Abstract

This paper intends to study an effect of strain and stress on static recrystallization. The result is expected to be used for a new thermo-mechanical control process (TMCP) that enables us precise control of microstructure distribution in a steel plate. In the TMCP, the strain energy by plastic deformation and the thermal energy by heat treatment lead to recrystallization and grain growth in a material, which improve the microstructure of the material. Among various metallurgical technology, TMCP is one of promising method to improve the material properties. In this paper, repeated shear strain is applied to the specimen by the press machine, which accumulates the strain energy in the grains in the clearance. By applying heat treatment, it is expected that the strain energy induces recrystallization, which results in refinement of grains. Effects of stress vibration condition and heat treatment condition on recrystallization are also studied by EBSD analysis.

1. Introduction

Recent years, it have been strongly demanded to improve material properties of conventional metallic materials due to severe requirements for energy saving and resource saving. Among various metallurgical technology, the thermo-mechanical control process (TMCP) is one of promising method to improve the material properties. Many high performance steels, such as high tensile strength steel [1], ultrafine grain steel and magnetic steel sheet [2], were developed by TMCP.
Those conventional TMCP steels have been developed for the rolling process. Although the rolling process is advantageous for mass production of large sheet steels, it cannot control spatial distributions of the microstructure, such as grain size and crystal orientation, in a product [3]. In order to overcome the limitation of a TMCP by the rolling process, the author is aiming to develop a sheet forming process for a new TMCP, which can apply shear strain at arbitrary position.

In this study, as for the first step to the goal, effects of repeated shear strain and post annealing on microstructure change were studied. A new apparatus for the sheet forming experiment was developed. A pure iron sheet was used as a work material, and change of the microstructure by the sheet forming was studied by EBSD analysis.

2. Experimental procedure

Fig. 1(a) shows the experimental apparatus to apply shear stress to a plate specimen. It consists of a frame, a die set, a loading screw, and a piezo actuator. The piezo actuator is installed on the end of the screw in order to arise vibration to the die set. The die set consists of a punch and a die. A plate specimen is placed between the die and the punch as shown in Fig. 1(b). There are clearances of 0.1 mm between the punch and the die at the both side of the punch edge.

The specimens were made from a pure iron sheet of 1 mm in thickness. It was cut into the size of 3 x 10 mm. The specimens were subjected to strain relief annealing at 700 °C for 60 min using an electric furnace. Press load is added by tightening the loading screw, and it causes shear stress to a specimen in the clearance of the punch and the die. The piezo actuator causes vibration of punch load at 5 Hz, which results in vibration of shear stress in the specimen. After a specimen is initially loaded by 250 N, vibration is applied by the piezo actuator. Repeat counts of shear strain vibration are 1 time and 18000 times. Fig. 2 illustrates an example of stress vibration in an experiment. $\sigma_a$ is average shear stress, and $\sigma_s$ is amplitude of shear stress. Table 1 shows experimental conditions for each specimen.

| Specimen A | - | - | - |
| Specimen B | 250 N | 1 | - |
| Specimen C | 250 N | 18000 | - |
| Specimen D | 250 N | 18000 | 600°C |
| Specimen E | 250 N | 18000 | 600°C |
| Specimen F | 250 N | 18000 | 800°C |
| Specimen G | 250 N | 18000 | 800°C |

Fig. 2. Variation of repeated shear stress.
After shear stress was applied, the specimen was annealed at 600, 700, 800 and 900 °C for 60 min in Ar gas atmosphere. In the furnace, the specimen was heated quickly, and kept constant for predetermined time, and then cooled down quickly by blowing cold Ar gas to the specimen. The cross sections of the specimens were polished with colloidal silica slurry as shown in Fig. 3(a). Then, their microstructures were analysed by EBSD. The directions of ND, RD, and TD in Fig. 3(b) are the coordinate system defined for EBSD analysis.

3. Influence of vibration conditions

Fig.4 shows (a) the image quality (IQ) map, (b) the crystal difference map, and (c) the inverse pole figure map (IPF map) of an annealed specimen A. An IQ value indicates measurement reliability in the EBSD analysis. Dark area in IQ map indicates a low IQ value, which represents distortion of crystal lattices. The crystal difference map shows the deviated angle of the <111> crystal orientation of each grain from the RD direction. The IPF map indicates crystal planes observed from the RD direction by the colour of the standard triangle of the inset. From Fig. 4, it is confirmed that grain size was about 200-500 μm, and no distortion is observed in the grains.

Fig. 4. EBSD data of the specimen A after strain release annealing.

