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Anisotropic Effect of Magnetohydrodynamics on Metal Solidification

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Anisotropic effect of magnetohydrodynamics on solidification of Pb–10%Sn alloy has been studied in a magnetic field generated by a superconducting magnet. Experimental castings have been conducted with a mold designed to solidify the alloy unidirectionally. It has been observed that equiaxed structure changes to columnar with increasing the intensity of magnetic field parallel to the solidifying direction. On the other hand, a structural change has been slightly obtained with the field perpendicular to the direction of the solidification.

Transport of heat in a mercury pool examined under the various conditions of magnetic fields has revealed that temperature distribution in mercury pool is affected strongly by the direction of a magnetic field through the anisotropic effect of magnetohydrodynamics on the convection. This has demonstrated that anisotropic effect of a magnetic field gives rises to the structural change of the solidification of the metal alloy.

KEY WORDS: D.C. magnetic field; magnetohydrodynamics; Hartmann number; Rayleigh number; thermal convection; unidirectional solidification; superconducting magnet; columnar structure; equiaxed structure; Pb–Sn alloy; mercury.

1. Introduction

It is well known that a moving electrically conducting fluid in a D.C. magnetic field induces electric currents, resulting in Lorentz force on the element of the liquid to suppress its own motion. Several metallurgists have been enchanted with this effect in terms of controlling the solidification of metal.

Uhlmann *et al.*[1] first experimentally examined the influence of D.C. magnetic field on the solidification structure of Cu–2%Al alloy. According to their results of investigation, the cast structure with a magnetic field of 0.2 T (Tesla) was completely columnar, while the structure without magnetic field was equiaxed. This change of morphology was understood as the result of suppression of the convection; less convection leads to the decrease of the remelting of dendrite branches and also to prevent the nuclei from being carried to bulk liquid.

Utech and Flemings[2] experimented crystal growth of tellurium doped In–Sb in a D.C. magnetic field. They reported that the solute band, which usually appears in a crystal without magnetic field, was eliminated in the presence of the magnetic field. This phenomenon was elucidated by the suppression of temperature fluctuations accompanied with a turbulent thermal convection.

Vives and Perry[3] reported, according to their experimental results of unidirectional solidification of Sn–Al alloy in an annular mold, that the effect of a magnetic field was characterized by both the reduction of release of metal superheat and the acceleration of the solidification rate.

All these metallurgical studies have simply demonstrated the effect of electromagnetic dumping of thermal convection on the morphorogy of solidified structure in relatively low magnetic field. From the viewpoint of magnetohydrodynamics of vortex like a thermal convection, on the other hand, interesting aspect of anisotropy has been theoretically produced by Chandrasekhar[4] and Thompson[5]; the magnetohydrodynamics behavior of liquid metal alloy affected not only by the intensity of magnetic field, but also by the coordination between the direction of the magnetic field and the convective motion of liquid. This anisotropic effect becomes dominant under the condition of a high Hartmann number where anisotropic Lorentz force superior to isotropic viscous force.

This study has been undertaken to examine the solidification phenomena of liquid metal including anisotropic effect in a high magnetic field generated with a superconducting magnet.

2. Apparatus and Procedure for the Experimental Solidification

Experimental arrangement is shown in Fig. 1. A solenoidal superconducting magnet was used to generate magnetic field of 4.0 T at maximum with the uniformity of 1% in the central region of the room temperature bore. Fig. 2 illustrates the configuration of the mold which was designed to solidify the metal unidirectionally. One of the vertical walls was made of copper and cooled by water at 20°C. Another three walls and a bottom plate were made of thermally insulating material of asbestos which was covered by fluorocarbon polymer film. The composition of alloy used in the experiments in Sn–10% Pb, the properties of which are listed in Table 1. The alloy was superheated to a temperature of 260°C and then poured into the mold outside the magnet. Within 10 s, the mold was inserted to the center of the bore of the magnet. Typical magnetic conditions for the solidification of metal are as follows:

1) with no magnetic field for reference,
2) with a magnetic field perpendicular to the solidifying direction, and
3) with a magnetic field parallel to the solidifying direction.

