Wettability of Liquid In and Bi on Flat and Porous Solid Iron Substrate

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Wettability of liquid indium and liquid bismuth on a solid iron was investigated to elucidate their different behaviors relating to the unusual wetting phenomena. Sessile drop method was performed to measure the contact angle of each liquid metal on the flat solid iron in H₂ from 700 to 1100 K. In addition, we observed wetting behaviors of liquid indium and liquid bismuth on the surface-porous iron substrate. It was found from these experiments that liquid indium wetted and penetrated into the porous layer at 773 K. On the other hand, liquid bismuth did not infiltrate the porous substrate at temperatures lower than about 950 K. The wetting behavior of these liquid metals on the porous substrates is supposed to be related to the wettability of each metal on the flat solid iron.

[doi:10.2320/matertrans.MRA2007094]

(Received April 26, 2007; Accepted July 17, 2007; Published September 5, 2007)

Keywords: wettability, porous structure, capillary phenomenon, contact angle, indium, bismuth, iron

1. Introduction

The wetting phenomenon between liquid metals with low melting points and solid metals such as iron is important in different processes, for example soldering in electronic devices or hot-dip coating of steels. A previous study¹ found that unusual wetting behaviors of liquid metals (Cu, Ag, Sn, and In) on iron substrates occurred when the metal droplets were attached to the substrates prepared by oxidation-reduction processes, and we have subsequently reported on the mechanism of this unusual wetting phenomenon. The aim of this paper is to investigate wetting behaviors of liquid indium and bismuth on flat iron substrates, and to relate these behaviors to unusual wetting phenomenon. The systems of In-Fe and Bi-Fe have no intermetallic compounds and little mutual solubility.² Thus, it is thought that they are appropriate systems to investigate a wetting behavior of liquid metal on solid metal. However, there is little information on the wetting behavior of these liquid metals with solid iron. Although wettability between liquid bismuth and solid iron substrate has been measured previously by two research groups,³,⁴ there is considerable difference between these two results, especially at relatively low temperatures. Moreover, the wetting behavior of liquid indium on solid iron has not been reported as long as our search. In this study, the wetting behavior of liquid indium and liquid bismuth on surface-porous iron substrates was investigated as well as on flat solid iron substrates.

2. Experimental

2.1 Wettability of liquid indium and bismuth on flat solid iron substrate

A substrate of 10 × 10 mm was cut from a rolled iron plate of 99.99% purity and 1 mm thickness. This iron substrate was polished using alumina powder of 0.3 μm and cleaned by ultrasonic agitation in acetone and ethanol.

Indium of 99.99% purity was cut from metal wire of φ2.0 mm. Bismuth rod of φ2.5 mm was obtained from vacuum melting of bismuth shots (99.99% purity) in a graphite crucible. Sessile drop method was performed to measure contact angles of liquid In on solid iron.

Fig. 1 Furnace used to observe wetting behaviors of liquid metals and to measure contact angles of liquid In on solid iron.

The contact angles of liquid indium were studied with two different heat processes, (A) and (B), as outlined below. The furnace shown in Fig. 1 was also used for these experiments. In experimental method (A), indium droplet was dropped through the alumina tube onto the iron for each of the temperatures 723, 773, 873, and 973 K. Then, the time dependence on the contact angles of liquid indium was investigated for 60 min. In experimental method (B), indium specimen was placed on the iron substrate in the furnace before heating. Then, the temperature in the furnace was raised to 1050 K at a rate of 2 K per minute in the same atmosphere. Above 723 K, the contact angles of the indium droplet on the iron substrate were measured against temperature.

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The wetting behavior between liquid bismuth and the flat solid iron substrate was investigated in the furnace shown in Fig. 2. Bismuth rod was set on the iron substrate in the furnace. Then, the sample was heated to 700 K in 90 min in H\(_2\). The contact angle of liquid bismuth on the iron substrate was measured as the temperature was raised from 723 to 1073 K in H\(_2\), at a heating rate of 2 K per minute.

2.2 Wetting behavior of liquid indium and bismuth on surface-porous iron substrate

In this experiment, a substrate of 20 x 20 mm was cut from a rolled iron plate of 99.5% purity and 1 mm thickness. The iron substrate was polished using alumina powder of 0.3 µm and cleaned by ultrasonic agitation in acetone and ethanol. The surface of the iron substrate was oxidized at 1073 K for 1 h in air and then air-cooled. Then, the oxidized iron substrate was reduced at 873 K for 1 h in H\(_2\). The contact angle of liquid bismuth on the iron substrate was measured from the temperature was raised from 723 to 1073 K in H\(_2\), at a heating rate of 2 K per minute.

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The experimental apparatus for sessile drop method is illustrated in Fig. 1. The surface-porous iron substrate was heated to 773 K in H\(_2\), and each liquid metal was dropped onto the substrate. After indium droplet of about 0.1 g was placed on the iron substrate, the wetting behavior of the liquid metal was observed for 80 s at a given temperature in H\(_2\). In the case of liquid bismuth, after dropping the liquid metal at 773 K, the specimen was heated to 1073 K at a rate of 2 K per minute to investigate the temperature dependence of the apparent contact angle of liquid bismuth in H\(_2\).

3. Results

3.1 Wettability of liquid indium and bismuth on flat solid iron substrate

The time dependence of contact angles of liquid indium on flat solid iron substrates, held for 60 min at different temperatures, is shown in Fig. 4. Within the first 5 min, an equilibrium shape of indium droplet was not established and the contact angle was decreasing. After 5 min, no significant change of the contact angle was observed for any temperature.

