EBSD investigation of the effect of strain path changes on the microstructure and texture of duplex stainless steel during hot deformation

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EBSD investigation of the effect of strain path changes on the microstructure and texture of duplex stainless steel during hot deformation

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Abstract. The effect of strain path changes on the microstructure/crystallographic texture characteristics was studied in a 22Cr-6Ni-3Mo duplex stainless steel subjected to several deformation regimes comprising forward and reverse torsion, performed at a temperature of 1000 °C using a strain rate of 1 s⁻¹. A high-resolution EBSD technique, utilising an FEI Sirion FEG SEM in conjunction with a HKL Technology EBSD attachment, was successfully implemented for precise phase and substructural characterisation of the above steel. The austenite/ferrite ratio as well as the crystallographic texture, subgrain size and misorientation angles corresponding to each phase were determined over large sample areas. The results indicated that the austenite and ferrite phases, present in approximately equal volume fractions, softened via dynamic recovery and extended dynamic recovery, respectively. The phase ratio appeared to remain stable during straining. There seemed to be generally more strain partitioned to the ferrite compared to the austenite. Twin relationships in the austenite appeared partly restored after the full strain reversal. The austenite crystallographic texture displayed a tendency to revert back to the original texture after the strain reversal whereas the ferrite texture evolution appeared more complex. The obtained subgrain characteristics indicated that the reversed torsion might have caused some dissolution (and possible re-formation) of subboundaries in both phases. Nevertheless, the effect of strain path changes on the substructure characteristics generally appeared relatively moderate.

1. Introduction
Fully automatic electron backscatter diffraction (EBSD) in conjunction with high-resolution field emission gun scanning electron microscopy (FEG SEM) has recently emerged as a powerful tool for microstructural analysis allowing rapid acquisition of large quantities of orientation data [1,2]. Orientation averaging techniques, such as the modified Kuwahara filter [3], can improve the angular resolution of EBSD to less than 0.5°, thus making it suitable for a quantitative characterisation of the hot deformation substructures [4].

The aim of the present work was to obtain internal state variable data, such as the austenite/ferrite ratio and phase morphology, crystallographic texture, subgrain size, misorientation angles and misorientation gradients, in a statistically meaningful way, for a 22Cr-6Ni-3Mo duplex stainless steel subjected to hot deformation in direct and reverse torsion. The data obtained will assist the development of physically-based models of the microstructural evolution during hot deformation of metallic materials.
2. Experimental methods
The material used was a commercial duplex stainless steel with the chemical composition of 0.012wt.% C, 0.86% Mn, 0.39% Si, 0.024% P, 0.001% S, 22.50% Cr, 5.83% Ni, 3.14% Mo, 0.15% N and the balance Fe. Cylindrical specimens with a diameter of 10 mm and gauge length of 20 mm were subjected to hot torsion at a temperature of 1000 °C using a strain rate of 1 s\(^{-1}\) and quenched. Initial torsion straining was performed to an equivalent strain level of 0.5, followed by unloading and reloading in either the same (forward torsion FT) or reverse (reverse torsion RT) sense using strain levels of 0.1 and 0.5. Four deformation regimes labelled FT0.5, FT0.5 + FT0.5, FT0.5 + RT0.1 (the partial strain reversal) and FT0.5 + RT0.5 (the full strain reversal) were thus produced. Microstructural investigation was undertaken on planar sections situated at 1 mm under the specimen surface and containing the shear plane normal and shear directions, using the high-resolution EBSD technique. An FEI Sirion FEG SEM, equipped with an automatic HKL Technology EBSD attachment, operated at 15 kV was used in the study. The data processing was carried out using the HKL Channel 5 software package and the VMAP software kindly provided by Prof. Humphreys of UMIST. The latter includes a modified Kuwahara filter routine for orientation averaging [3]. Large-area orientation maps, covering an area of about 5×1 mm\(^2\) and obtained using a step size of 3 \(\mu m\), provided information about the phase ratio and crystallographic texture. Detailed maps, covering an area of around 250×250 \(\mu m^2\) at each strain level and acquired using a step size of 0.2 \(\mu m\), provided substructural information.

3. Results and discussion

3.1. Phase morphology and crystallographic texture
The starting material was characterised by approximately equal volume fractions of austenite and ferrite and the phase ratio remained essentially stable during straining (table 1). Austenite islands embedded in the ferrite matrix, which were initially aligned roughly parallel to the shear plane, became more elongated and inclined to the above plane with increasing strain. After the full strain reversal these islands became preferentially aligned approximately perpendicular to the shear plane. There was considerable evidence of rotations of the pre-existing twin regions within the austenite away from their original \(\Sigma 3\) coincidence site lattice orientation relationship during straining [4]. Twin relationships in the austenite appeared partly restored after the full strain reversal.

