Refining Mechanism of Solidified Structure of Alloy by Electromagnetic Refining Process

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Refining mechanism of solidified structure in which a static magnetic field and an alternating electrical current are simultaneously imposed on the local area of a metal or an alloy, has been experimentally examined using a Sn–10mass%Pb alloy. The refining period of the structure was examined by changing the imposing period of the electromagnetic vibration on the sample and it was confirmed that the refining period was the initial stage of solidification. The refining region was specified to be around the electrodes by inserting a stainless steel wire net in the sample while it was independent of the inserting position of the electrodes. Convection was induced by the electromagnetic vibration because temperature difference in the sample drastically decreased as soon as the vibration was excited in the sample. From these experimental results, the estimated mechanism in this process is that dendrite tips around the electrodes are cut off by the electromagnetic vibration in the initial stage of the solidification and it spread to the whole area of the sample by the convection induced by the electromagnetic vibration. Furthermore, nucleation is induced by an intense electromagnetic vibration.

KEY WORDS: solidification; crystal refinement; electromagnetic processing of materials; local imposition of oscillation.

1. Introduction

It is well known that mechanical properties of a metal or metallic alloy such as strength and toughness highly depend on its structure so that many attempts have been done to obtain a refined structure. One of the most typical methods is inoculation. This is a very useful method in industry for ingot-casting of cast-iron and aluminum. But, added elements by the inoculation may prevent recyclibility of a product. Rapid cooling is an excellent way to refine the structure even though it is impossible to apply for a large size product because heat extraction rate from a metal is restricted by its size.

Vibration is also an attractive tool because it promotes nucleation in a liquid. A structure can be refined by mechanically vibrating a vessel filled with a liquid metal during solidification. But, this method has a difficulty to produce a large size product because high power is needed for vibration of a vessel with a metal. Then, an electromagnetic excitation method of vibration has been proposed and some researchers have succeeded to refine the structures. Vives and Radjai et al. refined aluminum alloy structures by applying the vibration, which was excited by the simultaneous imposition of a static magnetic field and an alternating current on the whole of the alloys during solidification. On the other hand, the authors proposed the other refining method in which a static magnetic field and an alternating current are simultaneously imposed on a local volume of a metal or an alloy. This method is useful for a large size product because of local imposition of the vibration.

In this paper, the mechanism of the solidified structure in the method proposed by the authors has been experimentally investigated.

2. Experiment

2.1. Experimental Apparatus

Experimental apparatus is shown in Fig. 1. An Sn–10mass%Pb alloy of 0.3 kg was poured into a glass rectangular vessel of 40 mm length and 25 mm width. This sample was set in the bore of a super-conducting magnet which can excite a downward static magnetic field of 7.5 T. A couple of copper electrodes were inserted in the vicinity of a short wall of the vessel to supply an alternating current to the sample. The amplitude and frequency of the alternating current were 80 A and 2 kHz, respectively. The electrodes were covered by an electrical insulator except 5 mm · 5 mm square tip as shown in Fig. 1. To control temperature distribution in the sample, one of short walls of the vessel was heated while the other one was cooled. Furthermore, the copper electrodes were heated to reduce temperature disturbance caused by heat extraction through the electrodes from the sample. Temperature profiles in the sample were measured at three points along the long wall and 20 mm above from the bottom. And each measuring point was located near the heating short wall and the cooling short wall.
and their middle, respectively. The alternating current was turned on when the sample temperature became 250°C which is 31°C higher than the liquidus temperature, and it was turned off when the temperature became 170°C which is 13°C lower than the eutectic temperature. On the other hand, the static magnetic field was imposed on the sample during the experiment. Then, an electromagnetic vibration was excited around the electrodes during the simultaneous imposition of the magnetic field and the alternating current.