The direction of the field was changed by turning the mold around the vertical axis. The variations of temperature were measured by three chromel–alumel thermocouples which were located at 40 mm in depth, and at 20, 30, and 40 mm horizontally apart from the copper cooling wall, respectively. The cast samples were sectioned in the vertical plane parallel to the solidifying direction to reveal the morphology of cast structure. The section so obtained were machined flat, polished and etched with Oberhoffer's reagents.

3. Experimental Results

3.1. Solidification Structure

3.1.1. Castings without Magnetic Field

Macrostructures of solidified ingots without magnetic field are shown in Figs. 3(a) and 4(a). With a loss of temperature during the pour of the melt into the mold, its initial superheat in the mold did not exceed 10°C. As expected in the solidification under the condition of low superheat, fine equiaxed structure was observed almost in all volume of the ingot except for a narrow chill zone just in front of the cooling plate.

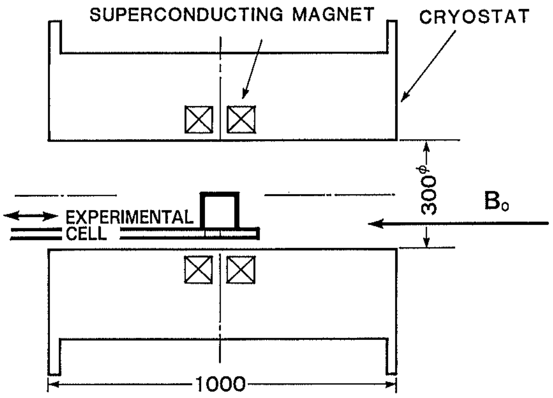


Fig. 1. Experimental arrangement.

3.1.2. Castings with a Perpendicular Magnetic Field

Fig. 3 shows macrostructures of the ingots in the presence of various intensity of the magnetic field perpendicular to the solidifying direction. The macrostructure remained equiaxed at the magnetic field less than 2 T. Then columnar zones slightly appeared among equiaxed grains above 2 T, and the size of equiaxed grains was larger than without magnetic field. However even at 4 T, the equiaxed structure was not entirely replaced by the columnar structure.

3.1.3. Castings with a Parallel Magnetic Field

Fig. 4 shows macrostructures in the various magnetic field parallel to the solidifying direction. Equiaxed structure turned to columnar with increasing the magnetic field. Fig. 5 indicates variation of the volume ratio of columnar structure except initial chill zones. Columnar structure began appearing at intensity above 0.2 T and completely supplanted equiaxed crystals at 0.7 T or more.

3.2. Heat Transfer

Figs. 6(a) to 6(c) show the temperature variation of the melt without magnetic field, with a perpendicular magnetic field of 4 T, and with a parallel magnetic field of 4 T, respectively. Three curves in each figure were measured by thermocouples which were located at different points in the metal pool as

Table 1. Properties of Sn–10%Pb alloy.

Liquidus	215°C
Solidus	183°C
Spacific heat	2.3×10^{2} J·kg/K
Latent heat	3.8×10^{4} J/kg
Coefficient of cubical expansion	1.02×10^{4} 1/K
Thermal conductivity	1.31×10^{-5} m^2/s
Density	6.97×10^{3} kg/m^3
Kinetic viscosity	3.16×10^{-7} m^2/s
Electric conductivity	2.08×10^{6} mho/m

