Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 58 (2014) 98 – 101

Physics Procedia

26th International Symposium on Superconductivity, ISS 2013

Mechanical properties of MgB_2 bulks

A. Murakami[a*], H. Teshima[b], T. Naito[c], H. Fujishiro[c], T. Kudo[d]

[a]Department of Mechanical Engineering, Ichinoseki National College of Technology, Takanashi, Hagisho, Ichinoseki 021-8511, Japan
[b]Nippon Steel & Sumitomo Metal Corporation, 20-1 Shintomi, Futtsu 293-8511, Japan
[c]Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[d]Advanced Course of Production Engineering, Ichinoseki National College of Technology, Takanashi, Hagisho, Ichinoseki 021-8511, Japan

Abstract

MgB_2 is one of promising bulk superconductors because grain boundaries are not weak-links in this material and thus the uniform distribution of trapped magnetic fields is easy to obtain even for large samples. In the present study, mechanical properties of MgB_2 bulks with different packing ratio have been evaluated through bending tests for specimens cut from the bulks. The mechanical properties of MgB_2 bulks are significantly influenced by their packing ratio or connectivity, and the fracture strength can be improved by a factor of 5 by increasing the packing ratio to 90 % or over.

Peer-review under responsibility of the ISS 2013 Program Committee

Keywords: MgB_2; Bulk superconductor; Bending test; Fracture strength

1. Introduction

MgB_2 is one of promising bulk superconductors because grain boundaries are not weak-links in this material. MgB_2 bulk superconductors can be fabricated by sintering and thus the uniform distribution of trapped magnetic fields is easy to obtain even for large bulk samples [1-3]. Since bulk superconductors are subjected to electromagnetic force and thermal stress in the superconducting devices [4-6], understanding of mechanical properties, such as fracture strength and Young's modulus, of bulk superconductors is indispensable for the practical application. So far, evaluations of mechanical properties have been carried out for various RE-Ba-Cu-O (RE: Y or rare-earth elements) bulks [7] and MgB_2 bulks [8]. However, mechanical properties of MgB_2 bulks have not been understood extensively in comparison with those of RE-Ba-Cu-O bulks. Further investigations are needed for the practical application of MgB_2 bulks. It is well-known that packing ratio of MgB_2 bulks depends on fabrication process. In the present study, evaluations of mechanical properties of MgB_2 bulks with different packing ratio have been carried out at room temperature through bending tests for specimens cut from the bulks. Observations on the fracture surfaces are also carried out.

2. Experimental

MgB_2 bulk samples with different packing ratio, 50, 63 and 92 %, were prepared through ex-situ or in-situ process. The packing ratios were measured by using the Archimedian method. Diameter of the bulk samples was 30-70 mm. Samples with the packing ratio of 50 % were fabricated by using capsule method [1], which are denoted as Sample 50. Samples with the packing ratio of 63 and 92 % were fabricated by using a HIP (Hot isostatic pressing) furnace, which

*Corresponding author. Tel.:+81-191-24-4734; fax: +81-191-24-4734.
E-mail address: amura@ichinoseki.ac.jp

1875-3892
Peer-review under responsibility of the ISS 2013 Program Committee
doi:10.1016/j.phpro.2014.09.034

are denoted as Samples 63 and 92, respectively. HIP pressure, temperature and time were 98-196 MPa, 1173 K and 3 h, respectively. Mechanical properties of these bulk samples were evaluated through four-point bending tests. Bending test specimens with the dimensions of 2.8 x 2.1 x 24 mm^3 were cut from the bulk samples such that the longitudinal direction of the specimens was almost perpendicular to the thickness direction of the bulk samples. In order to measure the strain caused by loading, one strain gage was glued to the centre of the 2.8 x 24 mm^2 surface of the specimens. The gage length of the strain gage was 0.2 mm. Four-point bending load was applied at room temperature in the 2.1 mm direction of the specimens under the crosshead speed of 0.2 mm/min. Stress σ caused by the loading was calculated by the following equation.

$$\sigma = \frac{3P(L-l)}{2wt^2} \qquad (1)$$

where P is the applied load, L is outer supporting span (21 mm), l is upper loading span (7 mm), w is width (2.8 mm) and t is thickness (2.1 mm) of the specimens. After the bending tests, fracture surfaces were observed by using scanning electron microscope.

3. Results and discussion

Fig. 1 shows stress-strain curves of specimens cut from the Samples 63 and 92. Non-linear stress-strain behavior was observed for the Sample 63. Slope of the stress-strain curves of the Sample 63 decreases with increase of the stress. On the other hand, stress-strain curves of the Sample 92 are almost linear until the fracture. Non-linear stress-strain behavior of the Sample 63 is presumably attributable to the opening or slow speed propagation of cracks by loading.

