JOURNAL OF MATERIALS SCIENCE **40** (2005) 903 – 908

The effects of thermal processing in a magnetic field on grain boundary characters of ferrite in a medium carbon steel

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Effects of a magnetic field on low-angle misorientation distribution and CSL boundary occurrence in ferrite in 42CrMo steel during the austenite to ferrite and pearlite transformation were investigated. The results show that a magnetic field can considerably lower the frequency of low-angle misorientations in ferrite lamellae and raise the occurrence of Σ coincidence boundaries, especially $\Sigma 3$ in ferrite. But no obvious effect on crystallographic orientation distribution, or texture, was detected.

1. Introduction

Grain Boundary Design, proposed by Watanabe [1, 2], is an innovative concept to achieve property control of polycrystalline materials. Indeed, grain boundaries are an important factor that affects the properties of polycrystalline materials as recently investigated, for example, experimentally [3] and theoretically [4]. Since the 1980's, the introduction of a magnetic field, especially a high magnetic field, to control the Grain Boundary Character Distribution (GBCD) has aroused much attention. This effect was first investigated experimentally by magnetic annealing of cold-worked ferro-alloys [5–8]. The effects of magnetic field annealing include the enhancement of {100} recrystallization texture component [5], retardation of recrystallization and an increase in the CSL boundary frequency. Quite recently, Watanabe and coworkers [9] enlarged the research scope to include electrodeposited nanocrystalline nickel in order to develop new materials processing routes to control the grain boundary structure. Significant effects have been revealed [9]. Since grain boundary microstructure depends remarkably on materials processing [10], the attempt to apply high magnetic fields during the austenite to ferrite and then pearlite transformation and investigate the effect of magnetic field on the GBCD that develops during this process may provide a new approach for microstructure modification.

Based on this consideration, hot-rolled 42CrMo steel was selected and treated with and without the application of a high magnetic field. The influence of the magnetic field on misorientation distribution and the GBCD in ferrite were investigated.

2. Experimental

The material used in this study was 42CrMo steel with chemical composition (wt%) 0.38–0.45%C, 0.90–1.20%Cr, 0.15–0.25%Mo, 0.20–0.40%Si, 0.50–0.80%Mn, ≤ 0.04%P, ≤ 0.04%S and ≤ 0.30%Cu. Specimens of dimensions 20 mm$\times$10 mm $\times$ 2 mm were cut from a hot-rolled rod with their longitudinal direction parallel to the hot-rolling direction. Heat treatments were carried out with a furnace installed in a 15 T cryocooled superconducting magnet with a bore diameter of 52 mm [11]. The specimens were kept in the central (zero magnetic force) region, with their longitudinal direction parallel to the magnetic field direction. The austenitization process was performed at 880°C for 33 min (Ac3 = 780°C). The specimens were cooled at a rate of 10°C/min. in an external magnetic field of 14 Teslas. For comparison, the heat treatment was also carried out under the same heating and cooling conditions with no field applied.

The above treated specimens were further cut out along their longitudinal direction for optical

