3D Reconstruction, Visualization and Quantification of Dislocations from Transmission Electron Microscopy Stereo-Pairs

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A wide range of properties in crystalline materials is affected by the presence of dislocations, the carriers of plastic deformation. Dislocations can be thought of as filiform structures, characterized by geometrical factors such as their Burgers vector, slip plane, length per unit volume (dislocation density) and line direction. In technical materials such as functional and structural alloys, as well as in minerals, the understanding of bulk deformation driven by dislocation activity is of paramount importance, and thus also the techniques that allow its characterization. Since decades, diffraction contrast in the transmission electron microscope (TEM) is widely implemented to image and describe two-dimensional (2D) projections of dislocation substructures in thin foils [1]. Recently, the use of electron tomography was applied for the first time to fully reconstruct a 3D dislocation network in a GaN epilayer [2]. Although this latter technique has gained popularity, it usually requires an elaborate experimental setup, as well as sophisticated image post-processing methods for a successful reconstruction. Stereoscopic methods in the TEM also have traditionally allowed the three-dimensional (3D) observation of dislocations [e. g. 3]. For this purpose, the same region of a TEM foil is imaged using the same diffraction vector with two beam directions slightly tilted from each other. Subsequently, the pair of images is observed with help of stereo-viewers or 3D glasses. Based on this principle, a system based on a special hardware and software combination was developed for segmentation and analysis of stereomicroscopy data in biological research, and it was also used to analyze simple dislocation structures [4]. In the present contribution a simple software tool is introduced, which has been developed to reconstruct, visualize and quantify dislocation substructures in the thicker regions of electron-transparent foils. A special focus is set on the use of scanning (S)TEM for its implementation.

As depicted in Figure 1, the tool is based on the separate tracing of dislocation line segments on both images of a stereo-pair. The points 1, 2 and 3 are marked on the images viewed by the left and right eyes (Figures 1a and b, respectively), showing an relative displacement Δx on the superimposed images in the anaglyph of Figure 1c. This Δx is given by the point's depth Δh and by the stereo-angle ϑ, as shown in Figure 1d. By knowing the beam direction for the left and right images ($\boldsymbol{B_L}$ and $\boldsymbol{B_R}$, respectively), ϑ can be determined, and hence also Δh. Once the depth information from all traced nodes is gained, a reconstruction is made (Figure 1e) where the line length can directly be read from the tool's interface. The setup is merely geometrical and only needs the relative tilt between both images, the direction of the tilt axis and the image calibration, thus allowing asymmetrical tilts with respect to the foil normal. The foil thickness is measured directly from the endings of the dislocations on the bottom and top surfaces of the TEM foil, and is determined as t ~ 370 nm for the region in Figure 1. With t, the volume is in Figure 1e is also known, and the total dislocation density of the region is calculated as $\rho_t = 44.4 \times 10^{12}$ m·m^{-3}. It is clear from Figure 1 that in the Ni-base superalloy presented here, the dislocation substructures are highly localized towards the interface between the two phases of which the microstructure is composed, γ and γ' (labeled in Figure 1a). The reconstructed model allows a separation of the dislocation densities within the γ and the γ' phases and at their interface, which would be rather difficult by using common methods such as the one proposed by Ham [5]. Thus the partial dislocation densities are measured as ρ_{γ} = 1.7 x 10^{12} m·m^{-3}, $\rho_{\gamma'}$ = 2.7 x 10^{12} m·m^{-3} and $\rho_{\gamma/\gamma'}$ = 40.0 x 10^{12} m·m^{-3}. The tool also incorporates the knowledge of the crystallographic positions at the two tilts to enable plotting the line segment orientations. One can chose to display the resulting line directions as an interactive table; as an additional spherical spatial graph, where all lines extend from the center of a sphere; as a 2D plot of the spherical coordinates θ and φ; or as points plotted on a stereographic projection.

Thus, a simple software tool has been developed that allows the reconstruction, visualization and quantification of foil thickness, localized dislocation densities (or other filiform substructures) and orientations based on only one stereo-pair.

