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Visualization of low-misorientation dislocation structures from orientation data using customized All-Euler maps

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Abstract. A method for visualization of low-misorientation dislocation structures from orientation data obtained by electron backscatter diffraction (EBSD) in scanning electron microscopy is presented. The method is termed “customized All-Euler maps”. The microstructure of high purity (99.996 wt.%) aluminum lightly rolled to a thickness reduction of 12% is presented as a case study. Dislocation structures with misorientations across dislocation boundaries approaching the orientation precision of standard EBSD (~0.5°) are revealed using the customized All-Euler maps. Cautions and limitations in using such maps are discussed.

1. Introduction
Low-misorientation dislocation structures, in which the misorientation angles across dislocation boundaries are often as low as 0.5° or even lower, are of both engineering and scientific significance, as they are the prominent microstructural features of lightly deformed metals and provide important insights into the early stage of the evolution of deformation-induced dislocation structures [1–5]. Although transmission electron microscopy (TEM) can reveal details of dislocation boundaries in lightly deformed metals [6–8], the technique has several main limitations — e.g. the field of view is relatively small, and the operation is often labor intensive. Electron backscatter diffraction (EBSD) in the scanning electron microscope (SEM), which typically has a precision in orientation measurement of around 0.5°, is widely utilized to characterize the microstructure of deformed metals. Since the orientation precision of EBSD is challenged in studies of low-misorientation dislocation structures, the capability of standard EBSD in resolving such structures needs to be examined. Furthermore, proper visualization of the orientation data becomes critical.

In the present work low-misorientation dislocation structures in a lightly rolled Al of high purity is characterized by EBSD, and optimal visualization of the orientations is explored by employing an in-house developed color scheme termed customized All-Euler maps.

2. Material and methods
Aluminum with a high purity of 99.996% was used in this study. The sample, in the form of a sheet of 94 × 46 × 3 mm³, was first annealed at 600 °C for 7 days, resulting in grain sizes ranging from a few to tens of millimeters. The sample was then rolled at room temperature to a thickness reduction of 12%. Details of the material and rolling process is available in [9,10]. Metallographic samples were prepared from the section containing the normal and the rolling directions, i.e. the ND-RD section. SEM-EBSD characterization was carried out on a Zeiss Supra 35 microscope, using a step size of 0.5 μm.
Figure 1 demonstrates the principle of customized All-Euler maps in comparison with standard All-Euler maps produced by the commercial EBSD software Channel 5. In standard All-Euler maps (figure 1a1–a2), the red, green and blue color components (r, g and b) cover the full ranges of the three Euler angles for aluminum, with φ₁ being 0–360° and Φ and φ₂ both being 0–90°. Here while Φ and φ₂ have reduced ranges by considering the symmetry of a cube crystal, φ₁ does not have a reduced range because by default the sample symmetry is not considered during EBSD data collection. For a specific EBSD map with low-misorientation dislocation structures (figure 1a2), the actual distribution of Euler angles can be much narrower than the full range (figure 1b1), which means the standard All-Euler maps only utilize a small portion of the color space. As a result, the microstructure is only weakly revealed due to the low color contrast (figure 1a2). The idea of customized All-Euler maps is to make full use of the color space by making the r, g and b color components cover only the actual distribution of Euler angles. For instance, in figure 1b1, the r, g and b color components represent the ranges of φ₁ = 305.2±7.6°, Φ = 25.9±7.6° and φ₂ = 62.5±7.6°. The center of the ranges corresponds to the mean orientation of the map, which has (φ₁, Φ, φ₂) = (305.2°, 25.9°, 62.5°), and the size of the ranges equals to 3 times the largest standard deviation of the three Euler angles of the map. The three Euler angles are set to have the same size of ranges to ensure their variations have a similar impact on the resulting contrast. This results in much-improved contrast in the customized All-Euler map in figure 1b2, in which a set of planar dislocation structures running from lower-left to upper-right (marked by the solid line) is most apparent whilst another set running from lower-right to upper-left (marked by the dashed line) is also identified.

The customized All-Euler maps in this work were generated using in-house developed Matlab codes. A previous example of this coloring technique can be found in a different application [11], where the local lattice rotations around voids in a shock-loaded Al single crystal were analyzed.

![Figure 1](image_url)

**Figure 1.** (a₁ & a₂) Color scheme and a standard All-Euler map. (b₁ & b₂) Color scheme and a customized All-Euler map of the same region. Refer to the text for a detailed description of the color schemes. The solid line and the dashed one in b₂ mark the direction of a profound set of planar dislocation structures and that of a less well-developed set, respectively.
3. Results and discussion

By using the customized All-Euler map method described above, it is found to be possible to visualize dislocation structures with low misorientations approaching the orientation precision (~0.5°) of standard EBSD. Figure 2 shows a region of such structures visualized by various techniques for comparison.

![Figure 2](image)

**Figure 2.** A comparison between different visualization techniques of the same orientation data containing low-misorientation dislocation structures. (a) Boundary detection with a threshold of 0.5°. (b) Boundary detection with a threshold of 0.3°. (c) Band contrast. Figures a–c are produced using the Channel 5 software. (d) Customized All-Euler map. All figures are of the same magnification, and the scale bars correspond to 100 µm.

