INVESTIGATION ON SOLIDIFICATION OF Bi-Mn ALLOYS UNDER A HIGH MAGNETIC FIELD

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Introduction. The solidification structure of Bi-Mn alloys solidified in a high magnetic field is always an interesting topic because the alloy is special in solidification behavior. Savitisky et al. [1] and Asai et al. [2, 3] found that MnBi phase aligned along the magnetic field and aligned regularly in Bi-0.9–10wt% Mn alloy solidified in the 2.5–5 T magnetic field. Ren et al. [4] found that the aligned solidification structure of MnBi phase was basically produced in the semisolid zone of the alloy. Yasuda [5] contributed the aligned solidification structure to rotation of the MnBi particles.

Obviously much more work is needed to do on the solidification structure of Bi-Mn alloys solidified in a strong magnetic field. In this paper, Bi-3–6%Mn alloys were solidified in a high magnetic field, and several new phenomena were found.

1. Experiment. The experimental apparatus is the same as that in Ref.[4].The Bi-3wt%Mn and Bi-6wt%Mn alloys were investigated in this research. The experiment procedure was as follows: the alloy specimen sealed in a graphite tube with its longitudinal axis along the direction of the magnetic field was heated at a rate of about 10°C/min to a certain temperature above the eutectic temperature or above the liquidus temperatures. (The eutectic temperature is 262°C, the peritectic transformation temperature is 355°C, and the liquidus temperatures of Bi-3%Mn and Bi-6%Mn alloys are 365°C and 446°C, respectively), and held at this temperature for a certain time, then cooled to below the eutectic temperature 262°C at a rate of 0.3°C/min. Quenching experiment was also carried out to investigate the evolution of solidification structure for different holding time. In this case, the sample held at the semisolid zone was dropped into a water tank and cooled down quickly, so that the solidification structure at the holding temperature was kept to room temperature.

The microstructures on both longitudinal and lateral sections of the solidified samples were examined.

2. Results and discussion. Fig. 1 shows the microstructures of the Bi-6%Mn alloys solidified from temperature 300°C with and without a magnetic field, respectively. As one can learn, the BiMn grains were aligned along the direction

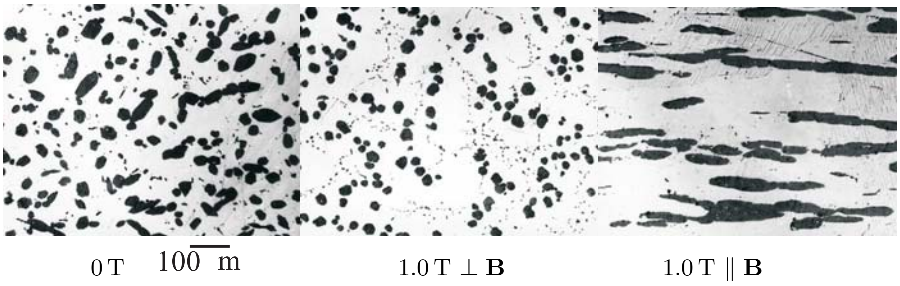


Fig. 1. The solidification structure of Bi-3%Mn alloy. Maintaining temperature was 300°C, cooling rate = 2.5×10^{-3} °C/sec.

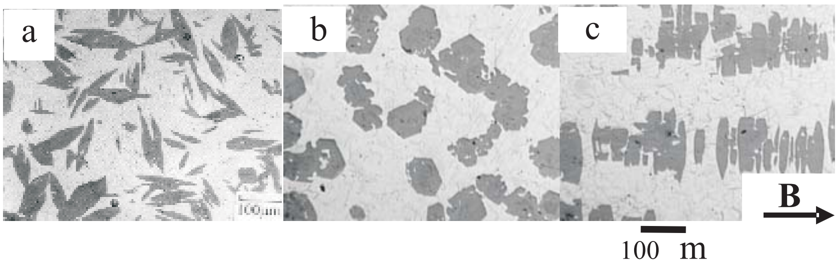
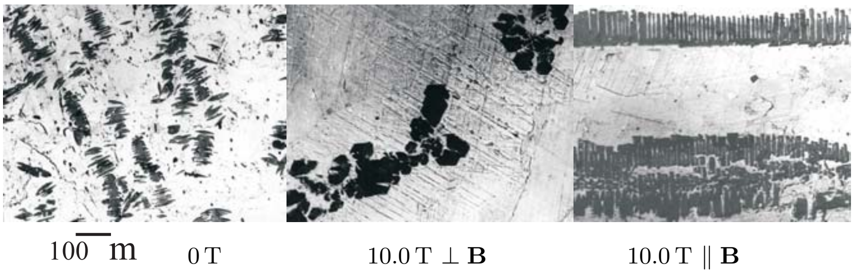


Fig. 2. The solidification structure of the Bi-6%Mn alloy solidified from temperature of 380°C at the cooling rate 0.15°C/sec.



