Intergranular Residual Strain Behaviour of Mild Steel and Interstitial Free Steel as a Function of Low Temperature Annealing

N. Kasai [1], R. Hutanu [2]*

[1] Graduate School of Environment and Information Sciences, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama, Japan 240-8501
[2] Canadian Neutron Beam Centre, National Research Council, Chalk River Laboratories, Chalk River, ON, Canada K0J 1J0
* Now with Atomic Energy of Canada Limited, Chalk River Laboratories, Chalk River, ON, Canada K0J 1J0

Introduction

While the relationship between stress, residual stress and magnetism has been recognized for many years [1], it is not well understood due to the complexity of its many variables: differing types of stresses, and differing magnetic and mechanical properties of materials. Residual stress is often present in engineering components after a non-uniform plastic deformation. It can exist on various length scales: macroscopic residual stress appears on the sample's length scale while intergranular residual stress occurs within the grain size range. Grains in a polycrystalline sample deform differently depending on their crystallographic orientation relative to the applied stress direction. Upon unloading, some grains will have larger intergranular residual strain then others.

We used neutron diffraction to measure directly the residual strains for the <200>, <211> and <220> crystallographic directions in steels, and the Magnetic Barkhausen Noise (MBN) technique to characterize the magnetic behavior that these residual strains induced (MBN results are not reported here). Large tensile intergranular residual strains accumulated along the magnetic easy axis for steels, that is, the <100> crystallographic directions. Importantly, for body centred steels, <211> is usually chosen as the direction for macroscopic strain or residual measurement since it is known to accumulate only small intergranular strains [3]. In addition, uniaxial deformation should produce only few residual macrostresses since samples are typically designed to deform uniformly.

While a definite correlation between the <200> intergranular residual strain and the magnetic easy axis development in steel samples was shown previously [2], a systematic study of the low temperature (at and below 500°C) annealing effect on intergranular stresses and magnetic behaviour is needed to clarify the intergranular stresses relief phenomenon and its influence on magnetic properties.

Samples

Several mild and interstitial-free (IF) steel samples were used in this study. The mild steel samples display discontinuous yield behaviour upon deformation due to the Luders bands formation. In contrast, IF steel, which contains very low levels of carbon and other interstitial elements, deformed continuously through the yield point with no Luders effect.

The mild and IF steel samples were cut from commercially available sheets of 3 mm and 1.7 mm thickness respectively. The cut samples had a 'dog-bone' shape and the gauge lengths of 155 mm x 30 mm. The width of the samples was chosen to accommodate the MBN probe. The axial direction of the samples coincided with the rolling direction (RD) of the sheet. The other two directions of the sample were the transverse direction (TD), perpendicular to the RD and in the sample's plane, and the normal direction (ND), which was normal to the sample surface.

Samples were then uniaxially deformed in tension at a strain rate of 0.1 in/min up to 20% engineering strain level using an 800 kN-capacity Riehle testing machine, followed by unloading. The loading direction corresponded to the original rolling direction (RD) of the sheet. Individual samples deformed at 20% strain were then annealed. The annealing temperatures were between 100°C to 500°C and annealing times between 0.5 and 10 hours. All heat treatments were performed in air using a radiant box furnace. Samples were then cooled slowly in air to room temperature.

Neutron Diffraction Experiments

The samples were wire-cut to 1×1 cm^2 using an electric discharge machine (EDM), and then stacked together forming an approximate cube with dimensions of 1 cm. The entire cube was immersed in the neutron beam using an Eulerian cradle mounted on the E3 spectrometer. The strain for the <200>, <110> and <211> crystallographic directions was measured on 0% (un-deformed), 20% (before annealing) and on after-annealing samples. Strain data were obtained in an angular fashion every 15° (or 30°) between the ND-RD, RD-TD and TD-ND planes (Figure 1).

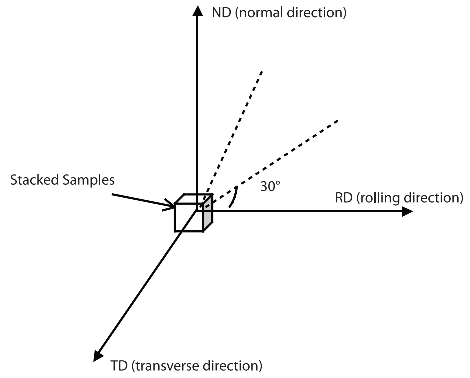

Fig. 1 *Residual strain measurements were performed along nine different directions within the RD-TD, TD-ND and ND-RD planes.*

Crystallographic texture data was also obtained in the form of pole figures for the <200>, <110> and <211> directions, before and after annealing. The experimental set-up and the wavelength were identical to those for the strain measurements.