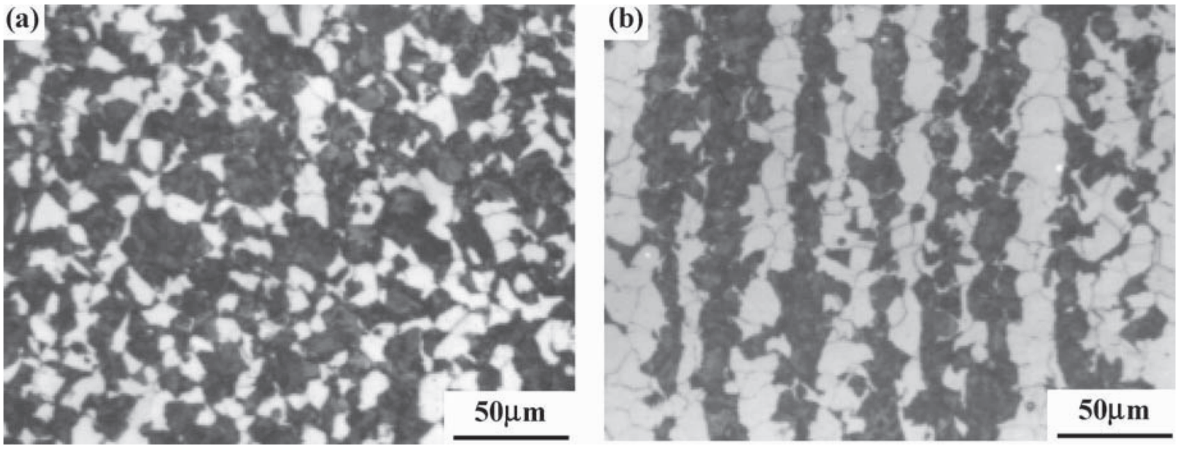

Figure 1 Microstructures of specimens heated at 880°C for 33 min and cooled at 10°C/min without (a) and with (b) the 14 T magnetic field. The hot-rolling direction and magnetic field direction are vertical.

microscopic and SEM observations and EBSD measurements. The morphologies of the as-treated microstructures were examined using optical and electronic (JSM-6500F SEM) microscopy. The EBSD technique was used to examine the misorientation distribution, GBCD and texture of the transformed proeutectoid and eutectoid ferrite. Orientation Imaging Microscopy (OIM) analysis was performed with the same FEG SEM equipped with HKL's Channel 5 software. The 'beam controlled' mode was applied with step sizes of 1 μm and 0.15 μm. The analyzed areas in each sample with the step size of 1 μm covered more than 2000 ferrite grains.

3. Results

Microstructures of the specimens treated without and with the magnetic field of 14 T are shown in Fig. 1. They are all composed of ferrite (bright areas) and pearlite (dark areas) that are nearly equiaxed. The only differences lie in their distributions. Without a field, ferrite grains and pearlite colonies are distributed almost randomly, while with a field, they are distributed in stripes along the direction of the magnetic field. This phenomenon has been analyzed elsewhere [12]. Fig. 2 shows the lamellar structure of the pearlite obtained without and with the magnetic field. In each pearlite colony, ferrite (dark areas) and cementite (bright areas) lamellae are distributed alternately. In the magnetic field cooled specimen, the mean inter-lamellar spacing of ferrite and cementite is evidently larger than that obtained without field (see Fig. 2).

The misorientation angle distribution of boundaries in the ferrite and the corresponding OIM maps of the specimens treated without and with the magnetic field are shown in Figs 3 and 4, respectively. For comparison, the misorientation distribution of a randomly oriented polycrystal is also displayed in Fig. 3. It is seen that in Fig. 3, the frequency of low-angle misorientations ($<15°$) is considerably lower in the specimen cooled with the magnetic field. The locations of these low-angle boundaries (from 1° to 15°) are displayed as thin black lines and the high-angle misorientations ($>15°$) are displayed as thick white lines in the OIM maps in Fig. 4. It is seen that most of these low-angle misorientations are congregated within clusters enclosed by high angle boundaries (thick white lines in the pictures). The zoom image in the top right corner in each map shows that the distribution of low-angle misorientation in each cluster is denser without a field than with a field. The lamellar structure in the pearlite colonies is not visible as the resolution of EBSD measurement

