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Effect of plastic deformation on the magnetic properties of non-oriented electrical steels

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Abstract

Total loss increase in electrical steels due to plastic deformation is mainly concentrated in hysteresis loss, while classical and anomalous components show a slight decrease. Deformation increases both low-induction and high-induction components. While the mechanical properties show a smooth evolution with the deformation, the magnetic properties show a large difference even at only 0.5% elongation.

Keywords: Electrical steel; Deformation; Losses separation

It is very important to evaluate the extent of magnetic properties deterioration when fully processed steel is plastically deformed. Hou [1] proposed that magnetic losses were directly proportional to the dislocation density, as a square-root-law-related losses to rolling strain. The paper did not discuss the strong magnetic loss increase for strain below 0.02 and the square root law fitted only for higher amounts of strain. The effect of small plastic deformation on the anisotropy of the magnetic properties was studied by Hug et al. [2]. We applied the hysteresis loss separation method, recently proposed [3], to evaluate the effect of plastic deformation on the high- and low-induction components and to discuss about loss mechanisms.

The starting point for all the experimental work was a 400 mm wide, 0.5 mm thick strip of a commercial 2% silicon fully processed electrical steel. Two meter long samples were cold rolled and deformation was controlled by the total elongation. Samples with true deformation between 0.005 and 0.08 were compared with the as-received sample. Epstein strips were taken from the rolling (RD) and transverse (TD) directions, and magnetic properties were measured in each direction. Loss components separation was performed measuring the total loss at 60 Hz and hysteresis loss at 0.005 Hz. The classical parasitic loss was calculated taking into account the thickness variation and the anomalous loss was determined by the difference between the total loss and classic plus hysteresis losses. 'Low-induction' and 'high-induction' components of hysteresis loss were calculated using the method described in Ref. [3]. The method assumes that the induction value at 'maximum permeability point' in the hysteresis curve separates regions where the energy dissipation mechanisms are different.

The grain size of the starting material is 60 μm, and its electrical resistivity is 38 μΩ cm. The monotonic increase of the 0.2% elongation yield stress and tensile strength with increasing deformation is shown in Fig. 1, where some anisotropy can also be detected. Fig. 2 shows that deformation decreases the B_{50} value in both measurement directions, parallel and perpendicular to the rolling direction, clearly significant even at 0.005 deformation, although, the difference between both directions remained almost constant. This suggests that, besides texture, dislocation distribution is also affecting B_{50}, even at

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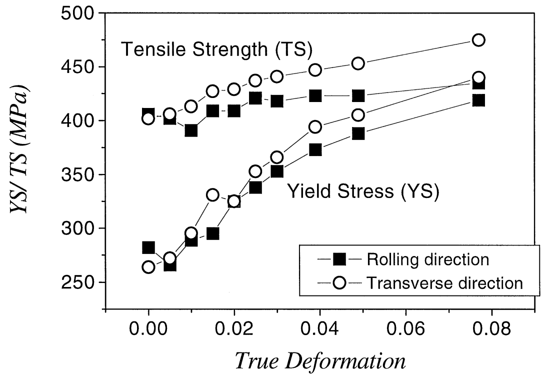

Fig. 1. Effect of cold rolling deformation, measured as true deformation ε, on the yield stress and tensile strength of a 2% silicon steel in the rolling and transverse direction.

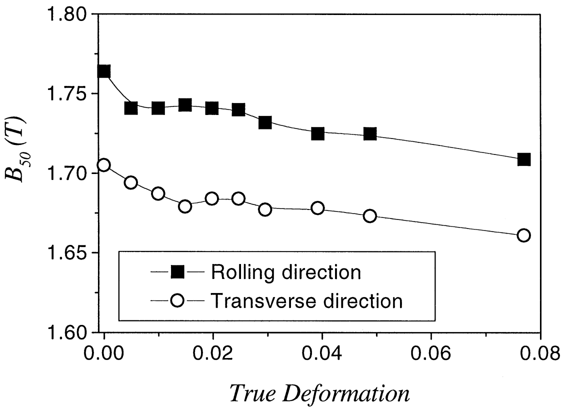

Fig. 2. Effect of cold rolling true deformation ε on the B_{50} value, measured in RD and TD directions.

