Control of Solidified Structure of Cast Metal by Imposing Electromagnetic Field

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In order to improve the quality of cast metal and to control solidification of metals, two new casting processes controlling metal solidification by imposing electromagnetic field are developed. One is simultaneous imposition of multiple-electromagnetic fields from the outside of a cold-crucible copper mold during continuous casting of Sn–4.5 mass% Pb alloy, and the other is the imposition of a rotating magnetic field during the unidirectional solidification to make in situ surface composite with special mechanical and physical properties. The experimental results show that multiple-electromagnetic fields can not only eliminate surface defects, but also improve solidification structure of cast metal. Moreover, a new kind of composite pipe and gear of Al–12.6 mass% Si eutectic alloy was made by imposing electromagnetic stirring during unidirectional solidification. This suggests a new method of making surface composite with special mechanical and physical properties. It is also found that a separated eutectic occurs in the anomalous eutectic and the separated phase is the leading faceted phase with solution entropy over 23 J/mol·K.

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1. Introduction

It is known that quality of cast metal can be improved by imposing electromagnetic field during the metal solidification. For example, a soft contacting solidification process has been proposed to improve the surface quality of cast metal, in which a high frequency magnetic field is imposed from the outside of a mold for reducing the metallic static pressure between the mold and the melt. Various mechanisms to improve the surface quality of cast metal in the soft contacting solidification have been discussed. It is also found that coarse columnar grains appear in the solidification structure of the cast metal. Electromagnetic stirring (M-EMS) could refine grains and decrease segregation of continuously cast metal. However, it also decreases the flux channel between the melt and the mold and causes defects in the cast metal, because the meniscus shape is changed due to action of centrifugal force generated by EMS. Another example is the anomalous eutectics that can be separated on macroscopic scale by imposing electromagnetic stirring to get in-situ surface composite with special mechanical and physical properties. The growth mechanisms of separated eutectic phenomenon have been discussed.

In this paper, the effect of simultaneous imposition of multiple-electromagnetic fields on quality of cast billet is investigated. Multiple-electromagnetic fields consists of high frequency magnetic field excited by a high frequency coil (HFC) around a mold and rotating magnetic field excited by a commercial frequency coil (CFC). Moreover, the EMS is adapted to directionally cast eutectic alloy to make composite pipe and gear. The mechanism to separate the anomalous eutectics by rotating magnetic field is investigated.

2. Metal Solidification under Electromagnetic Fields

2.1 Experimental method

2.1.1 Cast experiment under multiple-magnetic field

A schematic view of the experimental apparatus is shown in Fig. 1. The solenoid coil (HFC) and electromagnetic rotating coil (CFC) are installed to surround the square copper mold of 30 mm × 30 mm. The HFC is connected to a high frequency electric generator with maximum power capacity of 85 kW and maximum frequency of 80 kHz. The CFC is connected to a commercial frequency electric generator serving as a stirrer. During continuous casting, a steel-simulated alloy Sn–4.5 mass% Pb is poured into the mold through a submerged entry nozzle. The meniscus level is maintained at the position of 10 mm from the top of the mold. The solidification structures of cast metal are analyzed. The experimental conditions are shown in Table 1.

2.1.2 Separated eutectic experiment

In the separated eutectic experiment, the copper mold shown in Fig. 1 was substituted by aluminum oxide mold (ø60 mm × 200 mm) and was placed in a heating furnace. The unidirectional solidification is performed by lowering the mold from the furnace at a speed of 0.014–0.042 mm/s. The procedure is as follows: Firstly, about 1 kg alloy is loaded into an aluminum oxide mold; Secondly, the load is melted by the heating element. Thirdly, stirring is carried out for about 1800 s, to homogenize the melt. Fourthly, the drawing speed...
of the cast metal becomes smooth. Figure 4 indicates the surface roughness of the cast metals measured by a displacement sensor under the conditions with and without electromagnetic field. The surface roughness of cast metals is reduced from 150 to 30 µm when \( P_h \) increased from 0 to 20 kW.

Figures 5(a), (b), and (c) represent the effect of multiple-electromagnetic field on macroscopic structures of the cast metals. It is obvious that without rotating magnetic field \( (P_c = 0) \), the macroscopic structure of the cast metals is mainly comprised of coarse columnar crystal even if \( P_h = 20 \text{ kW} \); after rotating magnetic field is imposed, more equiaxed crystals appear. The stronger the magnetic flux density, the higher the fraction of the equiaxed grains. When \( P_c = 0.1 \text{ kW} \), the macroscopic structure of the cast metal consists completely of equiaxed grains.

