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Elastic interaction between twins during tensile deformation of austenitic stainless steel

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ABSTRACT

In austenite, the twin boundary normal is a common elastically stiff direction shared by the two twins, which may induce special interactions. By means of three-dimensional X-ray diffraction this elastic interaction has been analysed and compared to grains separated by conventional grain boundaries. However, the components of the Type II stress normal to the twin boundary plane exhibit the same large variations as for the grain boundaries. Elastic grain interactions are therefore complex and must involve the entire set of neighbouring grains. The elastic-regime stress along the tensile direction qualitatively depends on the grain orientation, but grain-to-grain variations are large.

The method of three-dimensional X-ray diffraction (3DXRD) is capable of producing large maps of grain structures [1–3], including crystallographic orientations and neighbour relations [4,5], and also allows measurement of the elastic strain tensor at the level of each individual grain during deformation [6–9]. The average stress tensor of each grain, known as the Type II stress tensor, may subsequently be derived. This gives a unique possibility of investigating elastic grain interactions. Such studies are motivated by line broadening studies, which reveal substantial deviations from the predictions of current elastic grain interaction models based on the orientations of the grains with respect to the tensile axis [10,11].

The present study attempts to study these complex elastic interactions by focusing on the interaction across annealing twin boundaries produced by recrystallization in 316L austenitic steel during uniaxial tension. Twin boundaries in the fcc crystal lattice are characterised by a well-defined crystallographic boundary plane, with a normal vector which happens to be the elastically stiffest <111> direction. The crystallographic misorientation between twins is a 60° rotation around the twin boundary normal, enabling selection of twin pairs for this study in which one part of the twin pair has its tensile axis aligned close to the elastically most compliant crystallographic <100> direction while the direction of the tensile axis of the other part is significantly stiffer. As a direct consequence of the crystallography of this selection, the inclination of the twinning plane to the tensile axis of the experiment is restricted to a range of 45–65°, ensuring not only crystallographically similar boundary planes, but also boundary planes that are comparable with respect to the macroscopically applied deformation.

The 316L austenitic steel material employed has a mean grain size of 70 μm. The texture is almost random, which further allows for comparison with the elastic interaction across conventional grain boundaries separating compliant grains with crystallographic tensile axes near <100> from stiffer neighbours, while having the same orientation of the grain boundary plane in the deformation system as the twin boundaries.

The diffraction experiment was performed at the F2 line of the Cornell High Energy Synchrotron Source using the RAMS2 load frame [12] to deform the sample in tension while allowing a full 360° illumination of the 0.7×0.7 mm^2 sample cross section. An X-ray beam of 55.681 keV (Ho K-edge) limited with a rectangular slit to 0.10 mm height by 2.0 mm width was used to illuminate five consecutive 0.10 mm thick vertical slices of the sample. Two detectors with a resolution of 2048×2048 pixels were used separately: one near-field detector (QImaging Retiga 4000DC with an infinity-corrected 5× objective lens) with an effective pixel size of 1.48×1.48 μm^2 at a distance of 5.1 mm and one large-area far-field detector (GE Revolution 41RT [13]) with a pixel size of 200×200 μm^2 at a distance of 700 mm from the specimen. Both detectors were used to characterise the undeformed state of the sample; the near-field detector for data on grain shapes and positions, and the far-field detector for data on grain orientations, elastic strains

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and stresses. The sample was then deformed in the elastic-regime in tension to 0.12% total strain confirmed by digital image correlation [14] and 168 MPa according to the RAMS2 load cell, and a second set of far-field data was collected to determine the stress states of the individual grains within the sample. The diffraction data were reconstructed using the FABLE software package. Grainspotter [15] was used for indexing and FitAllB [6] for fitting of the average elastic strain tensor in each individual grain from the far-field data, after which the Type II stress tensor was derived by using the following values for the stiffness tensor: $C_{11} = 206$ GPa, $C_{12} = 133$ GPa, and $C_{44} = 119$ GPa [16]. The 3D grain morphologies were reconstructed from the near-field data by employing a 3D generalisation of Grainsweeper [4]. The 3D grain map of the illuminated $0.7 \times 0.7 \times 0.5$ mm^3 sample volume with a completeness of 70% can be seen in Fig. 1(a).

