Fracture Toughness of $\text{Nd}_2\text{Fe}_{14}\text{B}$ Magnets

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$\text{Nd}_2\text{Fe}_{14}\text{B}$ is currently the best (highest energy product) hard magnet available. Like most magnetic materials, it is rather brittle. The fracture toughness of specimens of commercially available hard magnets were measured using a chevron notch, three-point bend test. Values for $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets ranged from 2.5 to 5.5 $\text{MPa}\sqrt{\text{m}}$. In comparison, SmCo_5 was measured to have a fracture toughness of 1.9 $\text{MPa}\sqrt{\text{m}}$. It appears that this testing technique will allow differences in fracture toughness to be measured between alloys with different compositions and fabricated by different production methods and should be able to track the fracture toughness as improvements are made to a particular alloy.

Keywords: magnets, permanent magnets, toughness, mechanical properties

I. Introduction

Since its development⁽¹⁻²⁾ in 1983, the production and use of $\text{Nd}_2\text{Fe}_{14}\text{B}$ as a hard magnetic material has grown rapidly. While $\text{Nd}_2\text{Fe}_{14}\text{B}$ is not quite as brittle as the previous highest energy product magnetic materials, SmCo_5 , it is still rather brittle. Due to the brittleness, grinding operations are sometimes required during final fabrication. In some demanding magnetic applications such as electric vehicle drive motors in which high rpm and small air gaps are necessary, the $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets need to be used as a structural element³. Any improvement in their fracture resistance will reduce the failure rates during commercial use.

Commercially, the material is produced either by a cast, crush, and sinter process or by a melt spin and hot press process. Some recent references provide excellent reviews⁽⁴⁻⁵⁾. $\text{Nd}_2\text{Fe}_{14}\text{B}$ has a large unit cell, low symmetry, and no slip deformation modes. In the optimized magnetic condition $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets are multiphase with some nonmagnetic grain boundary phases present. The amount, type, and morphology of these second phases affect both the magnetic and mechanical properties. Baseline fracture toughness measurements are needed to aid development of tougher materials. For this reason, techniques developed for other brittle intermetallic alloys were applied to this commercially important intermetallic alloy.

II. Experimental Procedure

Eight different types of $\text{Nd}_2\text{Fe}_{14}\text{B}$ commercial magnets

were used in this investigation. Fracture toughness was measured by a 3-point bend test. The chevron notches in the bend bars were wire electrodischarge machined (EDM), see Fig 1. During the 3-point bend test, the crack starts in the apex of the triangular cross section of material. As the crack propagates, the length of the crack front increases which decreases the chance for catastrophic failure and can often result in controlled crack propagation depending on the stiffness of the testing equipment. A span of 35 mm was used in the tests. The tests were performed in an Instron 4501 screw driven machine. The crosshead speed was 1 $\mu\text{m/s}$. Fracture surfaces were photographed in a field emission-gun-equipped scanning electron microscope (SEM).

$\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets produced by a cast, crush, and sinter process and manufactured by Sumitomo, Vacuumschmelze,

Fig. 1 Geometry of chevron-notch bend specimen.

Fig. 2 Load elongation curve of a Sumitomo 42 specimen.

and Shin-Etsu were obtained as blocks $5 \times 5 \times 40$ mm from Magnet Sales and Manufacturing, Inc., Culver City, CA. For comparison purposes, specimens of SmCo_5 and Alnico were also obtained from Magnet Sales. The advertised energy products ranged from 28 to 45 MGOe for the $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnets. In addition, three types of melt spun material were obtained as blocks $5 \times 5 \times 40$ mm from Magnequench International. In their process, rapid solidification in the form of melt spinning is used to produce fine grained materials. After a slight crushing, the powder is cold compacted and hot pressed to produce an MQ2 magnet. A further die upsetting operation will take an MQ2 magnet and produce an anisotropic MQ3 magnet.

III. Results and Discussion

In the case of the crushed and sintered material in which a span of 35 mm and a notch angle of 36° was used for the 3-point bend tests, controlled crack propagation occurred in all of the specimens tested. A typical load displacement curve is shown in Fig. 2. The fracture toughness, K_{IC} , is essentially a measure of the absorbed energy during crack propagation, where the absorbed energy is the area under the load displacement curve in Fig. 2. K_{IC} was calculated⁽⁶⁾ by an area method according to:

$$K_{IC} = \left[\frac{W_f}{A} \times E' \right]^{1/2}, \quad (1)$$

where W_f is the area under the load-displacement curve, A is the area swept by the crack, and E' is the plane strain Young's modulus given by:

$$E' = \frac{E}{(1 - \nu^2)}. \quad (2)$$

Poisson's ratio, ν , was assumed to be 0.25 and a value of 157 GPa was used for E for $\text{Nd}_2\text{Fe}_{14}\text{B}$, 150 GPa for SmCo_5 , and 193 GPa for Alnico.

In the case of the MQ2 and one set of the MQ3 specimens, controlled crack propagation did not occur. K_{IC} was calculated⁽⁷⁻⁸⁾ in this case by the following peak load formula:

$$K_{IC} = \frac{P_{\max} Y_{\min}}{B W^{1/2}} \quad (3)$$

$$Y_{\min} = \frac{\left[3.08 + 5 \left(\frac{a_0}{w} \right) + 8.33 \left(\frac{a_0}{w} \right)^2 \right] s}{w} \quad (4)$$

where $P_{\max}$ is the maximum load at fracture, B is the specimen thickness, W is the specimen height, s is the distance between loading points (span), and a_0 is the distance from the apex of the triangular intact material to the tension face of the specimen.

