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# A method to correct coordinate distortion in EBSD maps

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ABSTRACT

Drift during electron backscatter diffraction mapping leads to coordinate distortions in resulting orientation maps, which affects, in some cases significantly, the accuracy of analysis. A method, thin plate spline, is introduced and tested to correct such coordinate distortions in the maps after the electron backscatter diffraction measurements. The accuracy of the correction as well as theoretical and practical aspects of using the thin plate spline method is discussed in detail. By comparing with other correction methods, it is shown that the thin plate spline method is most efficient to correct different local distortions in the electron backscatter diffraction maps.



## 1. Introduction

Electron backscatter diffraction (EBSD) in a scanning electron microscope (SEM) has been widely used to characterize microstructure due to the wide availability of SEMs, the ease of sample preparation from bulk, the user friendly software for data collection and analysis, and the high speed of data collection [1–3]. With EBSD, individual grain orientations, local texture, and point-to-point orientation relationships can be determined routinely on the surfaces of bulk samples. In the last decade this technique has frequently been used for in-situ and ex-situ studies, from which dynamic information of microstructural evolution during thermal–mechanical processing has been reported [4–10].

Prior to EBSD measurements, regions of interest are defined, and grids, typically rectangles, covering the regions are specified. During scanning, thermal and mechanical drift of the electron beam and/or the sample (for instance mechanical instability of the column or the sample support, thermal expansion and contraction of the microscope components, and mechanical disturbances) can, however, distort the defined grid. Three examples of distortion are illustrated in Fig. 1, where the darker contaminated regions after EBSD measurements represent the real shapes of the scanned areas, which are clearly distorted to a different extent than the predefined rectangles. These distortions imply that the recorded coordinates of the EBSD maps do not correspond with the actual physical coordinates on the sample surface as predefined.

The drift is normally unpredictable and not constant, and it is more significant in the first few hours after the sample is mounted in the microscope and the electron beam is turned on, but less significant and relatively uniform afterwards (see Fig. 1 and Table 1). For EBSD scans lasting a few hours, the drift can result in coordinate differences from a few microns to dozens of microns along the x and/or y axes (see for example Fig. 1 and Table 1). Therefore, if large EBSD maps are collected using step sizes of several hundreds of nanometers or larger, conventional statistical information obtained from these maps, such as average boundary spacing, average grain size, and texture, can still be reliable because the drift-induced coordinate distortion is much smaller than the map sizes. However, if small electron beam step sizes such as 20–30 nm, or even 2–5 nm used in the transmission mode (i.e. the so-called t-EBSD or TKD (transmission Kikuchi diffraction) [11–13]) are utilized, the drift-induced coordinate distortion can significantly affect the data because the drift speed is comparable to the step sizes (see Table 1). This problem has been widely recognized, and is solved generally either by cutting off the initial part of the EBSD map, thus excluding the most distorted part from the analysis, or by starting EBSD measurements when there is no significant drift, i.e. after a long waiting period. Some commercial EBSD packages allow drift correction during data acquisition using linear image correlation of forescatter images. However, the drift correction based on the image correlation alone cannot correct both the beam drift and the sample drift simultaneously. If the drift correction is not perfect, resulting EBSD maps can contain additional artifacts typically in the form of extended straight boundaries.

The drift problems become more critical when EBSD techniques are used together with other techniques, such as electron channeling contrast (ECC) and transmission electron microscopy (TEM), to characterize the same microstructures [14–17]. Due to the different imaging

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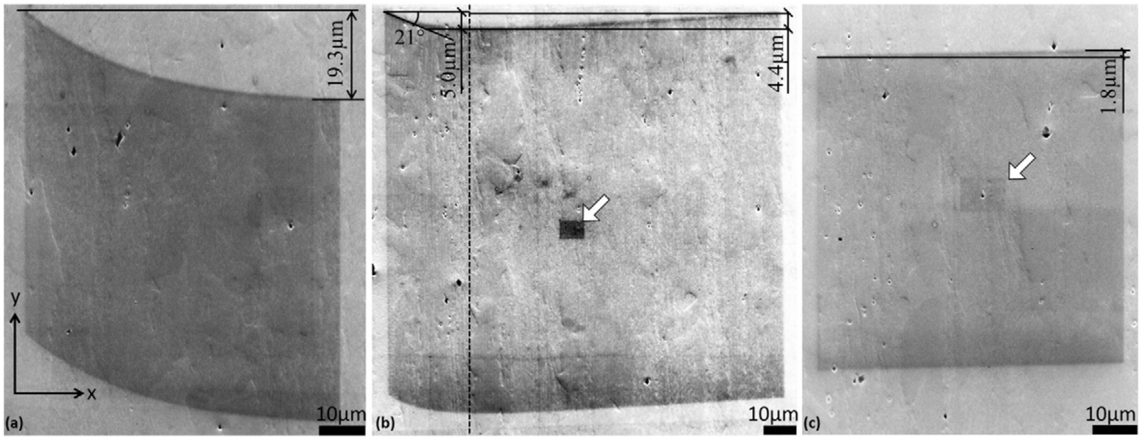


**Fig. 1.** Examples of secondary electron images showing the carbon contaminated regions (darker shaded areas) after EBSD measurements on a longitudinal section of a partially recrystallized pure nickel sample. The electron beam scanned vertically from left to the right during EBSD mapping. The maximum drift distances along the y axis are marked in each image. The small rectangles marked by white arrows in (b) and (c) are caused by focusing. Detailed information about the EBSD maps and drift speeds are summarized in Table 1. The dashed line in (b) separates the left 1/5 part of the scanned area from the rest 4/5 of the area. The angles and distances are used to quantify the curved outline of the maps, see text for details.

principles and acquisition time, the same microstructure characterized by EBSD can easily be more distorted than that with ECC/TEM. Consequently, quantitative comparison of some spatial-related microstructural parameters, such as grain shape and size, between the EBSD map and the ECC/TEM image can be difficult and not reliable.

