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Effects of a high magnetic field on the phase equilibria of Mn–Sb system during solidification process

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ABSTRACT

The effects of an 11.5 T magnetic field on phase equilibria of Mn–Sb system during solidification process were investigated with the aid of direct thermocouple measurements and quantitative metallography analysis. It was found that the magnetic field could increase the eutectic line and the area fraction of the MnSb in eutectics, and thus shift the eutectic point to the high Mn concentration side. It could also increase the Sb liquidus temperatures by a decreasing trend with an increasing Sb composition, but show little effect on the MnSb liquidus temperature. The above results could be related to the variation in the magnetic susceptibility during the phase transformation.

1. Introduction

Phase equilibria in alloys are of tremendous importance both from the fundamental and applied points of view [1]. Recently, the application of a high magnetic field to phase equilibria has drawn particular attention. Simulation results of previous studies [2–4] indicated that the eutectoid point of the Fe–C phase diagram shifts towards the high carbon and high temperature sides in the presence of a high magnetic field. Such shift has been evidenced by the increase in ferrite volume fraction [3,5–7] and the lamellar spacing of pearlite [8] and the decrease in proeutectoid cementite volume fraction [8] observed during the cooling of steels in a high magnetic field. However, these investigations have been limited to the solid state transformation, thermodynamic and kinetic descriptions of the changes in phase equilibria during the solidification process of alloys in a high magnetic field have generally not been well developed.

It is the aim of the present work to investigate the effect of high magnetic fields on the phase equilibria of alloys during solidification process. Various Mn–Sb alloys and pure Sb were solidified in a high magnetic field. The cooling curves were monitored by direct thermocouple measurements. The change in the volume fraction of the eutectic MnSb was characterized by quantitative metallography analysis.

2. Experimental

Mn–89.7 wt.%Sb, Mn–90.4 wt.%Sb, and Mn–95.2 wt.%Sb alloys were prepared from Mn and Sb (4 N) by induction-melting under a vacuum in graphite crucibles. The obtained ingots, including pure Sb (4 N), were machined into cylindrical specimens 9.5 mm in diameter and 15 mm in length and cleaned with acetone in an ultrasonic bath. The specimens were placed into alumina crucibles (inner diameter 10 mm; outer diameter 15 mm) and heated in an argon atmosphere to temperatures 150 °C higher than their liquidus temperatures at a heating rate of 5 °C/min. After holding at the same temperature for 30 min, the specimens were cooled down to 400 °C at a cooling rate of approximately 1 °C/min and finally furnace cooled down to room temperature. The above procedure was also performed in an 11.5 T high magnetic field. Further details of the experimental apparatus are given elsewhere [9].

The temperature/time curves were obtained by a Pt–13%Rh thermocouple. Further details of the assembly for temperature measurement are given elsewhere [10]. Before and after the experiment, the calibration of the thermocouple was checked using pure Al specimens with and without a high magnetic field of 11.5 T. From numerous calibration experiments, the accuracy in relative temperature measurements was estimated to be ±0.2 °C. The obtained microstructures were observed by optical microscopy. The average area fraction of MnSb in eutectic was measured using quantitative metallography analysis. Over 30 measurements were obtained for each specimen and the average values were determined.

3. Results and discussion

Fig. 1 shows typical cooling curves of the Mn–Sb alloys and pure Sb during solidification with and without an 11.5 T magnetic field. The growth temperatures, defined as the maximum temperatures reached after recalescence in the curves, for both primary and eutectic reactions are summarized in Table 1. According to its binary phase diagram [11], the eutectic composition of the Mn–Sb system is 90.5 wt.%Sb. However, the primary arrest for the Mn–90.4 wt.%Sb alloy without magnetic field cannot be clearly

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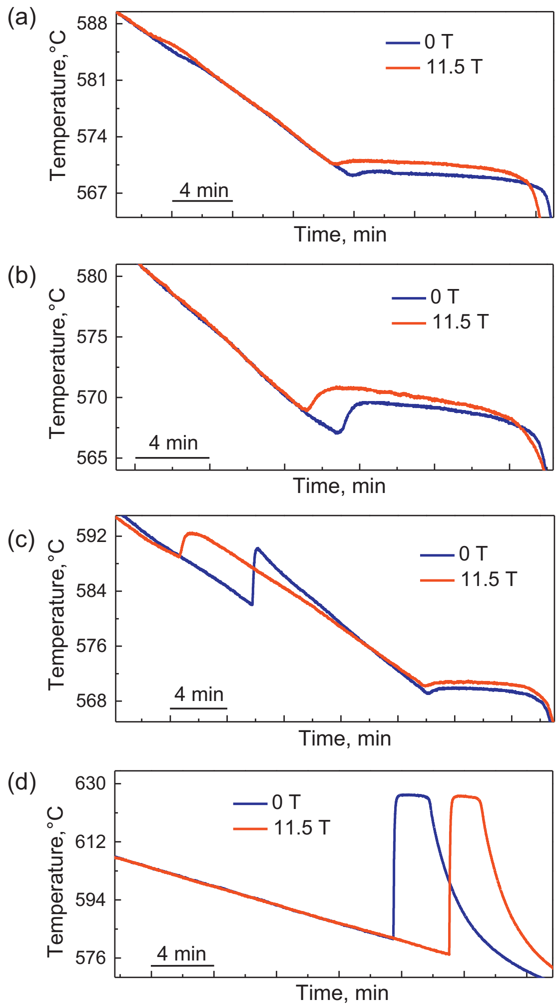

