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Fitting the flow curve of a plastically deformed silicon steel for the prediction of magnetic properties

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Abstract

We report measurements and modelling of magnetic effects due to plastic deformation in 2.2% Si steel, emphasizing new tensile deformation data. The modelling approach is to take the Ludwik law for the strain-hardening stress and use it to compute the dislocation density, which is then used in the computation of magnetic hysteresis. A nonlinear extrapolation is used across the discontinuous yield region to obtain the value of stress at the yield point that is used in fitting Ludwik's law to the mechanical data. The computed magnetic hysteresis exhibits sharp shearing of the loops at small deformation, in agreement with experimental behavior. Magnetic hysteresis loss is shown to follow a Ludwik-like dependence on the residual strain, but with a smaller Ludwik exponent than applies for the mechanical behavior.

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Keywords: Plastic deformation; Silicon steel; Magnetic effects; Hysteresis modelling

1. Introduction

In this paper, we report measurements and modelling of plastic deformation magnetic effects in a 2.2% Si electrical steel. Earlier, we reported measurements on rolled specimens undergoing compressive plastic deformation [1]. In this paper, we now include tensile plastic deformation measurements on the same type of steel. It is known that in this steel, in rolled specimens, the magnetic hysteresis behavior is sharply sheared by what is considered to be a rather small plastic deformation (0.5%) [1]. A new modification [2] to the Jiles–Atherton hysteresis model has made it possible to model the magnetic effects of plastic deformation on the magnetic hysteresis $B-H$ curve [3]. The flow curve of the steel, especially in the tensilely deformed specimens, shows evidence of discontinuous yield, which can be explained by a Cottrell atmosphere of carbon atoms initially pinning the dislocations [4]; hence, the ''apparent'' yield stress needed to start dislocation flow is actually greater than what is needed to continue dislocation flow. It is known that in discontinuous yield, slip is nonuniform at first, leading to the formation of Luders bands, which are visible plastic deformation fronts that move across the specimen as deformation continues [5]. Eventually, with enough deformation (1–2%), the localized Luders bands disappear, and plastic strain becomes uniform across the specimen [5]. The presence of discontinuous yield is manifested in the flow curve by a sharp drop at the end of the elastic line as the material begins to plastically deform, and then by a levelling off and a flat region of the flow curve, after which the flow curve joins the region of uniform strain and behaves as it would in a specimen undergoing uniform strain. This behavior is

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not only seen in electrical steels but in alloy steels as well [6].

The magnetic properties are known to be affected by the relationship between "strain-hardening" stress and the residual deformation e_r. The strain-hardening stress is given as $\sigma - \sigma_y$, where σ is the applied stress and σ_y is the stress value at the yield point. The residual strain e_r is the plastic strain that remains in a material after the deforming applied stress is brought back to zero. It can be shown that the residual strain e_r is equal to the "plastic" strain given as $e_{pl} = e - \sigma/Y$, where Y is Young's modulus and e is the total deformation produced by stress σ. The relationship between the strain-hardening stress and the residual strain e_r is phenomenologically given as Ludwik's law, which states that $\sigma - \sigma_y$ is equal to a constant multiplied by the residual strain e_r to some power n, where n is known as the Ludwik exponent and is material-dependent, and hence is an irrational number and not necessarily a rational fraction. We have shown that the magnetic properties are a function of this relationship [3], and hence it would not be surprising if hysteresis loss also satisfies a Ludwik-like relationship. We shall show that indeed they do exhibit such a relationship, but not with the same exponent as shown by the mechanical behavior. In demonstrating this behavior, we extrapolate the uniform strain flow curve nonlinearly to the elastic line, obtaining a value for σ_y that can be used in the Ludwik law for the uniform strain region.

2. Experiment

A 2.2% Si fully processed electrical steel was cold rolled with different elongations and was also deformed in two different tensile machines (one of them a mechanical "ball screw" EMIC tester model DL2000/700, and the other a servohydraulic MTS).

Magnetic losses at 1.5 T, 60 Hz were measured in rolled samples and in the central region of tensile specimens. The rolled samples were measured in the standard Epstein frame and using a single-sheet feature with a Soken electrical steel sheet tester model DAC-BHW-5. The tensile specimens were measured only with the Soken instrument.