Results

The <211> residual strain, which characterize the macroscopic residual strain, were found to be negligible for both steels and for all the measurement directions, and thus are of intergranular origin. Since the <200> residual strains are responsible for the magnetic behaviour in steels, only these strains will be discussed in this report.

As expected annealing at 500°C induces the strongest relief of intergranular residual strain for mild steel (Figure 2a). This effect can be observed especially within the TD-ND plane where the intergranular strain is the largest. Annealing data below 300C showed no significant effects on residual strain and MBN for both steels. The annealing effects at 300 and 500°C for the IF steel samples (Figure 3a) are smaller than for mild steel (Figure 2a), perhaps due to the fact that the IF steel <200> strains are in general smaller than <200> mild steel strains.

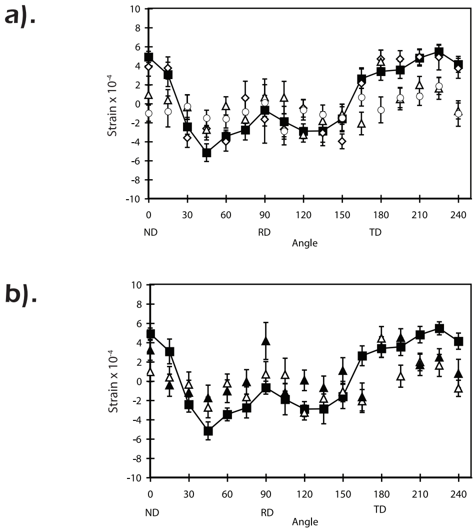

Fig. 2 *Annealing effects on <200> intergranular residual strain for mild steel. Figure 2a shows this effect for constant annealing time of 0.5 hrs for 300 (◇), 400(△) and 500 °C (○). Figure 2b shows the effect of the annealing time, 0.5 hrs (△) and 10hrs (▲), for samples annealed at 400°C. The solid lines connecting the ■ symbols in both plots represent the prior annealing, after deformation (20% strain) data.*

In general, the effect of the annealing time (0.5 and 10hrs) is not significant in the case of both mild and IF steel samples annealed at 400°C (Figures 2b and 3b). A similar result was obtained for the 500°C annealings.

Overall, the residual strain data obtained by neutron diffraction agree with the MBN annealing results not reported here.

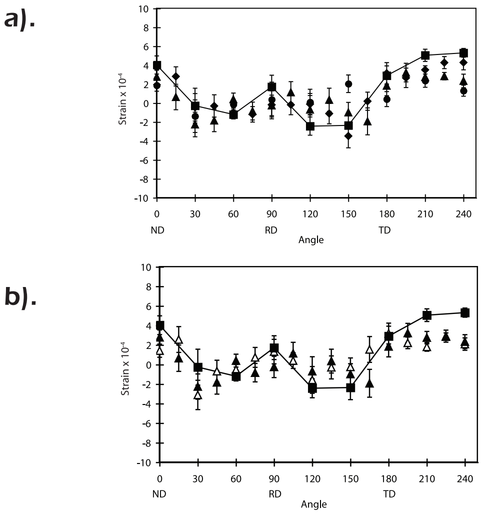

Fig. 3 *Annealing effects on <200> intergranular residual strain for IF steel. Figure 3a shows this effect for constant annealing time of 10 hrs for 300 (◆) and 500 °C (●). Figure 3b shows the effect of the annealing time, 0.5 hrs (△) and 10hrs (▲), for samples annealed at 400°C. The solid lines connecting the ■ symbols in both plots represent the prior annealing, after deformation (20% strain) data.*

A comparison between the pole plots (Figures 4 and 5) shows that the initial as well the after-deformation textures of the mild and IF steels are quite different, probably due to different manufacturing process of the two steels. However, in both cases, annealing at 500°C has only a minimal effect on texture, confirming that up to this temperature the heat treatment does not induce any recrystallization in the samples.