Table 1. The volume fraction of austenite \(V_A\) together with the mean subgrain size \(d\) and mean misorientation angle \(\theta\) estimated by EBSD (A and F denote austenite and ferrite respectively).

<table>
<thead>
<tr>
<th>Deformed state</th>
<th>(V_A) (%)</th>
<th>(d_A) ((\mu m))</th>
<th>(\theta_A) ((°))</th>
<th>(d_F) ((\mu m))</th>
<th>(\theta_F) ((°))</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT0.5</td>
<td>49.2</td>
<td>2.27</td>
<td>2.07</td>
<td>2.43</td>
<td>3.47</td>
</tr>
<tr>
<td>FT0.5 + FT0.5</td>
<td>49.7</td>
<td>1.59</td>
<td>2.64</td>
<td>1.78</td>
<td>3.97</td>
</tr>
<tr>
<td>FT0.5 + RT0.1</td>
<td>48.4</td>
<td>2.51</td>
<td>1.87</td>
<td>2.67</td>
<td>3.18</td>
</tr>
<tr>
<td>FT0.5 + RT0.5</td>
<td>48.1</td>
<td>1.97</td>
<td>2.30</td>
<td>2.17</td>
<td>3.63</td>
</tr>
</tbody>
</table>

Both the austenite and ferrite displayed typical simple shear texture components [5] after accumulation of significant strain in forward torsion (figures 1b, 1f). The austenite crystallographic texture displayed a tendency to revert back to the original texture after the strain reversal (compare figures 1a and 1c), whereas the ferrite texture evolution appeared more complex (compare figures 1e and 1g).

3.2. Deformation substructure
Both the austenite and ferrite substructure features seemed qualitatively similar for all the deformed states, however, there were significant quantitative differences in substructure characteristics between...
Figure 1. Crystallographic texture of the austenite (a-d) and the ferrite (e-h) expressed using the orientation distribution function [1]: (a),(e) starting material; (b),(f) FT0.5 + FT0.5; (c),(g) FT0.5 + RT0.5; (d),(h) locations of the ideal shear texture components.

Figure 2. (a) Subgrain structure of austenite: low-angle boundaries are curved and bounded complex-shaped subgrains interspersed with almost boundary-free areas containing tangled dislocation cells. This is consistent with gradual development of large-angle planar dislocation walls on the background of slightly misoriented tangled cells, revealed in hot deformed austenite at low strains by TEM [4]. EBSD can only detect the former boundaries. (b) Misorientation axis vectors across austenite sub-boundaries showed a strong tendency to cluster around the sample radial direction. (c) In contrast to the austenite, more homogeneous, roughly equiaxed subgrain structure was generally observed within the ferrite. (d) Misorientation axis vectors across the sub-boundaries showed a less pronounced tendency to cluster around the sample radial direction.

The mean values of subgrain dimensions and misorientation angles found within both phases for all the deformed states studied are summarised in table 1. These values indicate that reversed torsion might have caused some dissolution (and possible re-formation) of sub-boundaries in both phases, however, the effect appeared relatively moderate. Such modest strain path sensitivity of substructure characteristics might be attributed, in the case of the more strained ferrite, to the observed formation of the random, relatively isotropic subgrain structure, containing large-angle boundaries, resulting from high freedom in dislocation rearrangement. The less strained, complex-shaped austenite islands,
although having more directional substructure known to be rather sensitive to strain path effects [7], appeared to complement strain accommodation during strain path changes by significant rotations.

![Figure 2](image-url)

**Figure 2.** Example of EBSD analysis of the FT0.5 + FT0.5 deformation state: (a) boundary map (austenite and ferrite are coloured white and grey respectively, thin and thick lines correspond to boundaries with misorientations above 0.7 and 5° respectively, θ and z denote shear direction and shear plane normal respectively); (b),(c) misorientation axis vectors in the sample coordinates corresponding to angles between 0.7 and 5° for the austenite and ferrite respectively; (d),(e) misorientation histograms of sub-boundaries for the austenite and ferrite respectively.

### 4. Conclusions

The effect of strain path on the microstructure/crystallographic texture characteristics was studied in a 22Cr-6Ni-3Mo duplex stainless steel, subjected to several regimes of forward and reverse torsion performed at a temperature of 1000 °C and a strain rate of 1 s⁻¹, using a high-resolution EBSD technique. The starting approximately equal volume fractions of austenite and ferrite appeared to remain stable during straining. There seemed to be generally more strain partitioned to the ferrite compared to the austenite. Twin relationships in the austenite appeared partly restored after the full strain reversal. The austenite crystallographic texture displayed a tendency to revert back to the original texture after the strain reversal whereas the ferrite texture evolution appeared more complex. Subgrain characteristics in both phases were a function of strain path, however, the effect appeared relatively moderate.

### References