References:

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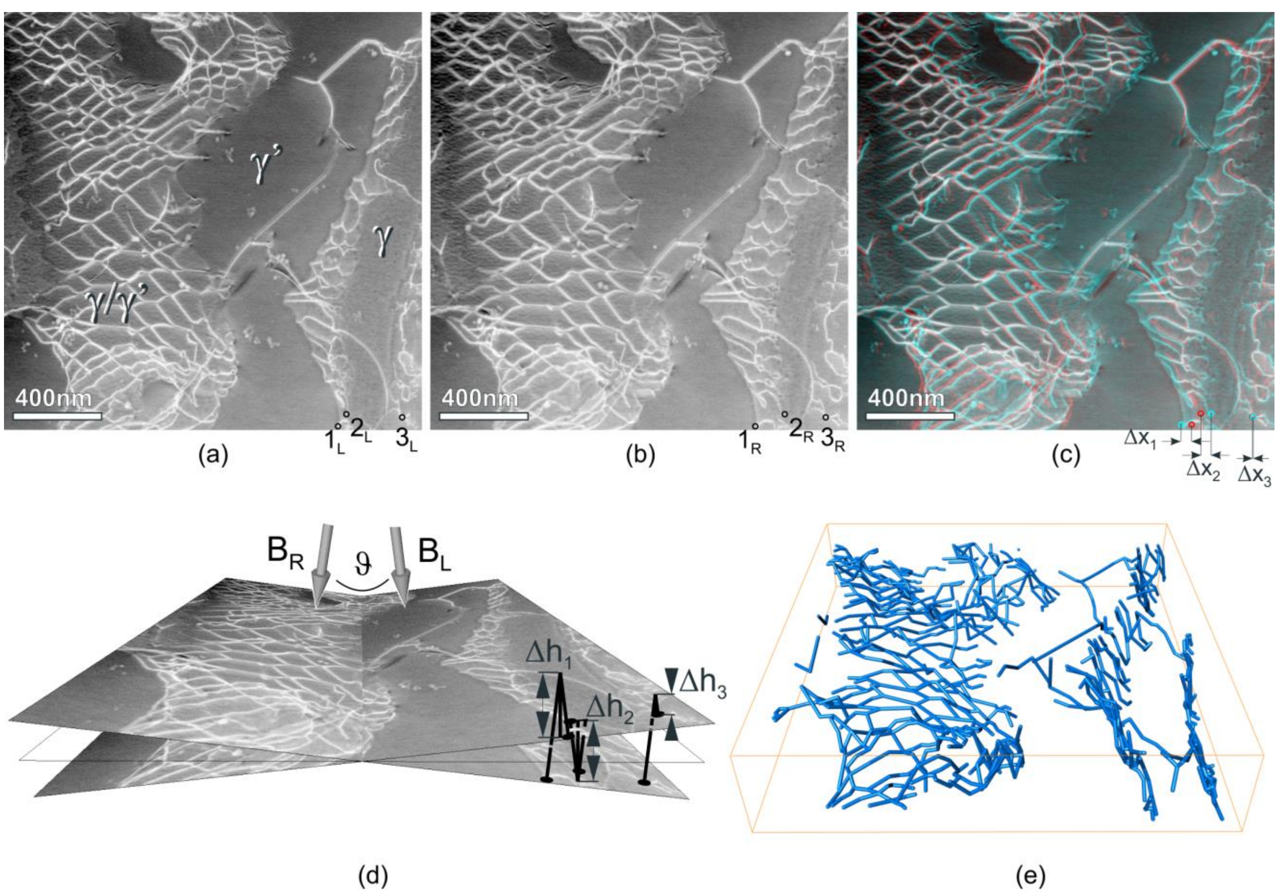

Figure 1. Dislocations in a Ni-base single crystal superalloy after creep. (a) left and (b) right images of a stereo-pair with labeled marked points *1*, *2* and *3*. (c) Anaglyph with apparent lateral displacement *Δx*. (d) Perspective view with depth information *Δh* (e) Reconstructed volume.