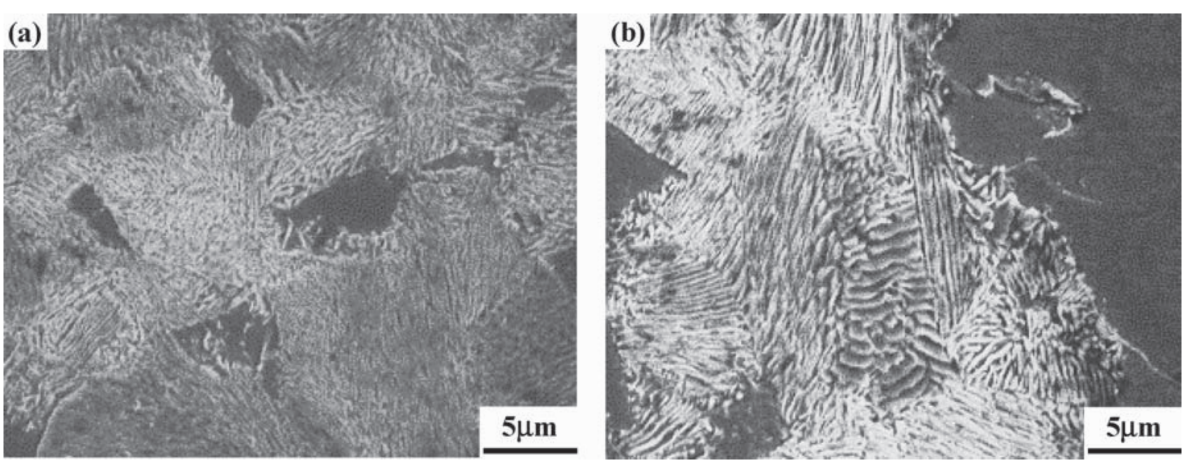

Figure 2 SEM secondary electron micrographs of pearlite colonies obtained without (a) and with (b) the 14 T magnetic field. The hot-rolling direction and magnetic field direction are vertical.

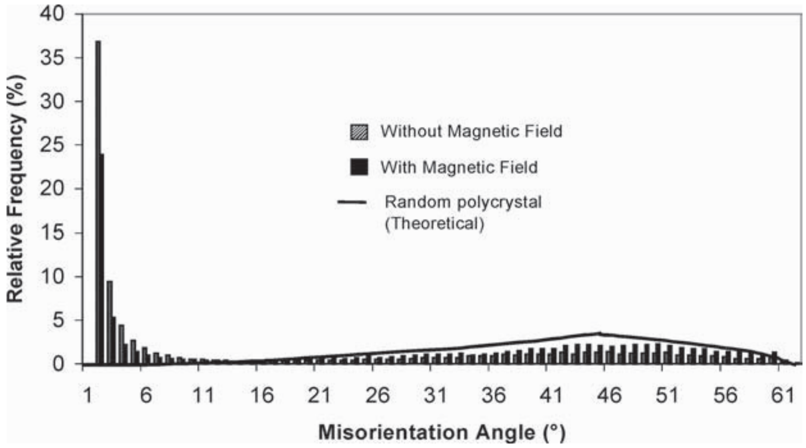

Figure 3 Misorientation angle distribution of specimens heated at 880°C for 33 min and cooled at 10°C/min without and with the 14 T magnetic field.

