing to the formidable difficulties in yielding a desired nanostructure.[8] The ideal nanostructure requires both high fraction (>20%) of homogeneously distributed soft-magnetic grains with a small size (~10 nm) and well-aligned hard-magnetic grains with their "easy magnetization axes" pointing to one direction. To fabricate such nanostructures in a composite system has been proved to be an engineering nightmare.

Conventional approaches such as ultra-fast cooling with subsequent thermal annealing and mechanical milling do not lead to effective control over the size and distribution of the soft magnetic phase; moreover, the resulted hard-phase grains in nanoscale size typically exhibit a random crystallographic orientation, giving rise to inferior magnetic performances.[5,6] Alternative methods have been developed to control the hybrid nanoscale morphology, including the bottom-up approach, self-assembling, and severe plastic deformation.[7-9] Although, the new methods can efficiently control the characteristics of the soft phase, it still remains particularly challenging to align hard-phase nanograins in a bulk material. For example, the agglomeration of magnetic nanoparticles hinders their alignment under a magnetic field, and the grain boundary-related processes, e.g., grain boundary sliding and grain rotation, prevent the development of crystal texture within small nanograins (≤20 nm) in a deformation process. As a result, simultaneously

achieving all of the desired characteristics for the soft and hard phases becomes extremely difficult. After decades of world-wide efforts, many researchers have declared that fabrication of such nanostructured composite magnets is a long shot and a formidable challenge.[1]

The group at Yanshan University[4] has been able to overcome the challenge by developing a strategy for inducing a texture in bulk nanocomposite magnets by mechanical deformation. The nanostructure developed by the group is based on the $SmCo_7$/Fe(Co) composite system. A record-high energy product (28 MGOe) for the SmCo/Fe(Co) systems is achieved (Figure 1) by the group while using less rare-earth metals compared to the single-phase counterpart (because of the addition of the soft magnetic phase Fe). This unprecedented performance was achieved by generating the desired nanostructure in bulk materials. The authors first dispersed Fe(Co) soft-phase grains into Sm−Co amorphous matrix through mechanical milling with controlled soft-phase grain size, fraction, and distribution. Then, vertically oriented growth of the hard-phase SmCo nanograins was realized in the amorphous matrix using strain energy anisotropy through a high-pressure hot deformation process (Figure 2). In this way, the authors have simultaneously controlled the characteristics of the soft and hard phases in the bulk $SmCo_7$/Fe(Co) nanomaterial.[4] Strikingly, they further found that the grain size (down to sub-10 nm), grain shape (sphere, rod or disc), and crystallographic orientation (isotropic or anisotropic) of the hard-phase nanograins can be tuned simply by varying the deformation temperature.[10] They

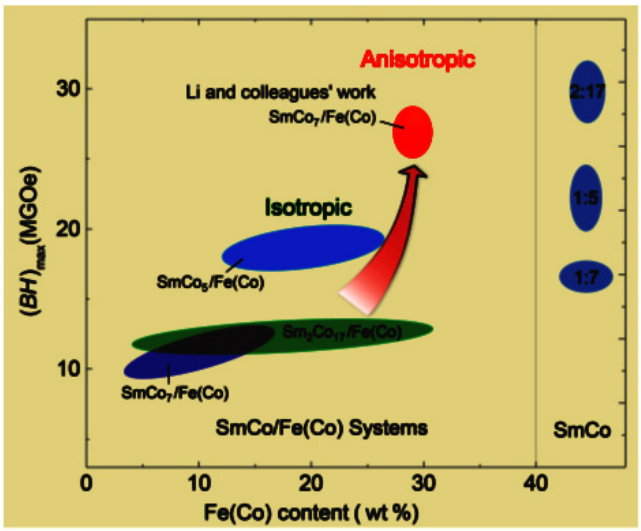

Figure 1: Comparison of energy products for different bulk SmCo/Fe(Co) nanocomposite systems (right panel) and their corresponding pure $SmCo_7$ (1:7), $SmCo_5$ (1:5), or $Sm_2(Co,Fe,Cu,Zr)_{17}$ (2:17) rare-earth magnet (left panel).

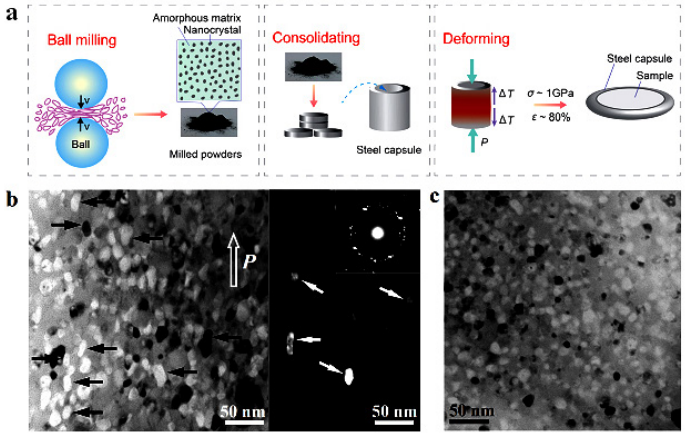

Figure 2: Fabrication of bulk anisotropic $SmCo_7$/Fe(Co) nanocomposite magnets containing ~ 28 wt.% Fe(Co). a)Schematic representation of the method. b) and c) TEM characterization of the nanocomposites along (b) and perpendicular to (c) the pressure direction.

explained the change of grain shape based on surface-energy *E* minimization (Figure 3): the rod-shaped nanograin has higher *E*, while the disc-shaped nanograin has lower *E*; and an appropriate temperature gradient is likely to facilitate the growth of the oriented crystals into the rod-shaped nanograins.