Figure 2a and b show dislocation boundaries detected by the software Channel 5, using a threshold of 0.5° and 0.3°, respectively. As shown in figure 2a, boundary detection with a threshold of 0.5° reveals incompletely the microstructure in part of the region, which seems to be cell-like. Random noise is already noticeable over the entire map, suggesting the limit of the reliability of boundary detection is being approached. A further decrease in the threshold angle for boundary detection simply increases the noise level with negligible gain in the microstructural feature detection. Figure 2b shows boundary detection with 0.3°, which contains high level of noise but has basically the same microstructural information as figure 2a. The band contrast map from Channel 5 (figure 2c) shows little of the dislocation structures; only two microbands with different alignments are noticeable, as indicated by the black and white arrows. By contrast, the customized All-Euler map (figure 2d) shows clearly two
intersecting sets of planar dislocation structures. Note that the dislocation boundaries in figure 2a mostly correspond to the orange-colored cells that have relatively well-defined boundaries, and the two microbands in figure 2c are found in figure 2d, both of which validate the potential of the customized All Euler Map method for detection of the microstructural features observed.

Figure 2 shows a clear advantage of the customized All-Euler map (figure 2d) over boundary detection (figure 2a) in terms of the visualization of low-misorientation dislocation structures. The results show that when the orientation precision of EBSD is being approached, boundary detection is very sensitive to the uncertainties in the measurement of the individual orientations, whilst the customized All-Euler maps are much less sensitive. This is attributed to the different principles for revealing microstructures between these two techniques. While boundary detection measures the differences between each pair of neighboring pixels and thus highlights measurement errors, customized All-Euler maps show the property of a group of pixels allowing human visual perception and are therefore more tolerant of individual uncertainties.

In figure 1 the orientation is relatively homogeneous over the entire region investigated, and the spread of orientation is mainly associated with misorientations associated with dislocation structures, which corresponds to a narrow distribution in Euler space. In this case the result is good contrast over the whole area in the customized All-Euler maps.

Under certain conditions, however, continuous orientation variations over a large length scale exist in the deformed microstructure [12,13], which can ‘overwhelm’ the relatively small local variations in orientations associated dislocation structures, making the latter invisible even in customized All-Euler maps. An example of such is shown in figure 3.

![Figure 3](image_url)

**Figure 3.** Customized All-Euler maps of a region with a continuous variation in orientation over a large length scale. (a) The map uses the distribution of Euler angles of the entire region. (b) The map is divided into three sub-regions, each of which uses the distribution of Euler angles in the sub-region.

In figure 3a, the orientation gradually changes by 5–9° between the top and the bottom parts of the region investigated. The upper part covers a height of 500–600 µm while the size of bottom part is even larger. The customized All-Euler map in figure 3a only shows the difference between the top and the bottom parts, and does not reveal much of the dislocation structure. In this case, the image contrast can be largely improved by dividing the map into smaller sub-maps of relatively homogeneous orientations.
By dividing figure 3a into three regions, as shown in figure 3b, the image contrast can be optimized for each region using the local distribution of Euler angles, resulting in much improved visualization of the underlying microstructures.

Any degeneracy in Euler space should be avoided in customized All-Euler maps. One such degeneracy is due to the selection of different equivalent variants of the same orientation during data acquisition of EBSD, which is removed during post-processing of the data by forcing all pixels of each given grain to choose the same variant. Another type of degeneracy is the discontinuity related to the periodic boundaries of the Euler angles at 0° or 360°. Both can be fixed by choosing values that are closest to the Euler angles assigned to the mean orientation of each grain. For instance, if the Euler angle $\phi_1$ of the mean orientation of a given grain is $\phi_{1m} = 1°$, then in this grain a pixel that has $\phi_1 = 359°$ will be assigned with a new value, $\phi_1 = 359° - 360° = -1°$, to ensure that $\phi_1$ has a continuous distribution that centers around $\phi_{1m}$.

The Euler space is known to have a singularity for $\Phi = 0°$, corresponding to the situation where the $z$ direction of sample reference frame, $z_s$, coincides with the $z$ direction of the crystal reference frame, $z_c$. This singularity can be avoided by choosing a different but equivalent assignment of the $x$, $y$ and $z$ directions to the crystal reference frame, which will result in a new equivalent set of Euler angles, whenever the mean orientation of a given grain has an Euler angle $\Phi$ that is very close to 0°.

Another factor to be considered is the non-linear nature of the Euler space. By avoiding the singularity problem, the most distorted region in the Euler space is already avoided. Moreover, in the study of low-misorientation dislocation structures, since the orientation of each map is only distributed over a small volume of Euler space, the effect of the non-linearity is expected to be further reduced in such small volumes.

The morphology of dislocation structures is closely related to the crystal orientation and reflects the slip systems that are active during deformation [2–4]. The morphology of dislocation structures has also been shown to have an impact on boundary migration during recrystallization of deformed metals [14–17]. Improved visualization of dislocation structures using customized All-Euler map is therefore of value for such studies. While the present work does not include quantification of the visualized dislocation structures, it has been shown that the subgrain structures can be detected by further data processing, e.g. using an orientation averaging technique [18,19].

4. Conclusions

As shown for high purity Al (99.996 wt.%) rolled by a thickness reduction of 12%, customized All-Euler maps are capable of visualizing dislocation structures with boundary misorientations approaching the orientation precision of standard EBSD (~0.5°). In cases where cumulative orientation variations exist over a large length scale, it is shown that the image contrast is largely improved by dividing the map into smaller regions of relatively homogeneous orientations and making customized All-Euler maps for each region. Artificial discontinuities in Euler space can be removed in customized All-Euler maps. Also, the singularity in Euler space can be avoided by choosing a different but equivalent set of Euler angles.

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