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Invited paper

Losses and permeability improvement by stress relieving fully processed electrical steels with previous small deformations

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Abstract

The strong increase in the 1.5 T total losses of a 2.2% Si electrical steel, when a small plastic deformation is applied, is almost exclusively due to the increase in its quasi-static hysteresis loss. Stress relieving at 700°C promoted no change in the grain size, a significant reduction of 1.5 T total losses and increased permeability, which did not reach, however, the non-deformed values. The anisotropy of total losses of the annealed samples is concentrated in the high-induction component of the hysteresis loss. © 2002 Elsevier Science B.V. All rights reserved.

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The punching of steel sheets imposes a plastic deformation gradient from the cut surface inwards. It is well known that plastic deformation deteriorates magnetic properties, and a stress relief annealing is necessary to recover them. A recent review [1] shows different estimates for the affected region, from 0.35 mm [2] to 10 mm [3] from the cut surface, based on magnetic measurements. Optical microscopy shows deformed grains and deformation lines up to 0.2 mm from the cut line. These features are usually visible when deformation is larger than 40%. Houbaert showed that the microhardness profile reaches the value of the non-deformed matrix further than 6 mm from the cut edge [4], indicating that the magnetically deteriorated region extends into the region of small deformations.

Träuble [5] made a comprehensive review of the effect of plastic deformation on the magnetic properties of single crystals. More recently, the effect of small plastic deformation on the magnetic properties has been investigated by many authors, some inducing deformation by means of tensile test [6–10] and others by rolling [11–12]. Theoretical considerations led Kersten [13] to propose that coercivity is proportional to the square root of the dislocation density. Dislocation density measurements in iron are not simple, due to the presence of several different strain heterogeneities (dislocation cells, transition bands, shear bands and grain-to-grain differences due to Taylor factors [14]). One of the most cited papers on the subject, Keh and Weissman [15], showed that the dislocation density in iron increases linearly with strain, at least up to 10%. Some authors confirmed an increase of coercive force [7] and magnetic losses [11] with the square root of strain, but Astié et al. [6] found a more complex behavior when investigating the effect of plastic deformation on the magnetic properties of pure iron, in the Rayleigh law domain. They defined three stages of magnetic hardening, associated with changes of the dislocation structure and of the residual stresses level. They found no change in the coercive force of pure iron, for deformation below 2%, where only isolated dislocations were present, whereas a large increase in coercivity occurred when dislocation tangles were formed, for deformation between 2% and 6%. A smaller rate of increase in coercive force is set as dislocation cells are organized, above 6% deformation. On the other hand, several authors found significant magnetic deterioration in non-oriented silicon steels even with only 0.5% strain [7,11,12].

The magnetic properties deterioration by plastic deformation has been related to domain wall pinning by the dislocation network [5,6] while some include the

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magnetomechanical effect of long range residual stresses introduced by the plastic deformation processes [9,10]. Some authors state that 90° domain walls are more sensitive to the stress field of dislocations than the 180° domain walls [5,6,8], which are more sensitive to the pinning by grain boundaries and dislocation cell walls.

When a punched lamination is submitted to a stress relief annealing, its magnetic properties are recovered, at least partially. The elimination of dislocations by recrystallization of the volume close to the cut edge, easily seen by optical microscopy, is restricted to a distance less than 0.5 mm from that surface. A grain size gradient is frequently observed, small grains in the previously high deformed cut edge, next to grains larger than the sheet average inside, as there is a region capable of strain induced abnormal grain growth. Little has been published about microstructural and magnetic changes due to annealing, further away from the cut surface, where probably only microstructural recovery occurs, with a decrease of the dislocation density and formation of subgrain-boundaries. The microstructural changes during recovery were described by Talbot [16] on pure iron and by Hu [17] on silicon iron. Some information on the effect of recovery on the magnetic properties was reviewed by Damiano et al. [18]. The present paper investigates the effect of annealing on the magnetic properties recovery of steel sheets with small deformation induced by rolling.

