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Intergranular strain and texture in steel Luders bands

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Abstract

Neutron diffraction was used to examine residual strains and deformation texture related to Luders bands phenomenon in uniaxially deformed mild steel samples. Samples of two different thickness, 1.5 mm (thin) and 3.0 mm (thick), were uniaxially deformed to between 0.5% and 20% engineering strain, followed by unloading. The shape and texture of the Luders bands depended on the sample thickness. Neutron diffraction texture measurements indicated that there was little texture within the Luders bands in the thicker samples. There was, however, significant texture in the Luders bands of the thinner samples, and this same texture intensified once the Luders bands covered the entire sample and up to 20% deformation. The residual strains in the Luders bands were similar for both sample thicknesses. In the bands the {200} planes exhibited the largest intergranular strain; even at only 1% deformation, the {200} strain in the Luders band was very high (400$\mu\varepsilon$). These high {200} strains were present only in the transverse and normal directions, with essentially no {200} strain in the rolling (applied stress) direction. Intergranular strains in the {220} and {211} were much lower and displayed much less variation with sample direction. In all samples the intergranular strains were essentially constant in the bands until the bands had propagated fully across the sample (~5%) after this there was a small but progressive increase in the intergranular strains up to 20% deformation.

Keywords: Luders bands; Intergranular residual strains; Neutron diffraction; Texture; Annealing

1. Introduction

Luders bands are localized regions of plastic deformation that are often observed in steel and other polycrystalline body-centered cubic metals. In steels they develop after the yield point has been exceeded and coincide with the lower yield point section of the stress strain curve. A Luders band grows at an almost constant stress level, therefore there is no strain hardening apparent in the stress–strain curve until after the band has spread across the entire sample.

Literature concerning Luders phenomena dates back to the mid 1800s [1,2]. A considerable number of studies were conducted from the late 1950s to the late 1980s to characterize Luders behaviour – these focussed on the general nature of the bands [3,4], velocity of the front [5], orientation of the front [6], kink angle and shear [4], and the kinetics of the Luders front propagation [7]. Experimental activity on Luders bands has been essentially dormant for the past 10 years, however, although theoretical and modelling work can be found in papers on plastic instabilities. To our knowledge there have been no experimental measurements of the residual stress state in steel Luders bands.

Residual stresses can be classified according to the length scale over which they operate. The strain

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response has been characterized as being Type 1 or Type 2. Type 1 corresponds to the macroscopic residual strain field across a sample. Type 2 strain, also known as intergranular strain, occurs on a microscopic scale. In response to an applied load, Type 2 strain can arise in because grains in a polycrystalline sample will deform differently depending on their crystallographic orientation. The incompatibilities between grains lead to the development of intergranular strains within the grains themselves. Although these intergranular strains have been recognized since the work of Greenough in 1952 [9], experimentally they have only been accessible within the last 10 years since the development of neutron diffraction techniques for strain measurements in engineering materials. The penetrating power of the neutron allows residual strains to be measured and mapped deep below the sample surface and/or averaged over large volumes (e.g., thousands of grains), while also being highly selective because the nature of diffraction simultaneously selects both a direction in the sample and a crystallographic direction.

In neutron diffraction studies of steel samples, the macroscopic (Type 1) residual stress state is usually determined by measuring strains in the {112} planes. This is because the {112} planes are believe to accumulate very little intergranular (Type 2) strain [8]. In a study of residual stresses in high strength steels, Pang et al. [12] found only slight {112} strains in samples that had been uniaxially deformed to 13% and then unloaded. Specifically, the sample was found to have compressive {112} strains of about $200\mu\varepsilon$ in the original stressing direction and essentially no residual strain in the other two orthogonal directions. This is consistent with the general expectation that a typical uniaxial test should produce little or no macroscopic residual stress in a sample. Conversely, the {200} planes exhibited very large strains which varied significantly from $-600\mu\varepsilon$ to $+900\mu\varepsilon$ depending on the sample direction. These were identified as intergranular (Type 2) residual strains. The other two planes studied by Pang et al. [12], the {220} and {222}, also exhibited some intergranular strain but not as significant as that seen in the {200}.

In the present study, mild steel samples were subjected to uniaxial loading to various levels up to a maximum of 20% engineering strain. Luders bands formed between approximately 0.5% and 5% strain, depending on the sample geometry. As in the Pang et al. study [12], the uniaxial deformation conditions were not expected to generate significant Type 1 residual stresses in the samples. After unloading, neutron diffraction was used to obtain residual strain and texture measurements on all samples, including measurements within the Luders bands regions and outside the banded regions. Residual strains were measured in the {112}, {200} and {220} planes.

