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FRACTURE TOUGHNESS OF SAMARIUM COBALT MAGNETS

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ABSTRACT

Samarium Cobalt (SmCo) magnets have been the magnet of choice for a variety of industries for many years due to their favorable magnetic properties. Their high coercivity, combined with a low temperature coefficient, make them the ideal permanent magnet for demanding high temperature applications. One of the biggest concerns with rare earth magnets is their brittleness. Samarium Cobalt magnets in particular are prone to fracturing during machining and assembly. In manufacturing, great care must be taken to avoid chipping or fracturing these magnets due to their brittle nature.

There are two main grades of Samarium Cobalt magnets, 1:5 and 2:17. These ratios define the nominal ratio of rare earth to transition metal content.

In this paper, an investigation is performed on the fracture toughness of permanent magnets based on the Samarium Cobalt 2:17 composition. Various techniques are used to characterize the microstructure of the material, and quantify the material properties.

Optical microscopy is used to characterize the grain structure of the material and quantify the porosity of the material after sintering. By comparing the average grain size and fracture toughness of several samples, grain size was shown to not affect fracture toughness in standard material. Latent cracks in defective material showed no preference to follow grain boundaries, oxides inclusions or voids.

River marks in fracture surfaces are seen through scanning electron microscopy, confirming the transgranular cracking pattern seen by Li et al [1]This suggests that the toughness of the material is an inherent property of the main phase, not of grain boundaries or contaminants.

Samarium Cobalt magnets exhibit both mechanical and magnetic anisotropy due to the alignment of their crystal structure in the manufacturing process.

Using Palmqvist indentation crack techniques, the magnetic orientation of the grains was seen to greatly influence the direction of crack propagation from the tip of the indenter. Measurements of fracture toughness using this technique produce highly scattered data due to this anisotropic nature of the material. Specimens loaded with the indenter axis parallel to the direction of orientation show normal Palmqvist cracks, while specimens loaded perpendicular to the direction of magnetization exhibit crack propagation initiating from the faces of the indenter.

To better quantify the material's brittleness, fracture testing is performed on specially prepared samples to obtain an absolute measure of fracture toughness (K1c). Results show that SmCo is measurably weaker than other magnetic materials such as neodymium iron boron magnets[2]. Furthermore, neither relative concentration of Samarium nor source of raw material show notable effect on the fracture toughness of the material.

INTRODUCTION

Samarium cobalt magnets can be broken into two main groups based on their overall composition. Magnets of the 1:5 type are of the general composition RE_1Tm_5 while magnets of the 2:17 type have a composition of $RE_2(CoFeCuZr)_{17}$[3]. The 2:17 type material is the subject of this paper. In 2:17 material, the majority of the transition metal content comes from cobalt and iron, with additions of minor alloying elements to improve specific properties[4]. In the case of SmCo 2:17 these elements are copper and zirconium to improve magnetic performance through increased coercivity, and improved squareness of the demagnetization curve[5], [6].

Samarium cobalt magnets, both of the 1:5 and 2:17 composition, demonstrate anisotropy both in their magnetic, and physical properties[5], [7]. The crystal structure is such that magnetization occurs only in one direction within the crystal, the c-axis of the structure[5]. The pulverized alloy powder is oriented during manufacture so that the crystal structure, represented by magnetic domains, is co-parallel. Magnetization can only take place in this "direction of magnetization" (DOM)[5], [7].

The chemical structure of 1:5 material is of the hexagonal type, while the addition of more TM to create 2:17 material creates either a hexagonal or rhombohedral structure which results in an improved Br and energy product for the material[3], [7].

In the manufacture of these materials, latent cracks are often formed in the material during the aggressive quenching process. A better understanding of the causes of these cracks is needed so the toughness of these materials can be improved to create a magnet with more favorable mechanical properties.