A commercial 2.2% Si fully processed electrical steel with grain size of 60 μm, and electrical resistivity of 38 μΩ cm was used. Sheets 400 mm wide, 0.485 mm thick and 2000 mm long were cold rolled in several rolling passes, resulting in samples with true deformation between 0.005 and 0.077, monitored by the total elongation of the sheets. Epstein strips of non-deformed and of the deformed samples were cut parallel (RD) and transverse (TD) to the rolling direction. Permeability (μ_{15}), total losses at 1.5 T and B_{50} (induction at 50 A/cm) values were measured at 60 Hz. Hysteresis loss, remanence and coercive force at maximum induction of 1.5 T were obtained from quasi-static hysteresis curves measured at 0.005 Hz. Both RD and TD samples were characterized. A stress relief annealing was performed at 700°C for 1 h, under nitrogen, including the non-deformed samples. Magnetic properties recovery was analyzed comparing the data from deformed samples with the non-deformed ones. The separation of total loss into its hysteresis, excess and classical components was applied for both deformed and recovered samples. Classical loss was calculated taking into account the thickness variation. Excess loss was determined as the difference between total loss and classical plus hysteresis losses. Hysteresis loss was subdivided in the "low induction" and "high induction" components, using the graphical method described in [19]. 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 concept of separating hysteresis in two parts has been also proposed for grain-oriented steels, with a different methodology [21]. The main magnetization mechanisms are well understood, but the energy dissipation mechanisms are not so clear. It is accepted that domain wall movement is the main mechanism in the low-induction region, but the situation is not so clear in the high-induction region: Is 90° domain wall movement predominant between 1.0 and 1.5 T? How do the domain nucleation and domain annihilation mechanism interact with microstructure?

Optical microscopy observation of the work-hardened samples did not show any sign of through-thickness deformation gradient, indicating that cold rolling was macroscopically homogeneous. Hardness measurements made at 30, 60, 180 and 250 μm from the sheet surface also did not show evidence of a deformation gradient. Annealing did not change grain size of the samples because grain growth is much too slow at 700°C, meaning that only microstructural recovery took place, except in the one previously submitted to the largest deformation. In this case, strain induced abnormal grain growth was able to start but 1 h at 700°C was not enough to complete it. So a few large grains are surrounded by the original grains. As expected, plastic deformation increased microhardness, but the annealing produced a total recovery of its non-deformed value, as shown in Fig. 1. Plastic deformation increased total losses, as expected, but Fig. 2 shows that very small deformations (0.5%) increase total losses by 30%, similar to what was observed in Hou's paper about silicon steel rolling [11]. Total loss increase is concentrated in the hysteresis component, as excess loss decrease with deformation. The magnetic properties of

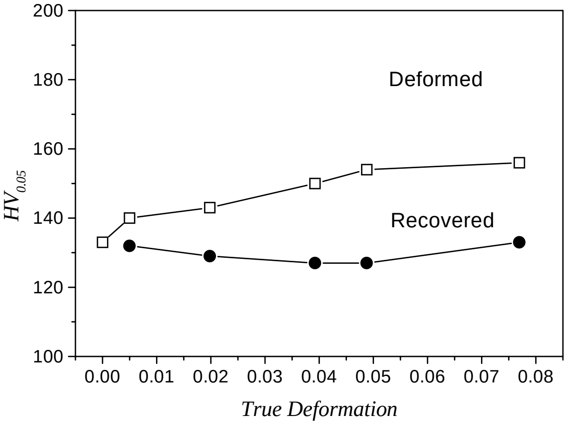

Fig. 1. Microhardness ($HV_{0.05}$) of samples before and after annealing, as a function of the amount of deformation.

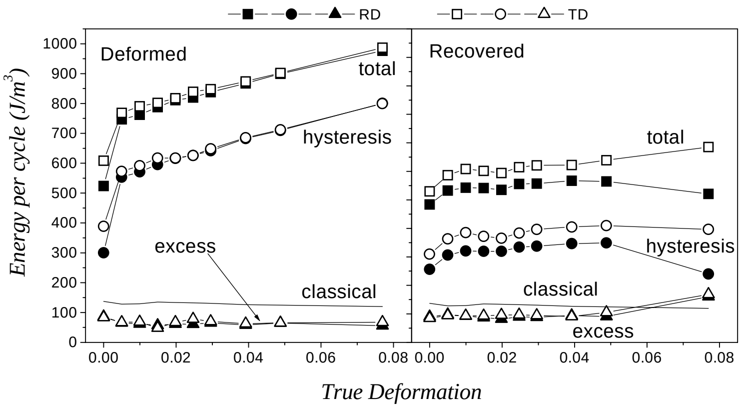

Fig. 2. Loss components of samples before (deformed) and after (recovered) annealing, as a function of the amount of deformation, measured in two directions, rolling and transverse.

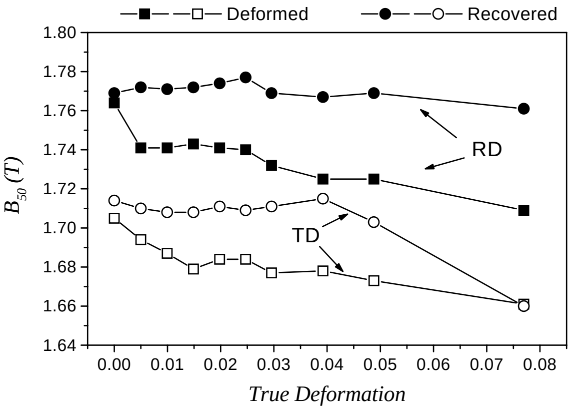

Fig. 3. Induction B_{50} of deformed and recovered samples, in rolling and transverse directions.

