Reverse martensitic transformation of ferrite to austenite under severe plastic deformation

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Abstract. Electron diffraction and high-resolution transmission electron microscopy show the presence of austenite in a heavily-deformed, initially pearlitic steel. This austenite must have formed as a result of the deformation, and it is shown that it could only originate from a reverse martensitic transformation from ferrite to austenite, stimulated by the high shear strains in the deformation. This reverse transformation could play the role of an additional and novel deformation mechanism in nanocrystalline steels.

1. Introduction

Nanostructured materials have thrown up a lot of surprises over the last few years, including unusual mechanical properties and deformation mechanisms. Much of this can be attributed to the fact that conventional deformation by the slip of lattice dislocations is impeded by the high density of grain boundaries, and by the difficulty of nucleating lattice dislocations in such small grains. In such circumstances, secondary deformation mechanisms can come to the fore, which would not normally be observed in coarse-grained materials at room temperature including grain boundary sliding, grain rotation, and deformation twinning and other shear transformations.

Recent studies have shown that severe plastic deformation of pearlitic steels results in the destruction of the lamellar pearlite structure, the dissolution of the Fe₃C cementite, and the formation of a nanostructured alloy [1,2]. This paper reports unusual phase transformations in this nanostructure, which can also act as a novel deformation mechanism.

2. Experimental procedure

Samples of the pearlitic carbon steel UIC 860 (0.6-0.8 wt. % C, 0.8-1.3 wt. % Mn, 0.1-0.5 wt. % Si, 0.04 wt. % P (max), 0.04 wt. % S (max), Fe-balance) were subjected to severe plastic deformation by high pressure torsion. In short, the sample is placed between two anvils and subjected to a high pressure, in this case 7 GPa, and the lower anvil is rotated at 1 rpm with respect to the fixed upper
anvil. The samples studied in the present work were subjected to 5 or 7 complete rotations. The strain is of course proportional to the distance from the centre of rotation, and samples for TEM were cut out so that their centres were approximately 3 mm from the axis of rotation, corresponding to a strain of about 300 for 5 rotations. Further details are given elsewhere [1].

The samples were prepared for TEM by a conventional process of grinding, polishing and electropolishing. The resulting specimens were then characterised with transmission electron microscopy using a FEI Tecnai TF20 equipped with a field emission gun at Karlsruhe and using a FEI Tecnai T20 equipped with a Gatan image filter (GIF) at Glasgow.

3. Results

Previous work has shown that the high-pressure torsion treatment refines the pearlitic structure to a nanocrystalline ferritic structure, with dissolution of the FeC cementite [1]. This structure may for instance be seen in the dark field image in Figure 1a, recorded using the (110) reflection of ferrite and shows small equiaxed ferrite grains with dimensions of the order of 10 nm. The zero-loss filtered diffraction pattern of Fig 1b also shows as its primary feature strong diffraction rings from the bcc ferrite, but additional reflections are also present. Some of these clearly belong to the cementite phase, and dark-field imaging has shown that these too are equiaxed nanosized grains. Additionally, some reflections can be clearly assigned to the fcc austenite structure, that normally only occurs at high temperatures above ~ 727°C for this steel composition.

Detailed investigations of the sample were performed using high-resolution transmission electron microscopy, and some areas were found where austenite could also be directly identified. Figure 2a shows a vertical boundary between two nanosized grains to the left and right. Using fast Fourier transforms (FFTs) of different areas it was straightforward to identify the structure and orientation of both crystals. To the right the structure can be identified as bcc ferrite (α) in the [111] orientation, and the indexing of the FFT (from the area in the box with a solid outline) is shown in Figure 2d. An FFT from the region from the dotted box to the left corresponds to a [110] orientation of austenite (γ) and is shown and indexed in Figure 2c. The FFT of Figure 2b corresponds to an area crossing the boundary as indicated by the large dashed box and allows us to determine the orientation relationship between the two grains. It is clear that [110]γ // [111]α and moreover that (111)γ // (110)α, which is of course the well-known Kurdjumov-Sachs orientation relationship {111}fcc // {110}bcc, <110>fcc // <111>bcc [3].

