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Magnetic properties of boron–silicon–iron alloys decarburized at the hot-band stage

H. G. LEE, H. B. IM
Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology, PO Box 131 Chongryang, Seoul, South Korea

Magnetic properties of boron–silicon–iron alloys with various amounts of carbon have been investigated by the measurement of magnetic induction at a magnetizing force of 800 A m^{-1}. The amount of carbon was varied before and after hot rolling by adding carbon to the melts and by decarburization of hot bands at 700° C. Results show that high magnetic inductions are obtained from heats with 0.043 to 0.070 wt % carbon but that the heat with 0.024 wt % carbon does not result in high induction. Results also show that complete secondary recrystallization and high induction are obtained from heats whose hot bands have been decarburized to a level of 30 p.p.m. provided that the heat contained 0.043 to 0.070 wt % carbon during heating for hot rolling. From these results it can be said that carbon plays a significant role during heating for hot rolling in determining the texture and magnetic induction of boron–silicon–iron alloys.

1. Introduction

High permeability grain-oriented silicon–iron, both boron–silicon–iron and Hi-B, are characterized by having more precise (1 1 0)[0 0 1] grain orientation and higher magnetic induction at a magnetizing force of 800 A m^{-1} (B8 > 1.9 Tesla) than conventional grain-oriented silicon steel. Development of strong (1 1 0)[0 0 1] texture through secondary recrystallization requires a heavy cold reduction and inhibition to normal grain growth in the final texture anneal.

It has become known recently that the presence of a small amount of carbon in the boron–silicon–iron alloy is also a necessary condition to develop strong (1 1 0)[0 0 1] texture [1, 2]: it has also been reported that the addition of a small amount of carbon in the heats increases the permeability of conventional grain-oriented silicon–iron alloy [3] and Hi-B grain-oriented silicon–iron [4]. Barisoni *et al.* [5] working with heavily cold rolled silicon–irons observed that samples in which patches of martensite present at the cold rolled stage had a stronger (1 1 0)[0 0 1] texture and a higher value of magnetic induction after the final texture anneal. It was also observed that the severely deformed region referred to as "transition bands", in a heavily cold rolled silicon–iron, was associated with pearlite nodules [6], and it was suggested that a hard constituent might be a favoured site for (1 1 0)[0 0 1] nuclei formation [2, 6, 7]. Recently it was reported that carbon affects the development of the final texture in the forms of cementite [8] and solute carbon [8, 9]. Fiedler [1], based on the results of heats that contained various amounts of carbon and of heats that were low in carbon but contained nickel (which is also an austenite former) in the melts, suggested that it is essential that austenite be present during heating for hot rolling.

However, all the above works were carried out by adding and varying the carbon content in the melts. Yang *et al.* [10] reported that a heat with an insufficient initial carbon content (0.014 wt %) did develop a strong (1 1 0)[0 0 1] texture when the carbon content was increased to 0.04 wt % by carburization of the hot bands at 900° C for 4 h. We noticed, however, that the carburization at 900° C, which is the range of normalizing temperature, for even 3 h not only changed the carbon content but also changed the microstructure of the hot band.

In the present paper we report the magnetic properties of heats of boron–silicon–iron which contained ranges of carbon during hot rolling by adding carbon to the melts and after hot rolling by carburization of the hot band at 700° C.

2. Experimental procedure

Three heats of boron–silicon–iron alloys containing carbon contents from 0.024 to 0.070 wt % were prepared in the present investigation. The compositions of the heat at the hot-bands stage were also shown in Table I.

The alloys were melted in an air induction furnace. The size of ingots was 5 × 5 × 15 cm^3. Slices 2.5 cm thick and 15 cm long from the ingots were soaked at 1250° C for 40 min and then hot rolled to a thickness of 2.5 mm in five or six passes. Twelve sets of hot bands were obtained by slicing each hot band into twelve pieces. Seven sets of hot bands, each set containing three carbon contents, underwent normalizing heat treatment for 5 min at normalizing temperatures ranging from 600 to 1100° C. The other five sets of hot bands were normalized at 950° C for 5 min, pickled and then decarburized to obtain five sets of hot bands whose carbon contents were varied after hot rolling. The decarburization was performed by coating with a slurry consisting of Fe_2O_3 powder and water and heat treating at 700° C for 1, 5, 10, 20 and 72 h. All twelve

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TABLE I

	wt % C	wt % Si	Mn	wt % S	B (added)
Alloy A	0.024	2.97	< 50 ppm	0.068	30 ppm
Alloy B	0.043	3.08	< 50 ppm	0.046	30 ppm
Alloy C	0.070	3.10	< 50 ppm	0.045	30 ppm

sets of hot bands were pickled and cold rolled to a thickness of 1.5 mm and then underwent intermediate heat treatment at 900° C for 3 min followed by a final cold rolling to a thickness of 0.3 mm. The final cold rolled strips were heat treated, for decarburization, at 800° C for 5 min in hydrogen with a dew point of 30° C. The final texture anneal consisted of heating in dry hydrogen at 40° C h^{-1} from 800 to 1200° C and holding for 3 h.