Fig. 1. Typical cooling curves for (a) Mn–89.7 wt.%Sb, (b) Mn–90.4 wt.%Sb, (c) Mn–95.2 wt.%Sb alloys and (d) pure Sb with and without an 11.5 T magnetic field.

Table 1
Liquidus and eutectic temperature data for Mn–Sb alloys and pure Sb solidified at 0 T and 11.5 T.

Composition (wt.%Sb)	Liquidus (°C)		Eutectic (°C)	
	0 T	11.5 T	0 T	11.5 T
89.7	586.0	586.2	569.7	571.1
90.4			569.6	570.8
95.2	590.2	592.4	569.9	570.8
100.0	626.5	626.2		

detected, indicating that the amount of primary phases formed was not enough to create an observable recalescence event. The temperature of this arrest is, thus, not included in the table. Furthermore, the liquidus temperature of 100 wt.%Sb for both with and without the magnetic field cases is about 4 °C lower than the equilibrium temperature reported in the binary phase diagram [11]. This can be attributed to the fast heat transfer from the sample to the environment and the large undercooling, which cause the result that the temperature is remarkably decreased and cannot reach the equilibrium one during recalescence. A comparison between the data of 0 T and 11.5 T suggests that the application of the magnetic field caused an increase in the eutectic temperature of about 1 °C. The eutectic microstructures and corresponding area fraction of MnSb in eutectics of the Mn–89.7 wt.%Sb and Mn–90.4 wt.%Sb alloys are shown in Fig. 2. It is seen that all eutectics consist of intermetal-

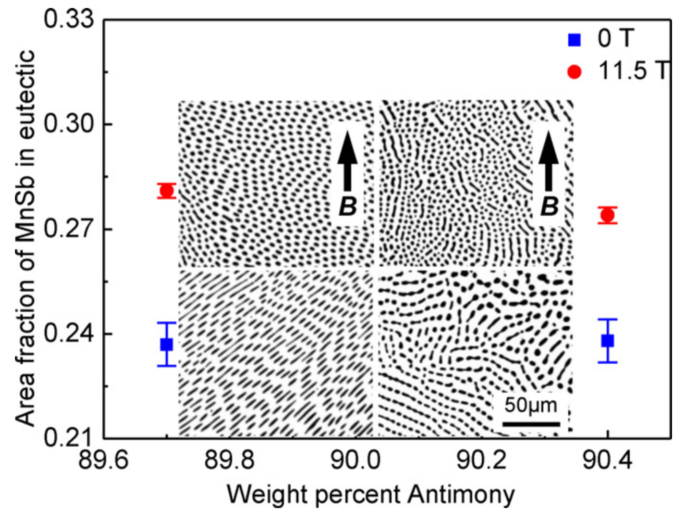

Fig. 2. Variation of the area fraction of MnSb in eutectics with and without an 11.5 T magnetic field. The insets are the typical micrographs of the eutectics.

lic MnSb rods and Sb phases and the magnetic field shows little effect on their morphologies. However, the area fraction of the eutectic MnSb increases from about 0.24 at 0 T to about 0.28 at 11.5 T.

According to the level rule, the increase of the eutectic MnSb amount should correspond with an increase in the difference between the 100 wt.%Sb and the eutectic composition of the Mn–Sb system, i.e. a shift of the eutectic point to higher Mn concentrations. Furthermore, careful microstructural observations show that the Mn–90.4 wt.%Sb alloy exhibits a hypoeutectic morphology at 0 T, but a eutectic morphology at 11.5 T. This phenomenon has been confirmed by the repeated experiment using specimens with a smaller size than that of above-mentioned specimens. Typical microstructures of the small specimens solidified with and without a high magnetic field of 11.5 T are shown in Fig. 3. Therefore, it can be concluded that the eutectic point of the Mn–Sb system is shifted from 90.5 to 90.4 wt.%Sb by the magnetic field.