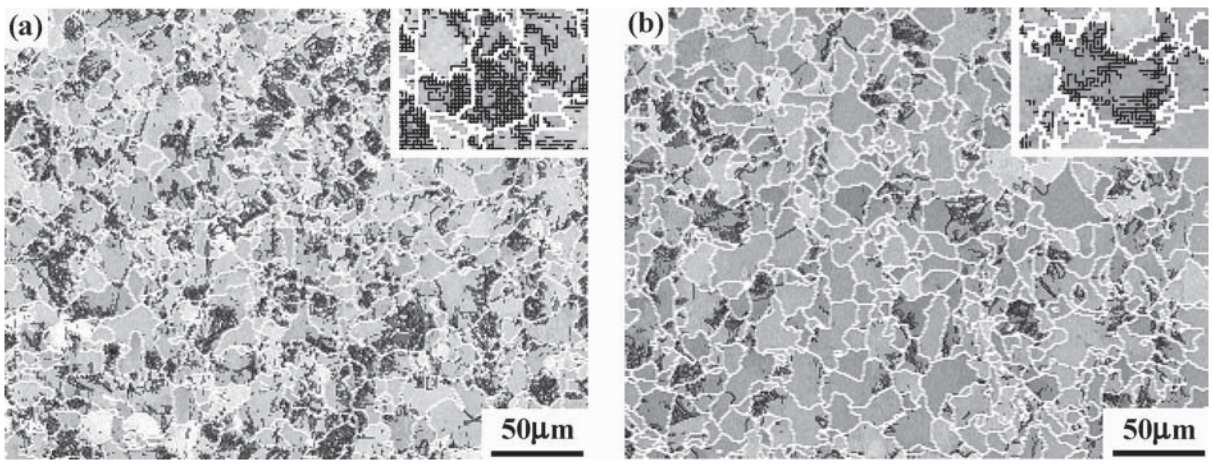

Figure 4 OIM maps of specimens heated at 880°C for 33 min and cooled at 10°C/min without (a) and with (b) the 14 T magnetic field. The hot-rolling direction and magnetic field direction are vertical. The zoom image in the right corner of each picture shows the detailed locations of low-angle (from 1° to 15°) and high-angle (>15°) misorientations. The magnification is twice that of the main map. Step size: 1 μm.

is not high enough to identify cementite. Instead, each pearlite colony is simply identified as one ferrite grain as all its ferrite lamellas have misorientations lower than 15°. Fig. 5 shows the CSL boundary distribution in the specimens cooled without and with the magnetic field. For comparison, the frequencies of CSL grain boundaries in a random polycrystal [13] are also plotted. It is seen that the magnetic field can considerably increase the occurrence of low Σ (Σ1–Σ29) boundaries, especially the Σ3 boundaries. This finding is largely consistent with the results found in magnetic field annealed nanocrystalline nickel [9] and Fe-9at%Co alloy [6] by Watanabe and co-workers. The corresponding locations of Σ3 boundaries are shown with black lines in Figs 6 and 7. Fig. 6 shows that without a field, although the length of Σ3 boundaries are inhomogeneous, most are obviously shorter than that obtained with field. The high magnification map in Fig. 7 shows that these Σ3 boundaries are located along both equiaxed ferrite grain boundaries (indicated by the hollow arrow) and pearlite colony boundaries[1] (indicated by the solid arrow).

[1] Although the lamellar cementite is not identified through indexing of the measured Kikuchi patterns, the band contrast of the OIM map obtained at small step size (0.15 μm) can display some parts of the lamellar structure of pearlite.

The pole figures of the specimens treated with and without the field are shown in Fig. 8. It is seen that the crystallographic orientation of the two specimens are random despite the fact that the easiest magnetization direction of ferrite is ⟨001⟩.

4. Discussion

For fully austenitized 42CrMo, austenite transforms first to equiaxed ferrite (called proeutectoid ferrite) between the Ar_3 and Ar_1 temperatures and then to pearlite (consisting of alternately distributed eutectoid ferrite and cementite lamellae) below Ar_1 during subsequent slow cooling. For hypoeutectoid steels, eutectoid ferrite forms ahead of eutectoid cementite. The lamellar spacing of pearlite is temperature dependent. High temperature results in the increase of the mean inter-lamellar spacing, as high temperature promotes carbon diffusion and increases its diffusion length.

The application of the magnetic field shows the effect of decreasing the frequency of low-angle boundaries (<15°), as seen in Fig. 3. Their congregated locations within colonies contoured by high-angle boundaries may be related to pearlite colonies. It is clearly seen in the zoom images in Fig. 4 that without a field, those low-angle misorientations are distributed more

