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Effects of High Magnetic Field on Recrystallization and Coarsening Behavior in Fe-Si Steel

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Effects of high magnetic field on recrystallization, coarsening after primary recrystallization were studied in a non-oriented 3% silicon steel. The highest applied magnetic field strength was 10 Tesla. It was found that primary recrystallization process and coarsening after primary recrystallization are both retarded by the application of magnetic field during annealing.

Key words: high magnetic field, Fe-Si steel, recrystallization, coarsening

1. INTRODUCTION

There are many studies showing that an external magnetic field can affect various properties of materials, such as magnetic properties[1,2], mechanical properties[3-5] and phase transformation behavior[6-9] as well. Limited studies over the past few decades have also shown the possibility of modifying the recrystallization structure of deformed ferromagnetic materials by using a magnetic field[10-14]. The early work on the effect of magnetic field on recrystallization texture was carried out by Smoluchowski et al.[10,11]. They found that a magnetic field produced some changes in the recrystallization texture of a cold-rolled Fe-Co alloy. Bhandary and Cullity[12] investigated the effect of the magnetic field on recrystallization behavior of swaged iron wire, and found that recrystallization in a magnetic field introduces <111> and <112> components. Martikainen et al.[13] studied the effect of the magnetic field on the recrystallization behaviour of Armco iron, and reported that annealing in the magnetic field retarded the recrystallization and increased the {100} recrystallization texture component. The maximum strength of magnetic field they used was about 1.5 T. Furthermore, Watanabe et al.[14] investigated the effect of magnetic annealing on recrystallization and grain-boundary character distribution (type and frequency of grain boundaries) in Fe-Co alloy. They found that the frequency of low-angle boundaries increased with increasing magnetic field strength from 0 to 0.5 T. Recently, we studied the effects of high magnetic field on recrystallization in Fe-Si steels[15-17]. Masahashi et al. also investigated the distributions of orientation of primary recrystallization grains in an Fe-3.25%Si steel annealed in a high magnetic field[18]. In this way, previous studies demonstrated that magnetic field can affect the recrystallization effectively. However, there were only a few reports on the effect of very high magnetic field on the recrystallization behavior, especially on the grain growth after primary recrystallization. In the present work, we investigated the effects of high magnetic field on recrystallization and coarsening after primary recrystallization in a non-oriented Fe-3%Si steel in details.

2. EXPERIMENTAL PROCEDURE

The non-oriented steel used in the present research has a composition of Fe-3%Si-0.002%C-0.002%S(mass%). It was hot rolled and annealed in order to get a homogeneously recrystallized structure, then cold rolled to the final thickness of 0.21-1.28 mm with various cold reduction rates from 20% to 87%. Heat treatment was carried out in a vacuum electric furnace installed in a superconducting magnet which can generate a high magnetic field of 10 T. The magnetic field was applied parallel to rolling direction(RD). Microstructure observation was carried out using optical microscopy and transmission electron microscopy (TEM). Hardness measurement was carried out using a MVE-K Micro-Vickers tester. Specimens for hardness measurement were chemically polished by a 95%H_2O_2+5%HF solution after mechanical polishing.

3. RESULTS AND DISCUSSION

3.1 Effects of high magnetic field on primary recrystallization

The microstructures of cold rolled specimens after various heat treatments with and without a magnetic field were examined. It was found that annealing in a magnetic field retards primary recrystallization for hot rolled specimens and lightly cold rolled specimens. Figure 1 shows the microstructures of 25% cold rolled specimen after annealing at 973 K for 0.6 ks without (a) and with (b) a magnetic field of 5 T, respectively. It shows that primary recrystallization process in the specimens annealed with a magnetic field of 5 T is slower than that in the specimens annealed without magnetic field. However, this retardation effect of magnetic field became weaker with the increase of cold rolling rate, and was hardly observed for highly cold rolled specimens. These results can be interpreted by considering that annealing in a high magnetic field may change the distribution and arrangement of dislocations and reduce the dislocation density, since the driving force for recrystallization arises from the elimination of the dislocations introduced during deformation. For highly cold rolled specimens, the dislocation density is high and the driving force for recrystallization is much high, and the retardation effect by a magnetic field becomes relatively weaker. This consideration was supported by the following hardness measurement results.

