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# THE EFFECT OF ELECTROMAGNETIC PROCESSING ON GRAIN BOUNDARY CHARACTERISTICS AND TEXTURE IN A MEDIUM CARBON STEEL[1)]

# WPŁYW ELEKTROMAGNETYCZNEJ OBRÓBKI NA TEKSTURĘ I CHARAKTERYSTYKI GRANIC ZIARN W STALI ŚREDNIOWĘGLOWEJ

A 12-T magnetic field has been applied to the austenite to ferrite and pearlite transformation of a forged medium plain carbon steel. The effects of the high magnetic field on misorientation angle frequencies, grain boundary characteristics and texture formation in ferrite have been investigated. Results show that the high magnetic field can considerably decrease the frequency of low-angle misorientations and increase the occurrence of low Σ coincidence boundaries, especially Σ 3 of ferrite. This may be attributed to the elevation of the transformation temperature by the magnetic field and the reduction of the transformation stress. The larger temperature range for grain growth allows the less mobile Σ boundaries to have longer time to enlarge their areas. Moreover, the magnetic field can slightly enhance the <001> fiber component along the transverse field direction (TFD).

*Keywords*: EPM-electromagnetic processing of materials; phase transformation; misorientation, coincidence site lattice (CSL) boundary; texture.

Dla próbek stali kutej średnio węglowej zastosowano przy transformacji z austenitu w ferryt i perlit, pole magnetyczne o indukcji 12-t. Badano wpływ pola magnetycznego na rozkład częstości kąta dezorientacji, charakterystyki granic ziarn i formującą się teksturę w ferrycie. Wyniki pokazują, że silne pole magnetyczne może znacząco obniżać częstości niskokątowych dezorientacji oraz powodować wzrost udziału granic koincydencyjnych o niskich Σ, szególnie granic Σ3 w ferrycie. Może to być powodowane wzrostem temperatury transformacji pod wpływem pola magnetycznego i obniżeniem naprężeń wywoływanych transformacją. Większy zakres temperatury dla rozrostu ziarn daje mniej ruchliwym granicom Σ więcej czasu na powiększenie swych obszarów. Dodać należy, że pole magnetyczne wywołać może nieznaczny wzrost udziału składowej włóknistej < 001 > wzdłuż kierunku poprzecznego pola.

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[1)] invited lecture

## 1. Introduction

Since 1980s, the introduction of a magnetic field, especially high magnetic field, to control grain boundary character distribution and textures of materials has received much attention from the area of materials science and engineering. The issue was first investigated experimentally in the cold rolled steels after magnetic field annealing [1–4]. It has been found that the magnetic field can enhance the < 001 > component in the field direction (< 001 > direction is the easy magnetization direction of iron and steels); retard the recovery and recrystallization processes and increase the occurrence of low Σ CSL boundaries. Later, Watanabe and coworkers [5] has enlarged the scope to the magnetic field annealing of electrodeposited nanocrystalline nickel. They found that the magnetic annealing enhanced grain growth at the early stage of annealing and increased the frequencies of low Σ CSL (Coincidence Site Lattice) boundaries. However they did not find the enhancement of the < 111 > component as they expected because the < 111 > direction is the easiest magnetization direction of the material. It appears that for different initial state of the treated materials, the magnetic field shows different effects. So far, the influence of the magnetic field on grain boundary character distribution (GBCD) and texture in steels undergoing a phase transformation from austenite to proeutectoid ferrite and pearlite has seldom been reported. Study on this aspect is surely helpful for gaining a better understanding of the influential mechanisms of the magnetic field.

Based on this background, a hot-forged medium plain carbon steel was selected and heat-treated without and with the application of a high magnetic field. The influence of the magnetic field on misorientation angle distribution, CSL boundary occurrence and texture of the product ferrite was investigated.