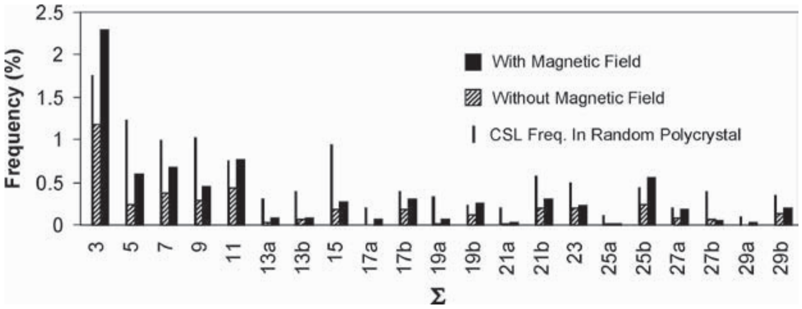

Figure 5 Distribution of CSL boundaries in specimens heated at 880°C for 33 min and cooled at 10°C/min without and with the 14 T magnetic field.

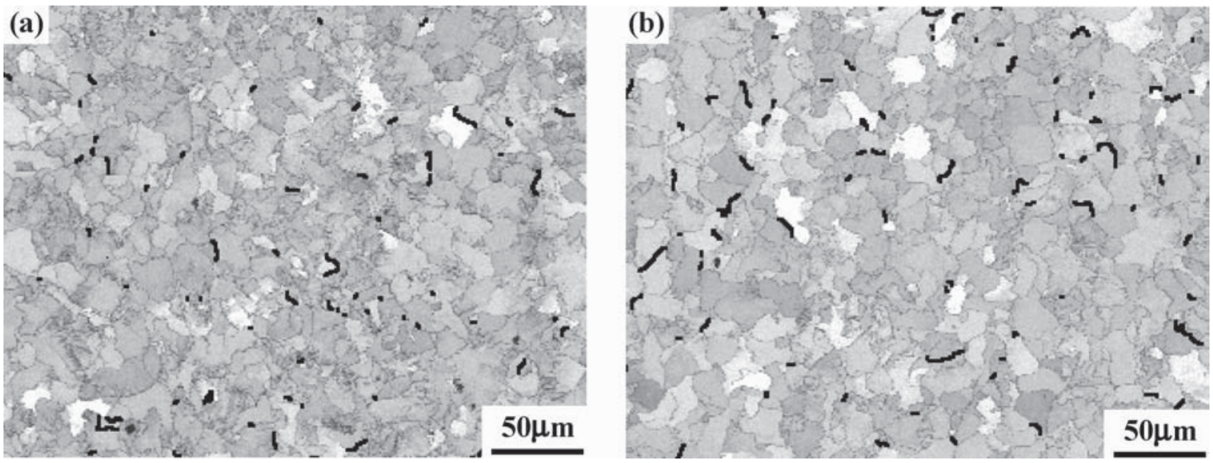

Figure 6 OIM maps of specimens heated at 880°C for 33 min and cooled at 10°C/min without (a) and with (b) the 14 T magnetic field. The black lines display the Σ3 boundaries. The hot-rolling direction and magnetic field direction are vertical. Step size: 1 μm.

Figure 7 Detailed locations of Σ3 boundaries. (OIM map of specimens heated at 880°C for 33 min and cooled at 10°C/min with the 14 T magnetic field. The magnetic field direction and hot-rolling direction are vertical in this picture. Solid arrow: pearlite boundary; hollow arrow: proeutectoid ferrite boundary. Step size: 0.15 μm.

densely than with a field. Correspondingly, in Fig. 2, the inter-lamellar spacing of pearlite obtained without a field is smaller than with a field. These two tendencies are consistent with each other. This indicates that these low-angle misorientations are from lamellar ferrite in pearlite. However, the total amount of areas densely covered with low-angle misorientations (or pearlite colonies) in the OIM maps is obviously less than the total amount of areas of pearlite displayed in Fig. 1. This suggests that in many cases, ferrite lamellae from the same pearlite colony have misorientations less than 1°. Therefore, the magnetic field shows a clear effect of reducing the amount of pearlite colonies in which the misorientation between neighboring ferrite lamellae are larger than 1°, compare Fig. 4a and b.