2.2. Temperature Profile

Typical temperature profiles in the sample solidified with and without the electromagnetic vibration are shown in Fig. 2. The solidifying duration of the sample with the alternating current was longer than that without the alternating current because of the Joule heating effect. The temperature near the heating wall was higher than that near the cooling wall in both samples while the temperature gradient in the sample without the electromagnetic vibration was large compared with that in the vibrating sample. The reason why the temperature was almost uniform in the latter case might be convection induced by the electromagnetic vibration in the sample as mentioned below. Recalescence was clearly observed in the case without the electromagnetic vibration. On the other hand, it was observed only at the cooling part in the case with the electromagnetic vibration.

2.3. Macrostructure

Macrostructure of the samples with and without the electromagnetic vibration are shown in Fig. 3. In the case with the electromagnetic vibration, most of the observed cross-section is refined while the whole observed area of the non-vibrating sample is coarse macrostructure. These results clearly showed that the electromagnetic vibration is required to refine the solidified structure. The macrostructure
is refined at the points where recalescence is not observed and it is coarse at the points where recalescence is observed in the both samples. Therefore, the electromagnetic vibration excited in the sample might affect on nucleation in this process.

2.4. Refining Period during Solidification

To confirm when the structure was refined during the solidification, the imposing period of the alternating current was changed while the static magnetic field of 7.5 T was imposed during all period of the solidification. The alternating current was turned on when the sample became 250°C and it was turned off when the solid fraction of the samples became certain values of 0.09, 0.44, 0.70 and 0.79, respectively. Solid fraction was evaluated from the measured temperature at the middle of the sample. The evaluated value of 0.09 might contain some error caused by the measuring accuracy of the temperature, because the corresponding temperature is only one degree lower than the liquidus temperature.

The average grain size was introduced as the index of solidified structure refinement. It was evaluated as the inverse of intersection numbers between grain boundaries and diagonals of the 10 mm · 10 mm squares. The squares A, B, C and D were drawn near each corners of the vertical cross section of the samples. These are shown in Fig. 4 with the evaluated average grain size indicated as a function of solid fraction of the sample when the imposition of the alternating current was finished.

In the case that the electromagnetic vibration was applied only in the initial stage of the solidification (solid fraction is 0.09), the refining effect is only observed in the neighborhood of the electrodes (squares C and D) while the average grain size at the opposite side of the electrodes (squares A and B) is approximately the same level with the sample without the electromagnetic vibration. For the sample in which the electromagnetic vibration was stopped when the solid fraction became 0.44, the average grain size decreases at all measuring points. And the decrease in the average grain size slows down and approaches to be a constant value. Therefore, the solidified structure is mainly refined in the initial stage of the solidification, especially in the vicinity of the electrodes.

2.5. Refining Region in Sample

To confirm whether refining takes place only around the electrodes or it takes place in the whole sample, a stainless steel wire net was inserted in the vessel as shown in Fig. 5. The experimental conditions are summarized in Table 1.

At the beginning, the alloy was solidified without an electromagnetic vibration to check the effect of the inserted wire net on the solidified structure. That is, the static magnetic field of 7.5 T was imposed on the sample while the alternating current was not imposed on it during the solidification. In this case, a coarse macrostructure similar to that without the wire net was obtained as shown in Fig. 5. This

![Fig. 4. Average grain size as a function of solid fraction when alternating current was turned off.](image)

![Fig. 5. Macrostructures with and without wire net (electrical current=0 A).](image)

| Table 1. Experimental condition. |
|----------------------------------|
| Magnetic field (T) | Electrical current (A) | Inserting position of electrodes | Wire net |
|-------------------|------------------------|---------------------------------|---------|
| 7.5               | 0                      | heater                          | ×       |
| 7.5               | 0                      | heater                          | ×       |
| 7.5               | 80                     | heater                          | ×       |
| 7.5               | 80                     | cooler                          | ×       |
| 7.5               | 80                     | cooler                          | ×       |
result showed that the wire does not affect the solidified structure in this experimental condition.