## 2. Experimental

The chemical composition of the medium plain carbon steel used in this study is given in Table 1. Specimens of dimensions 30mm× 10mm×2mm were cut from the hot forged bars of an ingot cast with an induction furnace, with their longitudinal direction either parallel or perpendicular to the deformation direction, respectively. They were first water quenched after fully austenitized at 860°C to refine the microstructure. Then they were re- austenitized at 870°C for 10 min and cooled at a rate of 23.5°C/min without and with a 12-Tesla high magnetic field. When the magnetic field was applied, the field was oriented either parallel or perpendicular to the deformation direction of the specimens. The specimens were placed in the central (zero magnetic force) region.

The above treated specimens were further cut out along their longitudinal direction for further analysis. The transformed microstructure is observed with a JEOL JSM 6500F SEM. The orientation imaging microscopy analysis was performed with the same FEG SEM equipped with the HKL's Channel 5. The 'beam controlled' mode was applied with a step size of 0.4$\mu$m. Three different areas were selected on each sample

TABLE
Chemical composition of the medium plain carbon steel (wt.%)

| C | Si | Mn | Cr | P | S | Fe |
|---|---|---|---|---|---|---|
| 0.49 | 0.027 | 0.074 | 0.24 | 0.0093 | 0.0086 | Bal. |

and the total area analyzed covered more than 2000 ferrite grains and pearlite colonies to obtain a statistical representation of the results. The microstructure, misorientation angle distribution, CSL boundary occurrence and texture were analyzed.

## 3. Results

The microstructures of the specimens cooled at 23.5°C/min without and with a 12-T magnetic field are shown in Fig. 1. The microstructures in both cases consist of proeutectoid ferrite and pearlite. The applied magnetic field did not exert much