A high frequency magnetic field imposed on the meniscus of melt can improve the surface quality of cast metal, but can not refine the coarse columnar grains in the solidification structure. Electromagnetic stirring can refine grains structure, but it also decreases the flux channel between the melt and the mold. When multiple-electromagnetic fields are imposed, electromagnetic pressure generated by the high frequency magnetic field \( (B_z) \) drives the melt away from the mold wall and widens the flux channel, and the stirring force generated by rotating magnetic field \( (B_x) \) refines the solidifi-

### Table 1 Experimental conditions of continuous casting.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Alloy</td>
<td>Sn-4.5 mass% Pb</td>
</tr>
<tr>
<td>Pouring temperature</td>
<td>548 K</td>
</tr>
<tr>
<td>Billet size</td>
<td>30 × 30 mm</td>
</tr>
<tr>
<td>Casting speed</td>
<td>5 mm/s</td>
</tr>
<tr>
<td>Mold oscillation</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>±3 mm</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.833 Hz</td>
</tr>
<tr>
<td>Mold flux</td>
<td>silicon oil</td>
</tr>
<tr>
<td>Electric power</td>
<td>20 kW, 30kHz (HFC)</td>
</tr>
<tr>
<td></td>
<td>0.1 kW, 50Hz (CFC)</td>
</tr>
</tbody>
</table>

and rotation rate are regulated and water-cooled through the bottom block. Finally, the microstructures are analyzed. The abrasive samples are measured with rectangle specimens, the model of the grinding machine being CPM-II.

### 2.2 Experimental results and discussion

#### 2.2.1 Distribution of magnetic field in the mold

When the high frequency electric generator \( (P_h = 20 \text{ kW}) \) and the commercial frequency electric generator \( (P_c = 0.1 \text{ kW}) \) were imposed, the magnetic flux density distribution along the central axis of the mold measured by a sensor coil is shown in Fig. 2. Curves 1 and 2 indicate the magnetic flux densities \( B_z \) and \( B_x \) (parallel and perpendicular to the casting direction). It is noted that, in the upper part of the mold, magnetic flux density \( B_z \) (parallel to the casting direction) is larger than \( B_x \) (perpendicular to the casting direction), but in the lower part of the mold, \( B_x \) is larger than \( B_z \). It is also found that \( B_z \) is uniform in the vicinity of the meniscus, benefiting to keep the meniscus stable, and the maximum value of \( B_x \) is at 70 mm from the top of the mold, producing a stirring force.

#### 2.2.2 Effect of multiple-magnetic field on quality of cast metal

The surface appearance of the cast metal under conditions with and without magnetic field is shown in Fig. 3. In the absence of electromagnetic field, regular oscillation mark is found. After imposing of electromagnetic field, the surface

![Fig. 2 Distribution of multiple-electromagnetic field in the mold.](Image)

![Fig. 3 Surface appearance of cast billet with magnetic field.](Image)

![Fig. 4 Effect of magnetic field on surface roughness.](Image)
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30 mm

Fig. 5 The effect of magnetic field on solidification structure of cast metal. (a) $P_h = 20 \text{kW}$, $P_c = 0 \text{kW}$, (b) $P_h = 20 \text{kW}$, $P_c = 0.04 \text{kW}$, (c) $P_h = 20 \text{kW}$, $P_c = 0.1 \text{kW}$.

Macrostructure of composite materials of Al–12.6 mass% Si eutectic alloy. (a) Composite pipe, (b) Composite gear.

Microstructures of some separated eutectic. (a) Fe–3.9 mass% C–1.2 mass% Si system, (b) Al–1.8 mass% Fe system, (c) Pb–55.5 mass% Bi system, (d) Sn–8.6 mass% Zn system.

2.2.3 Separated eutectics under rotating magnetic field

It is found that some eutectics may be separated on macroscopic scale by imposing rotating magnetic field\(^8,^9\) and can be used to make \textit{in situ} surface composite with special mechanical and physical properties, without adding any reinforced particles\(^10,^11\). To find the mechanism of the separated eutectic phenomenon, Al–12.6 mass% Si, Fe–3.9 mass% C–1.2 mass% Si, Al–1.8 mass% Fe, Pb–55.5 mass% Bi and Sn–8.6 mass% Zn alloys are investigated by experimental method explained in Section 2.1.2.

