Journal of Magnetism and Magnetic Materials 471 (2019) 200–208

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Experimental study on fracture process of sintered Nd-Fe-B magnets during dynamic Brazilian tests

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ARTICLE INFO

Keywords:
Nd-Fe-B magnet
Brazilian splitting
SHPB test
HSP with DIC
Tensile strength
Localized fracture strain

ABSTRACT

The deformation and fracture processes of the Nd-Fe-B magnets during dynamic Brazilian tests were investigated using a split Hopkinson pressure bar (SHPB) with a high-speed photography (HSP) and digital image correlation (DIC). The load and work applied to the specimens were determined with the strain signals of incident, reflected and transmitted wave of the SHPB tests. It was revealed with HSP and DIC that at a load time before the maximal load, some cracks along the loaded diameter on the specimen surface became visible. The localized fracture strains at representable points of the failed area were given by DIC. The tensile strength of the specimens was obtained based on the elasticity theory when the load reached the maximum. The widths of the failed area on the specimen surface at the maximal load were determined with DIC. Furthermore, the fracture work applied to the specimen per failed volume which corresponds to the maximal load was given and could be an energy criterion for the fracture of the Nd-Fe-B specimens. It was indicated that the tensile strength and fracture work of the Nd-Fe-B magnets increase with the increase of strain rate in the Brazilian tests. It was shown that the transgranular fracture became visible in the recovered specimens for the higher strain rate tests.

1. Introduction

Nd-Fe-B magnets are widely used in many fields including motors, generators, actuators, microwave and telecommunication equipments and so on. Therefore, it is very important work to investigate the failure of Nd-Fe-B magnets under dynamic loading. Wang et al. [1] examined the impact stability of experimental magnets with several kinds of permanent materials using a falling-hammer impact tester. Hu et al. [2] indicated that the impact toughness of sintered Nd-Fe-B magnets with the addition of Co first decrease, reaches a minimum and then starts to increase. Hu et al. [3] showed that addition of Nb could improve the thermal stability, and obviously increased the impact toughness of sintered Nd-Fe-B magnets. We [4] presented a study on the dynamic fracture of sintered Nd-Fe-B magnets under uniaxial compression using a split Hopkinson pressure bar (SHPB) with a high-speed photography (HSP) and digital image correlation (DIC). There is very few studies on dynamic tensile response of magnets. Rabinovich et al. [5] reported physical and mechanical properties of sintered Nd-Fe-B type permanent magnets including tension strength characteristics.

In this paper, the dynamic fracture of sintered Nd-Fe-B magnets during dynamic Brazilian tests was investigated using the SHPB. The deformation and fracture processes of the specimens were recorded by HSP with DIC. The tensile strength of the specimens was obtained based on the elasticity theory [6] when the load applied to the specimen reached the maximum. It was revealed by HSP with DIC that at a load time before the maximal load, some cracks along the loaded diameter on the surface of the specimen had become visible. The localized fracture strains at representable points of the failed area were given by DIC. The widths of the failed area on the specimen surface at the maximal load during the dynamic Brazilian tests were obtained with DIC. Furthermore, the fracture work applied to the specimen per failed volume which corresponds to the maximal load was given and could be an energy criterion for the fracture of the Nd-Fe-B specimen material. The effects of strain rate on the experimental results of the Nd-Fe-B specimens were shown in the dynamic Brazilian tests.

2. Experiment

The sintered Nd-Fe-B magnets used in this study are fabricated by the conventional powder metallurgy process. The chemical compositions obtained from energy spectrum of the magnets are listed in Table 1, and the microstructure of the magnets is shown in Fig. 1. The Nd-Fe-B specimen in the Brazilian test is a cylinder with a diameter of 40 mm and a thickness of 15 mm. The Brazilian splitting tests for the sintered Nd-Fe-B magnets under quasi-static loading were performed on the Electronic Universal Testing Machine as shown in Fig. 2. In the

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https://doi.org/10.1016/j.jmmm.2018.09.083
Received 12 June 2018; Received in revised form 27 August 2018; Accepted 22 September 2018
Available online 25 September 2018
0304-8853/

Table 1
The chemical composition (Wt% and At%) of the sinted Nd-Fe-B.

	C	O	Al	Pr	Nd	Fe
Wt%	6.7	2.6	0.3	8.9	27.1	54.4
At%	28.4	8.7	0.6	3.2	9.7	49.4

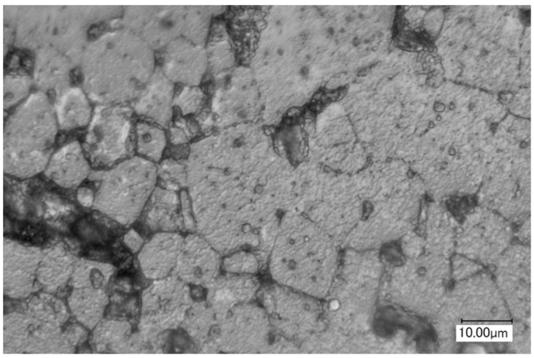

Fig. 1. The microstructure of the sintered Nd-Fe-B magnet.