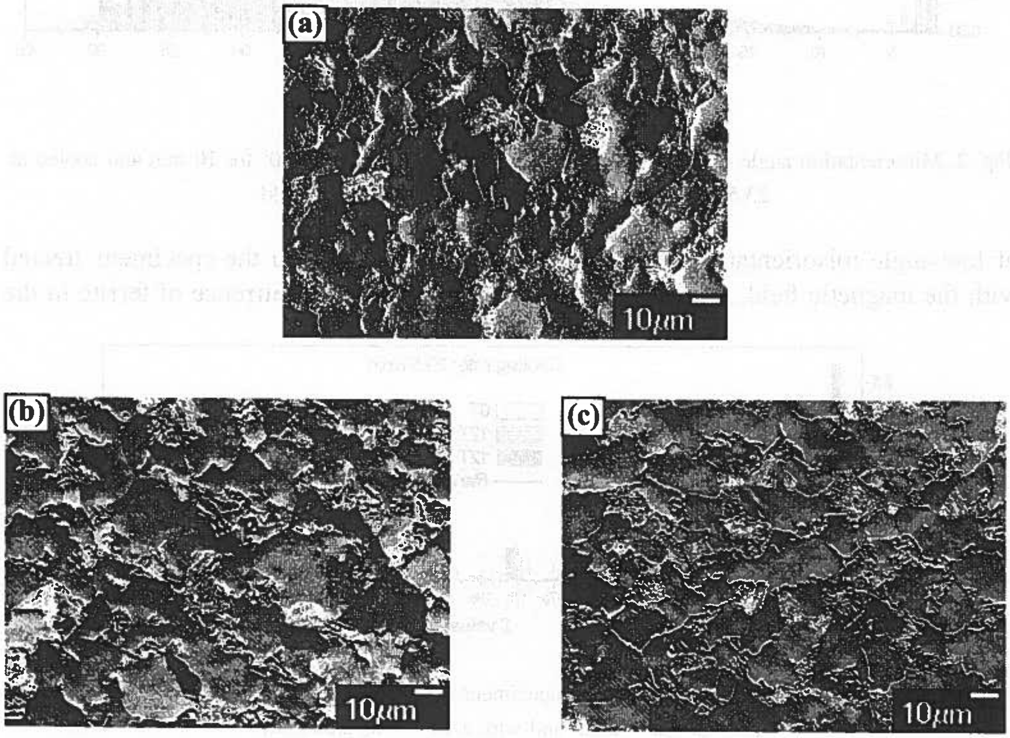

Fig. 1. SEM secondary electron micrographs of specimens austenitized at 870°C for 10 min and cooled at 23.5°C/min without and with a 12-T magnetic field. The equiaxed grain areas are proeutectoid ferrite grains and the lamellar areas are pearlite. The deformation direction (DD) is horizontal. (a) 0T; (b) 12T The Field Direction (FD)//DD; (c) 12T FD⊥DD

influence on the morphologies of the product phases. There is no aligned microstructure appearing either along the previous deformation direction or the magnetic field direction as observed in other steels subject to austenite decomposition under a high magnetic field [6–8].

The misorientation angle distribution of the both the proeutectoid ferrite and the eutectoid ferrite of the specimens treated without and with the magnetic field is shown in Fig. 2. For comparison, the misorientation angle distribution in a random cubic polycrystal is also displayed in Fig. 2. It is seen that, as a whole, the frequencies of low-angle misorientations (2-10°) are considerably lower in the specimens treated with the magnetic field. Figure 3 shows the CSL boundary occurrence of ferrite in the specimens treated without and with the magnetic field. For comparison, the frequencies of CSL boundaries in a random polycrystal [9] are also plotted. It is seen that the magnetic field can considerably increase the occurrence of low Σ (Σ3 — Σ29) boundaries, especially the Σ3 boundaries. This finding is largely consistent with the results found

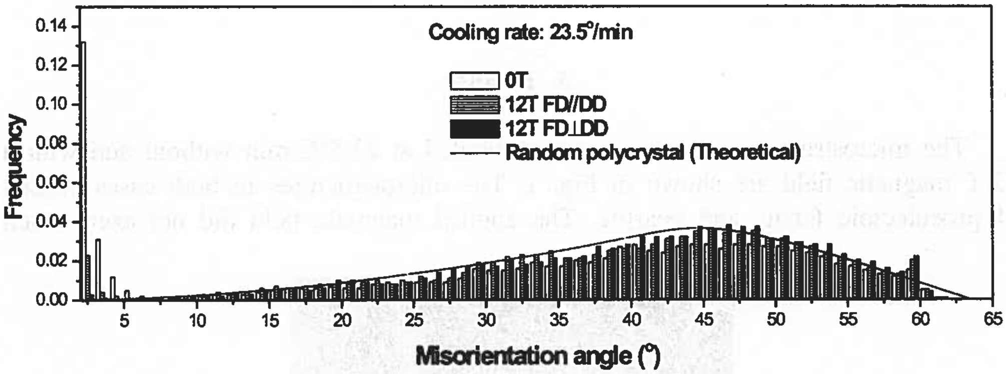

Fig. 2. Micorientation angle distribution of ferrite in specimens eated at 870° for 10 min and cooled at 23.5°C/min without and with a 12- T megnetic field

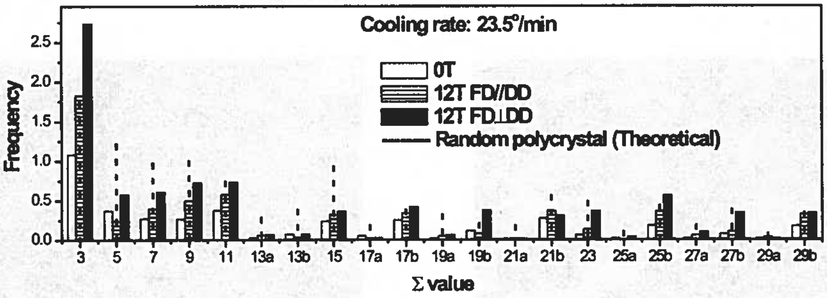

Fig. 3. Frequencies of CLS boundaries in specimens heated at 870°C for 10 min and cooled at 23.5°C/min without and with a 12-T magnetic field

in the magnetic field annealed nanocrystalline nickel [5] and Fe-9at%Co alloy [2] by Watanabe and co-workers. The corresponding locations of Σ3 boundaries, as an example, are shown with green lines in Fig. 3. It can be seen that without field, although the length of Σ3 boundaries are inhomogeneous, most are obviously shorter than that obtained with the field.