0 T 10.0 T ⊥ **B** 10.0 T ∥ **B**

Fig. 3. The solidification structure of the Bi-3%Mn alloy. Maintaining temperature was 400°C, cooling rate – 0.15°C/sec.

of the field. In the case without the magnetic field, as comparison, the phase was randomly orientated.

Fig. 2 compares the microstructures of the alloy solidified from 380°C under a 10 T field to that without field. It is shown that with a 10 T magnetic field the MnBi phase was transformed from a leaf to a disc like profile and aligned regularly along the direction of the field with its short axis along the field direction. Additionally, the edge of the disc was “missed”.

In the case of solidification form the melt, the BiMn grains were thin and compiled tightly along the direction of the field, as shown in Fig. 3.

Fig. 4 was one of the typical results of X-ray diffraction analysis on the above samples. It showed that in the case of no magnetic field, the MnBi particles were randomly orientated, and with the magnetic field, the MnBi particles were orientated with their [001] direction in line with the field. Keeping in mind that [001] is its easy magnetizing axis of MnBi particle, one can learn that the magnetic field turned the particles to make their easy magnetizing axis along the direction of the field.

Fig. 5 shows the results for the Bi-3%Mn alloy solidified from temperature

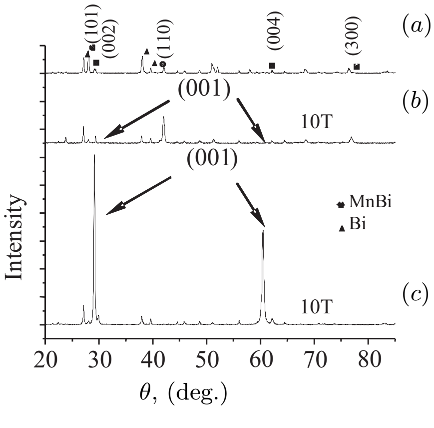


Fig. 4. X-ray diffraction of the Bi-20%Mn alloy solidified at the cooling rate 0.15°C/sec.

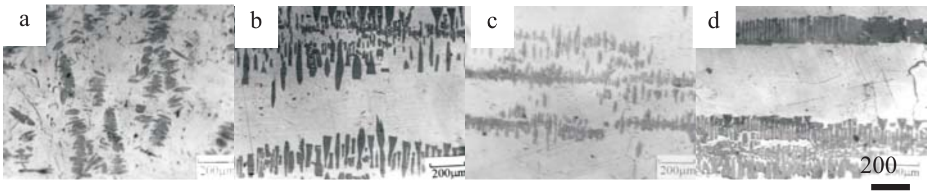


Fig. 5. The solidification structures of Bi-3%Mn alloys solidified from 400°C at the cooling rate 0.18°C/min. (*a*) 0T, (*b*) 0.5T, (*c*) 1.0T, (*d*) 10T.

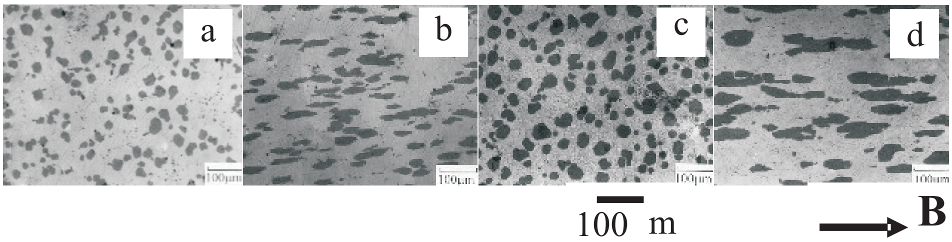


Fig. 6. The behavior of BiMn grains in the Bi-Mn alloys with alignment structure when the alloys were reheated to semi-melt zone and maintained at this temperature under a 1 T magnetic field, and then cooled at the rate of 0.15°C/sec without the field. (*a*) Bi-3%Mn, 300°C, ⊥ **B**, (*b*) Bi-3%Mn, 300°C, ∥ **B**, (*c*) Bi-6%Mn, 345°C, ⊥ **B**, (*d*) Bi-6%Mn, 345°C, ∥ **B**.

400°C. As one can learn, the morphology of the MnBi particles was flake. And they all aligned along the direction of the field with their short axis in line with the field. Along with the increase of the field intensity, the alignment became more apparent, and the flakes piled more tightly.

