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Effect of applied tensile stress on the hysteresis curve and magnetic domain structure of grain-oriented transverse Fe-3%Si steel

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ABSTRACT

The effect of an elastic applied tensile stress on the quasistatic hysteresis curve and domain structure in conventional (110) [001] Fe-3%Si steel, cut transversely to the rolling direction, is studied. The magnetic domains and magnetization processes were observed by longitudinal Kerr microscopy at different levels of stress. It is shown that above 8 MPa the bulk hysteresis loop can be described with a good accuracy by the action of an effective field, which is the product of the stress and a function of magnetization. Domain observation reveals that the reasons for the effective field are demagnetizing fields due to the disappearance of supplementary domains at low applied field and the formation of different domain systems in different grains at low and moderate fields. The latter are caused by differences in grain sensitivity to stress depending on the degree of misorientation and grain boundary orientation. A decrease of the effective field above 1 T is connected with a transformation of all grains into the same domain system – the column pattern. The hysteresis loop behavior is qualitatively the same as for strips cut in rolling direction and for non-oriented strips.

1. Introduction

Despite a large amount of research on the influence of mechanical stress on the magnetic properties of polycrystalline ferromagnetic materials (particularly on the magnetic hysteresis curve), details of the materials reaction to mechanical stress are still not fully understood, especially for iron-based materials. The most difficult and controversial case is the behavior of Fe-based materials under tensile stress. In such material with positive magnetostriction, an increasing tension should continuously improve the magnetic properties like susceptibility and coercivity. In reality it was noticed already 150 years ago by Villary that the magnetization change of iron-based polycrystalline, non-oriented material under tensile stress is not monotonous with magnetic field increase [1]. At low fields the magnetization change is also not monotonous with an increase in tensile stress – the magnetization rather first grows at very low stress, reaches a maximum and then continuously decreases with further stress increase [2–5]. In our previous work [5] we have shown that this behavior is also observed for grain-oriented (110)[00l] silicon–iron strips magnetized and stressed along the [001] direction. Since non-oriented material consists of grains oriented along all possible directions, it is advisable to study grain-oriented strips cut at various directions relative to the field and stress axis to get an access also to the changes in magnetic properties of non-oriented material. In this work we investigate grain-oriented Fe-3%Si sheets tensed and magnetized transversely to the rolling direction.

2. Experiment

The experimental setup used here is the same as in our previous work on compressed transverse samples [6]. Tensile stress up to 70 MPa was applied to Goss textured, grain-oriented Fe-3%Si sheets with dimensions of $0.5 \times 30 \times 280\ mm^3$, cut transversely to the rolling direction. The samples were magnetized in a horizontal sheet tester [6] (see Fig. 1) at 0.05 Hz using a triangular field waveform with a maximum field amplitude of 2000 A/m.

The magnetic domains were observed by longitudinal Kerr microscopy with sensitivity along the transverse direction (which corresponds to the surface-parallel [001] easy axis).

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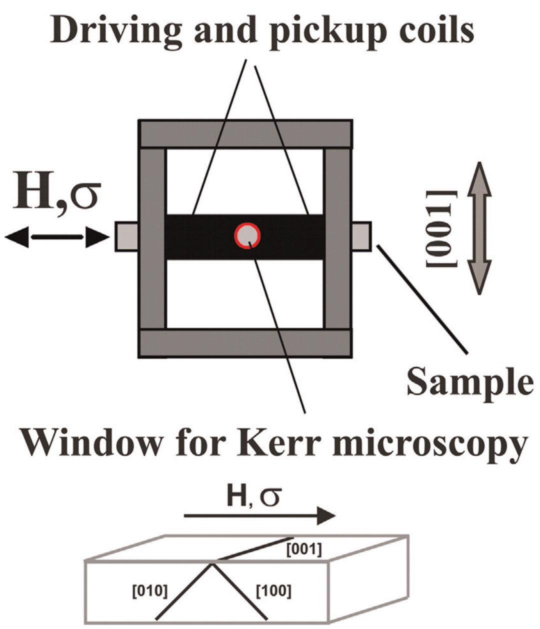

Fig. 1. Magnetizing setup. The field and tensile stress are applied perpendicular to the [001] easy axis.