4. Discussion

The discovery of any austenite at all in a steel of this composition at room temperature is highly surprising, especially considering that it has not even been significantly heated during deformation. The whole deformation process was carried out at room temperature and the sample was in intimate contact with the much more massive anvils at all times, thus precluding any significant bulk heating of the sample as a result of deformation. Moreover, local heating of the sample in shear bands can also be discounted, since such shear banding has never been observed, either in deformation of the original pearlitic structure or in the subsequent deformation of the nanocrystalline structure. Thus, we can easily rule out any temperature rises of the degree required to result in the reversion to austenite by a thermal process.

The only realistic alternative is a displacive transformation occurring at or near room temperature. Displacive or martensitic transformations are of course well known, but the most commonly observed in steels or iron alloys are those from the high temperature austenite to the low temperature α−ferrite or α′−martensite phases. The reverse transformation from ferrite to austenite may be conveniently observed in high-Ni alloys [4], and has also been demonstrated on rapid heating of iron whiskers [5] or pearlitic steel [6]. The mechanism for the transformation in the present work can only be speculated at, but it could feasibly proceed by the sort of shear process outlined in Figure 3. This is the reverse of the normal shear process for the martensitic transformation of austenite to ferrite and proceeds by a shear of 1/6 [110]bcc on every (110) plane of the ferrite, which could be accomplished by the passage of transformation partials with \( \mathbf{b} = 1/6 [1\bar{1}0] \). This would transform the stacking
from the ABAB type stacking of the bcc structure to the ABCABC type stacking of the fcc structure. A suitable atomic relaxation or second shear would then transform the symmetry to cubic.

Nevertheless, the question remains as to how this transformation could possibly occur at room temperature. Firstly, the ferrite is nanocrystalline and DSC measurements of enthalpy release on heating of about 2.5 kJ mol$^{-1}$ [7] show just how far from equilibrium this material is: this corresponds to more that 60% of the difference in Gibbs free energy between coarse grained austenite and ferrite at room temperature. Secondly, deformation by conventional mechanisms such as slip of lattice dislocations is greatly impeded in nanocrystalline materials, due to the difficulty of nucleating dislocations in such small grains, and the strong influence of the grain boundaries. Thus other processes come to the fore including grain boundary sliding and displacive transformations, for example deformation twinning in nanocrystalline aluminium [8]. Finally, applied shear forces can
activate martensitic transformations, as is well known in shape memory alloys, and Hornbogen [9] has developed a framework for the estimation of the magnitude of this effect in steels. New work by the present authors shows that the stresses applied provide easily enough driving force for this transformation, and this will be presented in detail in a forthcoming publication [10].

Finally, it should be noted that this displacive transformation could act as an alternative deformation mechanism for nanocrystalline ferritic steel, when conventional deformation mechanisms are impeded by the nanostructure. A similar transformation and deformation mechanism has been predicted for nanocrystalline iron by embedded atom method simulations of microcracking [11].

In summary, we have shown convincing evidence for the presence of austenite in an initially pearlitic steel after high strain shear deformation by high pressure torsion. It is shown that this could have only been formed by a reverse martensitic transformation of the ferrite phase to austenite. Such transformations are only observed where a nanocrystalline structure has been formed, and may constitute an additional deformation mechanism in such nanocrystalline steels.

Acknowledgements
The authors are grateful to H. Rösner for very valuable comments on the manuscript and kind assistance in performing TEM and HRTEM experiments and the European Bulk Metallic Glass Project (BMG HPRN-CT-2000-00033) for financial support (HJF).

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Figure 3: Schematic diagrams of the shifts needed to transform bcc stacking to fcc on the (110)$_{bc}$ plane. In the bcc diagram, the B layer sits at ½[011] out of the plane of the page, the shifts are of ½[110]. In the fcc diagram, the B layer sits at ½[111] out of the plane of the page and the C layer sits at ½[111] out of the plane of the page.