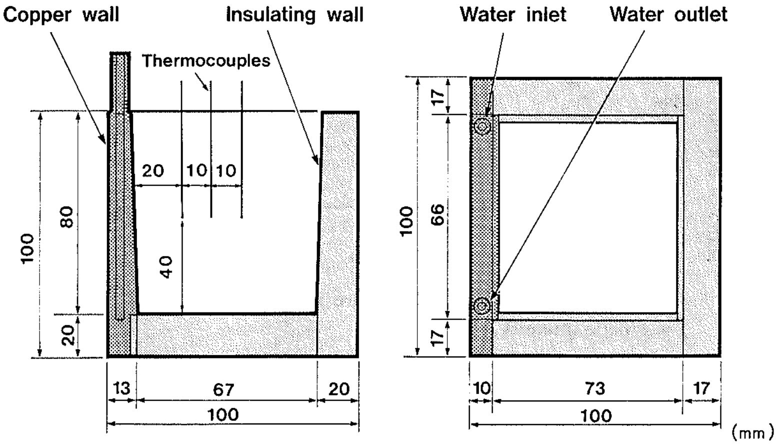
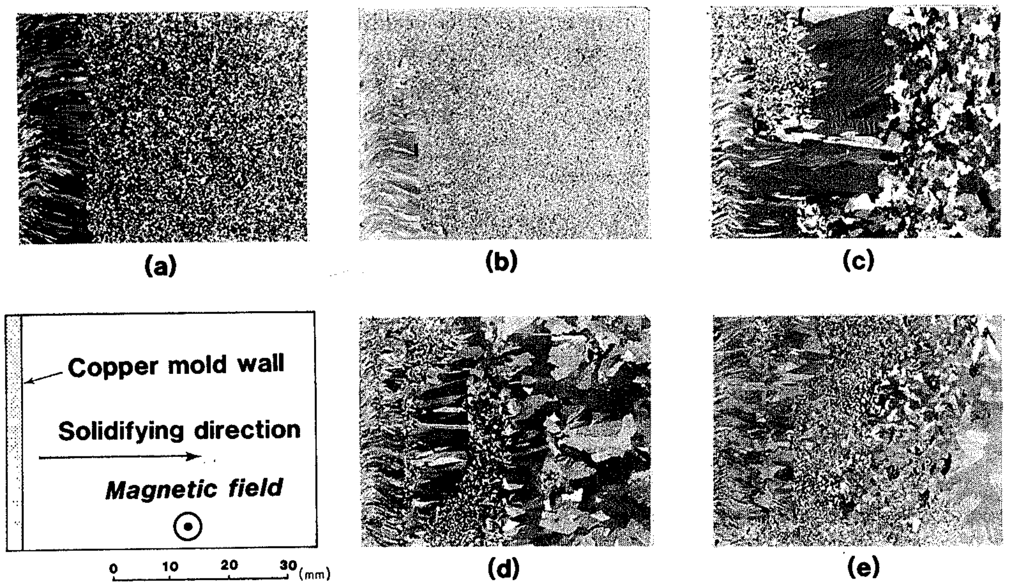


Fig. 2.
Schematic view of the mold.

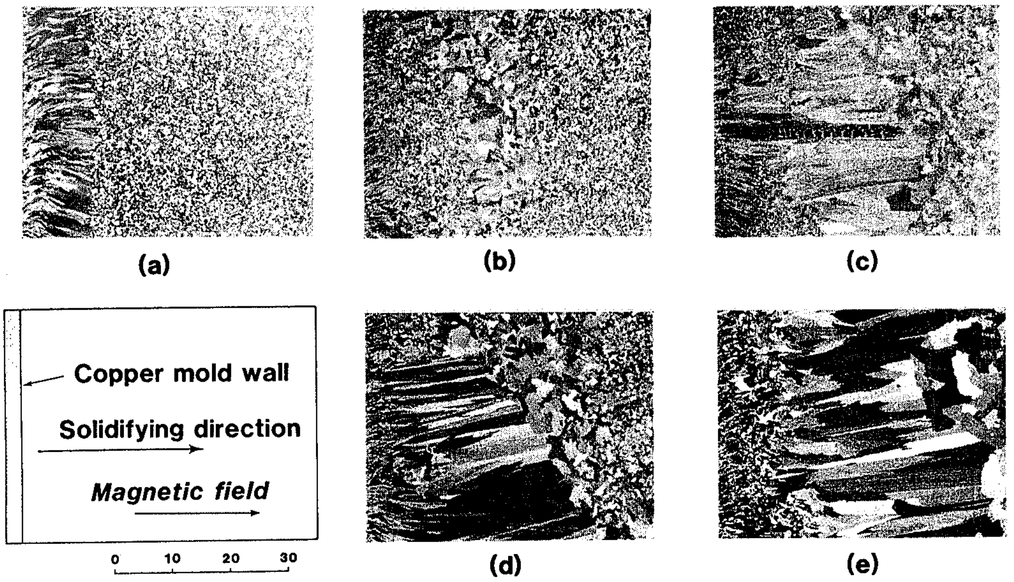
(a) Vertical

(b) Horizontal



(a) 0 T (b) 1.0 T (c) 2.0 T (d) 3.0 T (e) 4.0 T

Fig. 3. Macrostructure of Sn–Pb alloy solidified in a D.C. magnetic field perpendicular to the solidifying direction.



