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\(^1\) so that many attempts have been done to obtain a refined structure. Inoculation is one of the most popular methods. This is a very useful method in industry for ingot-casting of cast-iron, aluminum and their alloys. However, added elements by the inoculation may prevent recyclability of a product. Rapid cooling is an excellent way to refine the structure though it is impossible to apply for a large size product because of limitation of heat extraction rate from a metal or an alloy.

Vibration is also an attractive tool for the structure refinement during solidification because it promotes nucleation in a liquid.\(^2\) A solidified structure can be refined by mechanically vibrating a vessel filled with a liquid metal during solidification. However, this method has a difficulty to produce a large size product since high power is needed for vibration of a vessel with a metal. And the vibrating frequency is also limited because of the large inertia of the vessel. Then, an electromagnetic excitation method of vibration has been proposed and some researchers have succeeded to refine the structures. C. Vives\(^3\) and Radjai et al.\(^4,5\) 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 the local volume of a metal or an alloy\(^6\)–\(^9\).

In these processes,\(^4\)–\(^9\) the static magnetic field over one tesla has been applied using a superconducting magnet. Such a strong magnetic field is mainly used in a laboratory scale experiment because of its cost and limited magnetic field space. On the contrary, an electromagnet or a permanent magnet has been utilized in industry such as an electromagnetic brake in a continuous casting of steel though the maximum intensity of the magnetic field is less than one tesla. Therefore, decrease of the magnetic field intensity in the solidified structure refinement processes mentioned above is desired.

On the other hand, a direct current is an attractive tool to control molten steel because it has been applied in steel industry such as an electric furnace and a tundish plasma heating. Then, the simultaneous imposition of a direct current and a static magnetic field has been investigated for the refinement of the solidified structure.\(^10\)

In this study, solidification experiments have been done under the imposition of a direct current and a static magnetic field perpendicular each other for the excitation of an electromagnetic force in the local region of the sample to clarify the effect of operating parameters on the solidified structure. The electromagnetic force induced by the simultaneous imposition of the direct current and the static magnetic field does not excite the nucleation in this investigation. And the solidified structures obtained under the different intensities of the direct current and the static magnetic field are compared each other for optimization of the electromagnetic field in this process. Increase in the direct current is preferable for the refined structure formation under the constant magnetic field intensity. Under the constant product of the direct current and the static magnetic field, refining effect of the solidified structure is the same level under the certain value of the magnetic field. Over this critical magnetic field, the refining effect decreases because the melt flow caused by the imposed electromagnetic force is suppressed by the interaction between the magnetic field and the fluid motion.

KEY WORDS: solidification; crystal refinement; electromagnetic processing of materials; local imposition of electromagnetic force.
2. Experiment

2.1. Experimental Procedure

Experimental setup 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 superconducting magnet which can excite a static magnetic field in the vertical direction. A direct current was supplied to the sample through a couple of copper electrodes located in the neighborhood of a short wall of the vessel. To control the electric current passing region in the sample, the electrodes were covered by an electrical insulator except the 5 mm · 5 mm square tip. Because of the interaction between the electric current and the static magnetic field, an electromagnetic force was excited in the sample, which induced the melt flow in the sample.\(^{10}\) One of short walls of the vessel was heated while the other one was cooled for the temperature distribution control in the sample. Furthermore, the copper electrodes were heated to reduce temperature disturbance caused by heat extraction through the copper electrodes. Temperature curve in the sample was measured at the electrode tip. The imposition of the direct current was started when the sample temperature became 250°C which is 31°C higher than the liquidus temperature, and it was finished within 10 s after the temperature recovering accompanying the recalescence as shown in Fig. 2. On the other hand, the static magnetic field was imposed on the sample from the setting of the liquid sample into the superconducting magnet bore till its complete solidification. Therefore, an electromagnetic force was excited around the electrodes in the liquid state and in the initial stage of the solidification of the alloy. After the solidification, the vertical cross-section of the sample was cut and was polished by an emery paper of #2000 and was polished by a buffing compound with alumina particles of 0.05 μm. Then, it was chemically etched by a mixed liquid of distilled water, hydrochloric acid and iron(III) chloride.

2.2. Solidified Structure under Different Electric Current Intensity

Three samples were solidified to examine the effect of the direct current intensity on the solidified structure. The intensity of the direct current was changed between 0.3 A and 8 A while that of the static magnetic field was fixed at 5 T for the every sample. Imposing conditions of the electric current and the static magnetic field are summarized in Table 1. Temperature curves for the three samples are shown in Fig. 3. Because recalescence was clearly observed in the temperature curves for these samples, nucleation was not excited by the electromagnetic force in these experimental conditions.