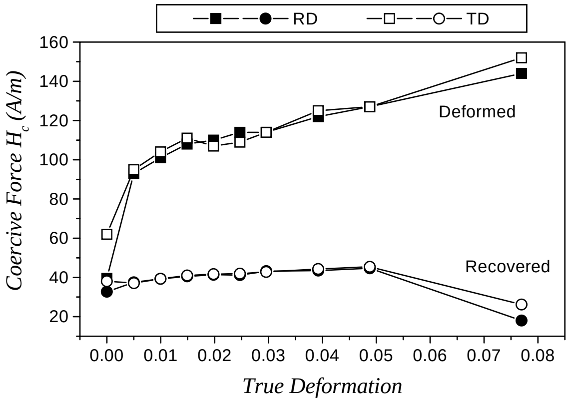

Fig. 4. Coercive force of deformed and recovered samples, in rolling and transverse directions.

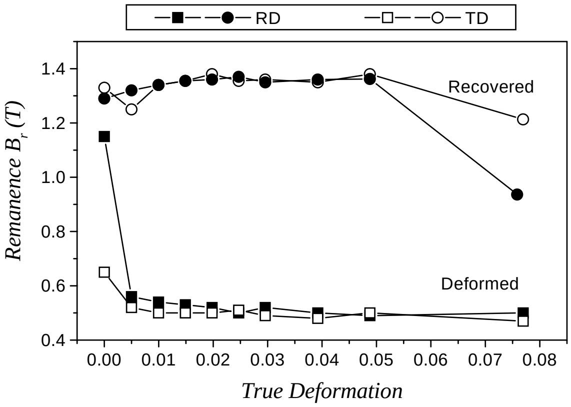

Fig. 5. Remanence of deformed and recovered samples, in rolling and transverse directions.

the non-deformed sample shows significant anisotropy, due to its texture. The change of properties with deformation is strong enough to overshadow the anisotropy, except in B_{50}. Annealing promotes a strong decrease of total losses, all due to hysteresis component, as excess losses increase (Fig. 2). It should be noted that even the non-deformed sample benefited from the annealing, as it eliminates (or at least reduces) the strain introduced by the cutting of the Epstein samples. Annealing also brought back anisotropy in total losses, again concentrated in the hysteresis component.

Deformation significantly decreased the B_{50} (Fig. 3), increased coercive force (Fig. 4) and decreased remanence (Fig. 5) and μ_{15} (Fig. 6), similar to the effect of compressive stresses, as shown by LoBue et al. [20], but it also reduced anisotropy (in terms of RD to TD differences) in all parameters. Annealing recovers all properties, but only remanence is taken back to the same level of the non-deformed sample. Coercivity, hysteresis loss and μ_{15} also showed a large recovery, but they are left with a memory of the deformation level they had been previously submitted: the higher the previous deformation, higher coercivity, higher hysteresis loss and lower μ_{15} after annealing, except the sample with the highest deformation in this series (0.077 deformation), where recrystallization has begun. Moreover, even the sample with only 0.005 deformation show hysteresis loss 20% higher than the annealed non-deformed sample.

The graphical subdivision of hysteresis loss in two components (Fig. 7) showed that, in the non-deformed and annealed RD sample, the high- and low-induction components of the quasi static hysteresis energy dissipation are, respectively, 130 and 120 J/m^3. 0.05 deformation increased its hysteresis value to 710 J/m^3, 62% of which is dissipation in the high-induction component. Annealing lowered energy dissipation to 350 J/m^3, again almost equally divided between the two components.

Another feature of this analysis is that the low-induction losses tend to be isotropic in all conditions (RD and TD values are very similar). Whatever the microstructures or residual stress left after annealing, they impose similar restrictions to domain wall movement—the main energy dissipation mechanism in the low-induction region of the hysteresis curve—irrespective of the direction of measurement. This is compatible with the isotropy of coercive force, shown in Fig. 3. It seems that texture has little influence on that. On the other hand, the high-induction component presented anisotropy of more than 30%. This indicates that 90° domain wall movement and domain annihilation and nucleation, the main sources of energy dissipation in the high-induction region of the hysteresis curve, are sensitive to texture.