2. Experimental procedure

2.1. Samples

Several tensile mild steel samples of gauge length 155 mm and width 30 mm were unaxially deformed to engineering strain levels of 1%, 3%, 5%, 10%, 15% and 20% followed by unloading. The loading direction corresponded to the original rolling direction of the plate, and the strain rate during tensile loading was 0.1″/min. The flow curves indicated a lower yield point of 300 MPa. Two sample thicknesses were considered – 1.5 mm, which will be referred to as the 'thin' samples, and 3.0 mm, which we will call the 'thick' samples. The high yield points for the thin and thick samples were 305 and 325 MPa. In the following discussion the three sample reference directions are the rolling and applied stress direction (RD), the normal or through-thickness direction (ND) and the transverse to both RD and ND and in the width direction (TD).

Neutron diffraction measurements were made on the unloaded samples along their length, encompassing both Luders banded and unbanded regions in samples having <5% deformation. Additional neutron diffraction measurements were made on 'cubes' of sample, created by cutting (using electro-discharge machining) the tensile samples into smaller pieces (1 cm × 1 cm) and stacking them to form a cube shape. These cube samples enabled a relatively large, consistent sampling volume for measurements in a number of different sample angles. After initial measurements, samples were stress relieved at temperatures up to 600 °C in a standard box furnace, followed by a second set of neutron diffraction measurements.

2.2. Neutron diffraction measurements

In neutron diffraction methods a neutron beam of constant wavelength λ is diffracted through a scattering angle (2θ). The spacing (d_{hkl}) between atomic planes in the lattice is then calculated according to Bragg's law

$$\lambda = 2d_{hkl}\sin\theta_{hkl} \quad (1)$$

Neutron diffraction experiments were carried out on the E3 and N5 spectrometers at the NRU reactor at Chalk River, Ont., Canada. The (115) plane of a Ge monochromator crystal was employed to produce neutron beams of wavelengths λ = 1.557 and 1.539 Å, for the N5 and E3 experiments, respectively. The spectrometers were calibrated against a standard Ni powder to obtain accurate wavelength values. In the sample the strain for three different families of crystallographic planes, the {200}, {211} and {220}, was measured, with the sample oriented to obtain results in each of the RD, TD and ND sample directions.

The diffracted peak was obtained using a multiple (32 wire) detector spanning an angle of ~2.5°. The scattering angle (2θ) of the peak was determined by fitting the observed profile of counts versus angular position to a Gaussian peak shape on a constant background. θ was then used in Eq. (1) to determine the value of d_{hkl}. To derive a strain value, a reference spacing $d_{hkl}(\text{ref})$ was obtained by measuring d_{hkl} in an undeformed sample. The strain was then calculated from

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}(\text{ref})}{d_{hkl}(\text{ref})} \tag{2}$$

Neutron diffraction texture measurements were made with the aid of a Eulerian cradle mounted on the E3 spectrometer, using the same wavelength as those for the residual strain measurements. The neutron diffraction intensity in the texture measurements was proportional to the volume fraction of correctly oriented grains, and therefore by varying the orientation of the sample, a direct measure of the distribution of grain orientations which formed the crystallographic texture could be obtained.

3. Theory

The results of the neutron diffraction strain measurements were compared with the elasto-plastic self-consistent (EPSC) model. This model, developed by Turner and Tome [10], provides a numerical code to predict the elastic and plastic behavior of each grain within the deformed polycrystalline aggregate. In this theory, the individual grains are characterized by their orientations relative to the sample's coordinate system (rolling, transverse and normal directions – RD, TD, ND respectively) and by 'weights' which account for the volume fractions estimated by the texture data. In addition, each grain is considered to be an ellipsoidal inclusion in a homogeneous effective medium (HEM) which gives the overall response of the sample. The fundamental interaction equation between grains and HEM is given by

$$\left(\dot{\sigma} - \dot{\Sigma}\right) = -L{:}(S^{-1} - I){:}(\dot{\varepsilon} - \dot{E}) \tag{3}$$

where $\dot{\sigma}$ and $\dot{\varepsilon}$ are the grain stress and strain rate tensors while $\dot{\Sigma}$ and $\dot{E}$ are the HEM overall stress and strains rate tensors. L is the overall elasto-plastic stiffness tensor describing the mechanical parameters of the HEM and S is the Eshelby tensor which is a function of L and the shape of the inclusion. The boundary condition requires that either $\dot{\Sigma}$ or $\dot{E}$ be specified.

The input parameters of the code are the elastic constants and the plastic deformation parameters of the sample, the number of diffraction directions and the initial crystallographic texture of the sample. The code calculates the strain of each grain subset (characterized by grains in the same orientation) incrementally as the process of loading or unloading evolves. The amount of residual strains in any selected direction is determined at the end of the unloading process.

