論 文

A Study on the Morphology of Solid/Liquid Interface of Solidifying Metal under the Centrifugal Force

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1. INTRODUCTION

Convection in liquid phase can be driven by various sources during upward unidirectional solidification[1].

When convection occurs, the composition of crystal will be less homogeneous than would be possible in the absence of convection.

When highly uniform crystal is needed, it may be essential to control this convective effect carefully.

Recent researches on the convective flow control by the microgravity of enhanced gravity (centrifugal force) have highlighted by the scientists and engineers[2~5].

In this paper, we will report on the morphology observed from the solid-liquid interface of Al-1wt.%Mg alloy unidirectionally upward solidified under terrestrial condition and centrifugal forces.

2. EXPERIMENTAL PROCEDURE

99.99% pure Al and 99.9% Mg has been melt and casted to make Al-1wt.%Mg ingot. It was drawn to make $4.8mm\phi \times 110mm$ L sample.

Graphite tube was used as ampule. It's dimension was 5mm inner diameter and 4mm wall thickness.

Without moving furnace or ampule, unidirectional solidification was acquired successfully in the furnace composed of 3 zone heater that could be controlled independently. Maximum temperature gradient acquired in this furnace was about 30K/cm.

Schematic diagram of centrifuge was shown in Fig. 1. Unidirectional solidification experiments under terrestrial and various centrifugal