The macrostructures of the samples are shown in Fig. 4. When the intensity of the direct current was 0.3 A (sample I), the solidified structure was refined only around the current passing region where the electromagnetic force was excited and the solidified structure in the other region was
coarse. In the cases that the intensity of the direct were 3 A and 8 A (samples II and III), all of the observed area was completely refined. That is, the electric current intensity of 3 A is enough for the solidified structure refinement in these experimental conditions.

An intersection number between grain boundaries and the diagonals of the 10 mm · 10 mm squares is introduced as the grain size index of the solidified structure. That is, a large intersection number indicates that the sample is composed of small grains. The square was drawn around the current passing region on the cut plane of the sample as shown in Fig. 4. Using this square, the intersection numbers were evaluated and the result is shown in Fig. 5. As the intensity of the direct current supplied to the sample increases, the intersection number increases. However, the intersection number is not linearly proportional to the DC electric current intensity while they show a positive correlation.

2.3. Solidified Structure under Constant Electromagnetic Force

Solidification experiment was done under the constant intensity of the electromagnetic force in which intensities of the direct current and the static magnetic field were varied. Imposing intensities of the electric current and the static magnetic field are summarized in Table 2. The sample II in this table is the same sample with that in Table 1.

The macrostructures of these samples are shown in Fig. 6. When the intensities of the static magnetic field and the direct current were 7.5 T and 2 A, respectively (sample VI), both the refined structure region and the coarse structure region were observed. The former region might correspond to the strong circulation flow region while melt flow in the latter region might be weak. In the case that the 0.3 T magnetic field and the 50 A electric current were imposed on the alloy (sample IV), most of the observed area except the below of the electrodes was refined. The solidified structures of the samples V and II were completely refined. Therefore, the solidified structure depends on the intensities of the electric current and the magnetic field though their product is the same value.

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The intersection number between grain boundaries and the diagonals of the 10 mm · 10 mm squares is also used for the evaluation of solidified structure grain size for these samples. The square for the evaluation of the intersection number is shown in Fig. 6. As the intensity of the direct current supplied to the sample increases, the intersection number increases. However, the intersection number is not linearly proportional to the DC electric current intensity while they show a positive correlation.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Field</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>0.3T</td>
<td>50A</td>
</tr>
<tr>
<td>V</td>
<td>3T</td>
<td>5A</td>
</tr>
<tr>
<td>II</td>
<td>5T</td>
<td>3A</td>
</tr>
<tr>
<td>VI</td>
<td>7.5T</td>
<td>2A</td>
</tr>
</tbody>
</table>

Table 2: Experimental condition under constant electromagnetic force.
Because recalescence was clearly observed in the temperature curves for not only the samples shown in Fig. 8 but also for the samples shown in Fig. 3, nucleation was not excited by the simultaneous imposition of the static magnetic field and the direct current in the conditions adopted in this investigation. From this result and the fact that the flow is induced by the simultaneous imposition of the static magnetic field and the direct current, it may be said that the mechanism of the structure refinement is multiplication caused by the melt flow.

The melt flow in the sample induces the eddy current. The eddy current density is indicated as follows when the electric field is neglected:

\[
\mathbf{J} = \sigma (\mathbf{v} \times \mathbf{B}) \quad (1)
\]

where \( \mathbf{B} \) is magnetic flux density, \( \mathbf{J} \) is current density, \( \mathbf{v} \) is velocity and \( \sigma \) is electric conductivity, respectively.

Because of the interaction between the eddy current and the imposed static magnetic field, an electromagnetic force is excited and its direction is opposite to the melt flow direction.

\[
\mathbf{F} = \mathbf{J} \times \mathbf{B} = \sigma (\mathbf{v} \times \mathbf{B}) \times \mathbf{B} = \sigma \mathbf{v} \times \mathbf{B}^2 \quad (2)
\]

This electromagnetic force is in proportion to the square of the magnetic field intensity. When the magnetic field intensity is over the critical value, this electromagnetic force exceeds the viscous force and the inertial force, and it becomes dominant braking force of the melt flow. On the other hand, the driving force of the melt flow is the same under the constant product of the imposed electric current and the static magnetic field. This is the reason why the refining effect decreases in the case of the 7.5 T magnetic field in comparison with the 0.3 T, 3 T and 5 T magnetic field cases.

3. Conclusion

The Sn–10%Pb alloy has been solidified under the simultaneous imposition of a direct current and a static magnetic field on the local region of the sample to clarify the effect of operating parameters on the solidified structure. The main results obtained in this investigation are as follows.

1. The simultaneous imposition of the direct current and the static magnetic field on the sample does not excite the nucleation.

2. Increase in the direct current is preferable for the refined structure formation under the constant magnetic field intensity.

3. Under the constant product of the direct current and the static magnetic field, refining effect of the solidified structure is the same level under the certain value of the magnetic field. The refining effect decreases over this critical magnetic field because the melt flow caused by the imposed electromagnetic force is suppressed by the interaction between the magnetic field and the melt flow itself.

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REFERENCES