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Influence of a multiaxial stress on the reversible and irreversible magnetic behavior of an iron-silicon alloy

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1. Introduction

Compared to conventional aircrafts, electrical power on the new generation aircrafts is multiplied by four. This induces an exponential increase in the number, mass and size of electrical equipment. To achieve the objective of weight reduction, solutions to optimize electrical systems must be found. A solution is to increase the power density of generators by using higher rotation speeds. This choice raises new material issues related to the increase of centrifugal forces and stress level in the rotor. A first point is to provide high yield stress materials. A second point is to evaluate the influence of multiaxial stress associated to centrifugal forces on the magnetic behavior [1]. The aim of this work is to propose an experimental illustration of the influence of multiaxial stress on the magnetic behavior of commercial non-oriented 3%Si-Fe alloy. Quantities associated to the dissipative part of the magnetic behavior are especially considered. These experimental results are used to assess the relevance of an equivalent stress approach.

2. Experimental procedure

The material is a commercial non-oriented 3%Si-Fe from Arcelormittal delivered in 0.5mm thick sheets. The basic idea of the multiaxial test is to load a cross-shaped specimen in tension-compression along two perpendicular directions [2]. Compression tests can be achieved thanks to a central core made of Bakelite avoiding buckling. Bakelite is non-magnetic and non-conductive so that it does not disturb the magnetic measurement. The local stress tensor in the center of the specimen can be calculated from the forces applied along the two loading axes according to an interacting matrix. The terms of the matrix have been computed thanks to a finite element mechanical modeling of the specimen. The magnetic measurements area is a 30mm diameter circle where both stress and magnetic field are fairly uniform. Magnetic field and magnetization are measured thanks to a calibrated H-coil and a needle-B sensor; strain field is obtained thanks to digital image correlation. Different loading (σ_1, σ_2) are successively applied to the sample. Magnetic measurements are carried out after demagnetization: they include hysteresis loops at low and high frequency measurements f (1Hz to 800Hz) and anhysteretic curves. The results selected in this paper are limited to hysteretic and anhysteretic measurements carried out when the magnetic field H is applied along the rolling direction (RD). 41 biaxial loading configurations have been tested, for stress level varying from -100MPa to +100MPa. Stress states can be divided in parallel uniaxial tests ($\sigma_1 \neq 0, \sigma_2 = 0$), orthogonal uniaxial tests ($\sigma_1 = 0, \sigma_2 \neq 0$), equibiaxial tests ($\sigma_1 = \sigma_2$), and shear tests ($\sigma_1 = -\sigma_2$) in order to map the stress plane.

3. Results

Figures 1 illustrates the evolution of the normalized secant susceptibility χ/χ_0 for $H=200\text{A/m}$ (1a), normalized coercive field H_c/H_{c0} (1b) and normalized power losses P/P_0 (1c) at low frequency (5Hz). χ_0, H_{c0} and P_0 are respectively the susceptibility, coercive field and power losses at zero stress. Secant susceptibility is defined by $\chi=M/H$ for a given value of magnetic field H and magnetization M . When a uniaxial stress is applied parallel to the magnetic field ($H//\sigma_1$ - Fig. 1a), a weak improvement of the magnetic behavior in tension and a strong deterioration in compression are observed. When a uniaxial stress is applied perpendicular to the magnetic field, the effect is opposite, and attenuated.

