

Strength Evaluation Method for Nd-Fe-B Rare Earth Sintered Magnets

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ABSTRACT

Application of the Weibull theory to an Nd-Fe-B rare earth sintered magnet was studied for use in evaluating the specific strength characteristics arising from the structure of this magnet. The validity of the Weibull theory was verified by the correlation with the Weibull distribution and by the existence of the size effect, whereby strength decreases with increases in size. The correlation with the Weibull distribution was verified by the close correlation shown by the resistance strength Weibull plot approximation line. While the existence of the size effect was verified due to the existence of the fixed relationship between effective volume, determined by the stress distribution, and fracture stress. Consequently, it was judged that the Weibull theory is valid for evaluation of the strength of this magnet. The strength of the magnet when incorporated into the rotor of a motor was also verified, thereby demonstrating the applicability of this theory to this type of magnet.

Introduction

Advances in magnet materials in recent years have made Nd-Fe-B rare earth sintered magnets (Nd-Fe-B magnets below), which have superior magnetic characteristics, available at a low cost. At present, permanent magnet motors utilizing these magnets make up the bulk of the drive motors used in electric vehicles (EV) and hybrid electric vehicles (HEV).

In addition to low cost, critical issues for these drive motors include achieving high efficiency, high revolution speeds and a lightweight construction. The interior permanent magnet (IPM) rotor structure shown in Fig. 1, in which the magnet is embedded in the yoke, is effective in these respects.

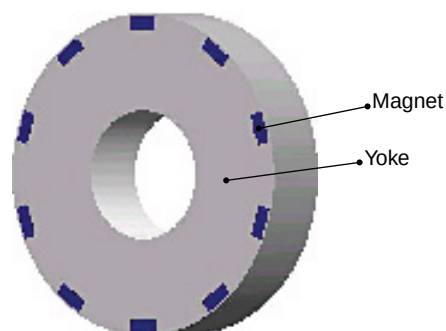


Fig. 1 IPM rotor

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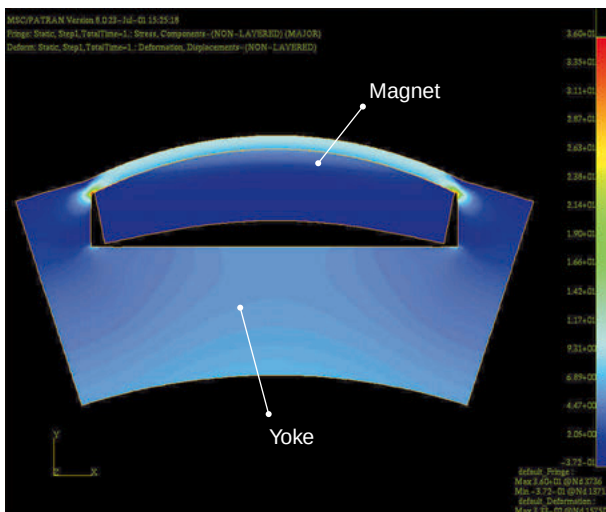


Fig. 2 Stress distribution of IPM rotor

In this type of motor, centrifugal force generates stresses on the magnet and electrical steel sheet when the motor is rotating, and thus it is very important to understand strength of these materials (Fig. 2). However, there are almost no examples of analysis of the strength of Nd-Fe-B magnets.

The tests described in this paper applied Weibull theory to the evaluation of the strength of Nd-Fe-B magnets and verified its suitability.