Even more frequently, an EBSD map has to be compared with other EBSD maps of the same series collected during in-situ and ex-situ experiments [18–23]. In these cases, the coordinates in each of the EBSD map can be distorted relatively to others because non-constant drift typically leads to different distortion among the series. For ex-situ EBSD experiments, unavoidable sample misalignment after the sample has been removed from the microscope for processing and remounted in the microscope even further worsens the coordinate distortion. Direct quantitative comparison among the sequential EBSD maps, for example to measure local boundary migration distance during annealing [17], is rather difficult because of the distortion. As a result, although many in-situ and ex-situ studies have been conducted in the last decade, in most cases only qualitative analysis has been reported [18,21–23].

To the knowledge of the authors, no commercial software is available yet to correct the coordinate distortion in the EBSD maps after data acquisition. The aim of the present study is to propose a method to correct the coordinate distortion between true coordinates and recorded coordinates in the EBSD maps after the measurements have been completed. A method called the thin plate spline (TPS) method is chosen for the correction because it is a widely used and powerful method in image processing for correction of nonlinear distortion, such as that shown in Fig. 1. The theory of the TPS method and the correction process are briefly introduced in the next section. Then the method is used to correct an EBSD map in Section 3, and details related to the use of the TPS method are discussed in Section 4.

**Table 1**
Details for the three EBSD maps shown in Fig. 1. The electron beam step sizes used for all these three maps are 200 nm. The drift along the x direction is much smaller than that along the y direction, and is not listed in the table.

| Scan no. | Grid size | Starting time[i] (h) | Scanned period (h) | Maximum deviation along y (μm) | Average drift speed along y (nm/s) |
|---|---|---|---|---|---|
| a | 350 × 350 | 0.5 | 1.75 | 19.3 | 3 |
| b | 600 × 600 | 0.5 | 5 | 5.0/4.4[ii] | 1.4/0.3[ii] |
| c | 350 × 350 | 3 | 1.75 | 1.8 | 0.3 |

[i] Starting time means the time spent from turning the electron beam right after mounting the sample into the microscope until starting the EBSD scan.
[ii] The two numbers are calculated for the left 1/5 part and the rest 4/5 part of the map as separated by the dashed line in Fig. 1b.

## 2. Correction Method

In order to correct for the distortion of the recorded coordinates in an EBSD map, a reference distortion-free image, e.g. an electron channeling contrast (ECC) image (see Section 4.1), that has the same or overlapping contents is assumed to be available. Image registration [24] is then conducted to find a computational way to determine the point-by-point (pixel-by-pixel) correspondence between the EBSD map and the reference image. The image registration is generally carried out in two steps [24]. First, a number of control points (CPs) are selected from the reference image and the EBSD map, and correspondence is established between them. Second, the positions of corresponding CPs in the images are used to determine a transformation function that is in turn used to map the rest of the points in the images. In the present study the CPs are selected manually and their correspondence is automatically established. They are denoted as $(x_i, y_i)$ and $(X_i, Y_i)$ $(i = 1, 2, 3, \ldots, \mathrm{n})$ in the reference image and EBSD map, respectively.

For the second step, many transformation functions can be used. Well-known examples are rotation, translation, similarity, affine, and perspective transformations, which transform images rigidly, i.e. line features in the image are reserved after transformation [24]. The coordinate distortion in the EBSD map is, however, generally nonlinear (see Fig. 1a and b), and nonrigid transformation functions are needed. In nonrigid image registration, thin plate spline (TPS) is a widely used transformation function [24], for example, in the registration of remote sensing images [25] and in the registration of medical images [26]. The TPS is a 2D generalization of the cubic spline, and in its regularized form it includes the affine transformation as a special case [26].

The TPS generally has the following form:

$$f(x,y) = a_1 + a_x x + a_y y + \sum_{i=1}^{n} w_i U(|(x_i,\ y_i) - (x,y)|) \tag{1}$$

where the kernel function $U(\mathrm{r})$ is defined as

$$U(r) = r^2 \log r^2 \tag{2}$$

and $U(0) = 0$. The first three terms in Eq. (1) correspond to the linear part that defines a flat plane that best matches all the CPs, i.e. the affine part. The last term corresponds to the bending forces provided by $n$ CPs with $w_i$ varying for each CP. The unknown coefficients of $w_i$, $a_1$, $a_x$, and $a_y$ are solved based on the coordinates of the two sets of corresponding CPs, $(x_i, y_i)$ and $(X_i, Y_i)$. Details on calculation procedure are presented in Appendix A.

By substituting the calculated values of $w_i$, $a_1$, $a_x$, and $a_y$ in Eq. (1), and scanning the reference image, the pixel to pixel relation from each pixel