4. Results and discussion

4.1. General observations of Luders band formation

Earlier work [3,11] indicated that the form of the Luders bands depends on sample geometry, with single, simple bands more likely to form when the sample length/thickness ratios were relatively high. This was confirmed in the present study. Thin samples ($l/t = 103.3$) typically exhibited single Luders bands which formed at around 0.5% strain near the end of the gauge length and propagated across the sample. Typically in these thin samples the bands had covered the entire gauge length by about 5% strain. In the thick samples ($l/t = 51.6$) banding began around 0.5% but appeared to be complete by 3%. The thick samples, however, displayed thinner and more complex bands than the thin samples. In both thick and thin samples the angle of the Luders band relative to the tensile direction was about 50°, consistent with that reported in other studies [3].

4.2. Texture measurements

Texture information was obtained in two ways.

1. {220}, {200} and {112} neutron diffraction pole figures were obtained for the un-deformed, and most of the deformed samples. In samples containing Luders bands, pole figure data was obtained from within the bands and also from un-banded regions.
2. The residual strain measurement experiments provided intensity data each of the three selected $\{hkl\}$ orientations, in each sample direction (the RD, TD and ND). These intensity values were an indirect measure of the sample texture. The pole figure and intensity measurements will be considered separately below.

4.2.1. {220}, {200} and {112} pole figures

Although many pole figures were collected, only a small selection will be shown here. All of the texture measurements in the thick samples displayed only a very weak texture, and therefore none of the thick sample pole figures will be shown, although data from the thick samples will be considered in the intensity section below.

Figs. 1(a) and (b) show the {220} and {200} pole figures for the un-deformed thin samples, indicating that a very weak texture is present, likely due to hot rolling. Figs. 2(a)–(c) show typical {220}, {200} and {112} pole figures from the 1% Luders band regions of the thin

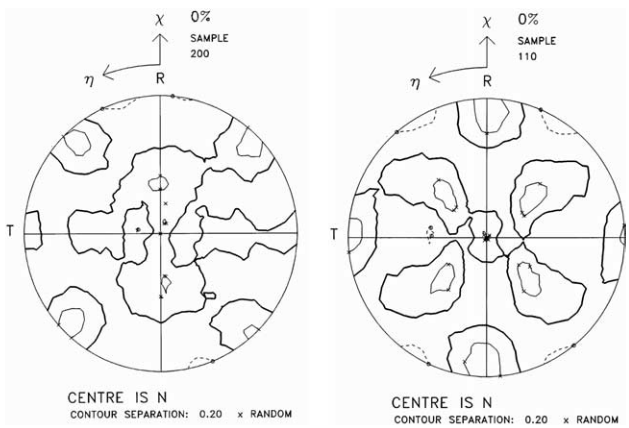

Fig. 1. {2 0 0} (a) and {1 1 0} (b) pole figures for the un-deformed (0%) thin sample.

samples. The results taken from the Luders band in all samples up to 5% deformation were essentially identical. Finally Figs. 3(a)–(c) show the results from the 20% deformed thin sample. These pole figures indicate that the texture at high strains is simply a more intense version of that present in the Luders band region at lower deformation levels.

4.2.2. {2 2 0}, {2 0 0} and {1 1 2} intensity results

All residual strain measurements were conducted under identical conditions, therefore the intensity data are a useful comparative measure of the relative texture for any given orientation in a particular sample direction. The parameter "relative change in neutron intensity" (ΔI) was determined as follows:

$$\Delta I = (I_{\text{strained}} - I_{\text{zero strain}})/I_{\text{zero strain}} \tag{4}$$

i.e. if the intensity is the same as that at zero strain then $\Delta I = 0$.

Figs. 4(a)–(c) show the ΔI values obtained from {2 0 0}, {1 1 2} and {2 2 0} residual strain measurements in each of the three sample directions – the RD, TD and ND. Results from the thin samples are indicated

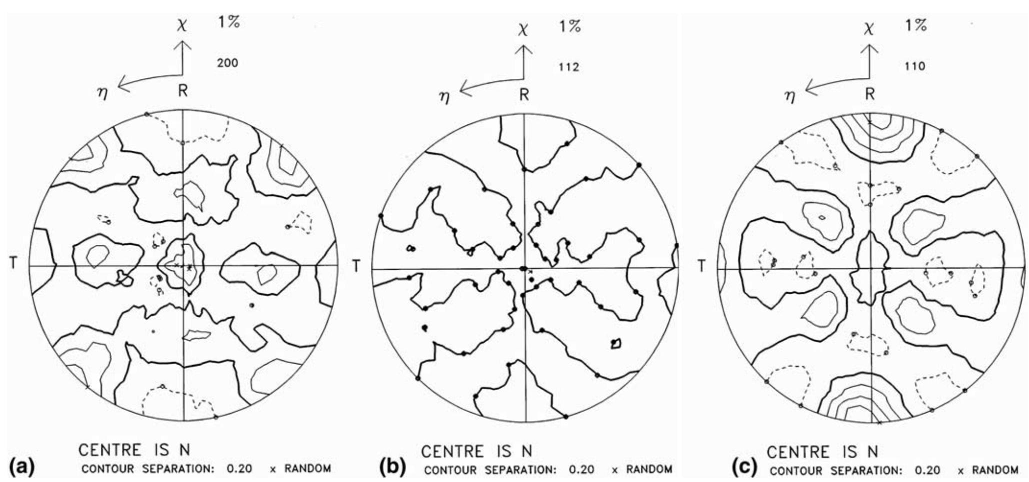

Fig. 2. 1% deformation (banded) thin sample: pole figures for {2 0 0} (a), {2 1 1} (b) and {1 1 0} (c) planes.