The macrostructures of the samples to which the alternating current of 80 A was supplied through the electrodes inserted near the heating short wall during the solidification were shown in Fig. 6. In the case with the wire net, refined macrostructure is obtained around the electrodes while coarse macrostructure is observed in the vicinity of the cooling short wall, and the wire net is approximately the boundary between these macrostructures. On the other hand, most of the cross-section is refined in the case without the wire net. This result suggests that the refining takes places around the electrodes in this experimental condition.

The solidified structures of the samples with and without the wire net in which the electrodes were inserted in the vicinity of the cooling short wall during the solidification are shown in Fig. 7. The whole region was refined in the case without the wire net. In the case with the wire net, the refined region is limited around the electrodes and coarse region is observed at the opposite side. And the wire net seems to be the boundary between the refined region and the coarse region. This result showed that the region where the refining takes place is around the electrodes and it is independent of its inserting position.

The microstructure of the sample with the wire net shown in Fig. 7 is shown in Fig. 8. Vertically aligned small circles in the middle picture are the cross-section of the wire-net. Then, dendritic microstructure observed in the coarse region drastically changes to equiaxed dendrites in the refined region at the boundary where the wire net exists. The size of dendrite arm observed in the right picture is approximately same with that of equiaxed grains. These results give us the refining mechanism that dendrite arms around the electrodes are cut off by the electromagnetic vibration in the initial stage of the solidification and it spreads to the whole area of the sample by convection. Convection induced by the electromagnetic vibration is described in the next section.

2.6. Effect of Electromagnetic Vibration on Nucleation

To confirm whether the electromagnetic vibration induces nucleation or not, the following experiment has been done. That is, one of the electrodes was added as a temperature measuring point to the three points mentioned in Sec. 2.1 as shown in Fig. 9, and the temperature measuring points were four. In this experiment, the turning on temperature of the alternating current was changed from the experiments mentioned above though imposing condition of the magnetic field was same with the former experiments. When the temperature at the electrode became 215°C which is 4°C lower than the liquidus temperature, the alternating current was turned on under the different electro-
magnetic conditions. The temperature profiles measured in the experiment are shown in Fig. 10.

In the case that magnitude of the static magnetic field was 1 T and effective value of the alternating current was 60 A, the measured temperature near the cooling short wall was lowest in the sample while that near the heating short wall was highest in it. And the temperature difference among each measuring point kept constant until the alternating current was imposed on the sample. As soon as the turning on the alternating current, the measured temperatures in the sample became almost uniform and decreased with oscillation. After 30 or 40 s, the measured temperatures suddenly rose due to nucleation in the sample. This result showed that the electromagnetic vibration did not induce nucleation but induced the convection in this case.

In the case that magnitude of the static magnetic field was 5 T and effective value of the alternating current was 60 A, the temperature distribution in this sample was similar to that in the former sample until the alternating current imposition. And as soon as the imposition of the alternating current, the temperatures measured at the four points became the liquidus temperature with oscillation because solidification started. This result means that the electromagnetic vibration induced the nucleation in this experimental condition. Therefore, the electromagnetic vibration induces nucleation when it is intense while it does not induce the nucleation when it is weak.

3. Conclusion

Experimental work has been done to investigate the refining mechanism of the solidified structure in the method proposed by the authors in which an alternating current and a static magnetic field are simultaneously imposed on a local region in a metal or an alloy.

The main results we obtained are as follows:

- Refining of solidified structure occurs in the initial stage of solidification around the electrodes and it is independent of inserting position of the electrodes.
- Convection is induced by electromagnetic vibration.
- The dendrite arm width in a coarse region is the same order with that in a refined region composed of equiaxed structure.
- An intense electromagnetic vibration induces nucleation. Therefore, mechanism in this process is estimated as follows.
- Dendrite arms around the electrodes are cut off by the electromagnetic vibration in the initial stage of the solidification and it spread to the whole area of the sample by the convection induced by the electromagnetic vibration.

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