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Magnetostriction measurements of high strength steel under the influence of bi-axial magnetic fields

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ABSTRACT

A detailed knowledge of a material's microscopic texture is required in order to produce a realistic model of the magnetization process under applied fields. Previous studies on the magnetostriction in high strength steels have ignored the internal anisotropies due to prior material handling. To this end, a measurement utilizing two perpendicular fields was designed to interrogate the magnetic texture and microstructure of high-strength steel rods. These magnetization and magnetostriction measurements were then fitted to an energy-based domain rotation model which had been altered to address vector fields and uniaxial anisotropies. Given the simplicity of the model it is surprising to see that it captures a number of the general trends in the Data, however the fit is generally poor. Improving upon this data set will allow us to determine general magnetic characteristics of microstructure in the steels. These measurements will be incorporated into a future Vector Preisach model allowing detailed predictions of the magnetic state after stress and field changes in multiple directions.

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1. Introduction

The magneto-mechanical effect in steels has been documented in the literature for well over a century. Although steels exhibit very small magnetostrictions, their prolific uses in industrial applications lead to situations in which those attributes may either be harnessed or deemed undesirable. The magnetostriction of high strength steels is useful in particular for noncontact torque sensing on high strength-to-weight ratio drive shafts [1].

Accordingly, many measurements and theories have been developed to characterize the magnetostriction of steels. Most studies of magnetostriction in high strength steels have ignored the internal anisotropies due to previous material handling. Cold-rolling steels leaves magnetic domains stretched in the direction of rolling, allowing for an additional easy axis to exist along with the six crystalline axes found in cubic lattices [2]. Our previous work has shown differences in magnetic properties of high strength steels with regard to their angles from the rolling direction in sheet steel [3].

While we have been able to show magnetic differences between sample directions due to the original forming of the material, it is not possible to fully characterize the shapes of the magnetic domains within the bulk of the material. Preparing the surface of a sample for microscopic measurements of domain shapes and sizes can alter the characteristics which one is aiming to measure. Even if the anisotropies on the surface are not destroyed during polishing, the visible surface domains which remain may not be an accurate description of the domains within the bulk of the sample [4]. Due to this fact, we have devised a way to interrogate those domains via the application of orthogonal magnetic fields and the rough fitting of the data to a magnetic rotation model. This experiment is part of a cumulative effort which will eventually allow the characterization of domain sizes, shapes, and distributions for use as future Preisach modeling parameters.

In this paper we report magnetic properties of a high strength steel oriented parallel, perpendicular and 45 degree to the rolling direction while under the influence of longitudinal and transverse fields. These measurements include the differential susceptibility, magnetization, and magnetostriction without additional applied stress. While our previous work [3] relied on applied compressive stress to deform the shape of the *J*–*H* loop, these new measurements utilize a constant transverse field in order to induce this domain-pinning. Fig. 1 shows the difference between these measurement types. The black lines (shown in a vertical top-down view of the cylinder samples) indicate the direction of magnetic domain "pinning" due to the compressive stressed and/or transverse fields applied. While the transverse field applied to the sample has a

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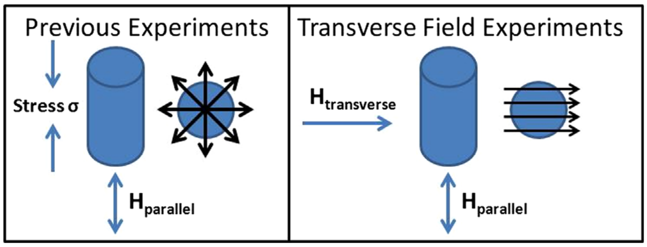

Fig. 1. Difference between these measurements and the previous measurements. (a) The previous experiment applied longitudinal field and stress, pushing the domains into any preferred direction along the central plane (b) the new experiments apply a longitudinal field as well, but replace the stress with a transverse field, pushing domains towards a preferred direction close to the transverse field direction.

similar overall effect as a compressive longitudinal stress, there are more options for lowest energy states in the latter.

2. Experiment

Solid cylinders with their longitudinal axis oriented parallel, perpendicular and 45 degree with respect to the rolling direction were machined from each of three locations on the original rolled plate of high strength steel, a total of nine samples. The sample compositions and details are listed in our previous publication [3]. All samples were taken from the same sheet of steel, and differences in composition and heat treatments are assumed to be negligible.

Each cylinder was ~5.71 mm in diameter and ~55.8 mm in length. A sample holder was constructed which would position a steel rod, which was wrapped in longitudinal field induction and pickup coils, between the iron pole faces of a large transverse field magnet. This transverse magnet was used to apply a constant transverse field H_T to the samples while a longitudinal applied field H_L was varied. Strain was measured by two MicroMeasurements WK-06-500GB-350 strain gauges mounted on opposite sides of the rod with AE-15 resin. The measurements of these strain gauges were averaged to give the magnetostriction shown in the results section.