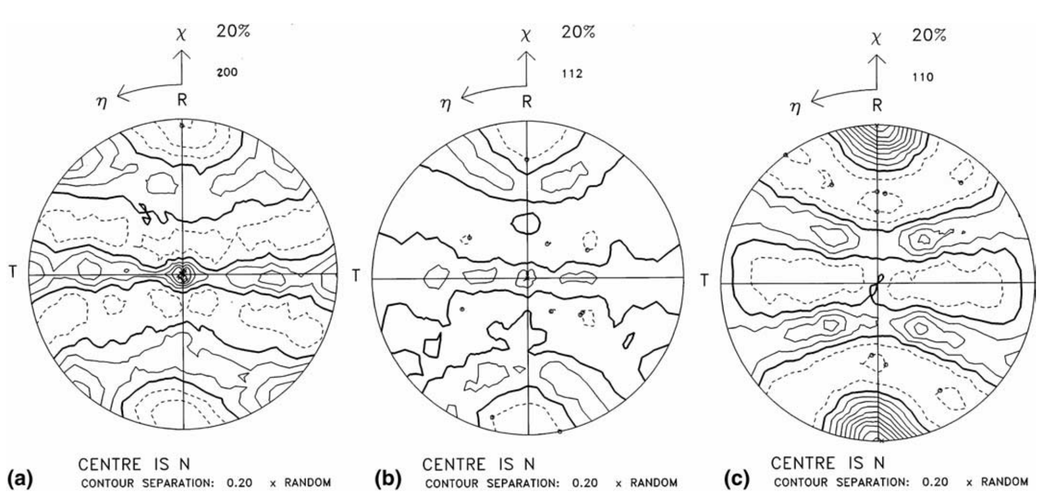

Fig. 3. 20% deformation thin sample: pole figures for {2 0 0} (a), {2 1 1} (b) and {1 1 0} (c) planes.

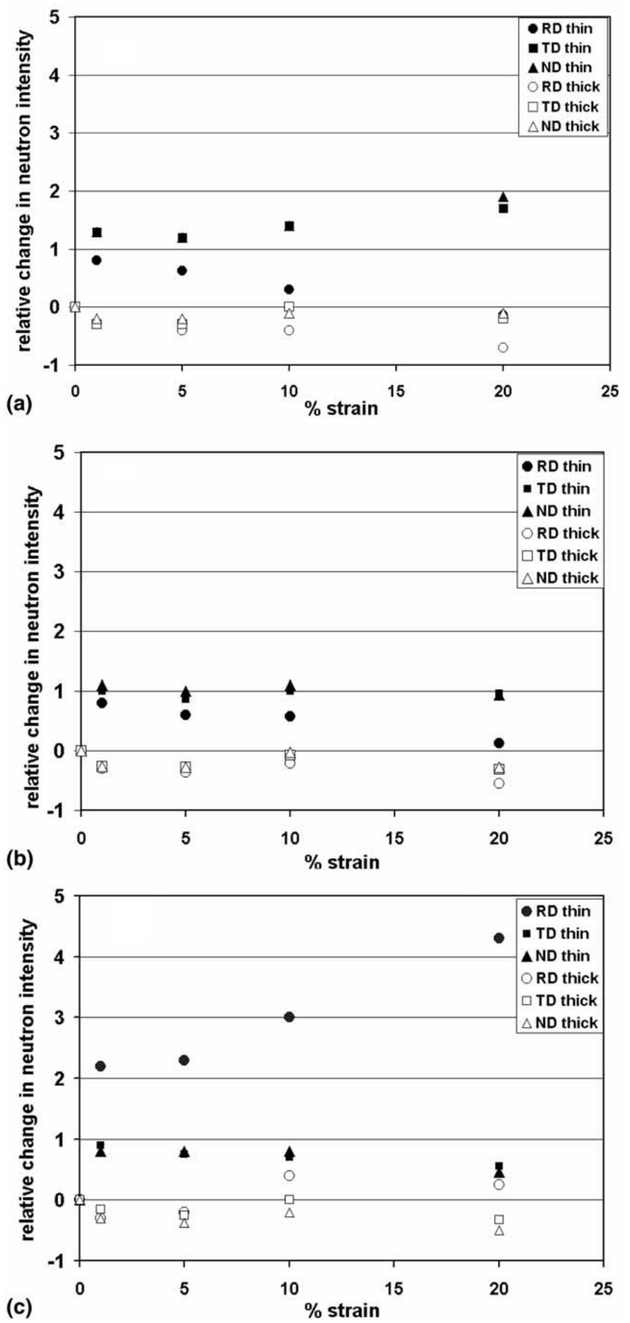

Fig. 4. Variation of the relative intensity of the {200} (a), {211} (b) and {220} (c) reflections versus the applied strain. The intensity results were obtained from the residual strain data.