Carbon and sulphur contents were analysed with a LECO CS-044 carbon–sulphur analyser. To follow the change in microstructure, a piece of strip was cut from each alloy after each processing step. From these strips samples showing cross-sectional areas normal or parallel to the rolling direction were prepared for optical microscopy. Inductions at a magnetizing force of 800 A m^{-1} were measured with a single sheet tester.

3. Results and discussion

It is known that the magnetic inductions with a magnetizing force of 800 A m^{-1} are generally 1.5 Tesla for non-oriented silicon–iron, 1.82 Tesla for conventional silicon–iron in which average dispersion of the (1 1 0)[0 0 1] orientation is to 6 to 7°, and higher than 1.9 Tesla for both boron–silicon–iron and Hi-B in which the average dispersion of (1 1 0)[0 0 1] orientation is 3 to 4°.

Fig. 1 shows the variation of induction with a magnetizing force of 800 A m^{-1} as a function of carbon content. For these samples the carbon content was varied by adding carbon to the melt at a normalizing temperature of 950° C. It can be seen that the induction is 1.42 Tesla for the specimen which contained 0.024 wt % C while the values of induction are higher than 1.8 Tesla for the specimens which contained carbon contents larger than 0.043 wt % C.

The microstructures of the final texture annealed specimens of Fig. 1 are shown in Fig. 2. Fig. 2a shows that the alloy with 0.024 wt % C did not develop secondary recrystallization. The microstructure of the alloy with 0.070 wt % C was almost identical to Fig. 2b which shows the microstructure of the specimen which contained 0.043 wt % C and developed complete secondary recrystallization. It appears that approximately 0.035 wt % C is necessary to develop complete secondary recrystallization and high induction in boron–silicon–iron (Fig. 1). This result agrees

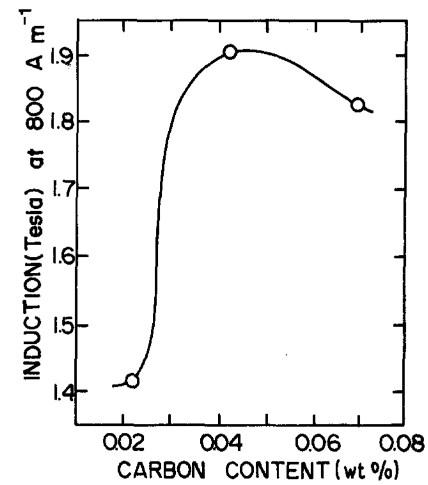

Figure 1 Magnetic induction as a function of carbon content. Carbon was added in the melt.

fairly well with the values of 0.03 wt % C reported by Fiedler [1]. Thus it appears that a small amount of carbon plays a significant role in the secondary recrystallization and magnetic induction in boron–silicon–iron.

Since most investigations on the role of carbon [1, 2] and carbon-associated phenomena [3–9] reported that the carbon content of alloy was varied by adding carbon in the melt, it is not clear at what stage of the process carbon plays the important role. Yang *et al.* [10] varied the carbon content by carburization of hot bands, which had initially an insufficient amount of carbon (0.014 wt % C) to develop secondary recrystallization, at 900° C for 4 h. We observed that carburization at 900° C for even 3 h changes the microstructure of the hot band. Thus in the present investigation the carbon content of the hot bands was varied by decarburization at 700° C, at which no significant change in microstructure was observed, for various periods of time.