The water-cooled transverse magnet was capable of applying uniform fields in excess of 1400 kA/m between the 15.24 cm diameter pole faces. The air gap between the pole faces was measured to be approximately 7.5 cm. The sample holder was placed with the longitudinal coil centered within this gap. A brass turnbuckle was utilized to hold the sample tightly within the sample holder. Fig. 2 shows a picture of the disassembled and assembled sample holder.

One drawback of this test setup was the lack of a closed flux path for the field lines. While iron end-pieces were originally used to try and contain the flux within the sample, they were found to disproportionally distort the field, creating a large dipole. This dipole, acted upon by the transverse field, put a significant torque on the sample and distorted the magnetostriction measurements. A finite element model was created in COMSOL Multi-physics in order to determine a suitable testing arrangement to alleviate the torque imparted on the sample. As the strain measurements and pickup coils are located in the center of the sample, it was determined that Aluminum end-pieces would be sufficient for holding the sample in place as they maintained a fairly constant field within the center region of the steel rod. This did not negate the longitudinal demagnetization factor within the sample, but the quadra-pole created did not feel the same realigning force from the transverse field.

The experimental procedure started with setting H_T=0 A/m, and the taking of calibration points at each longitudinally applied field extrema for later data correction. After the calibration points were obtained, a decreasing AC-field demagnetization was performed on each sample in the longitudinal direction. The demagnetization was completed at H_T=0 A/m. The temperature within the longitudinal coil was monitored and attempts were made to keep it fairly constant. However, the design of the sample holder made it impossible to cool the sample directly, so a correction was made to the data for the temperature-dependent drift of the strain gauges throughout the course of the measurements.

For the major loop measurements, once demagnetized, the sample was set to the desired H_T and the strain gauges zeroed. Then H_L was cycled over ± 80 kA/m. Each cylinder was tested for 10 different fixed transverse fields between 0 and 1400 kA/m. Each measurement set was preceded by this same demagnetization and application of H_T cycle. Each of the measurements listed above were repeated for all nine cylinders.

3. Model

The model used to fit the data was developed from a previous Energy-based domain rotation approach [5]. This single-domain rotation model utilizes the same α_i's as direction cosines of the magnetization with respect to the cubic crystal axes, but applies them in a different manner. In our notation below, z refers to the longitudinal direction, and x refers to the transverse field direction. The energy equation used is given by two terms, and is different for each individual rolling direction j (parallel, perpendicular, and 45 degree)

$$E_j = -\mu_0 M_s \sum_{i=x,z} H_{i,}\alpha_i + K_{\text{uniaxial}}\,\alpha_j \tag{1}$$

where M_s is the saturation magnetization, H_i is the field applied in each direction, and K_{uniaxial} is the anisotropy found in the sample due to the rolling of the original steel. The α_j value changes based on the direction of the sample being measured as follows

$$\alpha_{\text{parallel}} = \alpha_z^2; \quad \alpha_{\text{perpendicular}} = \alpha_x^2; \quad \alpha_{45\text{ degree}} = \alpha_x\alpha_z \tag{2}$$

This serves as a useful approximation for the effects of the transverse fields on the sample magnetizations. As they were calculated in [5], the strain S and magnetization M are calculated from energy weighted averages incorporating a smoothing factor Ω

$$M = \left[\sum_{i=x,z} M_i \exp(-E_i/\Omega)\right] \Bigg/ \left[\sum_{i=x,z} \exp(-E_i/\Omega)\right] \text{ and}$$
$$S = \left[\sum_{i=x,z} S_i \exp(-E_i/\Omega)\right] \Bigg/ \left[\sum_{i=x,z} \exp(-E_i/\Omega)\right] \tag{3}$$

where $M_i = M_s\alpha_i$ and $S_i = \lambda_s\alpha_i^2$

4. Results

Fig. 3 shows an example of the magnetization versus longitudinally applied field loops for one of the parallel cylinders. As expected, the magnetization curves do not start from zero. Due to the experimental procedure, the application of the transverse field after the AC demagnetization increases the starting magnetic induction before the application of longitudinal magnetic field. The increasing transverse fields can be seen in the tilting and deformation of the loops. Fig. 4 shows the same *J*–*H* loop with the center portion enlarged. It is interesting to note that the center of the *J*–*H* loops tend to skew upwards and towards the negative longitudinally applied field direction when a certain transverse field is applied.

The effect of the transverse field is difficult to quantify in this test setup. A useful visualization tool is the plotting of a number of