with solid symbols and thick samples with open circles. The thick samples showed only slight intensity variations, both in the Luders bands and up to 20% deformation. Conversely, intensity variation in the thin samples was pronounced. In all cases the texture in the Luders bands of the thin samples (even at only 1% strain) caused the intensity to increase by at least 80%. It is worth noting that the overall intensity trends seen here are consistent with those of Pang et al. [12], although Pang did not make measurements within the Luders band region.

The intensity variations in these thin samples correlate well with the pole figure data. The fact that the ΔI data points obtained from the bands follow the same trends as those at higher strains confirms the pole figure result that the Luders band texture simply intensifies as deformation progresses.

4.3. Residual strain measurements

4.3.1. Residual strain measurements along the sample length

Residual strain measurements were made along the length for samples deformed to 1%, 5%, and 15% strain. The residual strain results were very similar in both the thick and thin samples, so only selected thin sample results will be shown in this section. Fig. 5 shows the residual strains along the length of the 1% deformed thin sample. This sample has a Luders band region that had formed at the left-hand side of the sample during loading and was moving into the un-deformed region at the right when loading was halted. Results are shown for the {200}, {211} and {220} planes for all sample directions (RD, TD, ND). Fig. 5 shows that within the Luders region the {200} planes exhibit large tensile intergranular strains for both TD and ND, however there is little intergranular strain accumulation in the {211} and {220} in the TD and ND. Conversely, in the RD the {211} and {220} planes are slightly compressive but the {200} exhibits no intergranular strain. No significant residual strains were detected for the un-banded region.

Fig. 6 is a similar plot to Fig. 5, except that Fig. 6 shows the thin sample results after 15% deformation. This sample appeared to be uniformly deformed with no apparent macroscopic inhomogeneities along its length. Interestingly, in general the intergranular residual strain is similar at 15% to what it was at 1% in the banded region with a couple of exceptions:

- in the 15% deformed ND the {211} and {220} planes are more compressive than in the 1% deformed Luders band;
- in the 15% deformed TD the {220} result is slightly more compressive than in the 1% Luders band region.

This will be discussed in more detail in the following section on angular residual strain measurements.

4.3.2. Angular residual strain measurements – pre-annealing

Angular neutron diffraction measurements were made for thick and thin samples deformed to 1%, 3%, 5%, 10% and 20% strain. This technique is similar to that used by Pang et al. [12], with neutron diffraction

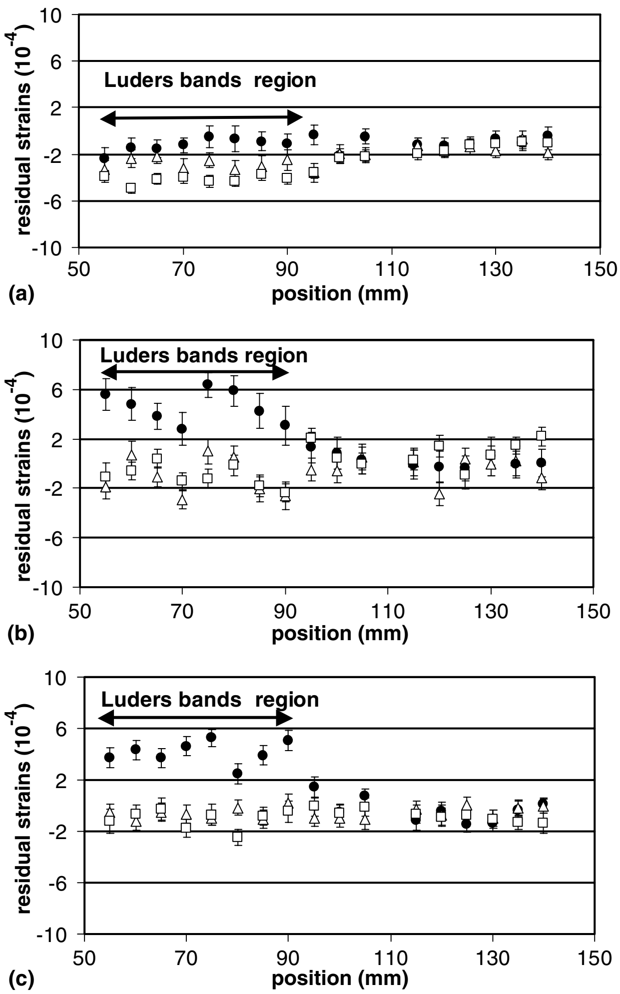

Fig. 5. {200} (●), {211} (△) and {220} (□) residual strain results along the length of the thin samples deformed to 0.5% engineering strain. Results are shown for all three sample directions: RD (a), TD (b) and ND (c). Luders band region of the sample is indicated on the left.