1. Characteristics of Nd-Fe-B Magnets

Fig. 3 shows a structural model of an Nd-Fe-B magnet. The magnet chiefly consists of an $\text{Nd}_2\text{Fe}_{14}\text{B}$ main phase and an Nd-rich grain boundary phase, which play important roles in producing magnetic characteristics. In addition to these, the structure contains traces of impurities (oxides, carbides, etc.) and pores, which are difficult to prevent in the sintering process. Fig. 4 shows an example of a graph of the load-strain relationship for Nd-Fe-B magnets. The magnet breaks (brittle fracture) without plastic deformation;

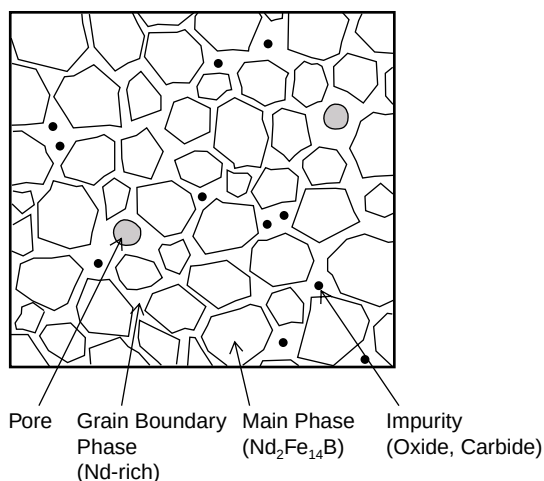


Fig. 3 Nd-Fe-B model

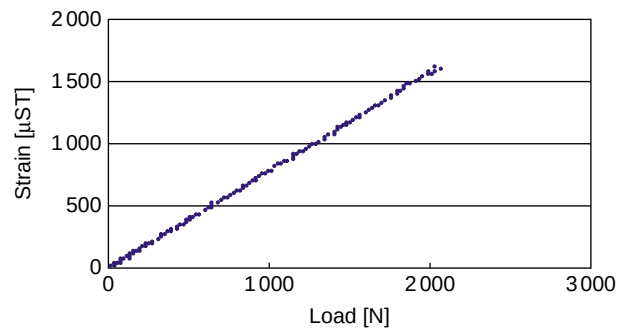


Fig. 4 Relationship between load and strain

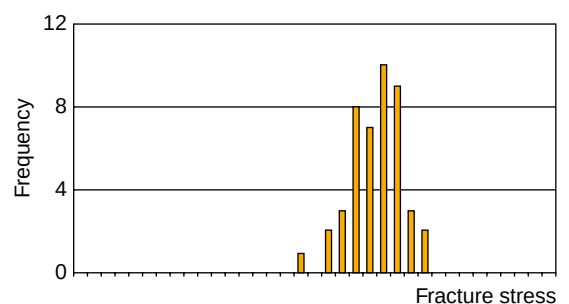


Fig. 5 Fracture test result

this is believed to occur because the main phase is composed of a hard, brittle intermetallic compound. Fig. 5 shows a histogram of the fracture stress values. The graph shows a large and broad variation in fracture stress on the low stress side, which is believed to be an effect of the impurities and pores. As demonstrated above, the unique structure of Nd-Fe-B magnets gives them different strength characteristics than those of ordinary steel. For this reason, methods of evaluation and design appropriate to these characteristics are necessary.

2. Weibull Theory

Statistical probability theory is effective in quantifying the strength of Nd-Fe-B magnets. Listed below are the elements that form the basis of this approach.

2.1 Weakest Link Theory

Nd-Fe-B magnets show great variations in strength. It is likely that this is caused by the presence of numerous tiny defects in the materials from which cracks are propagated to eventually become fractures. For this reason, fracture strength is not dependent on stresses occurring on the materials alone, but on the size and number of defects in the materials.

Because the size of the defects is several μm , it is impossible to detect them with present measurement technology without causing fracturing. For this reason, it is impossible to predict individual fracture characteristics.

Weakest link theory is effective in modeling materials with these characteristics. The following three items are necessary conditions for establishing weakest link theory:

- (1) The fractures are brittle fractures.
- (2) The cracks are independent of each other.
- (3) The defects are constant per unit volume.