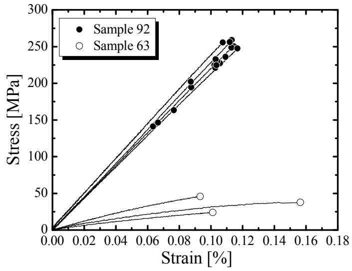

Fig. 1. Stress-strain curves of Samples 63 and 92.

Fig. 2 shows mechanical properties evaluated through the four-point bending tests. It is notable that the fracture strength is dramatically improved by a factor of 5 by increasing the packing ratio to 90 % or over as shown in Fig. 2 (a). Owing to the increase of the packing ratio, Young's modulus is also improved as shown in Fig. 2 (b). Such improvements of the mechanical properties are due to the increase of the net cross-sectional area and reduction of defects, where the stress concentration occurs, by increasing the packing ratio. Since it has been reported that improvement of the fracture strength with decrease of the porosity of ceramic materials can be expressed by using an exponential equation [9], data points in Fig. 2 (a) are approximated exponentially. From the approximation of the data points, the fracture strength at the packing ratio of 100 % is estimated to be about 350 MPa.

Scatter of the fracture strength data of the high-strength Sample 92 was evaluated through the Weibull plots; larger Weibull coefficient value means smaller scatter of the fracture strength data. The Weibull coefficient value is 6, which is slightly smaller than the value of RE-Ba-Cu-O bulks 8-10 reported in Ref. [10].

Fig. 3 shows fracture surface of the bending test specimen which showed the maximum fracture strength of the Sample 63. Fig. 4 (a) and (b) shows fracture surfaces of the bending test specimens which showed the maximum and minimum fracture strengths of the Sample 92, respectively. Bottom of the figures corresponds to the tensile side where the fatal crack initiates by bending loading. It is difficult to identify the crack initiation site on the tensile side fracture surfaces. The fracture surface of the Sample 63 is not smooth. On the other hand, the fracture surface of the specimen which showed the maximum facture strength of the Sample 92 is relatively smooth and the tensile side is flat in particular. Such a smooth fracture surface is commonly observed for fine ceramics. However, the fracture surface of the specimen which showed the minimum fracture strength of the Sample 92 is not smooth, which is similar to the fracture surface of the Sample 63. It is deduced that the rough fracture surfaces were formed by the crack propagations through the sintering defects and that higher connectivity is another reason for the higher fracture strength value observed for the Sample 92. Excluding the fracture strength data of exceptional specimens which have rough fracture surfaces, the Weibull coefficient value of the fracture strength of the Sample 92 would be 16, which is comparable to the Weibull coefficient values of conventional ceramics.

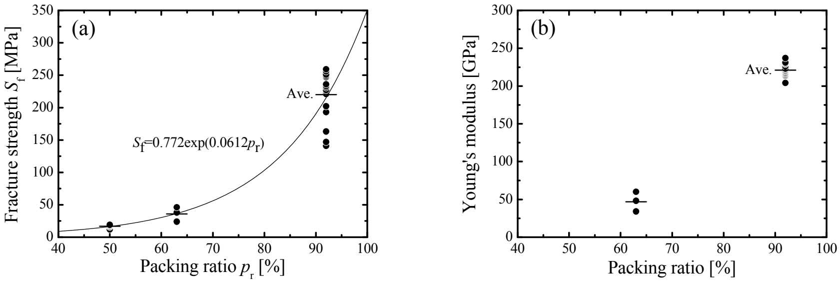

Fig. 2. Mechanical properties evaluated through four-point bending test. (a) Fracture strength of Samples 50, 63 and 92. (b) Young’s modulus evaluated from initial part of stress-strain curves of Samples 63 and 92.

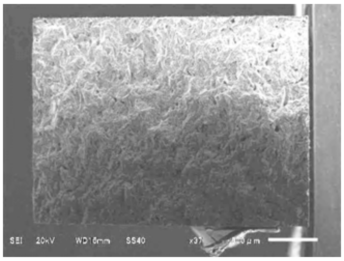

Fig. 3. Fracture surface of bending test specimen which showed the maximum fracture strength of Sample 63. Bottom of figure corresponds to tensile side.

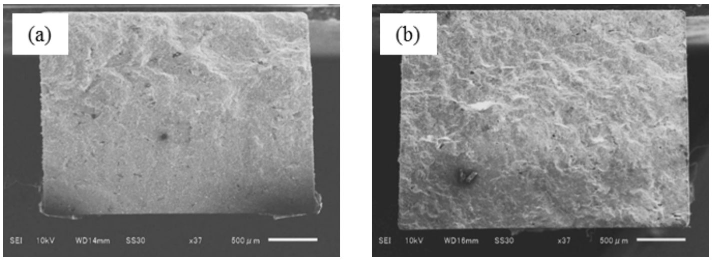

Fig. 4. Fracture surfaces of bending test specimens cut from Sample 92. (a) Specimen which showed the maximum fracture strength. (b) Specimen which showed the minimum fracture strength.