3. Results and discussion

Fig. 1 shows a tensile stress–strain curve that we have found for a particular specimen of 2.2% Si steel. Depending on the type of machine used, the low strain region may or may not show the peak associated with the discontinuous yield, but above 0.5% the curves were similar. The machine used here made evident the discontinuous yield, even though the carbon content is below 30 ppm. The better the alignment of the sample holders, the larger will be the flat yield region, here reaching up to 1% in this steel. Because of the discontinuous yield, it is difficult to estimate a dislocation density based on hardening, although the dislocation density is increasing. We have been able to extrapolate the curvature of the uniform strain region through the discontinuous yield region on down to an intersection with the elastic line part of the deformation. The intersection amounts to what would be the yield point if the discontinuous yield phenomenon did not occur. The value of S at that point we take as σ_y in Ludwik's law, and then from a log–log plot of $\sigma - \sigma_y$ vs. e_r, as in the inset, we obtain the Ludwik exponent from the slope of the plot.

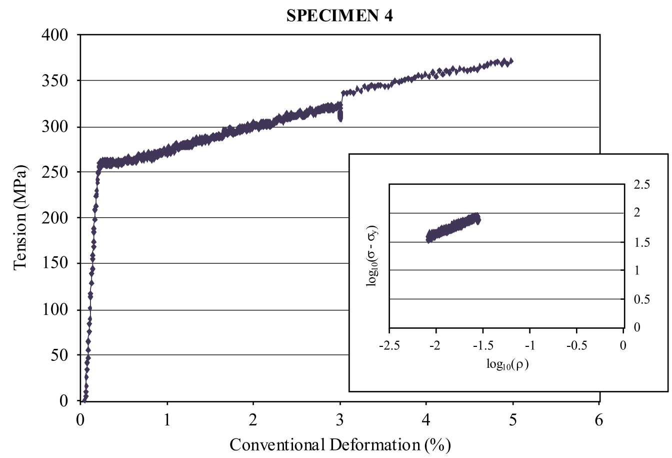

Fig. 1. A typical tensile stress–strain curve, with inset showing the plot used to obtain the Ludwik exponent.

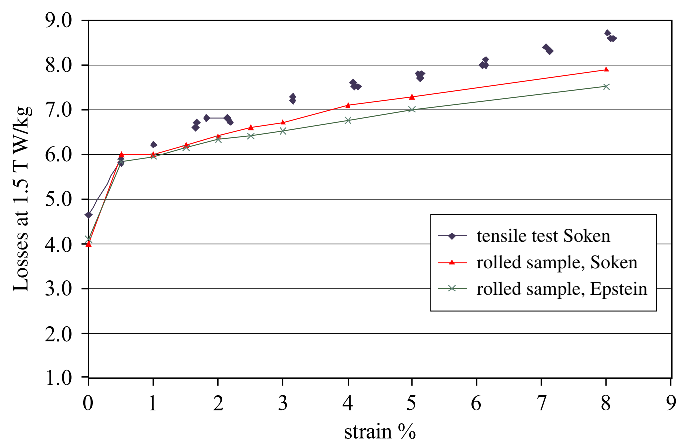

Fig. 2. Losses at 1.5 T, for tensile test specimens and cold-rolled Epstein specimens of 2.2% Si steel, as a function of residual strain.

Fig. 2 shows magnetic losses at 1.5 T, 60 Hz, as a function of deformation, for samples deformed by rolling and by tensile test. The step seen from zero deformation to slightly higher deformation is quite noticeable. A similar step was seen in coercivity vs. deformation in the rolled specimens [1]. It was found that the plot in Fig. 2 could be fitted to a Ludwik-like relation relating the losses to a power of the residual strain e_r. That power or exponent was found from log–log plots to be 0.33 for the tensile specimens and 0.33 and 0.29 for the rolled specimens, depending on whether one used Soken or Epstein data.

4. Modelling

The hysteresis modelling used for the tensile plastic deformation specimens is explained in Refs. [2,3], except that $n = 0.66$ is used now for the Ludwik exponent used in computing the strain-hardening stress that enters into the model. This value of $n = 0.66$ was extracted from the tensile mechanical data after using nonlinear extrapolation from the uniform strain region to obtain the Sy used in Ludwik's law. Also, the mechanical data yielded $Y = 178$ GPa, and that value too was used in the numerical computation. Otherwise, the computation was the same as used for the rolled specimens [3] except that for tensile specimens, the applied magnetic field was in the same direction as the stress axis, and so instead of using $v'(\sigma - \sigma_y)$, one uses $\sigma - \sigma_y$ (or the strain-hardening stress at the largest value of applied stress) for the residual stress.

On carrying out the computation for different deformations e_r, one finds hysteresis behavior as seen in Fig. 3. The zero deformation specimen shows a very sharp, almost vertical, and very narrow hysteresis loop. Loops at 0.5%, 2% and 5% deformation are qualitatively seen as strongly sheared, as found in experiment and in the case of rolled specimens [1,3].