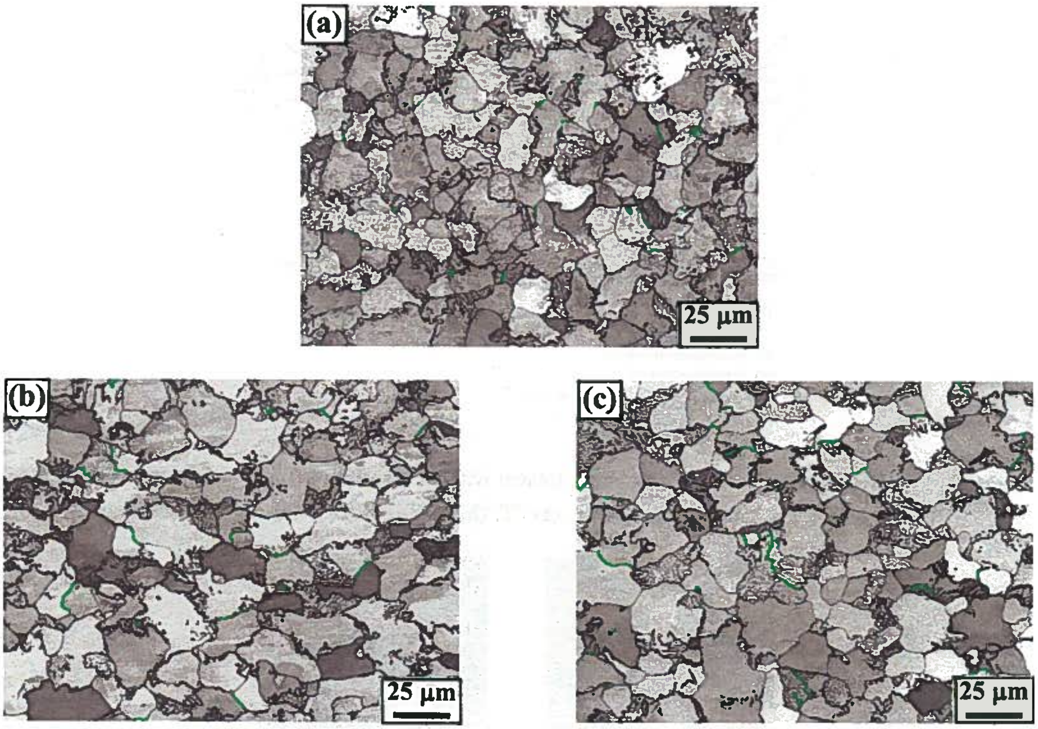

Fig. 4. Orientation maps of specimens heated at 870°C for 10 min and cooled at 23.5°C/min without and with a 12-T field. The deformation direction (DD) is horizontal. (a) 0T; (b) 12 T, FD//DD; (c) 12 T, FD⊥DD. Green lines display the Σ3 boundaries

The inverse pole figures of the specimens treated without and with the magnetic field are shown in Fig. 5 along with the corresponding sample coordinates. It is seen that there is a slight enhancement of the < 001 > fiber texture component along the transverse field direction (TFD) under the magnetic field whatever the orientation of the field with respect to the previous deformation direction is.