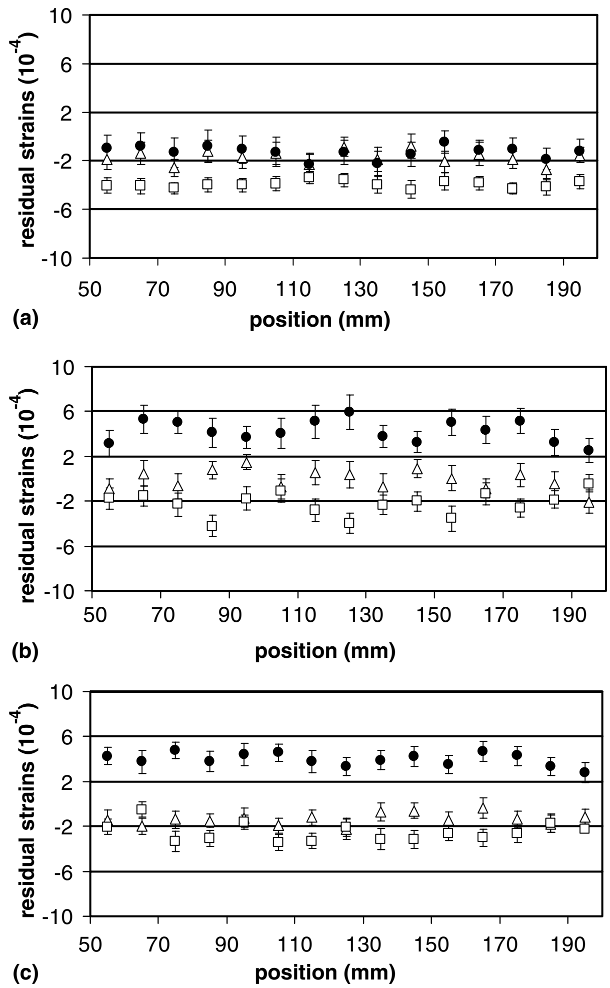

Fig. 6. {200} (●), {211} (△) and {220} (□) residual strain results along the length of the thin samples deformed to 15% engineering strain. Results are shown for all three sample directions: RD (a), TD (b) and ND (c). Sample appears uniformly deformed on a macroscopic scale.

measurements made at 15° angular intervals along the RD–TD plane, the RD–ND plane and the TD–RD plane of each stacked cube sample. As with the linear residual strain data, results for the thick and thin samples were similar, as shown in Fig. 7. The remainder of the figures in this paper show results from the thick samples only.

Fig. 8 shows the angular data from the Luders banded region of the 1% deformed thick sample, for all three planes. Also included in each plot is the modelled result from EPSC calculations. Fig. 9 shows similar data plots for the 20% (uniformly) deformed thick sample. The earlier linear scan data in Section 4.3.1 (Figs. 5 and 6) suggested that most of the intergranular strain data was similar in the 1% strain Luders band and the 15% deformed sample. However, a careful examination of Fig. 9, and also the other angular results between 1% and 20% deformation (not shown) indicates that this is not the case. These plots indicate that intergranular strain is approximately constant (and the same as Fig. 8) up to 5%. Above 5% there is a small, progressive increase in intergranular strain with plastic deformation, with the strains at 20% deformation being about 20% higher than those in the 1% Luders bands. This is not consistent with the work of Pang et al. [12] which indicated that intergranular effects level out after approximately 5% deformation.

Fig. 8 shows both data and also the result from the EPSC model. The EPSC model predicts the overall trend in strain with angle in the 1% Luders band region, and matches the experimental data quite well. The EPSC model result is not included in Fig. 9 for the 20% strain samples, since the EPSC model does not apply here (the basic assumptions in the model are no longer valid when the amount of plastic deformation is much greater than the elastic deformation).