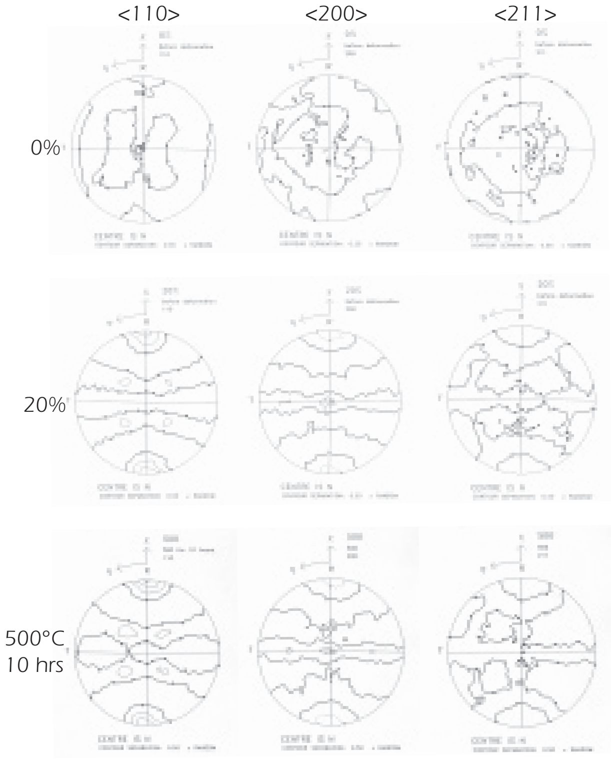

Fig. 4 *<110>, <200> and <211> pole figures for the un-deformed (0%), deformed and prior- annealing (20%) and after-annealing (500°C, 10hrs) mild steel samples. R, T and N directions are the same as RD, TD and ND directions from Figure 1.*

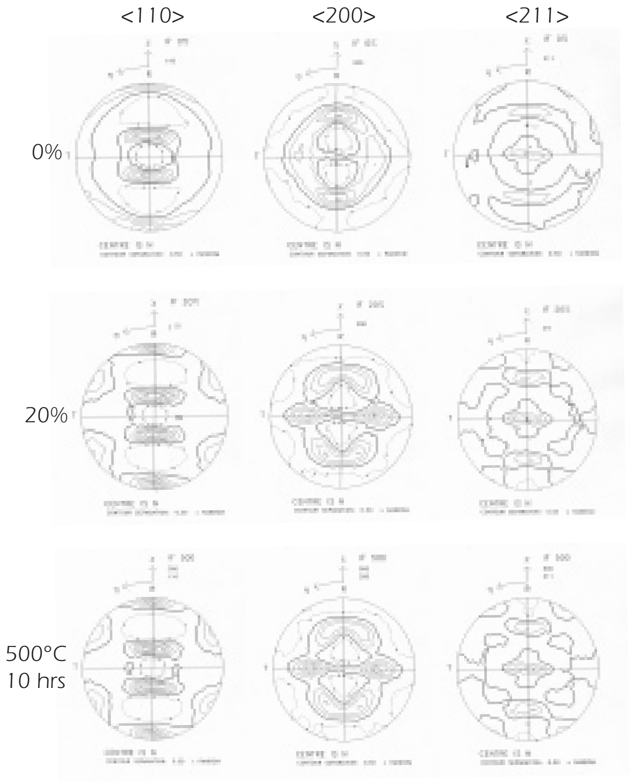

Fig. 5 *<110>, <200> and <211> pole figures for the un-deformed (0%), deformed and prior-annealing (20%) and after-annealing (500°C, 10hrs) IF steel samples. R, T and N directions are the same as RD, TD and ND directions from Figure 1.*

Acknowledgments

The authors wish to thank Dr. Ron Rogge and Dr. Lynann Clapham for their input with the experiments proposal and design. The authors are also thankful to John Fox for his help in setting up the experiment.

References

[1] Bozorth R. M. Ferromagnetism. D. Van Nostrand Company, Princeton, New Jersey, 1951.

[2] Roxana Hutanu. A correlation study between Magnetic Barkhausen Noise and intergranular residual stress in steel. Ph.D. Thesis, Queen's University, Kingston, Canada, October 2005.

[3] Pang J.W.L, Holden T.M., Mason T.E. J. Strain Anal. 33:373 (1998).