Table I is a summary of the fracture toughness measurements. (An earlier version with rather preliminary data was published previously⁹.) Clear and consistent differences were seen between the three manufacturers producing $\text{Nd}_2\text{Fe}_{14}\text{B}$ material by the cast, crush, and sinter method. These five sets of material exhibited controlled crack propagation. No orientation difference was observed between specimens fractured parallel or normal to the easy magnetization direction. Fracture toughnesses were calculated using the area method described above and yielded an average value of $3.9 \pm 0.2 \text{ MPa}\sqrt{\text{m}}$ for the Shin-Etsu 45 material, 3.9 ± 0.3 and $4.4 \pm 0.2 \text{ MPa}\sqrt{\text{m}}$ for the Sumitomo 28 and 40 material, respectively, and 5.5 ± 0.8 and $5.5 \pm 0.2 \text{ MPa}\sqrt{\text{m}}$ for the Vacuumschmelze 32 and 42 material, respectively.

The first two groups of MQ specimens in Table I from Magnequench fractured catastrophically. The peak load method described above was used to calculate K_{IC} . K_{IC} was also calculated by the peak load method for the specimens that fractured with controlled crack propagation for comparison purposes and gave comparable numbers. The MQ2 (hot pressed) specimens yielded an average value of $2.5 \pm 0.2 \text{ MPa}\sqrt{\text{m}}$ while the MQ3 (hot pressed and die upset) specimens yielded values of $2.7 \pm 0.5 \text{ MPa}\sqrt{\text{m}}$. The third entry for MQ material in the table used an H grade of powder and was die upset by Daido Steel Co. The fracture toughness of this material was measured to be $4.4 \pm 0.3 \text{ MPa}\sqrt{\text{m}}$, comparable to the cast and sintered material from Sumitomo.

For comparison purposes, specimens of SmCo_5 were tested and found to have a toughness of $1.9 \pm 0.2 \text{ MPa}\sqrt{\text{m}}$. Since uncontrolled crack propagation occurred for the

Table I Fracture Toughness, K_{IC} , of Commercial Permanent Magnets

	Process	Manufacturer	Grade	K_{IC} , MPa · m ^{1/2}	# of Tests
SmCo5		Vacuumschmelze	18	1.9 ± 0.2	5
Nd ₂ Fe ₁₄ B	Spin Cast, Hot Press	Magnequench, MQ2	E1	2.5 ± 0.2	8
Nd ₂ Fe ₁₄ B	Spin Dast, Die Upset	Magnequench, MQ3	E1	2.7 ± 0.5	6
Nd ₂ Fe ₁₄ B	Sintered	ShinEtsu	45	3.9 ± 0.2	7
Nd ₂ Fe ₁₄ B	Sintered	Sumitomo	28	3.9 ± 0.3	5
Nd ₂ Fe ₁₄ B	Sintered	Sumitomo	40	4.4 ± 0.2	6
Nd ₂ Fe ₁₄ B	Spin Dast, Die Upset	Magnequench, MQ3*	H	4.4 ± 0.3	8
Nd ₂ Fe ₁₄ B	Sintered	Vacuumschmelze	32	5.5 ± 0.8	5
Nd ₂ Fe ₁₄ B	Sintered	Vacuumschmelze	42	5.5 ± 0.2	8
Alnico		TDK	42	13.3 ± 0.9	5

* Die upset by Daido Steel Co.

Nd₂Fe₁₄B magnets with toughnesses of less than 3 MPa√m, the notch angle was changed from 36° to 45°. With this angle, the SmCo₅ alloy exhibited controlled crack propagation. Alnico, using the same specimen geometry and method of calculation showed a fracture toughness of 13.3 ± 0.9 MPa√m. For comparison purposes, the toughness of alumina ranges from 3 to 4 MPa√m.

Fracture surfaces were examined by SEM. Figures 3-5 shows fracture surfaces of specimens of Vacuumschmelze 42, Sumitomo 40, and ShinEtsu 45 and Fig. 6 shows a fracture surface of a specimen of MQ3. The crushed and sintered material in Figs. 3-5 has much larger grains and larger amounts of various second phases. Multiple cracks formed during fracture in some of these phases in the Vacuumschmelze magnet suggesting that more energy was absorbed during the fracture process and this correlates with the higher toughness in this material. The much smaller grain size in the melt spun material is apparent in Fig. 6. The strip with the elongated grains is apparently a prior flake boundary and was formed during the hot pressing operation. Further analysis will characterize the second phases and the role that they play in the fracture process. A further correlation between microstructure, alloy chemistry, BH behavior and fracture toughness is underway.

IV. Conclusion

Application of a chevron notch bend test used for brittle ceramics and some intermetallic alloys to measure fracture toughness was applied to Nd₂Fe₁₄B magnets. A series of fracture toughness measurements on commercially produced Nd₂Fe₁₄B magnets showed consistent differences between 8 sets of specimens from four different manufacturers utilizing

two different production methods. Fracture toughnesses ranged from 2.5 to 5.5 MPa√m. These baseline measurements are an essential first step to improving toughness utilizing techniques similar to those employed in some ceramics and in some intermetallic alloys.

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Fig. 3 Fracture surface of a Vacuumschmelze 42 magnet.

Fig. 4 Fracture surface of a Sumitomo 40 magnet.

Fig. 5 Fracture surface of a ShinEtsu 45 magnet..

Fig. 6 Fracture surface of a Magnequench MQ3-E magnet..