Solidification behavior of Al–20.6%Cu alloy under AC magnetic field

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In recent years, using the electromagnetic field to control the solidification process is getting more and more attention because of its unique and outstanding effect [1–6]. Phase diagrams play an important role in the development of new materials and in the establishment of working processing. Since the thermodynamics and dynamics conditions will alter by the application of an electromagnetic field during solidification, the liquidus and solidus temperatures of an alloy system are likely to change. It is therefore meaningful to study the variation of liquidus and solidus temperatures of an alloy solidified under electromagnetic fields. Some investigation of the influence of magnetic field on the solid phase transformation were reported, Kakesshita [7, 8] found that the magnetic field could increase the martensitic transformation temperature. So far the study of the effect of magnetic fields on the liquidus and solidus temperatures has not been seen in literature.

The resistance is one of the physical properties sensitive to the phase transformation of metals. Consequently, resistance survey is a useful assistant way for measuring phase transformation [9]. The resistance of metal is the statistical result of the scattering of a great amount of electrons. The bigger the scattering probability (P), the bigger the resistivity [10]. Since the degree of disorder of atoms in the liquid metal is much higher than that of the solid metal, the P of the liquid metal is much bigger than that of the solid metal. If measuring the resistance during the solidification process, there will be two saltations at the liquidus temperature and solidus temperature on the resistance–temperature (R-t) curve. We can find the liquidus and solidus temperatures from the two turning points.

The resistances were measured with double bridges. The experimental setup consists mainly of five parts: a resistance furnace, a working coil, a variable-frequency power supply, a temperature control power supply and a double bridge device. The working coil circles outside of the resistance an AC magnetic field can be generated. A cylindrical corundum crucible with Al-20.6%Cu alloy inside it was inserted into the resistance furnace, than heated to melt and held for 10 min at 700°C. An AC current was applied through the coil to generate AC magnetic field of intensity being 0.12T on the sample until the completion of solidification. The resistance of the sample was measured at the temperature interval for every 2°C during the solidification process. The other sample was treated in the same way except that no magnetic field was applied to. The liquidus and solidus temperatures of the alloy solidified under different conditions were determined from the R-t curves. In order to verify these results obtained hereinbefore, the quenching experiments were done. Some pieces of Al–20.6%Cu alloy inside the cylindrical corundum crucible was heated to melt and held for 10 min at 700°C. An AC magnetic field of 0.12T was applied on the sample, the melt was then cooled to 595 and 553°C respectively at a cooling rate of 5°C/min and held at each temperature for 15 min before being quickly quenched into water. The same procedure was repeated except that no magnetic field was applied to. Samples were cut at the middle part, polished and etched in a mixture acid for metallographic examination. The microstructures were observed by an optical microscope, Leica DMR.

Fig. 1 shows the R–t curves during the solidification of Al-20.6%Cu alloy. When the alloy solidified without a magnetic field, the liquidus temperature was 596°C, and the solidus temperature was 544°C (Fig. 1a). From the equilibrium phase diagram of Al–Cu system, the liquidus temperature is 600°C and the solidus temperature is 548°C. The measured liquidus and solidus temperatures are both lower than the equilibrium transformation temperatures by 4°C. This difference may be due to the existence of a little degree of supercooling during the solidification process. Under an AC magnetic field (Fig. 1b), the liquidus and solidus temperatures are increased by 8 and 20°C respectively comparing with the result without magnetic field (Fig. 1a). Because the cooling conditions of the solidification process without magnetic field or under an AC magnetic field are same, we may conclude that AC magnetic field can increase the liquidus and solidus temperatures of this alloy.

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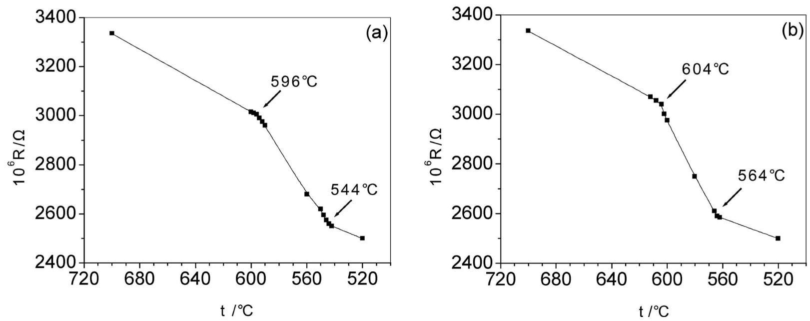

Figure 1 Resistance of Al-20.6%Cu alloy versus temperature under different conditions during solidification (a) without magnetic field (b) AC magnetic field (B=0.12T).