The corresponding <001> grains colored in red are shown in Fig. 6. By comparing respectively Fig. 6 (a) with (b) and Fig. 6 (c) with (d), it is seen that magnetic field enlarges the red TFD < 001 > grains. This suggests that the < 001 > fiber might be related to the preferential growth of those grains.

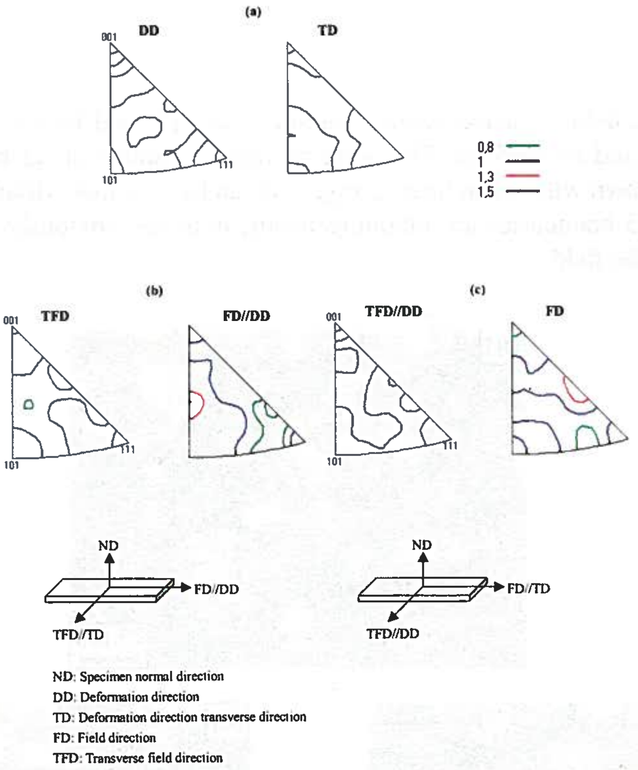

Fig. 5. Inverse pole figures of the specimens treated without and with a 12- T magnetic field and the corresponding sample coordinates. (a) 0T; (b) 12 T, FD//DD; (c) 12 T, FD⊥DD

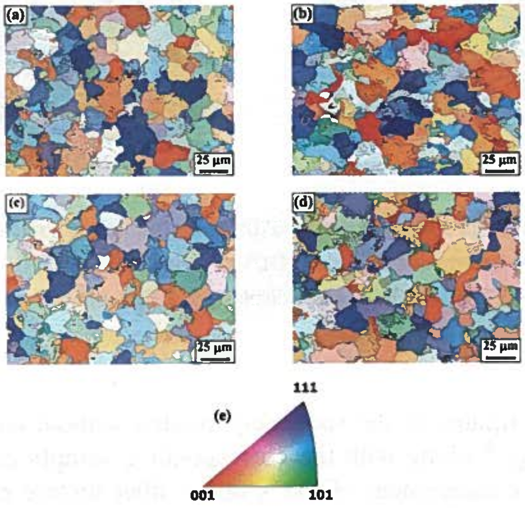

Fig. 6. Orientation maps of specimens heated at 870°C for 10 min and cooled at 23.5°C/min without and with a 12-T magnetic field showing the crystallographic orientation of ferrite grains by colors. The deformation direction is horizontal. (a) 0T, red: <001>//TD; (b) 12T, red: <001>//TD or TFD (c) 0T, red: <001>//DD; (d) 12T, red: <001>//DD or TFD; (e) Color code

## 4. Discussion

For fully austenitized medium carbon steels, 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 the subsequent cooling. Given the same amount of atoms, the volume of bcc ferrite is larger than that of fcc austenite. This gives rise to transformation stress and then strain. The transformation stress is temperature dependent. It increases with the decreasing transformation temperature. This stress will further be aggravated by austenite to pearlite transformation, as this transformation involves the formation of two phases with different volume change and hardness. When it accumulated to sufficient extend, it will be released through the deformation of the product ferrite, as the hard cementite has no capacity of deformation. Therefore, the low angle misorientations are related to this transformation strain.