The tensile elastic strain and Type II stress components of each grain in the mapped volume are given in Fig. 2 as a function of the crystallographic direction of the tensile axis. It is seen that neither the strain nor the stress components are constant for all grains, implying that the elastic grain interaction lies in between the grain interaction models of Voigt [17] and Reuss [18] assuming strain compatibility and stress equilibrium, respectively. Grains near <100> clearly tend to have the largest tensile strain and the smallest tensile stress, whereas the trend near <111> is opposite. This is in good agreement with the expectation that the <100> oriented grains are the most compliant and those near <111> the stiffest. However, the scatter in both strain and stress values is substantial. The crystallographic direction of the tensile axis thus has an influence on the deformation behaviour of individual grains, but local neighbourhood interactions have a large impact as well

In order to investigate the interaction between twins, the 3D space filling grain map is analysed to unambiguously identify twinned grains using both the determined boundary plane and the crystallographic misorientation. A representative example of a twin pair is presented in Fig. 1(b). The twin planes and normal vector have been illustrated for clarity. Fig. 3(a) shows the crystallographic orientations of the tensile axes of the 36 twin pairs selected for this study. The compliant part of the twin pair (near <100>) is coloured red and the stiffer part is coloured blue or green. For those coloured blue, the ratio between the single crystal elastic moduli along the tensile axes of the two parts of the twin pair exceeds 1.7. The green colour represents twins where this ratio lies between 1.7 and 1.2. For comparison with the interaction across conventional grain boundaries, Fig. 3(b) presents a set of 24 reference grain boundaries connecting 18 compliant grains (as marked in red) to 22 stiffer grain orientations (marked in grey) without fulfilling the boundary plane and crystallographic misorientation criteria for twinning. These reference grain boundaries are inclined 45–65° to the direction of applied tensile stress like the twin boundaries of the selected twin pairs. Fig. 1(c) shows a representative example of such a pair of neighbouring grains with the grain boundary plane and normal vector indicated for clarity.

With respect to the stress normal to the twin planes of the 36 selected twin pairs, Fig. 4(a) shows this stress component in the stiff part plotted versus that in the compliant part. By analogy with the stress along

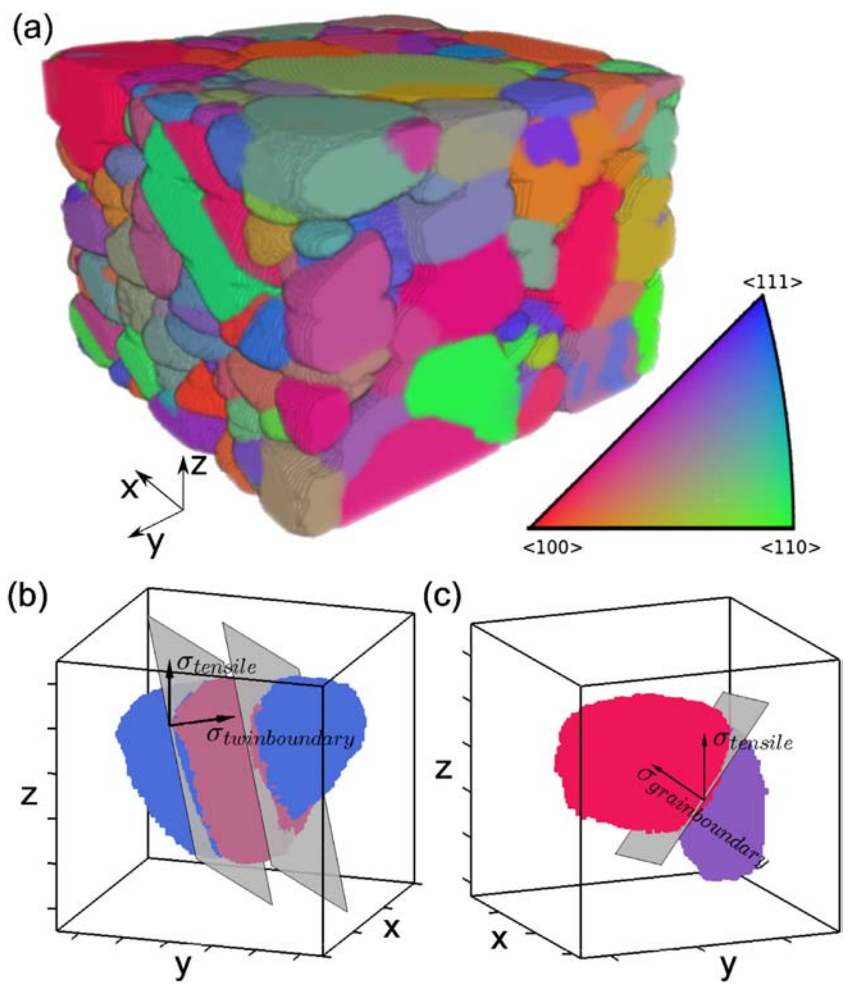

Fig. 1. Full 3D grain map of (a) the illuminated $0.7 \times 0.7 \times 0.5$ mm^3 section of the sample, (b) a selected twin pair (enclosing box $0.15 \times 0.15 \times 0.15$ mm^3) and (c) a representative pair of neighbouring grains (enclosing box $0.15 \times 0.15 \times 0.15$ mm^3) colour coded according to the orientation of the tensile axis. The tensile stress is applied along the *z*-direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)