As the product of transformation from austenite to pearlite includes two phases (ferrite and cementite) with different carbon contents and different crystal structures, the transformation introduces different volume changes of these two phases and creates transformation stresses. This stress is pronounced when the cementite lamellae are alternately embedded in the eutectoid ferrite and can only be released through deformation of ferrite lamellae (since cementite is much harder than

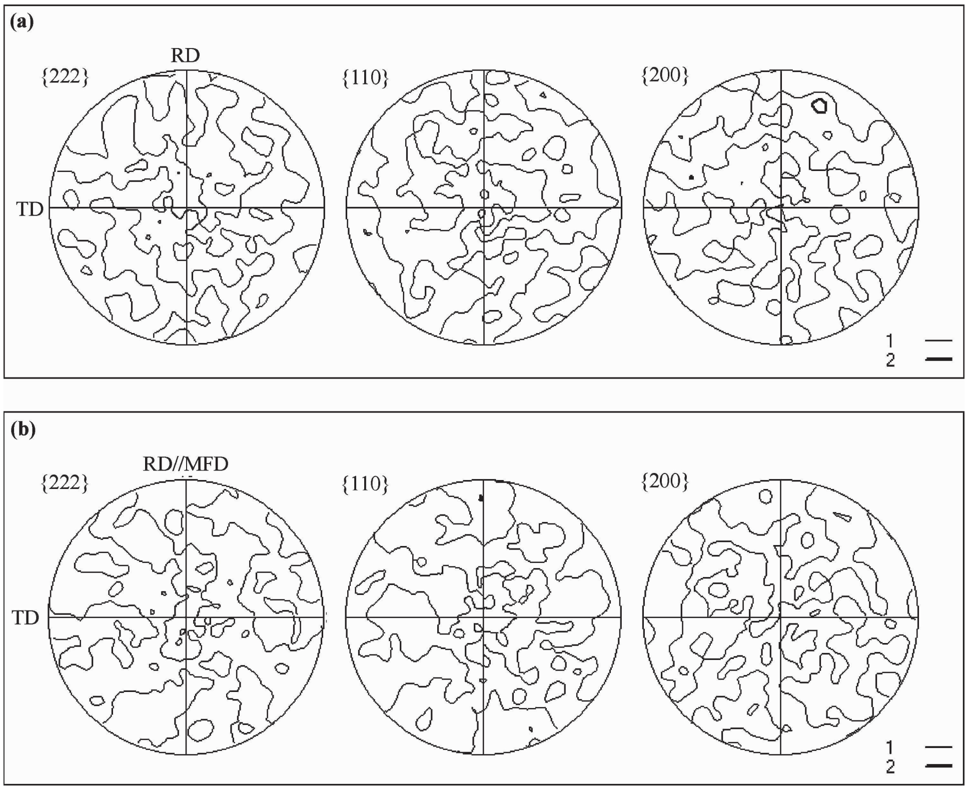

Figure 8 Pole figures of the specimens treated (a) without and (b) with the 14 T magnetic field. The magnetic field direction is parallel to rolling direction.

ferrite). The low-angle misorientations between ferrite lamellae originate mainly from this transformation stress. The transformation stress is also temperature dependent, and decreases with increasing temperature. As the transformation occurs during continuous cooling, only the pearlite forming at relatively low temperatures are subject to sufficient stress to deform, while those forming at high temperatures do not deform (as the stress level is too low).

As reported in [14], the magnetic field can considerably increase the eutectoid temperature in Fe-C binary system. Our calculations [12] showed an increase of 40 to 45°C. Then, the whole pearlite transformation shifts to the higher temperature range by the magnetic field. This temperature increase can be reflected in the larger inter-lamellar spacing of pearlite obtained under field in Fig. 2b. As a consequence, fewer ferrite lamellae undergo this deformation and create low-angle misorientations.