(a) 0 T (b) 0.2 T (c) 0.4 T (d) 0.6 T (e) 0.8 T

Fig. 4. Macrostructure of Sn–Pb alloy solidified in a D.C. magnetic field parallel to the solidifying direction.

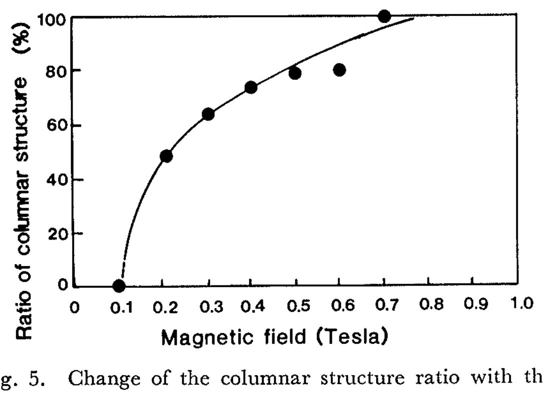


Fig. 5. Change of the columnar structure ratio with the magnetic intensity.

shown in Fig. 2. On a time axis of these figures, zero corresponds to the time when temperature of alloy becomes 225°C at the point 20 mm apart from the cooling wall. Fig. 6(a) reveals that in the case of no magnetic field the melt at three different positions reached the liquidus temperature almost simultaneously. In the presence of magnetic field, the time to reach the liquidus temperature was affected not only by the intensity but also by the direction of a magnetic field, as shown in Fig. 7. One should notice from this figure that magnetic field reduces the release of superheat, but accelerates the temperature decay below the liquidus temperature. Thus the parallel magnetic field has stronger effect on these phenomena than the perpendicular magnetic field.