Fig. 8 compares the shapes of the hysteresis curves of the non-deformed sample with the 0.5% and 5% deformation with the curves of the annealed samples (the non-deformed and the one with previous 5% deformation). It shows how deformation introduces a "shearing" of the hysteresis curve and increases coercivity. The "shearing" must be related to the compressive component of the residual stress, and it may be assumed to be equivalent to introducing an additional anisotropy term, perpendicular to the field direction [20]. As it is sheared in both RD and TD, it could be assumed that a large fraction of domains is spontaneously oriented in

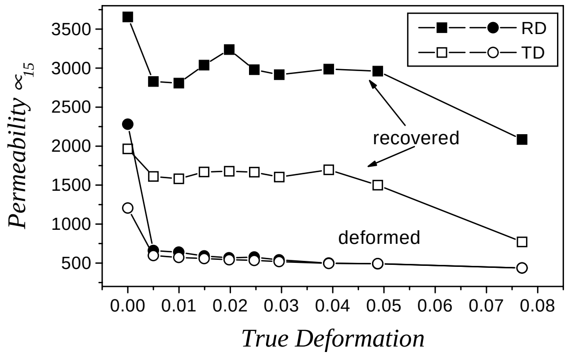

Fig. 6. Permeability at 1.5 T (μ_{15}) of deformed and recovered samples, in rolling and transverse directions.

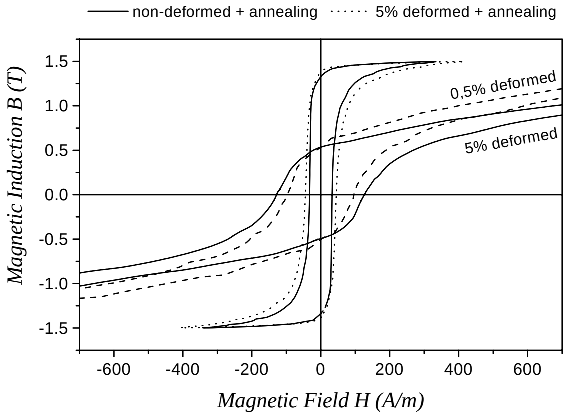

Fig. 8. Hysteresis curves of the non-deformed sample, the 0.5% and 5% deformation, and the 5% deformed plus annealing.

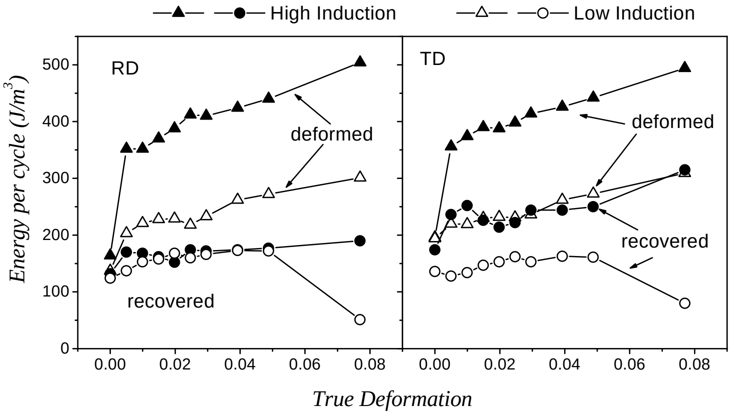

Fig. 7. Low-induction and high-induction hysteresis loss components, in rolling and transverse directions.

the ⟨1 0 0⟩ direction closer to the normal to the surface. If this was true, the magnetization process should have a strong fraction of 90° domain wall movement and a strong positive magnetostriction. Nevertheless, Makar and Tanner found the opposite effect: plastic deformation eliminated the positive magnetostriction region that existed for induction between 0 and 1.5 T in the non-deformed sample [8]. Domain observations made by Träuble indicates that plastic deformation inhibits 90° domain wall movement [5] which, in the non-deformed case, is the source of the positive magnetostriction region.

Annealing eliminated the shearing, taking remanence to its annealed non-deformed value. This might indicate that the macroscopic residual stresses were eliminated. On the other hand, the larger coercive force left in the deformed and annealed samples indicate that dislocation structures are still there, interacting with 180° domain wall movement. In the high-induction region of the first quadrant, the upper branch of both the non-deformed and the deformed and annealed curves are very similar, including similar values of remanence. This suggests that the subgrains produced by recovery did not affect this "reversible rotation region" [22]. The lower branch, on the other hand, indicates that much more energy is dissipated by "domain annihilation" in the deformed and annealed sample.

Applying these observations to the case of a punched lamination, its annealing will recover magnetic properties to a large extent, but not totally. As deformation extends far away from the cut edge, and as even 0.5% deformation still leaves a 20% increase in total losses after annealing at 700°C, a large volume of the lamination is affected. The effect of annealing temperature and atmosphere is yet to be investigated.

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