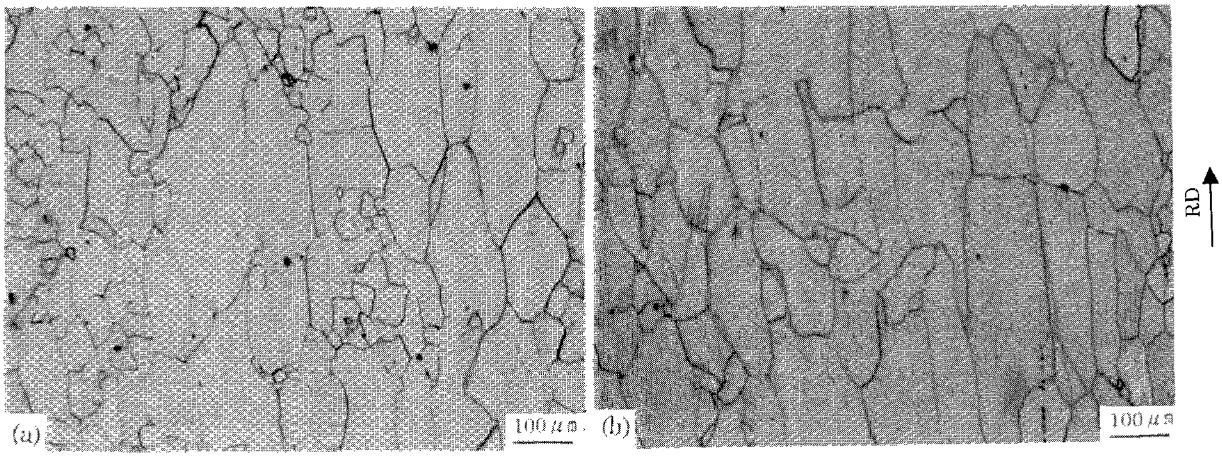

Fig. 1 Microstructures of the longitudinal section of 25% cold rolled specimens: (a) after annealing at 973 K for 0.6 ks without magnetic field, and (b) after annealing at 973 K for 0.6 ks with a magnetic field of 5 T.

Figure 2 shows the hardness measurement result for 87% cold rolled specimens after annealing at 773K

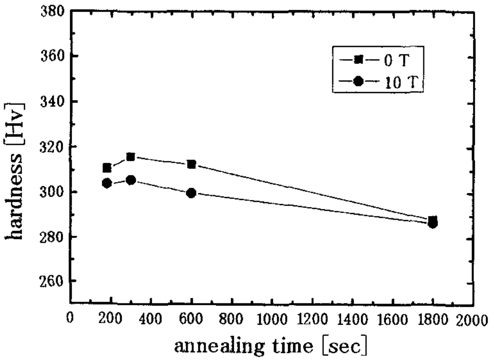

Fig. 2 Micro-hardness changes of 87% cold rolled specimens after annealing at 773 K for various periods of time with and without a magnetic field of 10 T.

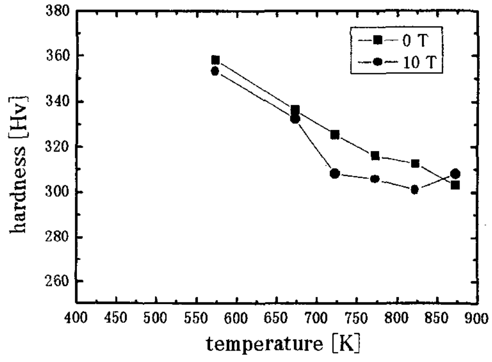

Fig. 3 Micro-hardness changes of 87% cold rolled non-oriented specimens after annealing at various temperatures for 0.3 ks with and without a magnetic field of 10 T.

for various periods of time with and without a magnetic field. For each specimen, 5-7 points were measured and the average was taken. It was found that annealing in a magnetic field of 10 T results in a decrease of hardness at the early stage of annealing. Figure 3 shows the hardness change after annealing at various temperatures for 0.3 ks. A decrease of hardness was also observed after annealing at a temperature range from 723 K to 823 K with a magnetic field. According to the microstructure observation, no primary recrystallization occurred after annealing below 823 K for less than 0.6 ks. Therefore the decrease of hardness must be due to a recovery prior to recrystallization. Thus, annealing in a magnetic field may accelerate recovery, and then retard the recrystallization because recovery lowers the driving force for recrystallization.

3.2 Effect of high magnetic field on coarsening after primary recrystallization

Figure 4 shows the time dependence of grain size of 87% cold rolled specimens during annealing at 973 K with and without a magnetic field. Here the grain size is an average grain diameter measured within an area of 0.18 mm^2 for each specimen. We found that with the increase of annealing time, the grain growth of the specimen annealed with a magnetic field of 10 T becomes a bit slower than that annealed without a magnetic field. Figure 5 shows the magnetic field dependence of the grain size of 50% and 87% cold rolled non-oriented specimens after annealing at 1023 K for 3.6 ks, respectively. The grain size is an average grain diameter measured within an area of 0.72 mm^2 for 50% cold rolled specimen. A tendency of decreasing grain size with increasing magnetic field was observed for both 50% and 87% cold rolled specimens. Since annealing a cold rolled specimen involves two stages, recrystallization and grain growth after recrystallization, it is necessary to separate them so as to appraise the effect of magnetic field on grain growth more accurately. We annealed the 87% cold rolled specimens at 923 K for 3.6 ks without magnetic field to make them completely recrystallized. Then these specimens were annealed at various temperatures from 973 K to 1033 K for 3.6 ks with and without a magnetic field, and the grain size was measured, as shown in Fig. 6. The grain growth in the specimens annealed with a magnetic field of 10 T is

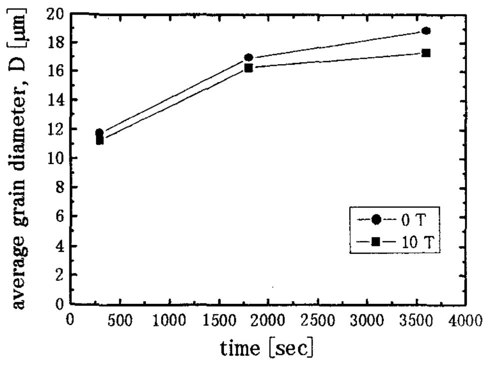

Fig. 4 Time dependence of grain size in 87% cold rolled specimens during annealing at 973 K with and without a magnetic field of 10 T.

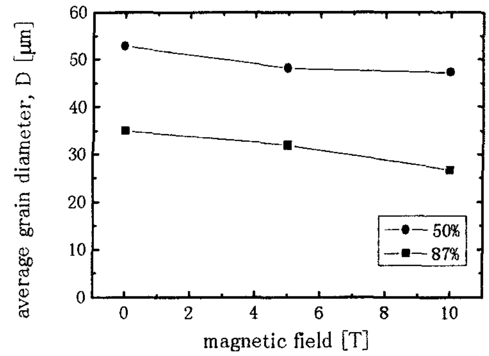

Fig. 5 Magnetic field dependence of grain size in cold rolled specimens annealed at 1023 K for 3.6 ks.

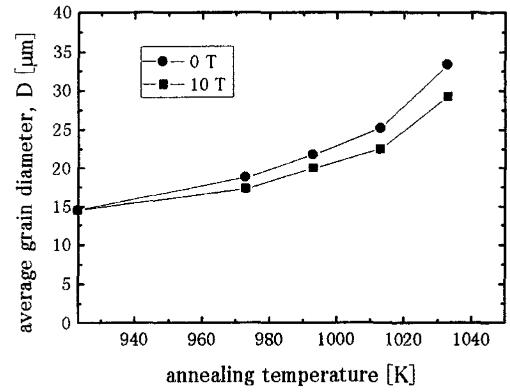

Fig.6 Grain size changes of 87% cold rolled Specimens recrystallized at 923 K for 3.6 ks after annealing at various temperatures for 3.6ks with and without a magnetic field of 10 T.

slower than that in the specimens annealed without a magnetic field. This indicates that a high magnetic field retards the grain growth after primary recrystallization.

The effect of high magnetic field on grain growth at higher temperature was also investigated using the hot rolled specimens. The specimens were first annealed at 1123 K for 1.8 ks without magnetic field to make them completely recrystallized. Then these specimens were annealed at 1223 K and 1273 K for various periods of time with and without a magnetic field, respectively. The grain size was measured within an area of 2.88 mm^2 for each specimen. Figure 7 shows the time dependence of grain size during annealing at 1273 K with and without a magnetic field. It was found that a high magnetic field retarded the grain growth after recrystallization even at a temperature up to 1273 K.

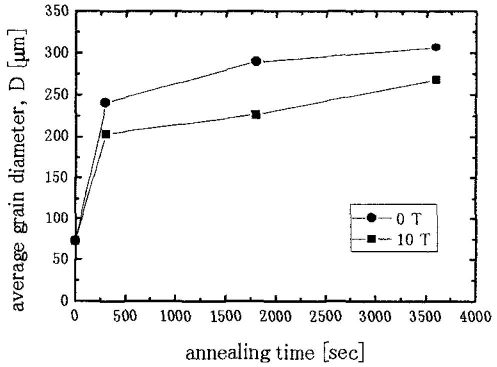

Fig.7 Grain size changes of hot rolled specimens recrystallized at 1123 K for 1.8 ks after annealing at 1273 K for various periods of time with and without a magnetic field of 10 T.

4. CONCLUSION

1. Primary recrystallization process is retarded by the application of a magnetic field up to 10 T during annealing, and this retardation effect is affected by the degree of cold rolling.
2. Coarsening after primary recrystallization is also retarded by the application of a magnetic field up to 10 T.

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