4. A Fundamental Aspect of Anisotropic Effect in a Mercury Pool

4.1. *Experimental Arrangement and Procedure*

In order to investigate the effect of a magnetic

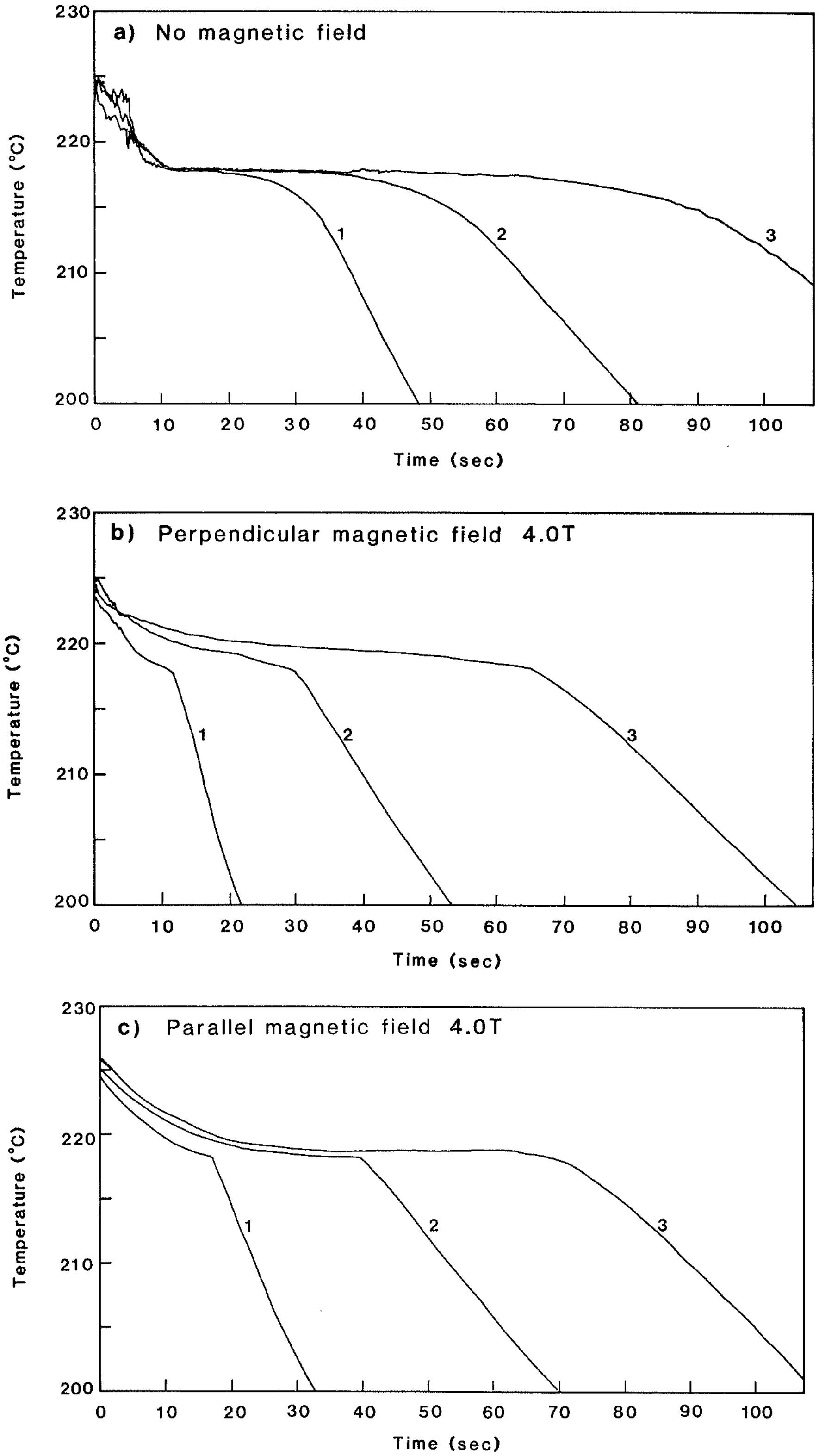


Fig. 6.
Temperature recordings at 20 mm from cooling plate (No. 1), 30 mm (No. 2), 40 mm (No. 3), respectively.

field on the thermal convection, the temperature distribution was measured in a mercury pool. Mercury was filled in a rectangular container with dimension of 50 mm × 50 mm × 50 mm as shown in Fig. 8. Two of the vertical walls were made of copper plate, and their temperatures were controlled independently with circulators. Other walls and a bottom plate were made of thermally insulating material of acylic resin. In order to adjust the Rayleigh number of this fundamental experiment to that of the experimental castings, temperatures of the two copper walls were kept at 24.0°C and 30.0°C, respectively. The temperature distribution and its fluctuations were measured by using 4 small NTC thermisters aligned at an interval of 10 mm along the horizontal axis in a depth of 25 mm. For the visualization of the temperature distribution in the mercury pool, one of the inner surfaces of the acylic walls was covered with a sheet of nematic liquid crystal. The color of the liquid crystal changes at temperature of between 27 and 29°C.

4.2. Temperature Distribution in the Mercury Container

Fig. 9 shows the temperature fields observed on the liquid crystal film in three different cases, in no magnetic field, in perpendicular field of 4 T, and in parallel field of 4 T. Temperature distributions measured by the thermisters along the center axis perpendicular to the copper plate were shown in Fig. 10. In a case of no magnetic field, horizontal isotherms were observed except for the boundary layers in front of the copper plates. This indicates that mercury underwent turbulent convection.

The temperature distribution with a parallel magnetic field of 4 T, was quite different from that without magnetic field. Isotherms observed by the liquid crystal film were almost vertical, and the temperature gradient along the horizontal axis was linear. This means that metal convection was almost suppressed. In the case of the perpendicular magnetic

