Effect of external stress on the orientation distribution of ferrite

J.-H. Kang a, D.-W. Suh b, J.-Y. Cho a, K.H. Oh a, H.-C. Lee a,*

a School of Materials Science and Engineering, Seoul National University, 151742 Seoul, South Korea
b POSCO Technical Research Laboratory, PO BOX 36, Pohang 790785, South Korea

Received 18 May 2002; received in revised form 30 July 2002; accepted 13 August 2002

Abstract

The effect of external stress on the orientation distribution of ferrite during the transformation was examined. Two types of carbon steel were used to evaluate the deviation angle of ferrite from the Kurdjumov–Sachs (K–S) relationship using electron backscattered diffraction. The K–S relationship was weakened when an external stress was applied during the transformation.

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Keywords: EBSD; Carbon steel; Transformation; Stress; Orientation relationship

1. Introduction

When a ferrite grain nucleates at prior austenite boundaries, it forms with a certain orientation to either of the austenite grains. The Kurdjumov–Sachs (K–S) relationship is the mostly cited orientation relationship when ferrite forms by a diffusion process [1]. Due to this orientation relationship with austenite grains, neighboring ferrite nuclei with an identical orientation coalesce during growth and film-like ferrite grains often form at the austenite grain boundaries [2,3]. In our previous work [4], it was reported that the aspect ratio of ferrite grains decreases when an external stress was applied during the transformation. It was thought that an externally applied stress affects the orientation relationship of ferrite with austenite and the coalescence of ferrite grains is suppressed. A finer ferrite grain size resulted in the specimens that transformed under externally applied stress.

In this study, the effect of an external stress on the orientation distribution of ferrite grains formed at prior austenite grain boundaries was investigated in terms of the deviation angle of the ferrite orientations from the K–S relationship. The ferrite, martensite and retained austenite orientations were measured using electron backscattered diffraction (EBSD) technique. Two types of carbon steel with high and low alloy contents were used for this experiment. In the low-alloyed steel, the orientation of austenite was calculated from the orientation of the martensite that formed within the austenite grain as proposed in Ref. [5]. The deviation angle of the ferrite orientation from the K–S relationship was calculated from
the measured ferrite and the calculated austenite orientation. The results were compared with the deviation angles obtained directly from the measured orientation of the retained austenite in the highly alloyed steel.

2. Experimental procedure

The chemical composition of the carbon steels containing a small amount of boron is given in Table 1. Boron retards the pro-eutectoid ferrite reaction at the austenite grain boundaries, which makes it easier to observe the microstructural development at the initial stages of the transformation [6]. A high temperature deformation simulator (THERMAC MASTER Z) was used for the thermo-mechanical processing. The routes for the thermo-mechanical processing are shown schematically in Fig. 1. The specimens were deformed with a reduction ratio of 10% at 700 °C after heating to 1200 °C. For steel A, the deformed specimens were held at 700 °C for 20 s after deformation under stressed or stress free condition for the ferrite transformation. In the case of steel B, the deformed specimens were held at 700 °C for 30 s. The specimens were subsequently held at 400 °C to stabilize the untransformed austenite. In the stressed condition, the displacement of the compression anvil was maintained at the top and bottom surface of the specimens after compression. The compression anvil was removed immediately after compression in the stress free condition. For steel A, the orientations of both the ferrite grains and the martensite packets that formed adjacent to the ferrite grains were measured by EBSD. The deviation angle of the ferrite grain from the K–S relationship was indirectly evaluated from the orientation of the adjacent martensite packets. The orientation of the ferrite grains as well as that of austenite were obtained for steel B. The deviation angle in steel B was calculated directly from the orientation of the retained austenite. The deviation angle of a ferrite orientation from the K–S relationship was evaluated for the two adjacent austenite grains. Of the two deviation angles, the smaller one was chosen as the deviation angle. The detailed procedure used to calculate the deviation angles of the ferrite grains from the K–S relationship is given in Ref. [5].

3. Results and discussion

3.1. Evaluation of the deviation angle from the K–S relationship

It is common in low-alloyed carbon steel (steel A) that the remaining austenite transforms to martensite after quenching to room temperature. Therefore, the orientation of austenite, which is the basis for calculating the deviation angle of ferrite from the K–S relationship, cannot be evaluated directly. It is known that, compared to the diffusion transformed allotriomorphic ferrite grains, martensite has a more rigorous orientation relationship with the mother austenite [7]. Assuming that the orientation of martensite meets the K–S orientation relationship with austenite, Suh et al. [5] proposed a method for evaluating the deviation angle of the ferrite from the K–S rela-

<table>
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<th>Table 1</th>
<th>Chemical composition of the two carbon steels (wt.%)</th>
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<td>Steel</td>
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<tr>
<td>A</td>
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tionship using an EBSD technique in low-alloyed steels. By measuring the orientation of the ferrite grains formed at the prior austenite grain boundaries and those of the adjacent martensite packets formed within the austenite grains, the orientation characteristics of the ferrite grains can be evaluated in terms of the angular deviation of the ferrite orientation from the K–S relationship.