The application of a magnetic field also has a considerable effect on the occurrence of coincidence boundaries as shown in Fig. 5. It increases the frequency of low Σ boundaries, especially $\Sigma3$. It is known that different types of grain boundaries have different energies and mobilities. The random high-angle boundaries have high energy and high mobility [15], while some low Σ boundaries, especially $\Sigma3$ boundaries, have low energy and low mobility [1]. For grains with different types of boundaries, the growth through boundary migration will lead the lower mobility types to enlarge their boundary areas while the high mobility types to shrink, as schematically illustrated in Fig. 9. Hence, after growth, the proportion of low mobility boundaries increases. Results reported in [14] also show that in addition to the eutectoid temperature, the magnetic field can also increase the Ae_3 or austenite to proeutectoid ferrite transformation temperatures. The increase is even larger than for eutectoid temperature and amounts to 50°C as calculated in [12]. Therefore under the influence of a magnetic field, both proeutectoid and eutectoid ferrite undergoes a wider temperature range for growth. As a result, the portion of low Σ boundaries, especially $\Sigma3$ obtained under magnetic field is increased.

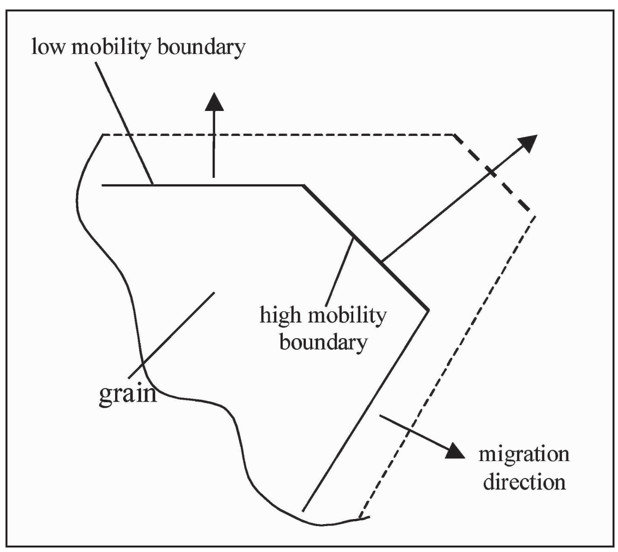

Figure 9 Schematic illustration of surface changes of different types of grain boundaries through migration at different velocities. Solid line: before migration; dashed line: after migration.

In this case, the occurrence of Σ boundaries shown in Fig. 5 is increased by enlarging their boundary surface, as seen by comparing Fig. 6b with a.

Although the easiest magnetization crystallographic direction of ferrite is ⟨001⟩ and the proeutectoid ferrite tends to align them to the field direction, no preferential crystallographic orientations were detected in the magnetic field treated specimen. This may be due to the quick saturation of magnetization in crystallographic directions at very low field [16] as opposed to the high field applied in this work. There is no evident directional effect of the magnetic field on the misorientation distribution and the frequency of coincidence boundaries along the magnetic field direction.

5. Conclusion

1. A magnetic field can considerably decrease the occurrence of low-angle misorientations between eutectoid ferrite lamellae in pearlite colonies. This is consistent with the increasing eutectoid transformation temperature to reduce the transformation stress.

2. A magnetic field can strongly increase the frequency of Σ3–29 coincidence boundaries, especially Σ3 boundaries, in the ferrite. This probably occurs through selective area enlargement of low mobility boundaries during the growth stage. There is no obvious directional effect of field on crystallographic orientation distribution.

Acknowledgments

This study was financially supported by the key project of National Natural Science Foundation of China (Grant No. 50234020), the National High Technology Research and Development Program of China (Grant No. 2002AA336010), the National Science Fund for Distinguished Young Scholars (Grant No. 50325102) and the TRAPOYT in Higher Education Institutions of MOE, P.R.C.

The authors also gratefully acknowledge the support obtained in the frame of the Chinese-French Cooperative Research Project (PRA MX00-03).

The authors would like to thank the High Magnetic Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University, for the access to the magnetic field experiments

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