Figure 5 shows temperature dependences of contact angles of liquid indium and bismuth on flat iron substrate. In Fig. 5, the contact angles of indium obtained from the experimental method (B) are indicated by solid circles. On the other hand, the open circles in Fig. 5 show the contact angles of liquid indium in the experiment (A) at 60 min seen in Fig. 4. The experimental results for bismuth are plotted with solid and open triangles for two different runs. The results for indium on the iron substrate by the methods (A) and (B) show good agreement. Therefore, it is supposed that the experimental
method does not affect the wetting behavior of liquid indium on the iron substrate. The contact angles of liquid indium on the flat solid iron substrate are slightly decreasing with increasing temperature, which are approximately 22° at 701 K and 18° at 1048 K. On the other hand, the contact angle of liquid bismuth was about 112° at 773 K. It means that liquid bismuth on the iron substrate does not show good wettability at relatively low temperature. However, bismuth did show better wettability at higher temperature. The effect of temperature on the contact angle of liquid bismuth on the flat solid iron substrate is more sensitive to temperature than that of liquid indium, and the contact angle of liquid bismuth on iron substrate is 90° at around 950 K, and about 80° at 1050 K. This is more or less similar to the results of A. T. Hasouna et al. than that of S. I. Popel.

3.2 Wetting behavior of liquid indium and bismuth on surface-porous iron substrate

The change in the wetting behavior with time of liquid indium on the porous layer formed at the iron substrate surface is shown in Figs. 6. In Fig. 6(a), liquid indium appears from an alumina tube. Figure 6(b) shows indium droplet just as it is dropped onto the iron substrate, and from that time the droplet wetted on the substrate, as shown in the subsequent figures. The apparent contact angle of liquid indium decreased with time. The apparent volume of the liquid metal at the surface of the surface-porous iron substrate decreased with time, and finally the droplet disappeared in 70 s, as shown in Fig. 6(f).

The effect of temperature on the apparent contact angle of liquid bismuth dropped on the surface-porous iron substrate is shown in Fig. 7. The contact angle between liquid bismuth and the substrate was about 116° at 773 K, which was the temperature of the liquid metal as it dropped. As the temperature was increased, there was no significant change to the apparent angle until around 950 K. Above 950 K, the apparent contact angle of liquid bismuth on the porous iron substrate started to decrease, and finally the bismuth droplet disappeared at around 1020 K.

4. Discussion

As shown in Fig. 6, liquid indium, which was dropped onto the surface-porous iron substrate at 773 K, disappeared from the surface of the substrate in 70 s. This is because the contact angle of liquid indium on the flat solid iron substrate is much lower than 90°. In other words, liquid indium with
solid Fe shows so-called good wettability. Therefore, liquid indium penetrated into the iron porous layer by capillary force. In addition to indium, unusual wetting behaviors have been confirmed on the reduced iron substrates with liquid metals such as Cu, Ag, and Sn. Contact angles of liquid copper on solid iron have been reported by L. H. Van Vlack and H.-H. Huang et al., which are almost 0° and 6.5° at 1373 K and 1393 K, respectively. Liquid silver has the contact angle of 35° on the solid iron at around the melting point. A. P. Tomsia et al. have also investigated the contact angle of silver on three kinds of substrates (Armco Fe, Marz Fe, and APT Fe) at 1273 K, and they reported that average equilibrium angles in the range of 36 to 57°. Protsenko found that 500 s after dropping liquid tin in He onto solid iron, liquid tin has contact angle of a nearly constant value of 25° at 673 K, although the initial value is close to 90°. The contact angles of liquid metals described above on the solid iron are always much smaller than 90°. Therefore, solid iron is wetted well by liquid indium, Cu, Ag, and Sn, probably even for temperatures just above the melting point of each metal. Thus, unusual wetting occurs with these liquid metals on the porous iron substrate prepared by the oxidation-reduction process. Bismuth droplet, which was put on the porous iron substrate at 773 K, did not show the unusual wetting phenomenon, because the contact angle of liquid bismuth on the flat solid iron substrate was more than 90° at this temperature. However, at 950 K, liquid bismuth on the flat iron has the contact angle of almost 90°. The apparent contact angle of liquid bismuth on the porous iron substrate was decreasing at temperature higher than 950 K. Finally, bismuth disappeared at the surface of the porous iron substrate. This was because liquid bismuth on the flat solid iron substrate has contact angle less than 90° above 950 K, showing good wettability. Therefore, liquid bismuth penetrated into the iron porous layer formed at the surface of the iron substrate, as did liquid indium. It is found that the unusual wetting depends on the normal contact angle of liquid metals on the flat solid substrates.

5. Conclusions

In the present study, we measured the contact angle of liquid indium and bismuth on the flat solid iron substrate to investigate the wetting behavior between the liquid metals and the surface-porous iron substrate.

At a temperature range of 701 to 1048 K, the contact angle of liquid indium on the flat solid iron is 22 to 18°. On the other hand, the contact angle of liquid bismuth on the solid iron changes about from 112 to 80° as temperature increases from 770 to 1050 K. Liquid indium penetrates into the porous layer formed on the iron substrate even at 773 K. Liquid bismuth also shows the unusual wetting on the porous iron substrate, when the temperature is higher than about 950 K, at which the contact angle for the flat iron substrate is less than 90°. Therefore, it is found that the unusual wetting depends on the normal contact angle of liquid metals on the flat solid substrates.

REFERENCES