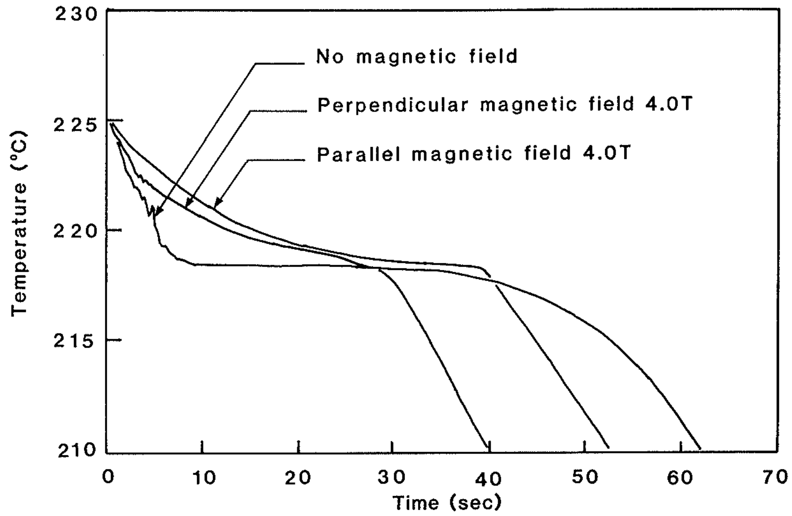


Fig. 7. Effect of magnetic field on the temperature at the same point 30 mm apart from the cooling wall.

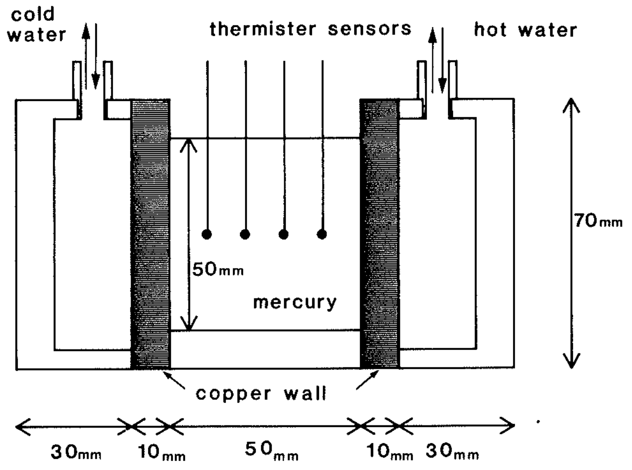


Fig. 8. Illustration of the cell used for a mercury experiment.

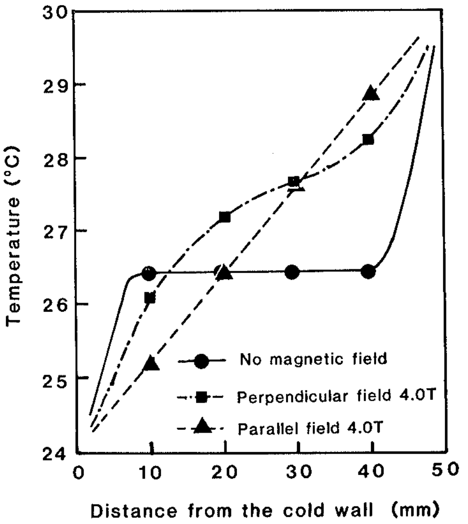
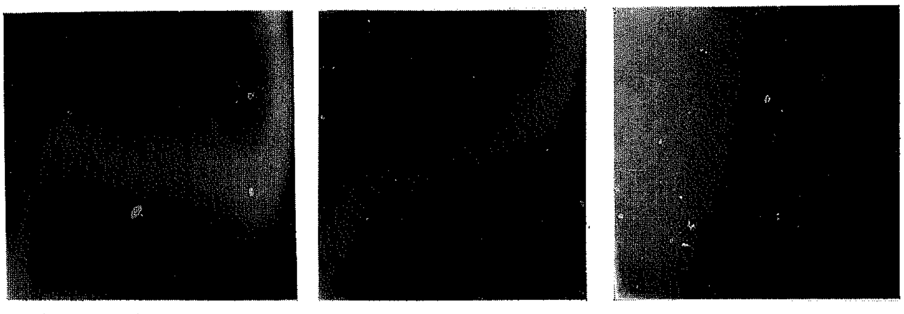


Fig. 10. Temperature distribution in the mercury pool along the center axis normal to the copper plate in the various magnetic field.



(a) (b) (c)

(a) No magnetic field
(b) Perpendicular magnetic field 4.0 T
(c) Parallel magnetic field 4.0 T

Fig. 9.
Temperature profile of the mercury visualized with liquid crystal film in the various magnetic field.