Fig. 3 shows the variation of carbon content of the hot bands as a function of decarburization time for Alloys B and C which obtained a sufficient amount of carbon during solidification and hot rolling. It shows that the carbon contents of hot bands which initially had 0.043 and 0.070 wt % carbon decreased to 30 p.p.m. and 0.010 wt %, respectively, after the decarburization of 72 h. For Alloy B (0.043 wt % C) the carbon content decreased to 0.020 wt % after the decarburization of 20 h. When all of these hot bands were first cold rolled, intermediately annealed, final cold rolled, decarburized further at 800° C and texture annealed, a high induction resulted. The magnetic inductions at 10 Oe for these specimens as a function of carbon content of hot bands after the decarburization

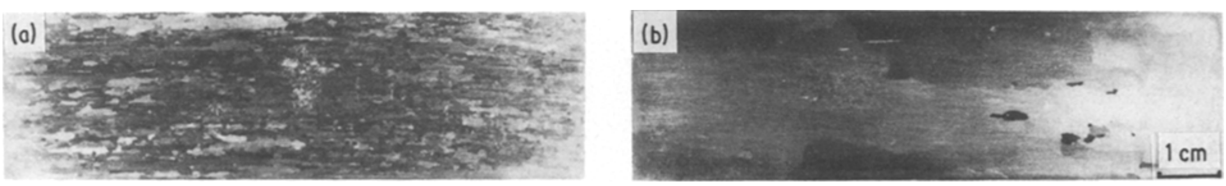

Figure 2 Microstructures of texture annealed specimens which contained carbon contents of (a) 0.025 wt % C, and (b) 0.043 wt % C, at ingot stage.

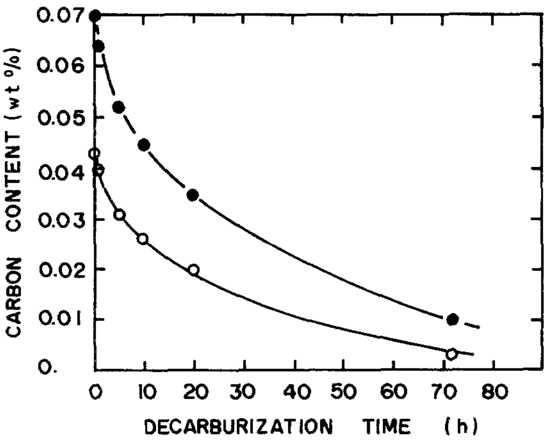

Figure 3 Carbon content of the hot band as a function of oxide decarburization time. Decarburization at 700° C. ○ Alloy B, ● Alloy C.

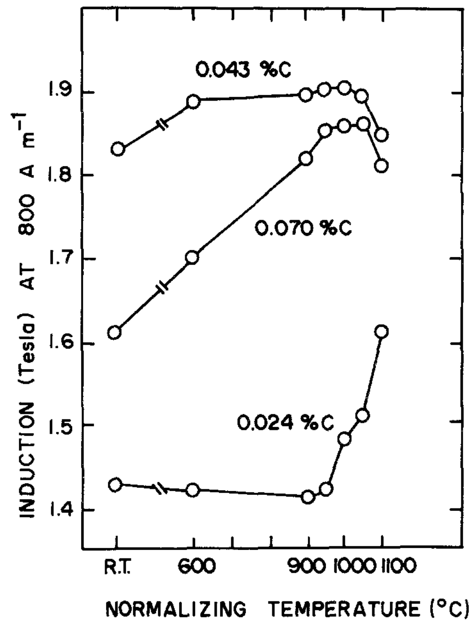

Figure 5 Variations of magnetic induction as a function of normalizing temperature. Normalized for 5 min.

are shown in Fig. 4. It can be seen that the induction is almost independent of carbon content, within experimental error, for both alloys. For Alloy B the inductions are higher than 1.9 Tesla for specimens whose carbon contents were reduced to less than 0.02 wt % (even to 30 p.p.m.) at the hot-band stage. This is an interesting and rather surprising result. If the carbon or hard particles associated with more than 30 p.p.m. carbon played a significant role after the hot rolling stage we would have expected a carbon content dependence like the dotted line in Fig. 4. The fact that the heats with carbon content less than a certain amount (0.02 wt %) do not result in high magnetic induction, whereas the specimens whose carbon content was reduced to less than 0.020 wt % at the hot-band stage do result in high magnetic induction, implies that carbon plays an important role in the secondary recrystallization and high induction, during heating for hot rolling. Comparing these results with the phase diagram of Leslie *et al.* [11], it can be said that austenite is present and results in a complete secondary recrystallization and high induction in boron–silicon–iron.