NOMENCLATURE

K_1c	Fracture toughness
RE	Rare earth element
TM	Transition metal element
Br	Residual induction
DOM	Direction of magnetization

EXPERIMENTAL DETAILS

Optical Microscopy

Optical microscopy analysis was performed on many samples to compare materials both with and without latent cracks for a variety of characteristics, including grain size, porosity, latent crack propagation, and the microstructure of the material. The equipment used for microstructural analysis was an Olympus Bx60M Optical microscope.

The material was prepared for visual analysis through normal metallographic techniques. Samples were chosen to represent healthy material, as well as material with latent cracks. Samples were polished in a six step process of abrasive disks, finishing with a 2μm diamond impregnated cloth. Samples were etched through the use of diluted Nital solution, and examined under the microscope for a variety of features.

Grain Size: The average grain size was determined by counting the number of grains in a given region, and dividing by the surface area of the region.

Porosity: The porosity of the material was determined by examining polished, unetched material. Voids in the material remaining after the sintering process appear as dark spots on a white background as seen in figure 1. Through the use of image processing software, the area percentage of voids in the cross section was used to calculate the porosity of the material.

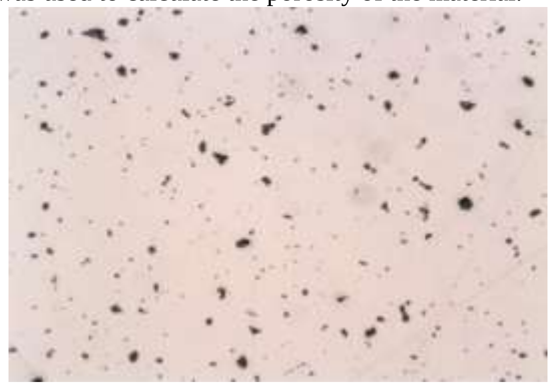

Figure 1: Typical image used for porosity measurement.

Scanning Electron Microscopy

Samples previously prepared for optical microscopy were also viewed with a JEOL 6400V Scanning electron microscope to further examine the microstructure and the nature of cracks found in the material. Materials with latent cracks, as well as material with cracks produced through fracture testing were examined.

Micro-Indentation Technique

A diamond indenter was used to create microscopic indents in the material through the use of a LECO LM247AT Microhardness Tester. Due to the brittle nature of SmCo magnets, small cracks propagate from the edges of the indentation. The size of these cracks are directly related to the fracture toughness of the material[8]–[10]. As seen in equation 1:

(1) $$K_c = 0.0889\left(\frac{H_v * P}{\sum c_i}\right)^{1/2} [8]$$

With H_v representing the Vicker's hardness, P is the indenter load, and c_i corresponds to the length of cracks propagating from crack tips[8]–[10].

Fracture Testing

Fracture toughness is directly measured by the chevron notched bending method[11]. The notch is created through the use of wire EDM to create a stress concentration for crack initiation and controlled propagation. The energy required to create the crack is related to the fracture toughness through the use of equation 2: [2]

(2) $$\boldsymbol{K_{1c} = \left(\frac{W_f E'}{A}\right)^{1/2}}$$

In this relationship, W_f is the area under the load-displacement curve, A is the area of the cracked surface, and E' is the plane strain Young's modulus.[2]

RESULTS AND DISCUSSION

Microstructure

Several magnetic grades of Arnold Magnetic Technologies' RECOMA 2:17 material were examined. It was seen that the microstructure of Samarium Cobalt 2:17 magnets consists of a primary phase of 2:17 composition, with grain boundaries consisting of 1:5 material[12]. Through the investigation, samarium oxides and voids appeared to show no preferential location within the material. For all testing, material with and without latent cracks was examined. Figure 2 illustrates typical microstructure of a 2:17 SmCo magnet using SEM microscopy.

Average porosity across all of the material tested was measured to be 3.3% of the total cross sectional area. No correlation was found between greater porosity and presence of latent cracks in the material.

The average grain size cross-sectional area found in the material was 2200 μm^2, and varied from 860-3900 μm^2. Although there was a large distribution in grain sizes, no correlation was seen between grain size and the presence of latent cracks. This is likely due to cracks propagating in a trans-granular nature.