Fig. 5. EBSD analysis data of a specimen B that shear stress is applied one time. \( \sigma_c = 51 \) MPa, \( \sigma_s = 80 \) MPa.
Fig. 5 shows (a) the IQ map, (b) the crystal difference map and (c) the IPF map of a specimen B, on which shear stress was added only one time. $\sigma_s$ was 51 MPa, and $\sigma_s$ was 81 MPa. In (a) the IQ map, it is observed that the IQ values distribute in the grains. This indicates that crystal lattices were distorted, and that dislocations were accumulated in the grains. Strain energy is stored in the dislocations. It is also found in the (b) the crystal difference map that the deviation of grain orientations is large, and the deviation angle distribute in the range up to 50 degrees. This indicates that a crystal orientation is random. (c) The IPF map also does not show any oriented crystal structure.

Fig. 6 shows EBSD data around the sheared zone in a specimen C that repetition of shear stress was applied for 18000 times. In the magnified figure of the IQ map, the distribution of IQ values is observed in each crystal grain. It is more apparent than that in Fig.5. This indicates that dislocation is accumulated more than in the specimen of Fig.5. This is attributed to stress repetition applied to the specimen. It is known that strain energy stored in the dislocation induces recrystallization. In the meantime, the distribution of deviation angles seen in (b) is smaller than 20 degrees. Also, it is found in (c) that crystal orientations are concentrated around the $<111>$ orientation in the most of the sheared zone. However, these trends are incidental, and data of other specimens tested under the same conditions exhibited more random distribution of crystal orientations.

Fig. 6. EBSD analysis data of a specimen C that shear stress is repeated for 18000 times. $\sigma_s = 29$ MPa, $\sigma_s = 59$ MPa.

4. Influence of annealing temperature

Fig. 7 shows EBSD data around the sheared zone in two specimens that were annealed at 600 ºC for 60 min after repetition of shear stress for 18000 times. Both specimen D and specimen E were tested under the same condition. In the specimen D (the left figure), a large grain ($4.59 \times 10^5 \mu m^2$) is found in the sheared zone. Since that grain is apparently larger than other grains, it is considered that grain growth occurred by repeated shear stress and followed annealing. The crystal difference map (upper figure) shows that the deviation angle of the grain is about 10 degrees. The IPF map (lower figure) shows that this large grain is oriented so that its nearly $<211>$ orientation (misorientation 5.6º) corresponds to the RD axis. However, in the specimen E, crystal grains in the sheared zone are almost the same size as those in the other area.
Fig. 7. EBSD data of specimens annealed at 600°C for 60 min after repetition of the shear stress for 18000 times.

Fig. 8 shows EBSD data around the sheared zone in two specimens that were annealed at 800 °C for 60 min after repetition of shear stress for 18000 times. In the specimen F, a large grain ($11.85 \times 10^5 \mu m^2$) is found around the sheared zone. The crystal difference map (upper figure) shows that the deviation angle of the large grain is about 10 degrees. The IPF map (lower figure) shows that the large grain is oriented so that its $<3 2 1>$ orientation (misorientation 3.7°) corresponds to the RD axis. On the other hand, in the specimen G, crystal grains in the sheared zone are fairly large, but they are not so large as those in the left specimen. Also, those crystal grains of the specimen G do not exhibit particular orientation distribution. One possible reason found from these results is that crystal grains oriented to a particular direction can grow up to large grains when they are subjected to repeated shear stress followed by annealing. Effects of shear stress and crystal orientation on the grain growth should be studied in the future work.

Fig. 8. EBSD data of specimens annealed at 800°C for 60 min after repetition of the shear stress for 18000 times.
5. Conclusions

(1) Effects of repeated shear strain followed by annealing on microstructure change of pure iron were studied using a newly developed experimental equipment, which can apply vibration of shear stress to a sheet specimen.
(2) Effects of repeated shear strain on the plastic deformation of crystal grains were studied by using EBSD analysis.
(3) Grain growth occurred in the sheared zone of a specimen that was subjected to repeated shear strain followed by annealing.
(4) Particularly in the case of a specimen which was annealed at 800 °C for 60 min after repetition of shear stress for 18000 times, a large grain \( (11.85 \times 10^5 \, \mu m^2) \) is found around the sheared zone. However, in the case of the other specimen tested under the same conditions, crystal grains in the sheared zone are not so large as those in the left specimen.
(5) Crystal grains oriented to a particular direction may grow up to large grains by repeated shear stress and post annealing.

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References

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