If the above conditions are satisfied, it is possible to model the strength of materials containing “N” number of defects by modeling the breaking strength of a chain comprised of a certain number, “N”, of links, as shown in Fig. 6. As the chain is steadily pulled more and more strongly, the weakest links break, and thus the chain is broken even though the other links remain intact. That is, the strength of the chain is determined by the strength of the weakest link. This is the weakest link theory.

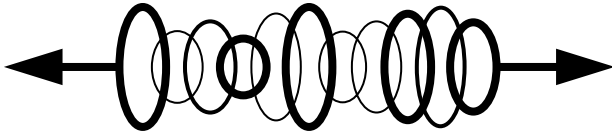


Fig. 6 Weakest link model

2.2 Weibull Theory^{(1) (2)}

The probability of the existence of “N” number of individual connected links S_N , is shown by the following equation, where F_N is the probability of breaking:

$$S_N = 1 - F_N = (1 - F(\sigma))^N \quad (1)$$

$$\doteq \exp(-N \cdot F(\sigma))$$

$F(\sigma)$: The probability of breaking for a link receiving stress σ .

When the risk of rupture, R_a , is used, equation (1) is converted to the following, because R_a is also a stress function:

$$F(\sigma, v) = 1 - \exp(-\int_v R_a \cdot dV) \quad (2)$$

$$= 1 - \exp(-\int_v f(\sigma) \cdot dV)$$

where v and V are variable volumes.

At this point, based on experimental results, Weibull hypothesized a power function as expressed by the following equation.

$$f(\sigma) = \left(\frac{\sigma - \sigma_\omega}{\sigma_o} \right)^m \quad (3)$$

where m , σ_ω and σ_o are material constants.

Accordingly, equation (2) is transformed as follows:

$$F(\sigma, v) = 1 - \exp\left\{-\int_v \left(\frac{\sigma - \sigma_\omega}{\sigma_o} \right)^m dV\right\} \quad (4)$$

In equation (4), σ_ω , known as the Weibull distribution function, is normally taken as $\sigma_\omega = 0$ to avoid excess evaluation.

$$\therefore F(\sigma, v) = 1 - \exp\left\{-\int_v \left(\frac{\sigma}{\sigma_o} \right)^m dV\right\} \quad (5)$$

If the effective volume, VE , as defined by equation (6) is applied, equation (5) can be simplified to equation (7).

$$VE = \int_v \left(\frac{\sigma}{\sigma_R} \right)^m dV \quad (6)$$

$$F(\sigma, v) = 1 - \exp\left\{-\left(\frac{\sigma_R}{\sigma_o} \right)^m VE\right\} \quad (7)$$

Using this equation with a fixed probability of breaking, the strength, σ_{R2} , of a target object of volume VE_2 , can be found from the strength, σ_{R1} , of a test piece of volume VE_1 .

$$\therefore \frac{\sigma_{R2}}{\sigma_{R1}} = \left(\frac{VE_1}{VE_2} \right)^{1/m} \quad (8)$$

3. Application of Weibull Theory to Magnets

3.1 Test Method

The test method for fine ceramics (JIS R1601) was used as a reference to establish a test method for Nd-Fe-B magnets according to the following criteria (Fig. 7):

- Test piece shape: $L40 \times W10 \times T5$ mm (Direction of magnetization)
- Distance between support points: 30 mm (L_1)
- Distance between load points: 10 mm (L_2)
- Cross head speed: 0.5 mm/min

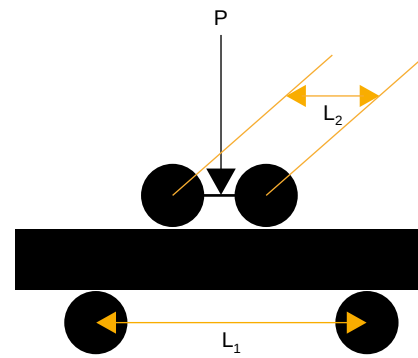


Fig. 7 Fracture test

The following equation was used to calculate stress σ from transverse load P :

$$\sigma = \frac{3P(L_1 - L_2)}{2WT^2} \quad (9)$$

3.2 Applicability of Weibull Theory

The applicability of Weibull Theory was judged according to the two items below. Results have demonstrated that Weibull Theory is applicable to the strength of Nd-Fe-B magnets. Details of the two verification items are as follows.