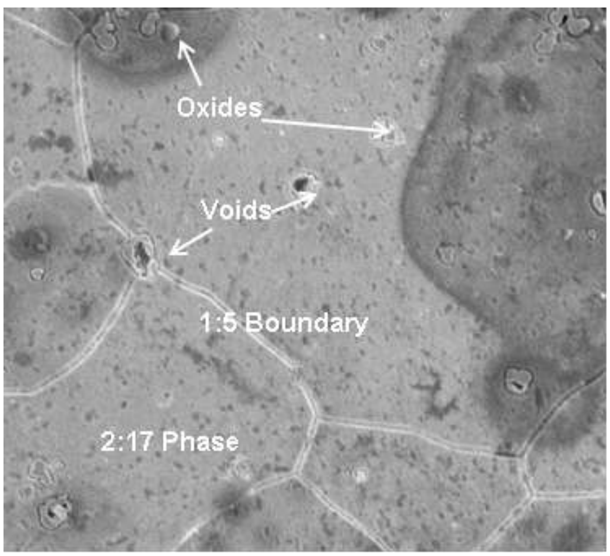

Figure 2: Typical image of SmCo 2:17 microstructure

Imaging of Cracks

Specimens with cracks from thermal shock during manufacturing were viewed through the use of scanning electron microscopy as well as optical microscopy. These latent cracks were not accompanied by any excess amount of impurity, or porosity in the material. Additionally, it was seen that these naturally occurring cracks showed no preference to follow grain boundaries in the material. This indicates that brittleness is a property of the main 2:17 phase present in the material. This is clearly illustrated in figures 3 and 4.

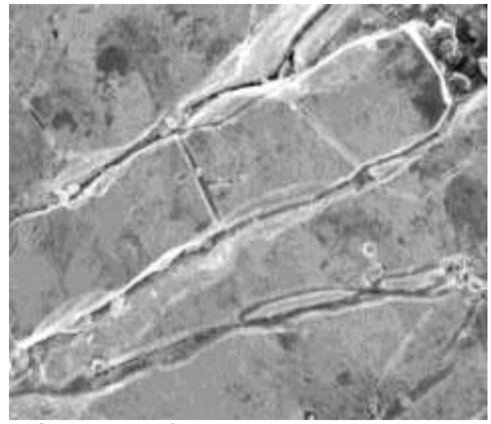
Figure 3: SEM image of cracks propagating through grains in material

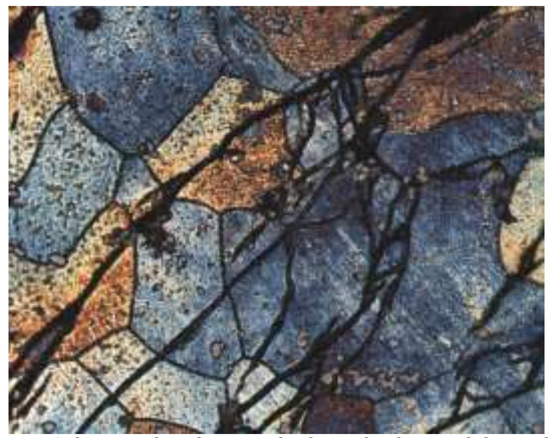
Figure 4: Image showing cracks in etched material passing through grains

Figure 5 shows an SEM image of an unpolished fracture surface created during fracture testing. The pattern of river marks further demonstrates the trans-granular fracture of the 2:17 material. Similar fracture was also seen by Anhua et al[13].