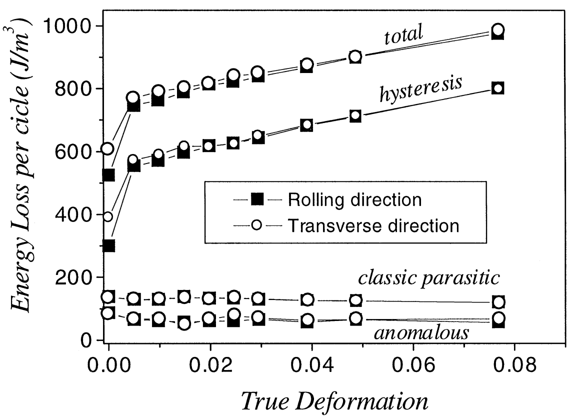

Fig. 3. Effect of cold rolling true deformation ε on the total, classical parasitic and anomalous losses, at 60 Hz, measured in RD and TD directions.

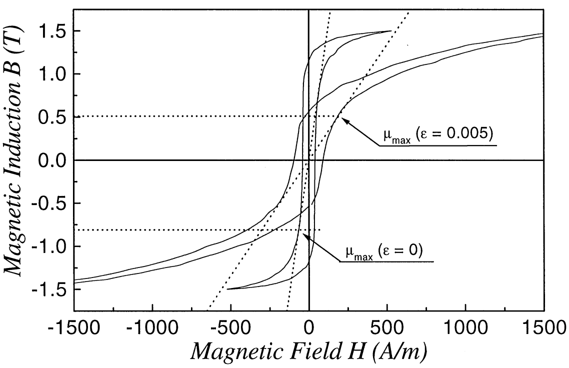

Fig. 4. Hysteresis loops of the as-received RD sample and the 0.005 deformation RD sample, showing the position of the maximum permeability line dividing the 'low-induction' and the 'high-induction' regions.

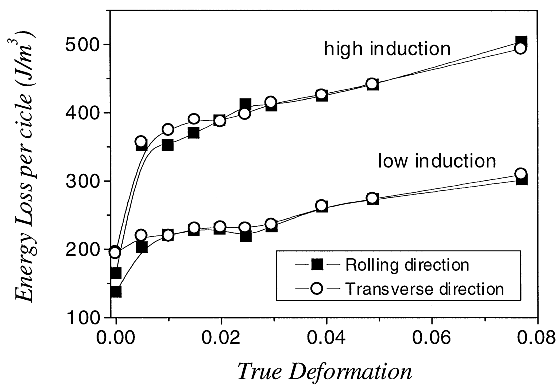

Fig. 5. Effect of cold rolling true deformation ε on the low- and high-induction hysteresis loss components, measured along RD and TD directions.

typical deformation levels of semi-processed steels (~0.05).

Fig. 3 confirms that very small deformation induces a sharp increase in total losses, followed by an almost linear increase between 0.01 and 0.08. The strong anisotropy of the as-received material is reduced with increase in deformation. From Fig. 3 it is clear that all the total losses increase with deformation is due to the hysteresis component loss, as both other components, parasitic and anomalous show an almost negligible change with deformation.

The large increase in hysteresis loss with very small deformation is better shown in Fig. 4 which shows the quasi-static hysteresis loop for the rolling direction samples of the annealed as-received sample and the 0.005 true deformation sample. The effect of deformation on the coercive force is well known, and it certainly increases the hysteresis loop area. A decrease in permeability is also observed. Remanence is decreased by deformation, which should act in an opposite way: the smaller the remanence, smaller should be the losses, everything else being constant. Fig. 5 shows how the high and low components of hysteresis loss respond to deformation: the high-induction component increases much more than the low-induction component. Reversible domain rotation is the main magnetization mechanism above the curve knee but, being reversible, it does not dissipate energy. The behavior of the loss components indicates that the effect of deformation is stronger on the domain annihilation and nucleation mechanisms than in the domain-wall movement.

While Hou [1] assumed that the interaction of domain walls and dislocation density was the main mechanism to explain the effect of deformation on the magnetic properties, Hug et al. [2] proposed that the anisotropic residual stresses due to deformation should also be taken into account for both the effect of deformation on losses and on losses anisotropy. It is yet to be analyzed, if the effect of residual stresses is larger on the low- or high-induction component.

Concluding, it is shown that magnetic properties are more sensible to small deformation than mechanical properties. Magnetic properties variations indicate that domain wall–dislocation interaction is not the only operative mechanism. Residual stresses due to the plastic deformation must have its effect, and it is possible that the wall–dislocation interaction affects the hysteresis loss low-induction component, and the residual stresses affect the domain annihilation–nucleation mechanisms responsible for the high-induction loss component.

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