If austenite remains after quenching to room temperature, as in the case of steel B, the deviation angle from the K–S relationship can be calculated directly from the ferrite and austenite orientation. In this case, an EBSD orientation map was used to determine the austenite orientation. The orientation of the nucleated ferrite was selected based on the pattern quality and the overlay of the electron image, because the ferrite and martensite orientations are recognized as a same crystal structure in EBSD.

Fig. 2(a) shows the orientation map of the austenite islands. The orientations of the austenite islands in a prior austenite grain show an almost identical orientation. Nevertheless, austenite orientation in a grain deviates 1–4° from the representative orientation as shown in Fig. 2(b) and (c). The representative orientation of the austenite grain was determined by the arithmetic average in the Euler angles via a cubic symmetry operation. The arithmetic average in the Euler angles is reasonable within the small range of orientations that can be assumed to be linear in Euler space [8]. The transformation strain of martensite is thought to be the main source of the orientation deviation of austenite islands within the austenite grain.

### 3.2. Distribution of the deviation angle of ferrite grains from the K–S relationship

Fig. 3(a) shows the distribution of the deviation angle of ferrite from the K–S relationship in steel A. The broken line in Fig. 3 represents the distribution of the deviation angle for the randomly oriented ferrite grains [5]. If the orientations of the nucleated ferrite grains are well matched to the K–S relationship, the misorientation will be close to zero. Fig. 3(a) shows that the deviation angle of the ferrite from the K–S relationship increases when an external stress is applied during the transformation. The maximum frequency also moves from 0–5° to 5–10° with the application of external stress. This means that the orientation relationship between ferrite and austenite is weakened by the applied external stress. A similar behavior was also observed in steel B, as shown in Fig. 3(b). In this case, where the deviation angle was directly calculated from the representative orientations of austenite, the deviation of the ferrite orientation from the K–S relationship also increases under the stressed condition. Although a different method was used to evaluate the deviation angle for steel A and B, the results are similar in that the deviation of the ferrite orientation from the K–S relationship increases when the transformation occurs under stress. The deviation angle of ferrite grains with other austenite grains was much larger, average of 20–25°, and can be best explained by random distribution. The film-like ferrite grains with a high aspect ratio in Fig. 4(a) changed into round shaped grains with a low

![Fig. 2. (a) Orientation map of austenite, (b) (1 1 1) pole figure of grain A in (a); the white dots means a representative orientation, (c) misorientation distribution with respect to the representative orientation.](image-url)
aspect ratio in Fig. 4(b) when transformed under an external stress. Grain growth within impinged allotriomorphs was reported by Carpenter and Robertson [9]. Slower growth rate is expected from the results of Fig. 3 in the unstressed specimens because of the smaller misorientation between adjacent grains. Much higher nucleation rate in the externally stressed specimens is a necessary to explain the change in ferrite morphology due to applied stress. Recently, Ameyama et al. reported that [3] the film-like allotriomorphs were formed by the coalescence of several ferrite grains of a similar orientation. In this case, if the ferrite orientation deviates more from the K–S relationship under the applied stress, it will become increasingly difficult for the ferrite grains to coalesce into film-like grains. The ferrite grain morphology will change from the film type to polygonal round shape. In other words, an applied external stress can increase the number of ferrite grains at the austenite grain boundaries, even if the nucleation rates are similar. These results suggest that the applied stress during ferrite transformation can play an important role in refining the ferrite grain size during the dynamic transformation of austenite.

4. Conclusions

The effect of external stress on the orientation distribution of the ferrite grains was investigated.
The deviation angle of the ferrite orientation from the K–S relationship increases when the transformation occurs under an external stress. The increase in the deviation angle of ferrite grains from the K–S relationship is thought to make it difficult for the ferrite grains to coalesce during growth and is mainly responsible for the decrease in the aspect ratio of the ferrite grain.

**Acknowledgements**

This work was supported by POSCO and was performed as a part of the project titled “The Development of a High Performance Super Structural Steel for the 21st Century”.

**References**