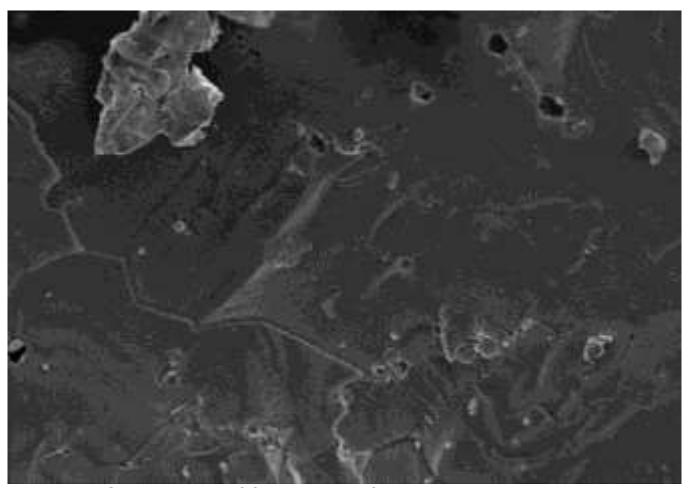
Figure 5: SEM image of fracture surface, illustrating river marks indicative of trans-granular fracture

Micro Indentation

Micro-indentation methods were used to attempt to quantify the toughness of the material. Average values of toughness for valid tests were in the range of 1.4 MPa√m, but values varied by upwards of 50% even within one sample. This method was not found to be adequately reproducible for the testing of SmCo magnets. Many samples exhibited cracks that propagated from the sides of the indenter, rather than the tips, which we attribute to the anisotropy of the material. Specimens in which the indenter was loaded parallel to the DOM were more likely to produce cracks propagating from the indenter tips, as seen in figure 6, while specimens where the loading axis was perpendicular to the DOM exhibited cracks that propagated from the edges as shown in figure 7.

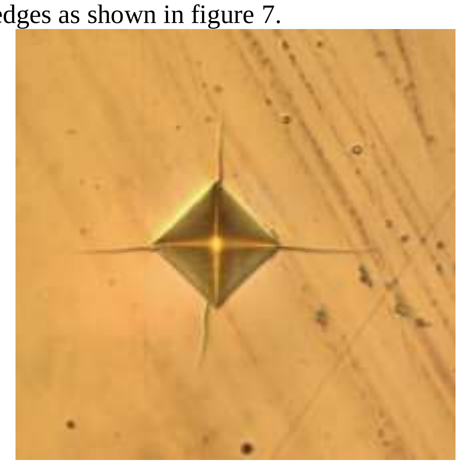

Figure 6: Mico-indentation showing good crack propagation from tips of indenter with loading axis parallel to DOM

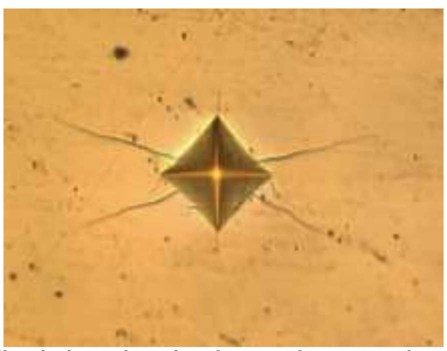

Figure 7: Mico-indentation showing crack propagation from edges of indenter with loading axis perpendicular to DOM

Fracture Testing

Results of 3-point bend fracture testing on 2:17 material showed an average fracture toughness of 1.36 MPa√m. This is less than the fracture toughness of 1.9 MPa√m measured for 1:5 material, and substantially less than 2.5 and greater MPa√m found for neodymium iron boron magnets by Horton and Wright[2].

CONCLUSIONS

Samarium Cobalt magnets of the 2:17 composition exhibit brittle fracture. Experiments have shown that the presence of latent cracks does not correlate to an increase in porosity of the material, or a difference in grain size.

Based on SEM imagery, this brittle fracture is trans-granular in nature. Cracks in the material show no preference to follow grain boundaries, or impurities in the material. It is likely that any improvements in the toughness of Samarium Cobalt magnets will have to come from compositional change of the main 2:17 phase.

FUTURE WORK

Future research will attempt to improve the fracture toughness of Samarium cobalt 2:17 sintered magnets. Compositional changes will be used in an attempt to disrupt the cleavage plane found in the hexagonal/rhombohedral structure of the material.

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