Since MgB_2 bulks have brittleness, understanding of fracture toughness as well as fracture strength is important for the practical application. Fracture toughness evaluations are commonly carried out through fracture strength tests for specimens with an artificial pre-crack or V-shaped notch. In the present study, fracture toughness of the Sample 92 is estimated from the fracture strength of specimens without the pre-crack and V-shaped notch. Fracture toughness K_{IC} is represented by the following equation.

$$K_{IC} = \beta\sigma\sqrt{\pi a} \qquad (2)$$

where σ is the maximum applied stress, *a* is length of crack or notch, π is the ratio of circumference of a circle to its diameter and β is shape factor, respectively. Eq. (2) can be rewritten as follows [11].

$$K_{IC} = \beta\sigma\sqrt{\pi\sqrt{area}} \qquad (3)$$

where *area* is defect area projected to the plane perpendicular to the maximum principal stress. In order to obtain β, fracture strength, fracture toughness and defect size of RE-Ba-Cu-O bulks were substituted for σ, K_{IC}, and *area* of Eq (3), respectively. Fracture strength of an RE-Ba-Cu-O bulk is 93 MPa [12], which has been evaluated through bending tests under the same conditions as those in the present study. Fracture toughness of the same RE-Ba-Cu-O bulk is 0.8 MPa $m^{1/2}$ [12]. Defect observed on the crack initiation site of an RE-Ba-Cu-O bulk had area of about 100 x 100 μm^2 [13]. As a result, 0.5 was obtained as β. Thus, K_{IC} is expressed as follows.

$$K_{IC} = 0.5\sigma\sqrt{\pi\sqrt{area}} \qquad (4)$$

Since it is difficult to identify the fatal defect on the fracture surfaces as mentioned above, relationship between the fracture toughness and fatal defect area has been estimated by using Eq. (4) as shown in Fig. 5. If the fatal defect size of the Sample 92 is about 100 x 100 μm^2 same as that of a RE-Ba-Cu-O bulk, the fracture toughness is estimated to be about 2 MPa $m^{1/2}$.

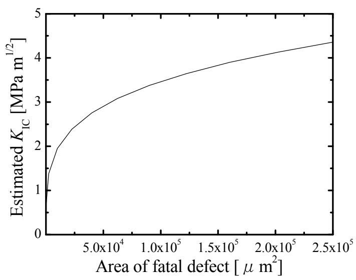

Fig. 5. Fracture toughness estimated from fracture strength of Sample 92.

4. Conclusion

In order to evaluate mechanical properties of MgB_2 bulk samples with different packing ratio, four-point bending tests for specimens cut from the bulk samples were carried out at room temperature. The mechanical properties of the MgB_2 bulks are significantly influenced by their packing ratio or connectivity, and the fracture strength can be improved by a factor of 5 by increasing the packing ratio to 90 % or over. Relationship between the fracture strength and fracture surface morphology has been revealed. Fracture toughness has been estimated from the fracture strength data.

Acknowledgements

We appreciate experimental supports by students of Ichinoseki National College of Technology. This work was supported in part by the NIFS Collaboration Research Program (NIFS13KECA019).

References

[1] T. Naito, T. Sasaki, H. Fujishiro, Supercond. Sci. Technol. 25 (2012) 095012.
[2] J.H. Durrell, C.E.J. Dancer, A. Dennis, Y. Shi, Z. Xu, A.M. Campbell, N. Hari Babu, R.I. Todd, C.R.M Grovenor, D.A. Cardwell, Supercond. Sci. Technol. 25 (2012) 112002.
[3] M. Muralidhar, A. Ishihara, K. Suzuki, Y. Fukumoto, Y. Yamamoto, M. Tomita, Physica C 494 (2013) 85-88.
[4] Y. Ren, R. Weinstein, J. Liu, R.P. Sawh, C. Foster, Physica C 251 (1995) 15-26.
[5] T. Miyamoto, K. Nagashima, N. Sakai, M. Murakami, Supercond. Sci. Technol. 13 (2000) 816-819.
[6] M. Tsuchimoto, K. Murata, Physica C 392-396 (2003) 575-578.
[7] K. Katagiri, A. Murakami, K. Kasaba, Cryogenics 48 (2008) 87-94.
[8] C. Terzioglu, A. Varilci, I. Belenli, J. Alloys Comp. 478 (2009) 836-841.
[9] W. Duckworth, J. Am. Ceram. Soc. 36 (1953) 68.
[10] S. Nariki, N. Sakai, M. Murakami, I. Hirabayashi, Physica C 412-414 (2004) 651-656.
[11] Y. Murakami, Metal fatigue, Elsevier Sci. Ltd. (2002) 321-350.
[12] Unpublished data.
[13] A. Murakami, K. Otaka, A. Iwamoto, J. Phy.: Conf. Ser. 234 (2010) 012027.