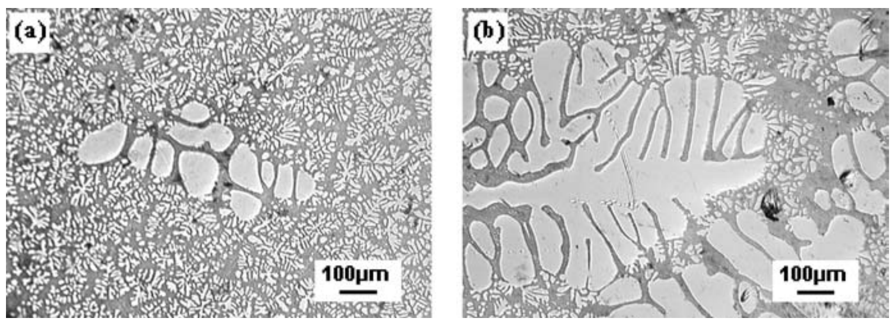

Figure 2 Microstructures of Al-20.6Cu alloy quenched at 595°C (a) without magnetic field (b) AC magnetic field ($B = 0.12$T).

The microstructures of Al–20.6%Cu alloy samples quenched at 595°C are shown in Fig. 2. Fig. 2a shows the microstructure of the sample without magnetic field, we can see that in addition to some eutectic structure and fine α-Al, there is a little amount of coarse primary α-Al. We know that if the sample is quenched from the liquid state, the quenching microstructure should be very fine, and if is quenched from the two-phase region, the quenching microstructure should include both fine structure and coarse structure formed prior to quenching. Therefore, the existence of the coarse primary α-Al can be regarded as the indicator as to whether the quenching temperature is below the liquidus temperature. The microstructure in Fig. 2a indicates that under the solidification condition without magnetic field the liquidus temperature is at the quenching temperature of 595°C or slightly above. The microstructure of the sample solidified under AC magnetic field is shown in Fig. 2b, there is a lot of coarse primary α-Al. This indicates that under AC magnetic field the liquidus temperature is much higher than the quenching temperature of 595°C. In a word, from Fig. 2, we can estimate that with the application of AC magnetic field during solidification, the liquidus temperature of the alloy increases. This result accords with that obtained by resistance method.

Fig. 3 shows the microstructure of Al-20.6%Cu alloy quenched at 553°C. Under the condition without a magnetic field (Fig. 3a), the microstructure consists of eutectic structure, big primary α-Al and fine α-Al. The existence of fine α-Al indicates that there is some amount of residual liquid in the sample at the quenching temperature, i.e. the solidus temperature is lower than 553°C. Observing the microstructure of the sample solidified under AC magnetic field (Fig. 3b), there is not any fine α-Al, only have big primary α-Al and eutectic structure, indicating that under AC magnetic field the solidus temperature is higher than 553°C. We might conclude from this phenomenon

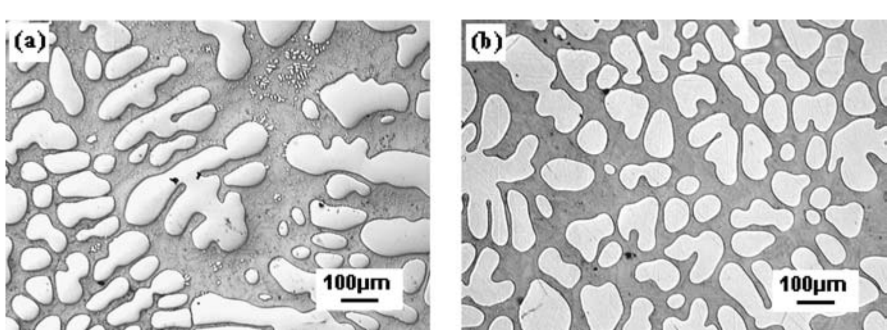

Figure 3 Microstructure of Al-20.6Cu alloy quenched at 553°C (a) without magnetic field (b) AC magnetic field ($B = 0.12$T).

that the solidus temperature increases with application of AC magnetic field during the solidification process of the alloy. The result also accords with that obtained by resistance method.

From Faraday's law of Electromagnetism, when an AC current goes through the solenoid coil, the coil will generate an alternation magnetic field $\vec{B}$, which in turn, gives rise to an induced current $\vec{j}$ in the molten metal. Thus, the interaction between $\vec{j}$ and $\vec{B}$ produces the electromagnetic body force: $\vec{f} = \vec{j} \times \vec{B}$. This force can bring the compelled convection and vibration in the melt. Therefore the energy fluctuation and structure fluctuation of melt increase by the influence of AC magnetic field. The increase of energy fluctuation makes the barrier potential required by the atom clusters jumping from liquid phase to solid phase at the front of liquid–solid interface decrease, and the increase of structure fluctuation brings the increase of the formation probability of the atom cluster, which has the radius of critical crystal nucleus. Therefore, the solid phase will appear at a higher temperature, and the liquidus temperature increases. On the other hand, the increase of energy and structure fluctuation also speed the growth velocity of crystal, thus the transformation from liquid to solid could be completed at a higher temperature, and the solidus temperature increases as a result.

In conclusion, when the molten metal solidified under AC magnetic field, the liquidus and solidus temperatures increase. The solidification microstructures of quenched samples can nicely verify the result obtained by resistance method.

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