3.2.1 Correlation with weibull distribution

Fig. 8 shows an example of a Weibull plot for the breaking strength of an Nd-Fe-B magnet. The plotted points approach a straight line, and demonstrate a coefficient of correlation of above 0.9. Therefore, it was verified that these strength characteristics satisfy the relationships in equation (5), and the strength characteristics of Nd-Fe-B magnets were judged to follow a Weibull distribution.

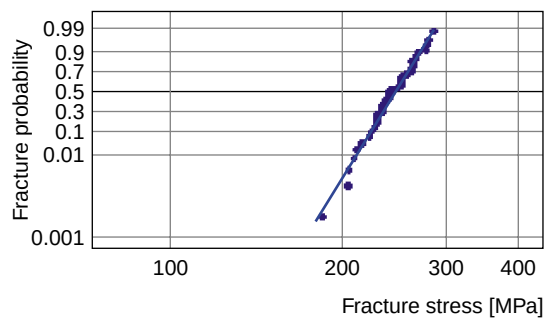


Fig. 8 Weibull plot for magnet strength

3.2.2 Size effect

Fig. 9 shows a plot of fracture stress for different widths as an example of strength when width is varied. Fig. 10 shows this as a Weibull plot.

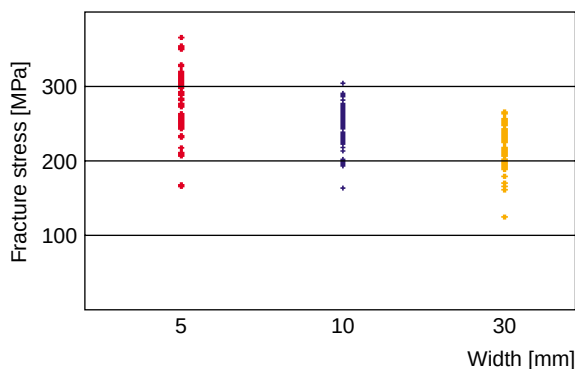


Fig. 9 Fracture stress for each width

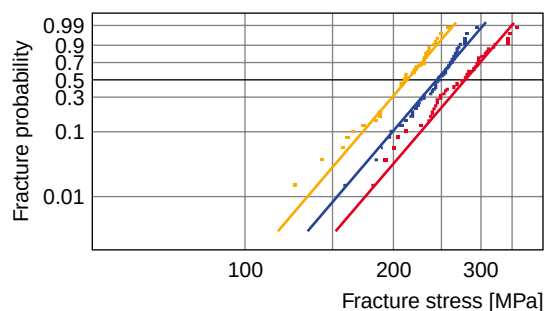


Fig. 10 Weibull plot for each width

These graphs demonstrate that while the average strength (fracture stress) varies for different widths, the Weibull number, which expresses variation conditions, is almost exactly the same. To clarify the relationship between test piece size and average strength, the relationship between effective volumes and average fracture strengths was plotted. The slope of the approximated straight line is the opposite of the negative of the Weibull number, m , and it was verified that the relationships in equation (8) were satisfied (Fig. 11).

