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Experimental and numerical investigations of fracture behavior of magnetostrictive materials

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Abstract

The purpose of this work is the characterization of the fracture behaviour of giant magnetostrictive materials subjected to a magnetic field. Both experimental and numerical investigations have been performed, focusing on iron and rare earth alloys, such as the commercially named Terfenol-D. Tests have been carried out on single-edge precracked specimens subjected to three-point bending in the presence of magnetic fields of various intensities and fracture loads have been measured at different loading rates. Recent studies on local stress fields in proximity of crack and notch tips have shown that Strain Energy Density (SED), averaged in a circular control volume which includes a crack tip, could be a robust parameter in the assessment of brittle fracture resistance of several materials. Coupled-field analyses have then been performed on both plane stress and plane strain finite element models and the effect of the magnetic field on fracture resistance of Terfenol-D alloy was predicted in terms of averaged SED. A relationship between the SED's control volume size and the loading rate has also been proposed.

Keywords: strain energy density; strain energy release rate; smart materials; giant magnetostrictive materials; fracture toughness; magnetic field.

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1. Introduction

Magnetostrictive materials exhibit deformation in response to external magnetic fields and magnetization change in response to applied forces. Among giant magnetostrictive materials, the commercially known Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.9}$) alloy, made out of iron, terbium and dysprosium, has been recording much interest over the years. The remarkable elongation and the high energy density storing capacity at room temperature are advantages which ensure the great Terfenol-D potential in many applications. Such material is employed in automotive industry, in avionics and in robotics, where magnetostriction based sensors and actuators are commonly used. Terfenol-D is also expected to be used in energy harvesting devices as shown by Zhao et al. (2006).

According to Peterson et al. (1989), giant magnetostrictive alloys such as Terfenol-D are very brittle and then susceptible to in-service fracture. Despite defects caused by manufacturing and cracking could have important influence on the material performances, really few works can be found in literature dealing with this topic. It is therefore of interest to grow the mechanical knowledge around defect's sensitivity to magnetostrictive materials. Numerous methods have been proposed by scholars to evaluate the fracture behavior of different materials (Ayatollahi et al. (2015, 2016); Rashidi Moghaddam et al. (in press)). Lazzarin and Zambardi (2001) introduced the averaged Strain Energy Density (SED) criterion to predict brittle failures, which occur without any plastic deformation. The criterion states that brittle fracture failures occur when the strain energy density averaged in a circular control volume, which includes a crack or notch tip, reaches a critical value dependent on the material. Thereafter many researchers worked on this criterion and proved that it could successfully predict brittle and high cycle fatigue failures of precracked, U- or V-notched specimens made out of several materials, including metals and ceramics. Narita et al. (2012) studied the effect of the magnetic field on fracture behavior of Terfenol-D both experimentally and numerically by means of the energy release rate and showed that the fracture resistance, under mode I, is greater in absence of the magnetic field and decreases with the increase of the latter. They also proved that the resistance decrease may be related to the increase of the energy release rate with increasing magnetic fields. Colussi et al. (2016) showed that SED criterion could be extended to the assessment of brittle behavior of giant magnetostrictive materials, under mode I loading condition, and proposed the use of a control volume having radius 0.07 mm. Here, experimental data set on fracture behavior of Terfenol-D specimens under three point bending has been extended and fracture loads were measured in presence and absence of the magnetic field and at different loading rates. By performing coupled-field finite element analyses the effect of the magnetic field and of the loading rate on Terfenol-D brittle failure has been discussed. The capability of the SED criterion to capture these effects has then been analyzed and, for this purpose, a relationship between the radius of the control volume and the loading-rate has also been proposed.

2. Analysis

2.1. Basic equations of the material

The basic equations for magnetostrictive materials are outlined as follows. Considering a Cartesian coordinate system, $O\text{-}x_1\,x_2\,x_3$, the equilibrium equations are given by:

$$\sigma_{ji,j} = 0; \quad \varepsilon_{ijk} H_{k,j} = 0; \quad B_{i,i} = 0 \tag{1}$$

where σ_{ji}, H_i and B_i are respectively the components of the stress tensor, the intensity vector of the magnetic field and the magnetic induction vector, whereas ε_{ijk} is the Levi-Civita symbol. A comma followed by an index denotes partial differentiation with respect to the spatial coordinate x_i and the Einstein's summation convention for repeated tensor indices is applied. The constitutive laws are given as: