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Effects of a High Magnetic Field on Bainitic and Martensitic Transformations in Steels

Hideyuki Ohtsuka

High Magnetic Field Station, National Institute for Materials Science, Tsukuba 305-0003, Japan

Effects of magnetic fields on transformation temperature, transformation behavior and transformed structure have been investigated for bainitic transformation in an Fe-3.6Ni-1.45Cr-0.5C steel and for transformation to lath martensite in 18Ni maraging steel. Bs temperature was determined by observing the transformed structure and Ms temperature was measured from the cooling curve of the specimen. It was found that both Bs and Ms temperatures increase with increasing applied magnetic field. Bainitic transformation behavior is accelerated by the applied magnetic field. Elongated and aligned structures were observed for austenite to ferrite transformation in an Fe-0.4C alloy, but no elongation or alignment of transformed structure has been observed for transformations to bainite and lath martensite. [doi:10.2320/matertrans.MI200718]

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1. Introduction

Processing in a high magnetic field is a promising method to control microstructures and properties of steels. Several magnetic field effects on the formation of microstructures have been found in steels. An austenite to ferrite transformation is accelerated by magnetic fields,[1,2] and elongated and aligned microstructures are formed in a high magnetic field for austenite to ferrite transformation[1,3–6] and reverse transformation from lath martensite to austenite.[7–9]

A phase diagram is indispensable for the structural control of materials and one of the straightforward methods to ascertain the effects of a magnetic field on phase diagram is to measure the transformation temperatures in a magnetic field. Recently, we reported our experimental works on the effects of magnetic field on phase transformation temperature and microstructure in Fe based alloys.[10,11] Fukuda *et al.* also measured the transformation temperature of Fe-Co alloys in a magnetic field up to 10 T.[12] It is very important to know how the transformation temperatures are affected by a magnetic field for clarifying the effects of a magnetic field on transformation and for evaluating the driving force provided by a magnetic field.[13] In this study, the transformation start temperatures for bainite and lath martensite in steels have been measured in high magnetic fields since no one has ever measured these transformation temperatures.

It is also very important to know how the transformed structures are affected by a magnetic field in order to elucidate the effects of a magnetic field on transformation mechanism. In this research, the effects of a magnetic field on macroscopic structure of bainite and lath martensite have been studied because the effects of a magnetic field on lath martensite structure which had been formed at around 200°C have never been investigated, and only one paper reports the effects of a magnetic field on bainite structure.[14]

2. Experimental

An Fe-Ni-Cr-C and 18Ni maraging steels, which were prepared by vacuum induction melting, were used in the present study for transformations to bainite and lath martensite, respectively. The chemical composition of specimens is shown in Table 1. Specimens were machined to 5 mm × 5 mm × 1.5 mm and set in a vacuum furnace, then the furnace was installed in a magnet. Two magnets were used for experiments. One is a helium-free type superconducting magnet with a 10 T maximum field strength and a ϕ100 mm room temperature bore. Another one is a hybrid magnet with ϕ52 mm room temperature bore to apply a magnetic field up to 30 T. Specimen was fixed at the center of magnetic field, therefore the magnetic field gradient and the magnetic force to the specimen are negligible. The direction of magnetic field was perpendicular to the 5 mm × 5 mm specimen surface. The magnetic field was increased and kept at a constant value, and specimens were heat treated, and then the magnetic field was decreased. The specimen temperature was measured by a thermocouple (W5Re/W26Re type) which contacts with the specimen surface, and recorded by a digital recorder. For the transformation to lath martensite, specimens were austenitized at 1100°C for 30 min, cooled to 273°C at a cooling rate of 55°C/min, and then to 223°C at a cooling rate of 2°C/min, and heat treated at 500°C for 20 min. The specimen temperature was plotted as a function of time to draw a cooling curve, and Ms temperature was determined from this cooling (temperature vs. time) curve. The Ms temperature corresponds to the onset of recalescence during transformation. For bainitic transformation, specimens were austenitized at 1150°C for 15 min and isothermally transformed at various temperatures between 360 and 530°C for various periods of time up to 60 min. Bs temperature was

Table 1 Chemical composition of specimens (mass%).

Fe-Ni-Cr-C steel

C	Si	Mn	P	S	Al	Ni	Cr	Fe
0.50	0.02	0.01	0.004	0.005	<0.01	3.60	1.45	Bal.

18Ni maraging steel

C	Si	Mn	P	S	Al	Ni	Mo	Co	Ti	Fe
0.003	0.006	0.02	0.002	0.001	0.063	18.51	5.80	8.57	0.72	Bal.

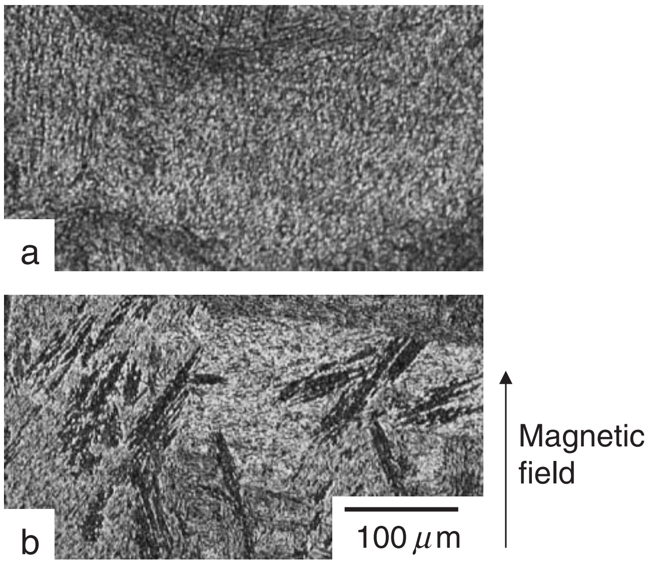

Fig. 1 Optical micrograph showing the effects of a magnetic field on the isothermally transformed structure at 490°C for 10 min (a) without magnetic field and (b) with a magnetic field of 10 T in an Fe-3.6Ni-1.45Cr-0.5C steel.

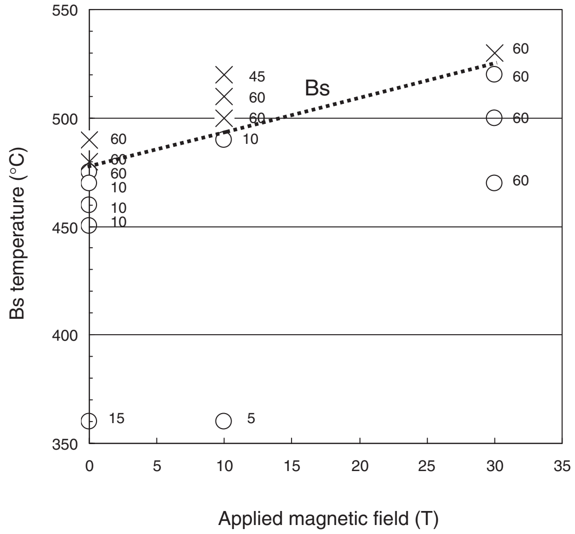

Fig. 2 Effects of magnetic fields on Bs temperature in an Fe-3.6Ni-1.45Cr-0.5C steel.

roughly determined by observing the microstructure of the heat treated specimen. Bs temperature is usually determined from TTT or CCT curve of the specimen, but this method was impossible because the time to keep a high magnetic field over 10 T is limited and recalescence is observed only at some range of cooling rate. It is expected from the TTT curve of this alloy[15] that isothermal heat treatment for 1 h is enough to determine the upper limiting temperature of this curve (the kinetic-Bs). Microstructure observation was performed on the plane parallel to the direction of magnetic field by optical microscope after polishing and etching by 3% nital.

3. Results and Discussion

3.1 Effects of a magnetic field on bainitic and martensitic transformation temperatures

Figure 1 is the optical micrograph showing the effects of a high magnetic field on Bs temperature. After austenitization, specimens were isothermally heat treated at 490°C, which is in the bay area in this alloy,[15] for 10 min without magnetic field (a) and with a magnetic field of 10 T (b). The bay area is in the range of 460 to 560°C for this alloy.[15] Bainitic transformation does not proceed in this temperature without magnetic field and only lath martensite can be seen in Fig. 1(a). On the contrary, bainite plates can be observed as dark areas in Fig. 1(b). Bainite plates and lath martensite can be easily distinguished on the optical micrograph as is shown in Fig. 1(b), and this is also confirmed by measuring Vickers hardness. It can be easily speculated that Bs temperature is increased by applied magnetic field. It is difficult to determine the kinetic Bs in this alloy, Bs temperature has been determined by observing microstructure. Specimens were isothermally heat treated at various temperatures between 360 and 530°C for various periods of time up to 60 min in various magnetic fields up to 30 T. Figure 2 shows Bs temperature as a function of applied magnetic field. The circular mark denotes that bainite plates have been observed and the cross mark denotes that they have not been observed. Bs temperature cannot be determined precisely, but it can be roughly shown by the dotted line in Fig. 2. The number in the figure shows the isothermal holding time for each specimen. Bs temperature increases with increasing applied magnetic field as is already reported for ferrite, pearlite and martensitic transformations.

The effects of a magnetic field on Ms temperature for 18Ni maraging steel were also investigated. The increase of Ms temperature is 19.8°C and 39.0°C with applied magnetic field of 10 T and 20 T, respectively. The Ms temperature for lath martensite also increases linearly with increasing applied magnetic field.

3.2 Effects of a magnetic field on bainitic and martensitic transformation behavior

Figure 3 is an optical micrograph showing the effects of a magnetic field of 10 T on bainitic transformation behavior. Specimens were austenitized and isothermally transformed at 360°C for 5 min without magnetic field (a) and with a magnetic field of 10 T (b). The volume fraction of bainite is much larger in the specimen transformed in a magnetic field, and bainitic transformation is accelerated by applied magnetic field as is already reported for ferrite and pearlite transformations.[1,16] The driving force for transformation is larger in a magnetic field since the additional driving force is supplied by a magnetic field due to the ferromagnetism of ferrite, pearlite, bainite and martensite, and transformation temperatures are increased, and transformation behavior is accelerated by applied magnetic field.

3.3 Effects of a magnetic field on a transformed structure

Figure 4 is an optical micrograph showing the effects of a magnetic field on transformed structure for austenite to ferrite transformation. An Fe-0.4C alloy was austenitized at 1000°C for 15 min and isothermally transformed at 785°C for 4 h in a magnetic field of 10 T. Most of the ferrite grains are

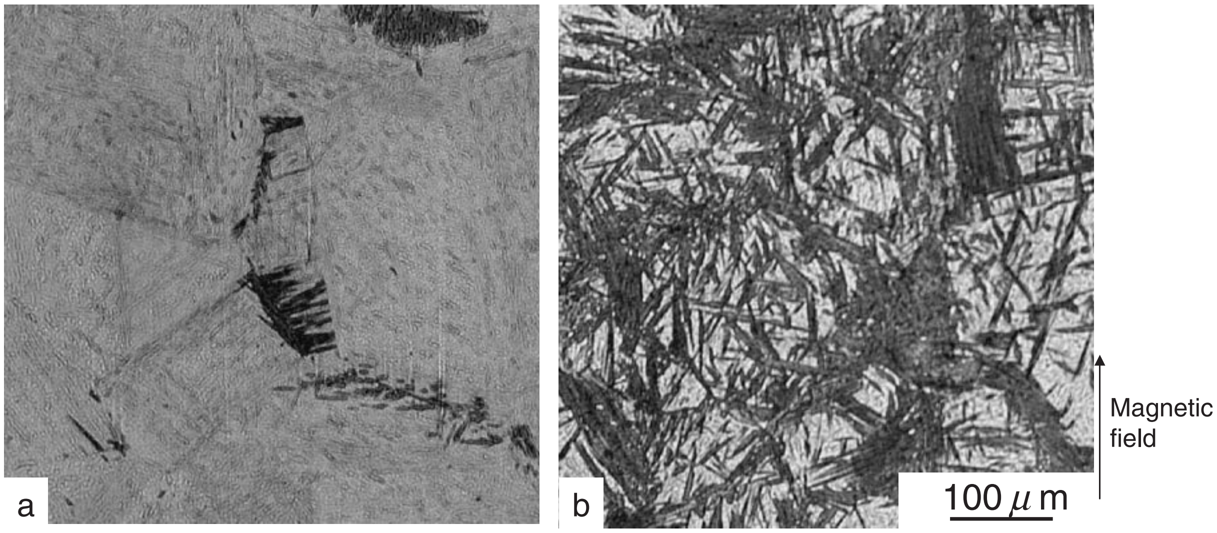

Fig. 3 Optical micrograph showing the effects of a magnetic field on the isothermal transformation behavior at 360°C for 5 min (a) without magnetic field and (b) with a magnetic field of 10 T in an Fe-3.6Ni-1.45Cr-0.5C steel.

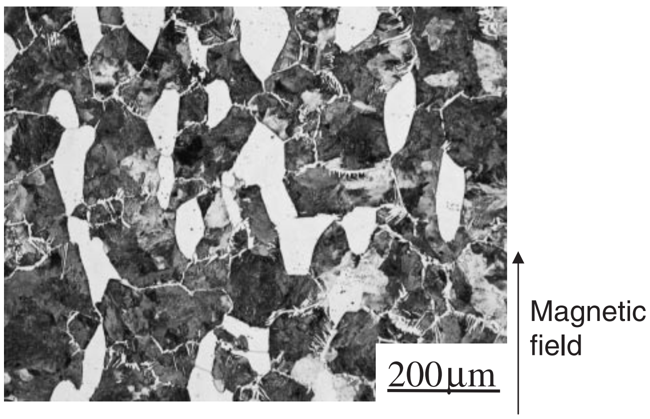

Fig. 4 Optical micrograph showing the effects of a magnetic field on the isothermally transformed structure at 785°C for 4 h with a magnetic field of 10 T in an Fe-0.4C alloy.

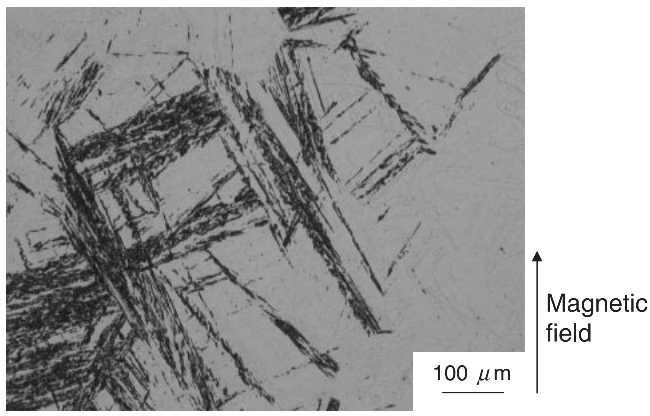

Fig. 5 Optical micrograph showing the effects of a magnetic field of 10 T on a transformed structure in 18Ni maraging steel. A specimen was austenitized at 1100°C for 30 min and cooled to 223°C and then isothermally heat treated at 500°C for 20 min for tempering martensite and cooled down to room temperature. The dark region is the tempered martensite and other region is the martensite formed during final cooling.

elongated along the direction of applied magnetic field and some of them are distributed head to tail and connected with each other along the direction of applied magnetic field. On the other hand, in the case of bainitic transformation, as shown in Fig. 3(b), no elongation or alignment of bainite plates is observed. The bainitic laths with various directions of long axis are observed inside of austenite grain, and no significant difference is found between the transformed structures per se with and without magnetic field except for the fraction transformed.

Figure 5 is an optical micrograph showing the effects of a magnetic field of 10 T on a transformed structure in 18Ni maraging steel. A specimen was austenitized at 1100°C for 30 min and cooled to 270°C at a cooling rate of 55°C/min, and cooled to 223°C at a cooling rate of 2°C/min and then isothermally heat treated at 500°C for 20 min for tempering martensite and cooled down to room temperature. Martensite formed by the cooling to 223°C is tempered at 500°C and this tempered martensite can be easily distinguished in the micrograph from other martensite formed during the final cooling. In Fig. 5, the dark region is the tempered martensite and other region is the martensite formed during final cooling. No elongation or alignment of lath martensite plates along the direction of applied magnetic field is observed and significant difference cannot be found between the transformed structures with and without magnetic field. Ferrite grains are elongated and aligned along the direction of applied magnetic field, on the contrary, effects of a magnetic field cannot be observed so far for macroscopic transformation structure in bainitic and lath martensitic transformations.

The reason for elongation and alignment of ferrite grains is not clear yet, but one of the reasons will be the shape magnetic anisotropy. T. Koyama *et al.* have modeled the structural change and carbon distribution for lath martensite to austenite transformation in a magnetic field using the phase-field method.[17] They found that the carbon distribution is also affected by a magnetic field and it leads to the formation of elongated structure. E. Beaugnon *et al.*[18] considered that the local magnetic force causes the elongation of particles. Near a ferromagnetic particle, the local magnetic field is distorted with a maximum value at the vertical poles (along the external field direction) and a minimum value at the equatorial plane. Strong local magnetic gradients exert forces on the diffusing ferromagnetic solute atoms in the surrounding matrix, and ferromagnetic solute atoms are attracted to the vertical poles with higher magnetic field.[18] These two models expect the anisotropy of diffusivity in a magnetic field, but they have not been proved yet by an experiment.

A shear model and a diffusional model are claimed for the mechanism of bainitic transformation, and in the shear model, carbon diffusion mainly occurs after the formation of bainite plate, and partitioning of carbon is necessary during growth of bainite in the diffusional model. If any anisotropy of carbon diffusivity is expected in a magnetic field, the effects of a magnetic field on the transformed structure in bainitic transformation might be different in these two models, and the transformed structure might give some clue to determine the transformation mechanism of bainite. The effects of a magnetic field on the carbon diffusivity is reported by Nakamichi *et al.*[19] and H. Ohtsuka *et al.*[20] and they both found that carbon diffusivity is retarded by a magnetic field, but they didn't find anisotropy of diffusivity. So the effects of a magnetic field on the diffusion of carbon have to be clarified in the first place.

4. Summary

Effects of magnetic fields on transformation temperature, transformation behavior and transformed structure have been investigated for bainitic transformation in an Fe-3.6Ni-1.45Cr-0.5C steel and for transformation to lath martensite in 18Ni maraging steel. Bs temperature was determined by observing the transformed structure and Ms temperature was measured from the cooling curve. It was found that both Bs and Ms temperatures increase with increasing applied magnetic field. Bainitic transformation behavior is accelerated by the applied magnetic field. Elongated and aligned structures were observed for austenite to ferrite transformation in an Fe-0.4C alloy, but no elongation or alignment of transformed structure has been observed for transformations to bainite and lath martensite.

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