We also extracted from the areas inside the hysteresis loops the quantity known as hysteresis loss W_h, which amounts to static magnetic loss due to hysteresis and which does not have an eddy current loss component. Corresponding to the loops in Fig. 3 and to other computed loops for other deformations not shown in Fig. 3, we extracted W_h as a function of residual strain e_r. This is plotted in Fig. 4, and a log–log plot of W_h vs. e_r is seen in Fig. 5. From Fig. 5, we find a Ludwik-like exponent of $n = 0.39$ for the relationship between W_h and residual strain e_r, where W_h is equal to a constant times e_r to the power n. The value of 0.39 is certainly different from the mechanical Ludwik exponent, which was 0.66. The value 0.39 is also not too different from the experimentally determined values of $n = 0.33$. The slight departure in values could well be that eddy current losses are not considered in the modelled hysteresis losses.

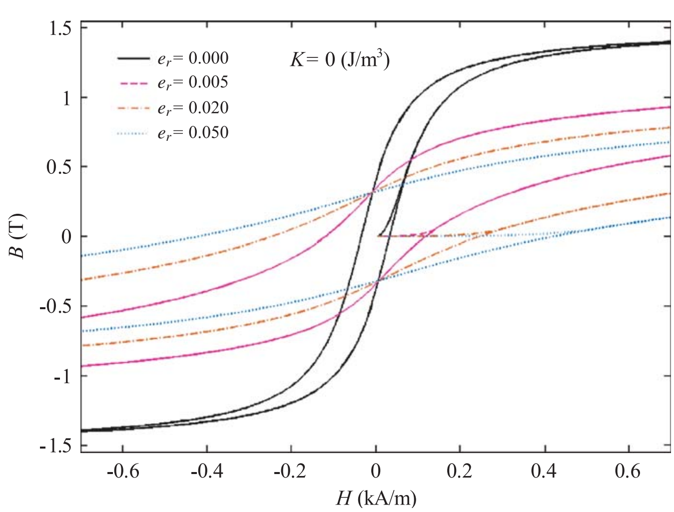

Fig. 3. Computed hysteresis loops for various deformations of 0%, 0.5%, 2%, and 5%.

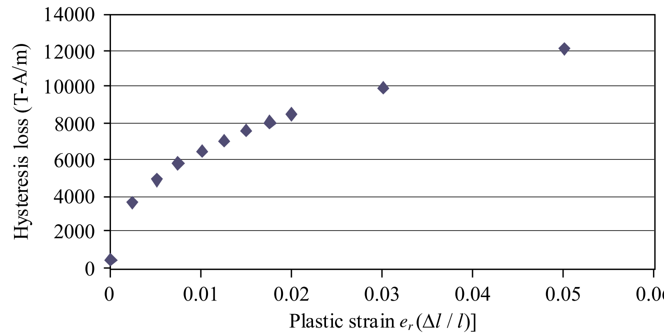

Fig. 4. Computed hysteresis loss as a function of residual strain.

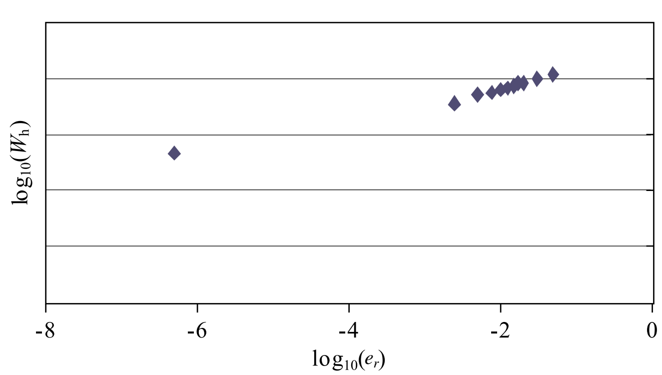

Fig. 5. Log–log plot of the computed hysteresis loss as a function of residual strain.

5. Conclusions

It is possible to find Ludwik-like exponents for mechanical and magnetic data, provided one uses a nonlinear extrapolation from the uniform strain region through the discontinuous yield region to the elastic line to obtain σ_y to use in Ludwik's law for the strain-hardening stress $\sigma - \sigma_y$. One finds that the magnetic loss exhibits a Ludwik-like relationship with the residual strain, but with a different value for the Ludwik exponent. Since mechanical properties are controlled by dislocations, and magnetic properties are controlled by domain wall motion, the two sets of properties are governed by physically different (even though related) phenomena, and so it is not surprising that mechanical properties and magnetic properties exhibit different exponents.

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