It is suggested by several researcher [2, 3, 4, 5] that the alignment of the grains is due to a magnetization force exerted on the grains which causes rotation of the grains with their easy magnetizing axis along the direction of the field.

In the presence of a high magnetic field, even paramagnetic grains of BiMn can be magnetized and rotated. After the magnetizing of the particles, the attractive force between them would draw them and pile up along the magnetic field. The attractive force [6] will increase with the increase of the field. The volumes of the particles influence the force linearly. Therefore, the length of the MnBi phase increased significantly with the increasing of the magnetic field, because more particles may adhere together under a stronger magnetic field. It is also easy to understand that with the increase of holding time in the mushy zone, the adhering rate of the particles will accelerate due to the enlarging of their volumes.

Fig. 6 is the results of the solidification without the magnetic field after maintaining at a certain temperature in the semi-melt zone under a 1 T magnetic field. It shows that in the maintaining period, the alignment of the structure has already happened and this alignment could be kept without magnetic field.

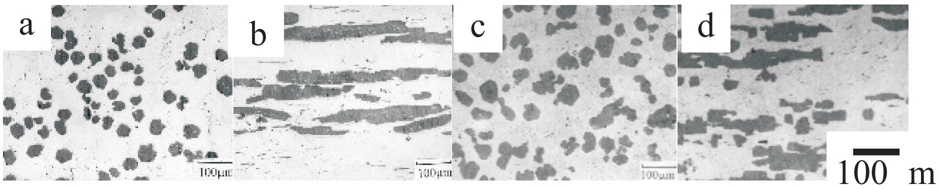


Fig. 7. The results of the solidification of the samples without the field with aligned BiMn grains obtained by solidification from the semi-melt zone below the Curie point in a 1 T field. (*a*) Bi-3%Mn, reheating temp. 300°C, ⊥ **B**; (*b*) Bi-3%Mn, reheating temp. 300°C, ∥ **B**; (*c*) Bi-6%Mn, reheating temp. 345°C, ⊥ **B**; (*d*) Bi-6%Mn, reheating temp. 345°C, ∥ **B**.

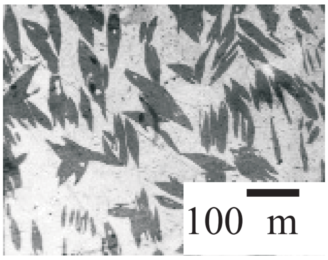


Fig. 8. The structure on the longitudinal section of the sample solidified from 380°C after its reheating with the aligned structure obtained by slow solidification in a 1 T field. Bi-6%Mn alloy.

In order to learn the possibility to keep the alignment of structure in the case of reheating to semi-solid zone, an experiment on reheating the alloy with the aligned structure was carried out. Fig. 7 is the result of the reheating to a temperature below the Curie point and re-solidification of the sample with the alignment structure obtained by solidification in a 1 T magnetic field. As one can learn, the alignment was basically kept. When the reheating temperature exceeded 355°C, the Curie point, the alignment of structure was destroyed, as shown in Fig. 8.

These result suggested that the BiMn grains were attracted to each other due to the magnetization in the magnetic field in the case of the temperature below the Curie point. This attractive force was strong enough to overcome the influence of the thermo-disturbance in the ferromagnetic state. When the temperature was over the Curie point, the attractive force was very weak and the influence of the thermo-disturbance was apparent, hence, the alignment was destroyed by the thermo-disturbance.

3. Conclusion. During the solidification with a high magnetic field, the primary BiMn grains in the Bi-Mn alloy rotated and aligned along the direction of the magnetic field. There were 3 kind of structures of BiMn phase according to the starting solidification zone. In the zone below the Curie point rod-like BiMn grains appeared, in the zone above the Curie point and below the liquidus flake-like BiMn grains appeared, and in the case of the melt tightly piled flake-like BiMn grains were produced. In all these cases, the grains were aligned orientated with $< 001 >$ along the direction of the field.

When the alloy with the aligned rod-like BiMn grains was reheated to below the Curie point, the alignment of BiMn was kept; and when reheated to above the Curie point, the alignment was destroyed.

Due to the magnetic attractive force among them, which was generated by applying a magnetic field during maintaining the alloy below the Curie point and above the eutectic temperature, the grains could keep alignment of the BiMn grains in the further solidification even without the magnetic field.

Acknowledgment. The authors acknowledge the supports of the National Natural Science Foundation of China (No. 59871026, 50225416, 50234020), the Science and Technology Committee of Shanghai (No.02DJ14031).

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