The group has also made a significant advance in fabricating high-performance isotropic nanocomposite magnets. They introduced a self-assembly approach for fabricating three-dimensional (3D) core/shell-like nanocomposites (Figure 4).[11] The resulting $Nd_2Fe_{14}B$/a-Fe core/shell nanostructure allows both large remanent magnetization and high coercivity, yielding a record-high energy product of 25 MGOe for isotropic nanocomposite magnets;[11] and the achieved energy product reaches the theoretical limit of isotropic $Nd_2Fe_{14}B$/a-Fe nanocomposite magnets and is 56% larger than the value (16 MGOe) for pure isotropic $Nd_2Fe_{14}B$ magnets. Of course, potential for further increase in the energy density is huge: the theoretical value for anisotropic SmCo/FeCo systems can be as high as 65 MGOe[8] and the experimental value for anisotropic $SmCo_5$/Fe thin-film model materials has been achieved above 39 MGOe.[12]

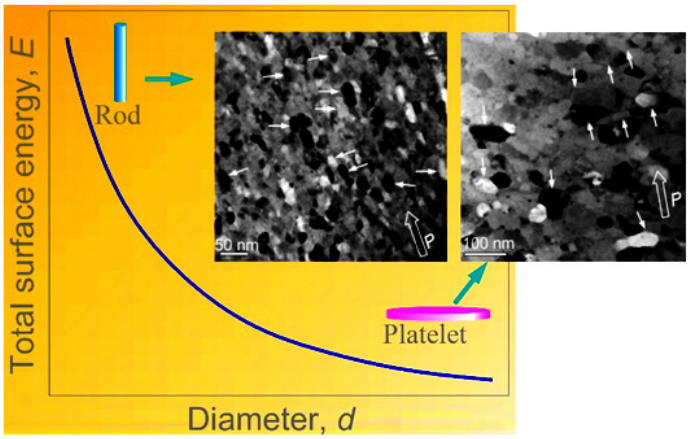

Figure 3: Schematic of the total surface energy *E* of an oriented nanocrystal (along the normal direction of low-surface-energy faces) as a function of crystal diameter. The insets show the bright-field TEM images for hard-phase nanograins with a rod or disc shape in the magnets yielded at different deformation temperatures.

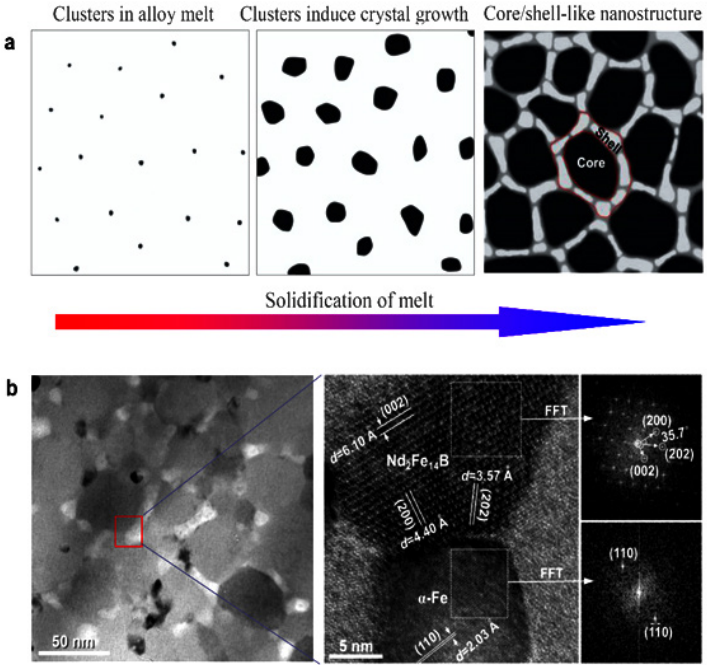

Figure 4: 3D self-assembly of core/shell-like hybrid nanostructures. a) Schematic representation of the self-assembly process. b) TEM characterization of the core/shell-like nanostructure with $Nd_2Fe_{14}B$ core and α-Fe shell.

Although, there are some remaining issues to be addressed in the future for approaching further high energy density,[13] the findings by the group constitute a substantial advance for high-performance bulk nanocomposite magnets, especially for the alignment of hard-phase grains in such nanocomposites that has long been recognized as the key step to the high energy product, but has been elusive for more than two decades.

Figures by Courtesy of Prof. Xiangyi Zhang.

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