The variation of magnetic induction as a function of normalizing temperature for Alloys A, B and C are shown in Fig. 5. The alloy with 0.024 wt % carbon has low values of induction when normalized in the temperature range 600 to 1050° C. When the alloy has

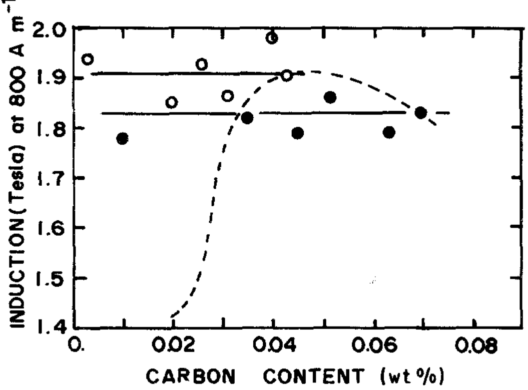

Figure 4 Magnetic induction as a function of carbon content after decarburization at the hot-band stage. ○ Alloy B, ● Alloy C.

been normalized at 1100° C the induction is slightly increased. Examination of microstructures of texture annealed specimens revealed that the alloy did not undergo secondary recrystallization when normalized up to 1050° C and develop partial secondary recrystallization when normalized at 1100° C. On the other hand, the alloys with 0.043 wt % carbon showed high inductions for normalizing temperatures of 600 to 1050° C, then showed slight decrease in induction when normalized at 1100° C. Fig. 6 shows the microstructures of the cross-sectional area of hot bands of Alloy B normalized at 950 and 1100° C. The microstructures of hot bands normalized in the range 600 to 1050° C were similar to Fig. 6a. For normalizing temperatures up to 1050° C, the elongated layers in the interior of the hot band are unrecrystallized but when the hot band has been normalized at 1100° C the elongated layers recrystallized to show a significantly different microstructure. Thus it appears that the magnetic induction of the final texture annealed specimen is related to the microstructure of the hot band. Analysis of the microstructure of the cross-sectional area observed at various stages of processing revealed that the carbon content determines, through austenite transformation, microstructure of the hot band and subsequently the cold rolled sheet. Detailed and lengthy results of analysis of microstructures will be presented elsewhere [12].

4. Conclusion

Magnetic properties and microstructures of boron–silicon–iron alloys containing various amounts of carbon have been investigated by the measurement of magnetic induction and by analysis of the microstructure of the cross-sectional area of the specimen. The specimens were processed by a two-stage cold reduction method. The amount of carbon content was varied before and after hot rolling by adding carbon to the melts and by decarburization of the hot band at 700° C.

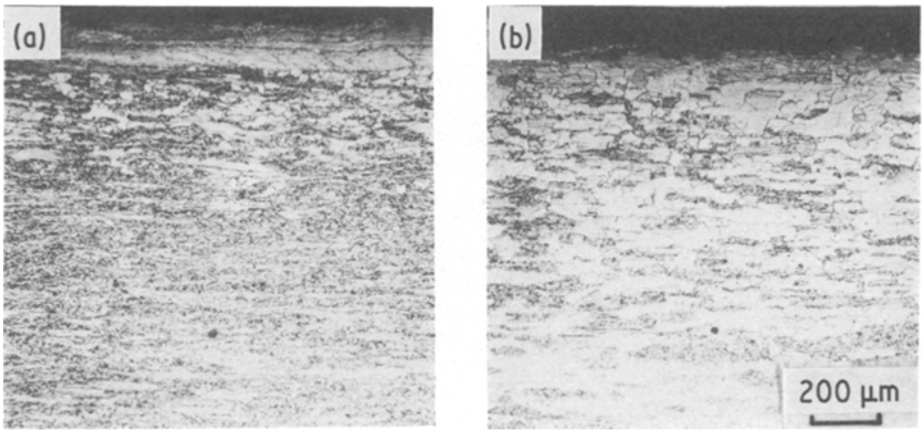

Figure 6 Microstructures of cross-sectional area of hot bands of Alloy B normalized at (a) 950° C, and (b) 1100° C.

High magnetic induction (1.9 Tesla) can be obtained if the heat contained more than 0.35 wt % C in the ingot. It can also be obtained from heats whose hot bands have been decarburized to a level of 30 p.p.m. provided the heat contained 0.043 to 0.070 wt % carbon during heating for hot rolling. From these results it can be concluded that carbon plays a major role during heating for hot rolling in determining the magnetic induction of boron–silicon–iron alloys. It can also be concluded that the carbon or hard particles associated with more than 30 p.p.m. carbon present in the specimen after the hot rolling do not play a significant role in determining the magnetic induction in boron–silicon–iron.

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