Figure 6 shows the typical macrostructures of a new kind
composite pipe and gear of Al–12.6 mass% Si alloy under the condition of electromagnetic stirring. Obviously, silicon-rich layer composed of large silicon particles exists on the periphery of the specimen. For the pipe, the Si-rich layer of inner surface is obviously thicker than that of outside surface. For the gear, the silicon mainly distributes along the teeth contour.

Typical microstructures of separated eutectics of some eutectic alloys are shown in Fig. 7. Figures 7(a), (b), (c), and (d) show the microstructures of a series of separated eutectic systems: Fe–3.9 mass% C–1.2 mass% Si, Al–1.8 mass% Fe, Pb–55.5 mass% Bi and Sn–8.6 mass% Zn alloys. It is noted that two component phases of the eutectics, formerly growing cooperatively, are separated. There are hypo-eutectic structures in the inner area and rich layers of faceted phase C, Al, Fe, Bi, Zn accumulated on the periphery of specimens.

According to the solidification theory, the metal/metal eutectic is usually described as nonfaceted/faceted, and the metal/nonmetal eutectic faceted/nonfaceted. However, for the metal/intermetallic eutectic, the condition is very complex: the same materials can behave either metallic or nonmetallic depending on the two constituents’ thermodynamic properties, i.e., on their solution entropy $\Delta S$, controlled by the heat exchanges of the two constituents. The solution entropy is found to be the key thermodynamic factor dominating the eutectic microstructures. Croker et al.\textsuperscript{12,13} consider that normal eutectics exist when $\Delta S \leq 23 \text{ J/mol K}$; while anomalous eutectics take place at higher values of solution entropy. The results in Figs. 6, 7 show that the separated eutectic can occur in Al–12.6 mass% Si, Fe–3.9 mass% C–1.2 mass% Si, Al–1.8 mass% Fe, Pb–55.5 mass% Bi and Sn–8.6 mass% Zn alloys, which belong to anomalous eutectic alloys ($\Delta S > 23 \text{ J/mol K}$). Other experimental results\textsuperscript{9} show that the separated eutectic can not occur in normal eutectic alloys ($\Delta S \leq 23 \text{ J/mol K}$).

For the anomalous eutectic, the solid/liquid interface is usually uneven due to its interface boundary energy anisotropy, thermal anisotropy as well as growth anisotropy,\textsuperscript{12} so that the faceted phase protrudes into the liquid before the growth of solid/liquid interface. It is owing to this reason that the leading faceted phases, generally nonmetal or intermetallic phases, are sensitive to forced flow and easy to be broken and carried to the mold wall to form the faceted phase rich layer on the periphery of specimen.\textsuperscript{14} This process is shown in Fig. 8.

In order to prove the above process, a round stainless steel net of φ30 mm × 200 mm is placed into the melt to test the movement of solid particles before the solidification of Al–12.6 mass% Si alloy. Figure 9 shows the macroscopic structures of the ingot with the stainless steel net. It is found that the Si-rich layer is accumulated along the net, with little on the surface of ingot. This proves the physical process of separated eutectic. In fact, the rich layer exists before 20 mm of solid-liquid interface once quenched.

The abrasive measurement result shows that the surface composite samples fabricated by this method are superior to the usual solidification samples of same composition, as shown in Fig. 10. This suggests a possibility of making in situ surface composite.

3. Conclusions

The effect of electromagnetic field imposed from the outside of a mold on solidification of cast metal is studied. The experimental results are as follows:

1. The surface quality of cast metal is improved and the fraction of equiaxed crystals in the solidification structure increases by imposing multiple-magnetic field.

2. A separated eutectic only occurs in the anomalous eutectic and the separated phase is the leading faceted phase with solution entropy over 23 J/mol K.

3. The electromagnetic stirring during unidirectional solidification can be used to fabricate composite pipe and gear.

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Fig. 8 Schematic illustration of the formation of the separated eutectic.

![Fig. 8](image)

Fig. 9 Macrostructure of composite ingot of Al–12.6 mass% Si alloy with stainless steel net.

![Fig. 9](image)

Fig. 10 Weight loss versus abrasive time of Al–12.6 mass% Si eutectic.

![Fig. 10](image)
This suggests a new preparation method for surface composite.

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