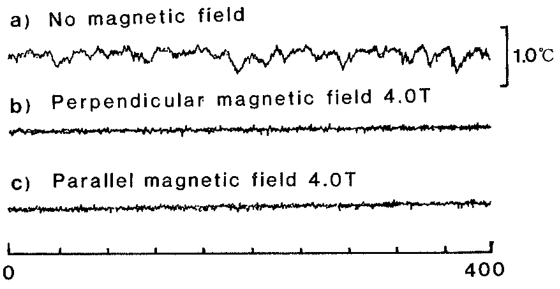


Fig. 11. Temperature fluctuation in the various magnetic field.

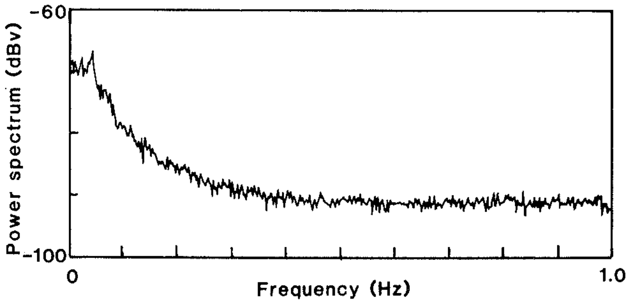


Fig. 12. Power spectrum of temperature variation with time in no magnetic field.

field of 4 T, the inclination of the isotherms lays between two cases mentioned above. This indicates there still exists thermal convection.

Typical changes of temperature with time were compared among these three cases in Fig. 11. In the case of no magnetic field, temperature fluctuation observed was 10% of imposed temperature difference. Fig. 12 shows the power spectrum of this fluctuations which indicates that turbulence develops in the pool. In other cases temperature fluctuation has not been observed, which means turbulent motion changes to laminar one.

5. Discussion

5.1. *Solidification without Magnetic Field*

The magnitude of velocity of thermal convection W can be estimated by using Rayleigh number $\boldsymbol{Ra}$,

$$W = k/L\,\boldsymbol{Ra} \quad \text{..........................(1)}$$

where, k: thermal diffusivity

L: the characteristic length of the mold.

$\boldsymbol{Ra}$ is defined as Eq. (2),

$$\boldsymbol{Ra} = \alpha g \Delta T L^3/k\nu \quad \text{....................(2)}$$

In Eq. (2), g: acceleration of gravity

ΔT: the characteristic temperature difference

α: cubic expansion coefficient

ν: kinematic viscosity of the melt.

$\boldsymbol{Ra}$ and W are estimated as follows in the case of $L=$ 70 mm and $\Delta T=30$°C,

$$\boldsymbol{Ra} = 2\times10^5,$$
$$W = 9\times10^{-2}\ \text{m/s}$$

According to the diagram of Krishnamurits,[6] the convection with this value of $\boldsymbol{Ra}$ is turbulence. The Reynolds number $\boldsymbol{Re}$ is estimated to be 2×10^4, which also implies that the induced thermal convection is turbulence. That is confirmed by the temperature fluctuation shown in Fig. 11. The efficient heat transfer due to turbulent convection uniforms the temperature distribution in the melt.

Several mechanism have been proposed to explain the formation of equiaxed structure.[7,8] Although our experiment could not distinguish the governing mechanism, it was reconfirmed that the strong and turbulent convection without magnetic field concluded to be favorable for the formation of equiaxed structure;

(1) Strong convection may lead to sufficient transport of nuclei from the solidification front to the center region of the mold.

(2) Homogenization of temperature distributions may result in heterogeneous growth of equiaxed crystals.

(3) Temperature fluctuations due to turbulence might enhanced the opportunities of generation of nuclei.

5.2. *Solidification with a Magnetic Field*

According to the theory of Chandrasekhar,[4] vortical movement of the fluid can be suppressed when a D.C. magnetic field is applied parallel to a plane of circulation, on the other hand no motion is suppressed in a magnetic field perpendicular to the plane. Thompson[5] studied the effect of a horizontal magnetic field on the Bénerd convection, which occurs in the presence of the temperature difference between top and bottom plates. His analysis gives the critical Rayleigh number $\boldsymbol{Ra}^*$ to suppress the disturbance in terms of Hartmann number $\boldsymbol{M}$ and wave numbers of the fluctuations as,

$$\boldsymbol{Ra}^* = \boldsymbol{M}^2 l^2 L^2[1+s^2/(l^2+m^2)] \quad \text{...........(3)}$$

where, l: the horizontal wave numbers of the fluid motion parallel to the applied magnetic field

m: perpendicular to the field

s: vertical wave number of disturbances.