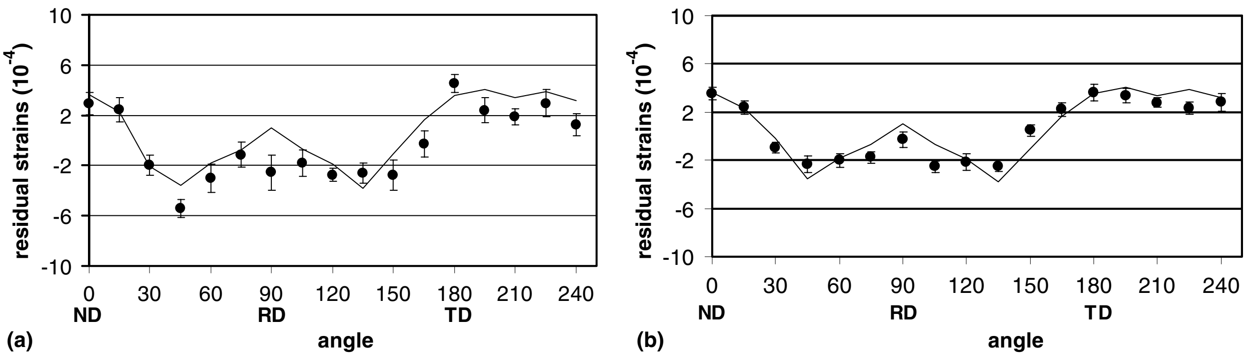

Fig. 7. Angular {200} residual strain data within the Luders band region for the samples deformed at 1% engineering strain for (a) the thin sample, and (b) the thick sample. Results are similar in both cases. Also shown on both plots is the theoretical result (solid line) based on EPSC calculations.

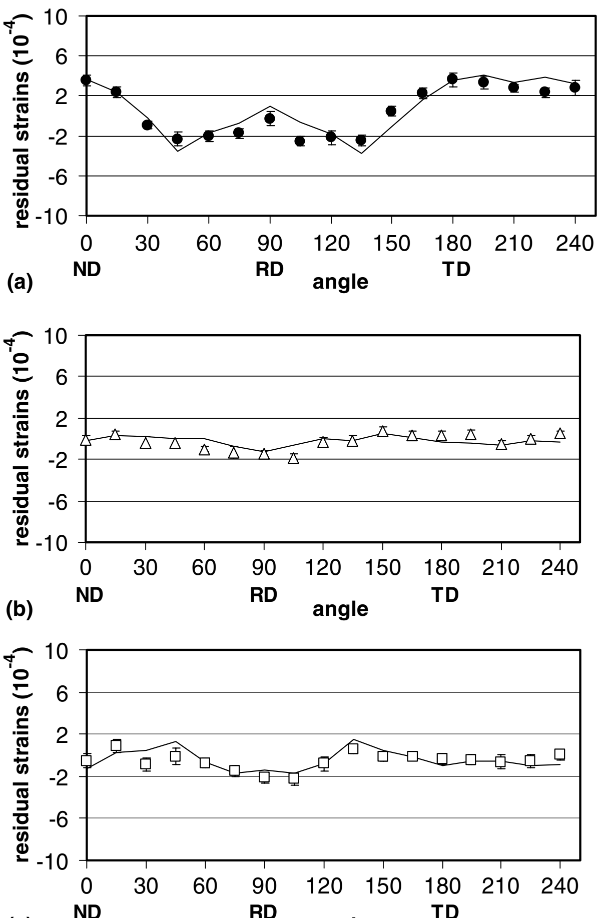

Fig. 8. {200} (a), {211} (b) and {220} (c) angular neutron diffraction data and results from the EPSC simulations (solid line) for the Luders bands region of the thick sample deformed at 1% engineering strain.