Brazilian test, the load applied along two diametrically opposite generatrices creates a biaxial stress state within the cylinder. The Brazilian test is an indirect tensile test proposed by Carneiro et al [7], which overcomes the difficulties associated with the application of the direct tensile load on the brittle specimen. The applied force and loading displacement can be recorded simultaneously. The tensile stress perpendicular to the loaded diameter of the specimen is almost uniform and can be given by [6]

$$\sigma_t = 2P/\pi DT \tag{1}$$

where P is the applied loading, D is the diameter of the disc specimen, T is the thickness of the specimen. Eq. (1) was deduced based on the elasticity theory [6]. The tensile stress σ_t is equal to the tensile strength σ_s of the specimen when the specimen fails. For the quasi-static Brazilian test of the Nd-Fe-B magnet shown in Fig. 2, the strain rate $\dot{\varepsilon} = 2 \times 10^{-4}\,\mathrm{s}^{-1}$, the tensile strength $\sigma_s = 75$ MPa and the recovered specimen is also shown in Fig. 2.

The fracture mechanism of the Nd-Fe-B specimens under dynamic Brazilian tests was investigated using a SHPB apparatus shown in Fig. 3. A pulse shaper is necessary to deform the specimen with a nearly linear response at constant strain rates as indicated by Frew et al. [8]. The pulse shaper in this study is a copper sheet with an outer diameter of 19.7 mm and an inner diameter of 16 mm and a thickness of 3 mm. A steel bar of 400 mm in length and 37 mm in diameter accelerated by compressed air impacts an incident bar of 2000 mm in length at a velocity V_0, producing in it an elastic wave with a length that is large with respect to the diameter of the specimen. The elastic wave travels through the incident bar and then reaches the specimen, which is sandwiched between the incident and the transmitted bar of 2000 mm in length. The incident, transmitted and reflected pulses are measured at the points of the attached strain gages. The signals from the strain gages are monitored and acquired by an oscilloscope. The load *P(t)* applied to the specimen is given by

$$P(t) = A_0 E[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)]/2 \tag{2}$$

where A_0 is the cross-section area of the incident bar, E is the elastic modulus of the incident bar, $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$ are the strain signals of the incident, reflected and transmitted wave, respectively.

The relative displacement between the two ends of the specimen is given by

$$D_s(t) = -2C_0 \int_0^t \varepsilon_r(t)dt \tag{3}$$

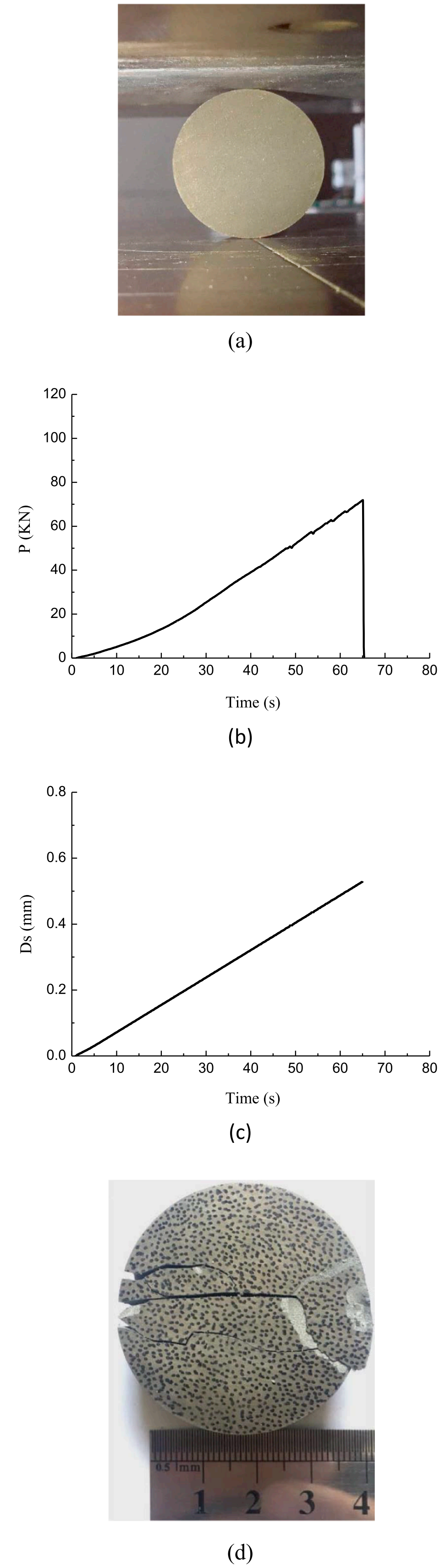

Fig. 2. The Brazilian splitting test for the Nd-Fe-B specimen under quasi-static loading (a) The installation (b) Force (c) Displacement (d) Recovered specimen.