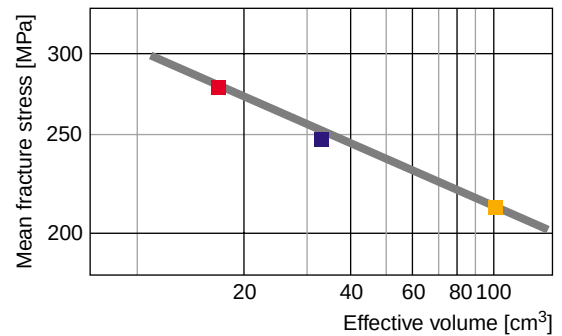


Fig. 11 Size effect

4. Verification in Actual Applications

The foregoing discussion has been concerned with the applicability of the Weibull Theory to the evaluation of the strength of Nd-Fe-B magnets. The authors also verified that this method was effective with actual magnets. Specifically, first, a rotor spin test was conducted to fracture the magnet, and the motor speed at the time the magnet fractured was measured. Next, CAE analysis was used to calculate stress values from these results, which were then Weibull plotted (Fig. 12). As the graph shows, it was possible to verify the applicability of Weibull distribution even when the magnet is in its actual form within the rotor.

Moreover, strength was predicted on the basis of Weibull Theory, using the results of four-point bending tests as the material constants.

Fig. 13 shows a graph of the results of both the calculation predictions and the actual measurement results from Fig. 12.

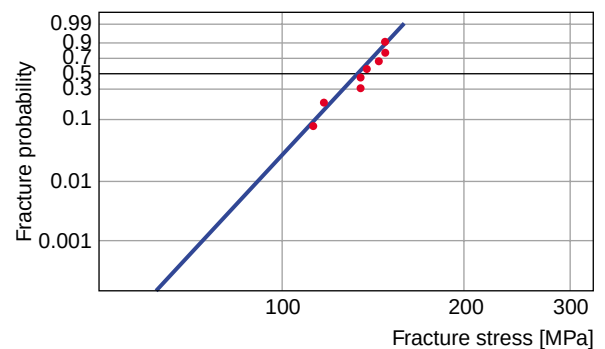


Fig. 12 Weibull plot of magnet strength of rotor (spin test result)

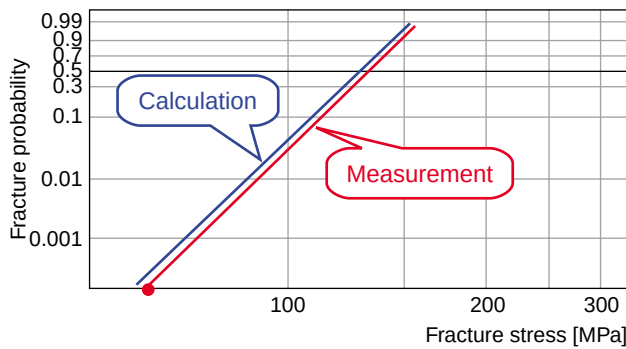


Fig. 13 Comparison of the measurement and calculation results

Results of the predictions and measurements correlate well in this graph, thus verifying the validity of the method. It is believed that in the future the application of this method will enable the prediction of the strength of the magnets from material constants during the motor design stage.

5. Conclusion

The applicability of Weibull Theory to Nd-Fe-B rare earth sintered magnets was tested, and the following results were obtained:

- (1) As a result of verifying the size effect and the applicability of four-point bending test results to the Weibull distribution for a basic test piece shape, the validity of applying Weibull Theory to strength evaluations of Nd-Fe-B magnets was demonstrated.
- (2) The applicability of the Weibull distribution to magnets in their actual application shape was also verified. A shape effect (size effect) was also verified from four-point bending test results for a basic test piece shape and from spin test results for actual magnets. As a result of the above verifications, it was found that this method enables the prediction of the strength characteristics for the actual shapes through the application of the Weibull Theory constants as the material constants.

The foregoing demonstrates the effectiveness of this evaluation method for strength design of magnets for motor applications.

References

- (1) Matsuo, Y., The Life and Destruction of Ceramics, Tokyo, Uchidaroukakuho, 1992, p. 120
- (2) Abe, H., et al., Engineering Ceramics, Tokyo, Gihoudou, 1998, p. 164

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