The reduction of those low angle misorientations by the application of the magnetic field may be related to the influence of the magnetic field on the transformation temperature. It has been well clarified that the magnetic field can increase the Ae3 temperatures and hence Ae1 temperatures of steels [10, 11]. Therefore the practical transformation temperatures of Ar3 and Ar1 under different cooling conditions will also be shifted to the higher temperature range. In this way, the formation of both proeutectoid and eutectoid ferrite occurs in a higher temperature range due to the presence of the magnetic field and thus the transformation stress is reduced. As a result, the amount of low angle misorientations is decreased.

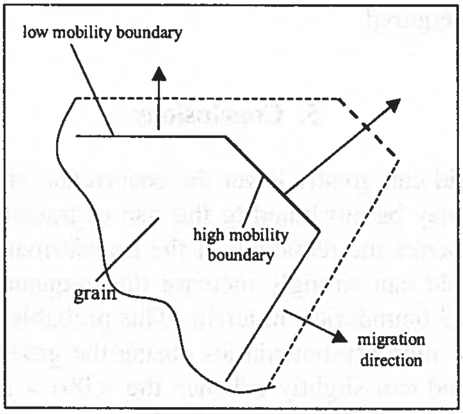

Fig. 7. Schematic illustration of surface changes of different types of grain boundaries through migration at different velocities. Solid line: before migration; dashed line: after migration [13]

The fact that the applied magnetic field increases the frequencies of low Σ boundaries, especially Σ3, is also related to the same influence of the magnetic field on transformation temperature. It is known that different types of grain boundaries have different energies and mobility. The random high-angle boundaries have high energy and high mobility, while some low Σ boundaries, especially Σ3 boundaries, have low energy and low mobility [12]. For grains with different types of boundaries, the growth through boundary migration will cause the low mobility types to enlarge their boundary areas while the high mobility types to shrink, as schematically illustrated in Fig. 7 [13]. Hence, after growth, the proportion of low mobility boundaries increases. As the magnetic field can obviously increase the transformation temperature, both the proeutectoid and eutectoid ferrite grow within a wider temperature range. Consequently, the portion of low Σ boundaries, especially Σ3, obtained under the magnetic field is increased. In this case, the higher occurrence of Σ boundaries shown in Fig. 3 is related to the enlargement of their boundary areas, as seen by comparing Fig. 4 (b) and (c) with (a).

The applied magnetic field also enhances the <001> fiber texture component along the transverse field direction (TFD), as seen in Fig. 5, regardless the orientation of the field with respect to the former deformation direction. By comparing respectively Fig. 6 (b) with (a) and (d) with (c), it is seen that the magnetic field slightly enlarges grains whose <001> direction is parallel to the TFD. This suggests that the enhancement of the <001> fiber component be attributed to the preferential growth of these grains. This result is quite different from the result found in the magnetic field annealed cold-rolled steels. In those cases, the enhancement of the <001> component is along the field direction [1–4]. The magnetic field showed an effect on promoting the growth of grains with their easy magnetization direction <001> parallel to the field direction [1]. However, in the present study, the enhancement of <001> component appears in the TFD, which suggests that the field affects in a different way. To clarify the effect further investigation is required.

## 5. Conclusions

1. The magnetic field can greatly lower the occurrence of the low angle misorientations of ferrite. This may be attributed to the rise of transformation temperature by the magnetic field and hence the reduction of the transformation stress.
2. The magnetic field can strongly increase the frequency of Σ3-29 coincidence boundaries, especially Σ3 boundaries, in ferrite. This probably occurs through selective area enlargement of low mobility boundaries during the growth stage.
3. The magnetic field can slightly enhance the <001> texture component along the transverse field direction (TFD). This results from the preferential growth of grains with their <001> parallel to the TFD.

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