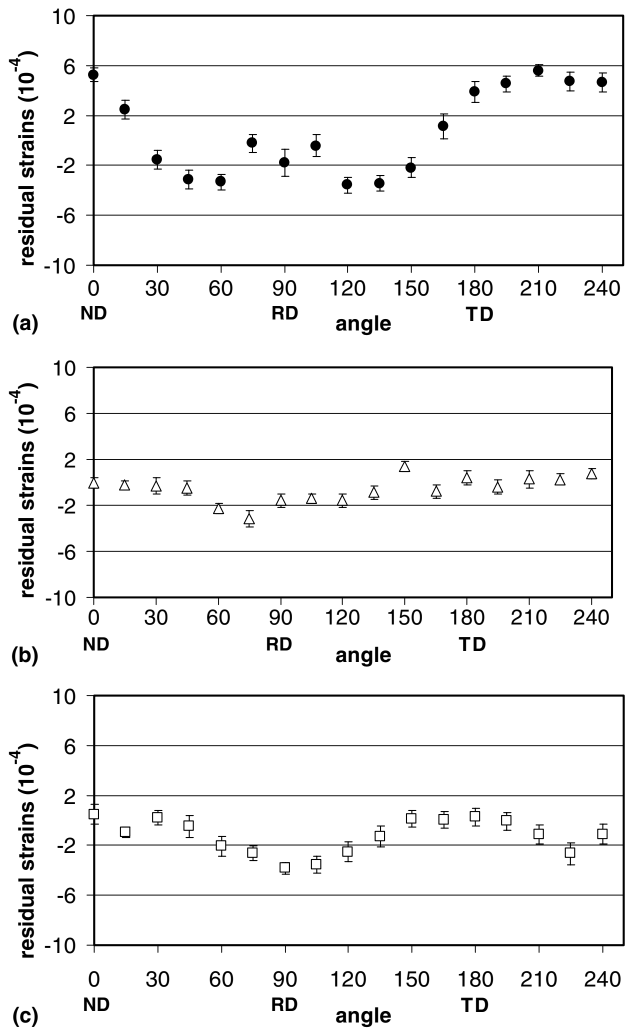

Fig. 9. {200} (a), {211} (b) and {220} (c) angular neutron diffraction data for the thick sample deformed at 20% engineering strain. EPSC modeling is not considered valid at this strain level.

4.3.3. Angular residual strain measurements – annealing studies

Samples used for the angular strain results were subjected to stress relieving heat treatments at temperatures up to 600 °C for times up to 100 h. Although intergranular strain changed in all cases, only the {200} results are shown here. Figs. 10(a) and (b) show the thick sample results before and after annealing. The sample deformed at 1% strain was annealed at 500 °C for 80 h followed by an annealing at 550 °C for 1 h. The sample deformed at 20% strain was annealed at increasing

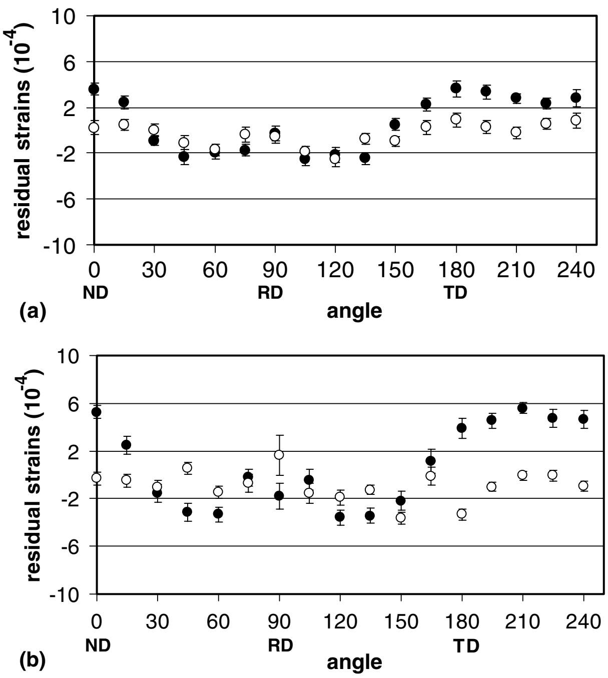

Fig. 10. Angular neutron diffraction data before (●) and after (○) annealing for the 1B (a) and 20% (b) thick samples for the {200} planes only.

annealing temperatures (the last temperature was 600 °C) and annealing times up to 100 h. In general the stress relieving reduces the intergranular strains, with behavior similar in the Luders band regions and in the 20% deformed sample. A more detailed study of annealing behavior and intergranular strain is currently underway.

5. Summary and conclusions

- The macroscopic form of the banding was different in the thin and thick samples. Consistent with other studies, thin samples having a high *l/t* ratio displayed simple bands, while thicker samples with a low *l/t* exhibited complex, thinner bands. The banding began around 0.5% deformation in both types of sample. Bands had propagated fully along the gauge volume by 5% deformation for the thin sample and 3% deformation for the thick ones.
- Luders bands may or may not display a texture, depending on the sample geometry. In the thin samples, the texture in the Luders band produced an approximate doubling of the diffracted intensity for the planes of interest. The texture initially formed in the Luders bands then strengthened with increasing deformation to 20% strain. Conversely, in the thick samples the texture was very weak, both in the Luders bands and after 20% deformation. In general, it appears that the texture development in the Luders band is a precursor to that at higher deformations.
- Despite the fact that the macroscopic form, and texture behaviour of the Luders bands in the thin and thick samples was different, the intergranular strain response was very similar. The {200} planes exhibited the largest intergranular strain, and even at 1% in the Luders band region these strains exceeded $400\mu\varepsilon$ in some sample directions. Intergranular strain in the {220} and {211} was much lower and displayed much less variation with sample direction. The {200} expansion with no corresponding change in the {220} or {211} suggests a very slight tetragonal distortion.

There was no observable difference in the intergranular strain within the Luders bands between 1% and 5% deformation. After 5%, however, there was a small but progressive increase of about 20% in the intergranular strain as the sample was deformed to 20%.

Typical stress relieving treatments reduced, but did not eliminate the intergranular strains in both types of samples. A more detailed study of annealing behaviour is underway.

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