By combining the above experimental results, the effects of the high magnetic field on the phase equilibria of the Mn–Sb system during solidification process can be determined. As seen in Fig. 4, the magnetic field increases the eutectic line, shifts the eutectic point to a high Mn concentration side, and, accordingly, increases the Sb liquidus temperatures. But, the increase of the liquidus temperatures is diminished with an increasing Sb concentration. Furthermore, the MnSb liquidus temperature is believed to be unaltered. During a phase transformation process in a magnetic field, if the difference in the magnetic energy induced by the magnetic susceptibility difference between the parent and product phases is large enough, the phase equilibrium should be altered as a manner that those phases with higher magnetic susceptibilities will be more stable than those with lower magnetic susceptibilities [2–4]. Therefore, the above-mentioned changes in the phase equilibria of the Mn–Sb system in the magnetic field can be related to the variation in the magnetic susceptibility during the phase transformation. However, because the data about the magnetic susceptibilities of phases in the this system as a function of temperature remain of limited value, the phase transformation of the Mn–Sb system during solidification process in a high magnetic field cannot been quantitatively characterized yet. To reveal the mechanism of observed magnetic field effects, we must await future research.

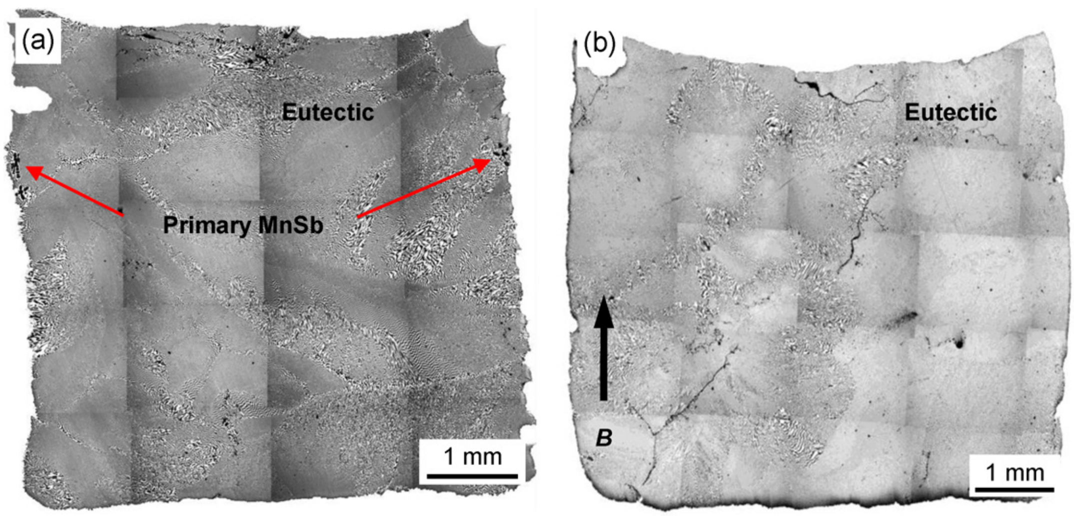

Fig. 3. Microstructures of the Mn–90.4 wt.%Sb alloys with smaller size (5 mm in length and 5 mm long) solidified at (a) 0 T and (b) 11.5 T.

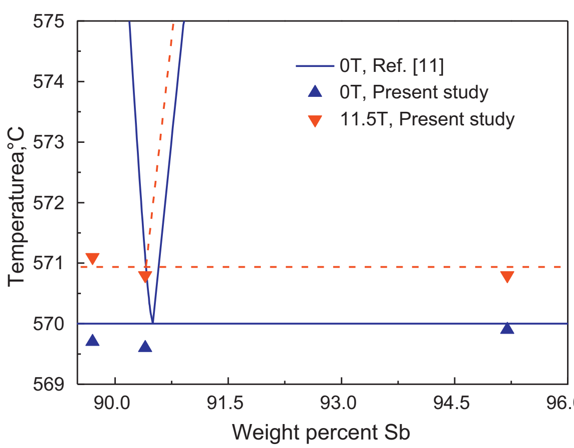

Fig. 4. Liquidus and eutectic temperatures based on the cooling curves of the Mn–Sb alloys. The dashed lines indicate variations in the magnetic field obtained in this work.

4. Conclusions

In summary, the phase equilibria of the Mn–Sb system during a solidification process in an 11.5 T magnetic field were investigated. It was found that the magnetic field could increase the eutectic line and the area fraction of the MnSb in eutectics, and thus shift the eutectic point to the high Mn concentration side. It could also increase the Sb liquidus temperatures by a decreasing trend with an increasing Sb composition, but show little effect on the MnSb liquidus temperature. Our results experimentally confirmed the possibility that the high magnetic field can alter the phase equilibria of materials during a solidification process.

Acknowledgments

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