Hartmann number is defined as,

$$\boldsymbol{M} = \sqrt{\frac{\sigma}{\rho\nu}}\,LB, \quad \text{.....................(4)}$$

where, σ: the electrical conductivity of the fluid.

When the Rayleigh number is smaller than $\boldsymbol{Ra}^*$, convective motion is suppressed. The critical Rayleigh number varies with not only the intensity of a magnetic field but also the wave number, as is known from Eq. (3). If the wave number l is reduced to zero, $\boldsymbol{Ra}^*$ becomes zero. This means that a magnetic field has no effect on the movement perpendicular to the field. On the other hand $\boldsymbol{Ra}$ has a large value for the short range fluctuation, so that the turbulent motion which contains many disturbance of large wave number can be easily suppressed by a magnetic field. Although the system in Thompson's analysis is rather different from ours, physical concept of the magnetic effect on the fluid motion is almost the same. Therefore his criteria conditions to inhibit the fluctuations may be applicable to our system for the rough estimation.

In the experiment of the casting with a parallel magnetic field to the solidifying direction, the convective motion occurs in a plane parallel to the field. According to the analysis mentioned above, the suppression of the convective motion of liquid can be elucidative. With increasing the intensity of a magnetic field, a dominant mechanism of heat transfer changes from turbulent convection to laminar one and ultimately to conduction. Deceleration of the temperature decay of the superheat shown in Fig. 7 is inferred to be due to the suppression of turbulent convection. Transition of the solidified structure can be also explained as follows; suppression of the convection leads to decrease of nucleation at the solidification front and to insufficient transport of nuclei to the center region of the molten pool, and large temperature gradient prevents the equiaxed crystals from growing. As the result, equiaxed structure turns to columnar one with increasing a magnetic field. In equiaxed crystal growth solidification occurs almost at the same time over the melt, while in columnar crystal growth at solidification front proceeds successively.

The critical magnetic field B^* for the transition of morphology of cast can be estimated from Eq. (3). In the case of present work B^* is predicted approximately 0.1 T, if the wave number is assumed to be $l/L=1$. Critical magnetic field obtained experiment is almost consistent with the predicted field.

On the other hand, as mentioned above, the magnetic field perpendicular to the solidifying direction hardly suppress the convective motion. Hence the convection which is enough to transport heat and generate nuclei to the center of the molten pool still exist even at high Hartmann number. The results of mercury experiments indicate that a magnetic field successfully stabilized the thermal convection. Therefore convection hardly becomes turbulence at high Hartmann number, where a dominant mechanism of heat transfer becomes laminar. Thus the deceleration of the temperature decay of the superheat in the case of perpendicular field lied between in no magnetic field and in parallel field. Temperature gradient along the solidifying direction in perpendicular field is not steeper than in parallel field. In this situation, both columnar and equiaxed crystals develop in the mold forms the mixed structure shown in Fig. 4.

6. Conclusions

Experimental results show that the solidification is strongly affected not only by the intensity of magnetic field but also by its direction. In the parallel field of several tenths Tesla, the equiaxed structural changes to columnar one. While in the case of the perpendicular field, equiaxed structure remained even at 4 T.

In connection with this anisotropic effect of the magnetic field during solidification, the mechanism of heat transfer was studied in a mercury pool. The change of the temperature profile with magnetic field was successfully visualized with nematic liquid crystal film, and temperature fluctuation was measured by thermisters. Obtained results revealed that temperature fluctuations was eliminated in either perpendicular field or parallel field. Magnetic field has an effect to suppress turbulent motion. And convective motion could be dumped almost completely by a parallel magnetic field, while it was hardly suppressed by a perpendicular field.

From these findings, metallographical change was explained by these anisotropic magnetohydrodynamics effects on a transport mechanism during solidification, summarized as follows:

a) turbulent convection in no magnetic field,
b) laminar convection in a perpendicular field, and
c) suppressed convection in a parallel field.

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