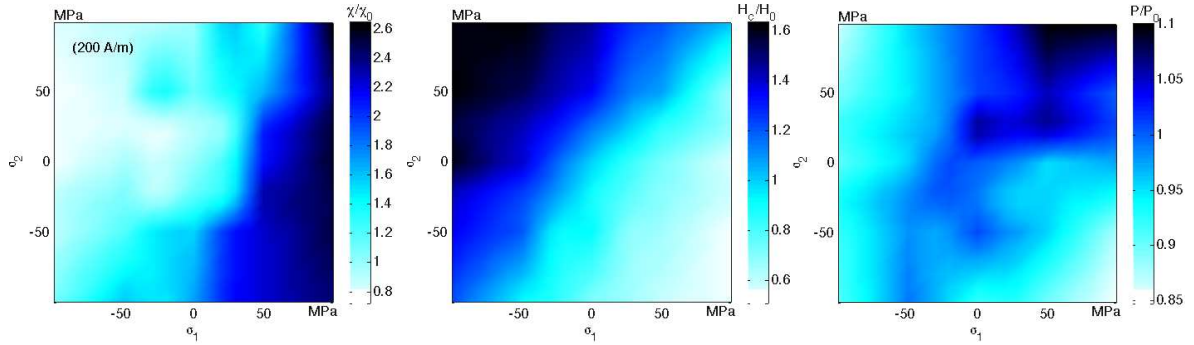


Fig1. (a) Normalized secant susceptibility for $H=200\text{A/m}$ ($\chi_0=1312$) (b) Normalized coercive field ($H_{c0}=83\text{ A/m}$) (c) Normalized power losses ($P_0=0.15\text{ W/kg}$) ($B_{\max}=1,7\text{T}$).

The lowest values of χ are reached in the upper left side of the graph, corresponding to the shear situation when $\sigma_1 < 0$. The tension-compression asymmetry is very perceptible. The bi-tension increases the susceptibility, while a bi-compression can divide it by two. Figure 1b and 1c show respectively the influence of the frequency on the evolution of the normalized coercive field and the magnetic power losses under biaxial loading. It can be noted that the minimum coercive field is obtained for shear stress with positive stress in the direction of applied. The bi-tension state slightly increases the magnetic power losses P (about 10% for $\sigma_1=\sigma_2=+100\text{MPa}$). Highest power losses are obtained along the equi-biaxial stress axis.

4. Equivalent stress

Available modeling tools are often limited to the case of uniaxial stress. The extension to multiaxial stress can be made through the use of the concept of equivalent stress. In the case of magneto-elastic behavior, the equivalent stress for a given multiaxial loading is defined as the uniaxial stress applied parallel to the magnetic field that leads to the same magnetic behavior than the actual multiaxial loading.

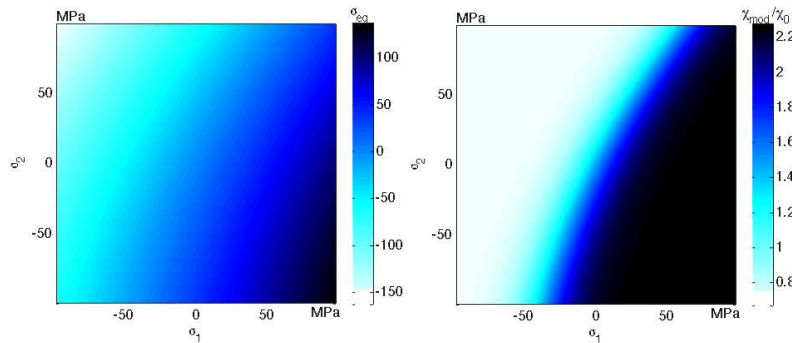


Fig2. (a) Equivalent stress in the stress plane (b) associated prediction of normalized secant susceptibility ($\chi_0=1312$).

Figures 2a illustrates the prediction of the equivalent stress σ_{eq} thanks to the criterion proposed by Hubert and Daniel [3]. Figures 2b shows the associated theoretical evolution of normalized secant susceptibility in the stress plane (an experimental evolution of the normalized susceptibility with uniaxial stress has been used for that purpose). Modeling and experiments are qualitatively in good agreement (Fig. 1a vs. Fig. 2b). The criterion reflects especially the major influence of the stress level along the magnetization axis. It will be shown in the full paper that coercive field and power losses follow the same rule than susceptibility.

References

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