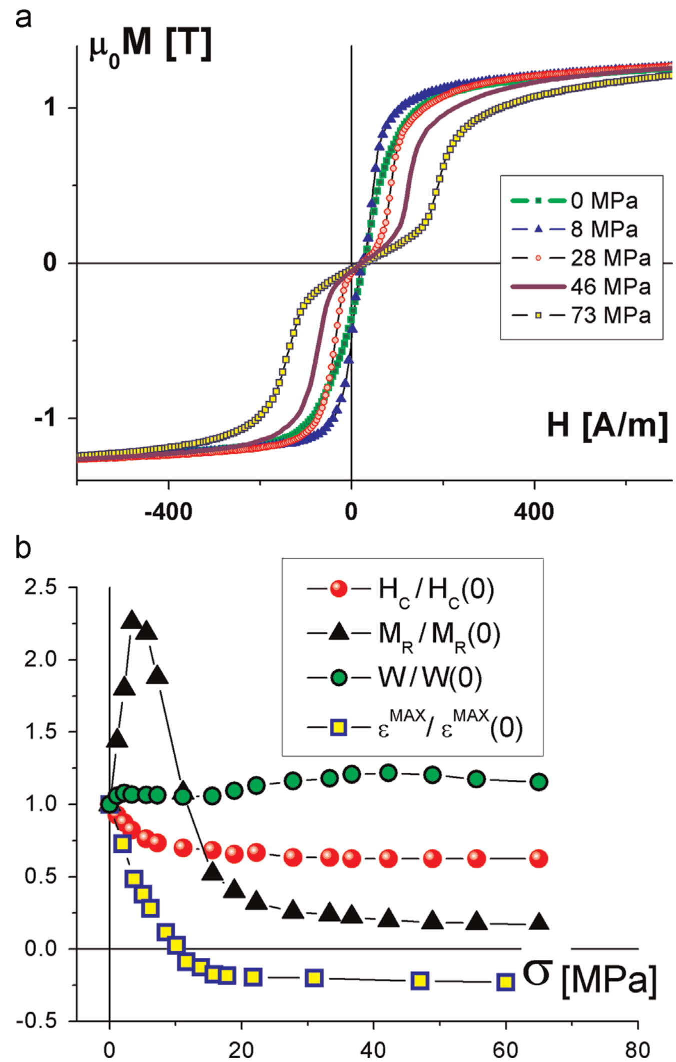

Fig. 2. (a) Bulk hysteresis curves (ascending branches) for different stress values and (b) relative changes of parameters obtained from these curves: coercivity H_C, remanent magnetization M_R, losses W and maximum magnetostrain ε^{MAX}.

3. Results

3.1. Bulk hysteresis loops

In Fig. 2a the ascending branches of the hysteresis curves for tensile stress up to 73 MPa are shown. It is seen that the change of the magnetization curve is not monotonous – up to 5.6 MPa the magnetization shifts to lower fields and above 8 MPa it continuously shifts to higher fields with increasing stress. The coercive field first decreases by 25% up to 8 MPa and then remains constant with further stress increase. The remanent magnetization first increases at low stress and then drops by approximately one order of magnitude with stress increase from 8 to 73 MPa (Fig. 2b). All parameters show the same behavior as already found for strips under tension cut *parallel* to the rolling direction [5] except for the losses that change very little for transverse strips. All hysteresis curves show a characteristic constricted shape.

3.2. Domains in the demagnetized state

In Fig. 3 the magnetic domains in the ac-demagnetized state in a perfectly oriented grain are shown for different stress levels. The domain character changes from simple bar domains (0 and 4 MPa) to stress pattern I (6.5–21 MPa) and stress pattern II (> 35 MPa) with increasing stress. As it was shown in our work on compressed samples [6] it is not sufficient to study the domains just in a single, perfectly-oriented grain to come up with an explanation of the changes in the magnetization curves with stress. Therefore the domains at nine neighboring rectangular spots B1–B9 (as indicated in Fig. 4) are studied. In Fig. 5 the demagnetized state for stresses from 0 to 72 MPa is imaged. The domain images were taken separately for each spot with the sample being demagnetized prior to each observation so that there is no exact one-to-one correspondence between the domains at the different spots. As it was discussed in detail in Ref. [6], each grain consists of more or less complex domains in the nominally stress-free demagnetized state, which vary between simple bar domains, supplementary domains (lancet pattern) and branched domains depending on the degree of misorientation and residual stress. Also different stress patterns can coexist at some stress levels. In grains with weak out-of-plane misorientation, lancets are also seen within the “basic” closure domains of stress pattern I (see Fig. 5 for stresses of 7 and 16 MPa). These lancet domains reduce in size with stress and finally completely disappear beyond approx. 30 MPa (see spots B4–B7 in Fig. 5). Note also the considerable refinement of Stress pattern II domains as stress is increased from 36 to 72 MPa.

In Figs. 6–10 the domains for tensile stress from 0 to 60 MPa are imaged at lower magnification (spot size 3×2.5 mm^2), again at nine neighboring spots A1–A9 as indicated in Fig. 4. In addition to the features already found in the previous series of images, it is seen that for large stresses (above 30 MPa) most of the sample is occupied with Stress Pattern II, while in the central area stress pattern I is preserved to higher stress levels, transforming to stress pattern II reluctantly with stress increase.

4. Discussion

4.1. Hysteresis loops, effective field model

Since both, tensile stress and applied magnetic field favor the “transverse” [100] and [010] easy axes and disfavor the