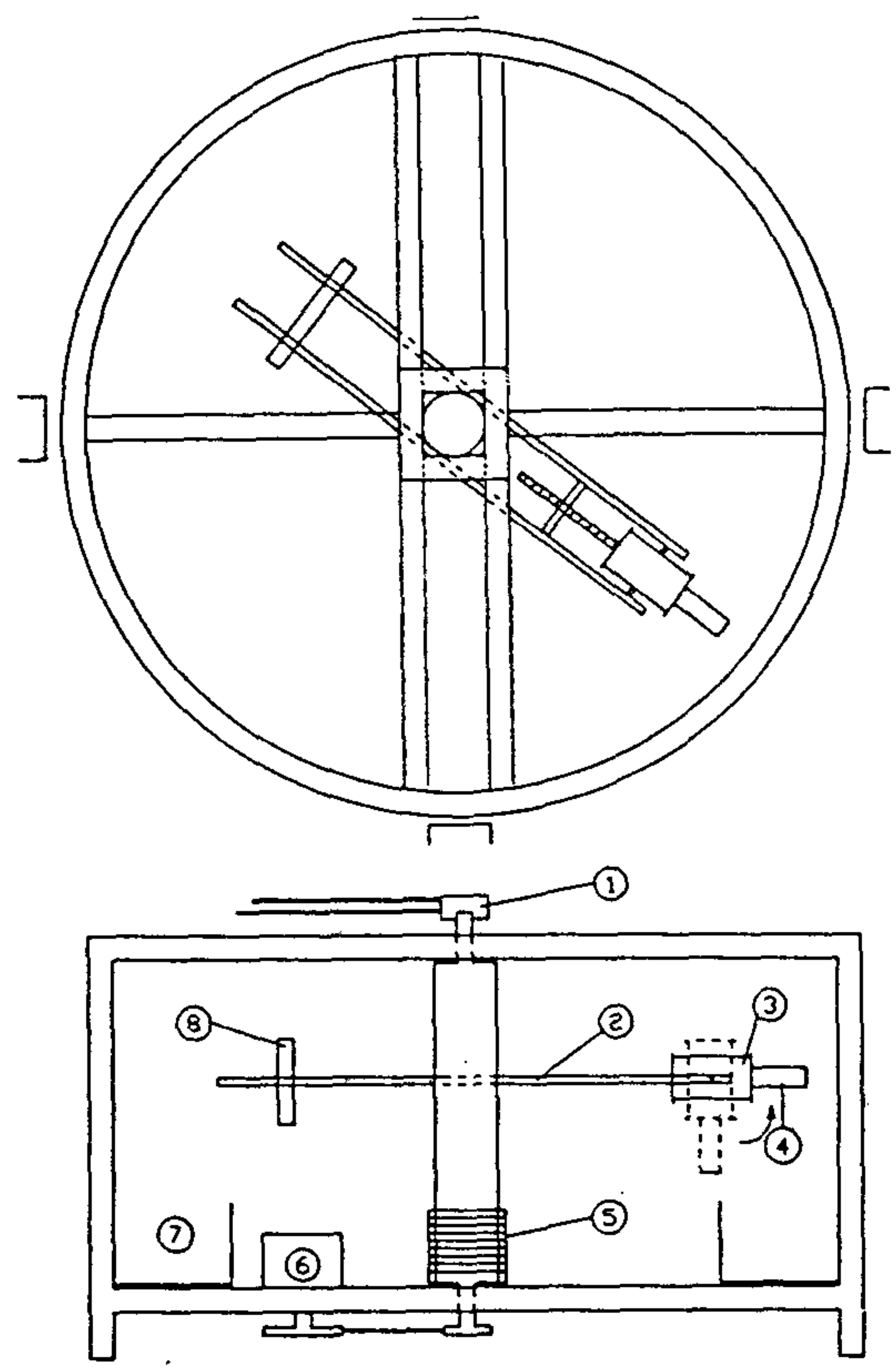

Fig. 1. Schematic diagram of centrifuge.
① 2-hole rotary joint ② rotating arm(L=0.67m)
③ 3-zone furnace ④ quenching tank
⑤ slip rings ⑥ motor
⑦ water gutter ⑧ balance weight

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※ 본 논문은 1992년 10월 일본 센다이에서 열렸던 제2회 아시아주물대회에서 발표된 것이다.

forces have performed with this equipment and furnace atmosphere controlled by Ar gas and quenching water was supplied through the hole drilled on the shaft.

Power and thermocouple were switched with equipement by slip rings.

Temperature gradient in ampule was maintained about 16K/cm by furnace and growth velocity was controlled in the range of $2\sim0.1\mu$ m/s.

Sample was cut along the longitudinal direction and metallographic characteristics and solute distribution profile were measured.

3. RESULTS AND DISCUSSION

3.1 CONVECTION IN THE UPWARD UNIDIRECTIONAL SOLIDIFICATION

Density driven convection in upward unidirectional solidification may be divided into two categories.

1) Threshold convection : convection driven by vertical density gradient.

2) Thresholdless convection : convection driven by horizontal density gradient.

If a thermal gradient is present in vertical solidification without a solute gradient, convection will not occur unless the gradient produces a positive density gradient which exceeds a certain threshold valve. Hydrodynamic stability analysis shows that the critical condition for onset of flow is characterized by the thermal Rayligh number :

$$Ra_T = -\frac{g\alpha_T G_T R^4}{\nu K} \quad (1)$$

where g = gravitational acceleration constant

α = thermal volume expansion coefficient

K = thermal conductivity

R = tude radius

G_T = temperature gradient

Convection requires $Ra_T > Ra_T(Cr)$ the critical Ra number.

Solutal Rayligh number is also defined in similar way.

$$Ra_S = -\frac{g\alpha_S G_C R^4}{D} \quad (2)$$

where α_S = solutal expansion coefficient

G_C = concentration gradient

D = diffusion coefficient

In case of both thermal and solutal gradients being present(In this expriment, thermal gradient is positive and solutal gradient is negative. Because Mg is lighter than Al and $k_0<1$), there is the critical condition for onset of flow which is a function of both Ra_T and Ra_S. According to McFadden[6], R can be replaced by characteristic length(D/V). Using D/V and simple approximation $|Ra_T| < |Ra_S|$, Jamgotchian[7] explained morphology of Pb-Ti upward growth.

On the other hand, when a fluid is subjected to a horizontal thermal gradient, motion is always generated even for infinitesmal temperature difference[8]. In the real case that gradient is not strictly parallel with the gravity vector, thermal buoyancy due to unbalanced pressure distribution gives rise to thresholdless convection.

3.2 UPWARD UNIDIRECTIONAL SOLIDIFICATION OF AL-1wt.%Mg UNDER TERRESTRIAL CONDITION

Shapes of solid-liquid interface for unidirectionally solidified Al-1wt.%Mg under terrestrial condition were shown in Fig. 2. At growth velocity $V=0\mu m/s$, shape of interface was nearly flat(Fig. 2-(a)) At growth velocity $V=0.2\mu m/s$, shape of interface was convex into the liquid (Fig. 2-(b)). When solid-liquid interface goes into liquid phase, the difference in thermal conductivity of solid and liquid makes temperature of central part become lower than periphery. This horizontal temperature gradient creates thresholdless convection, by which solute is moved from central part to periphery along the

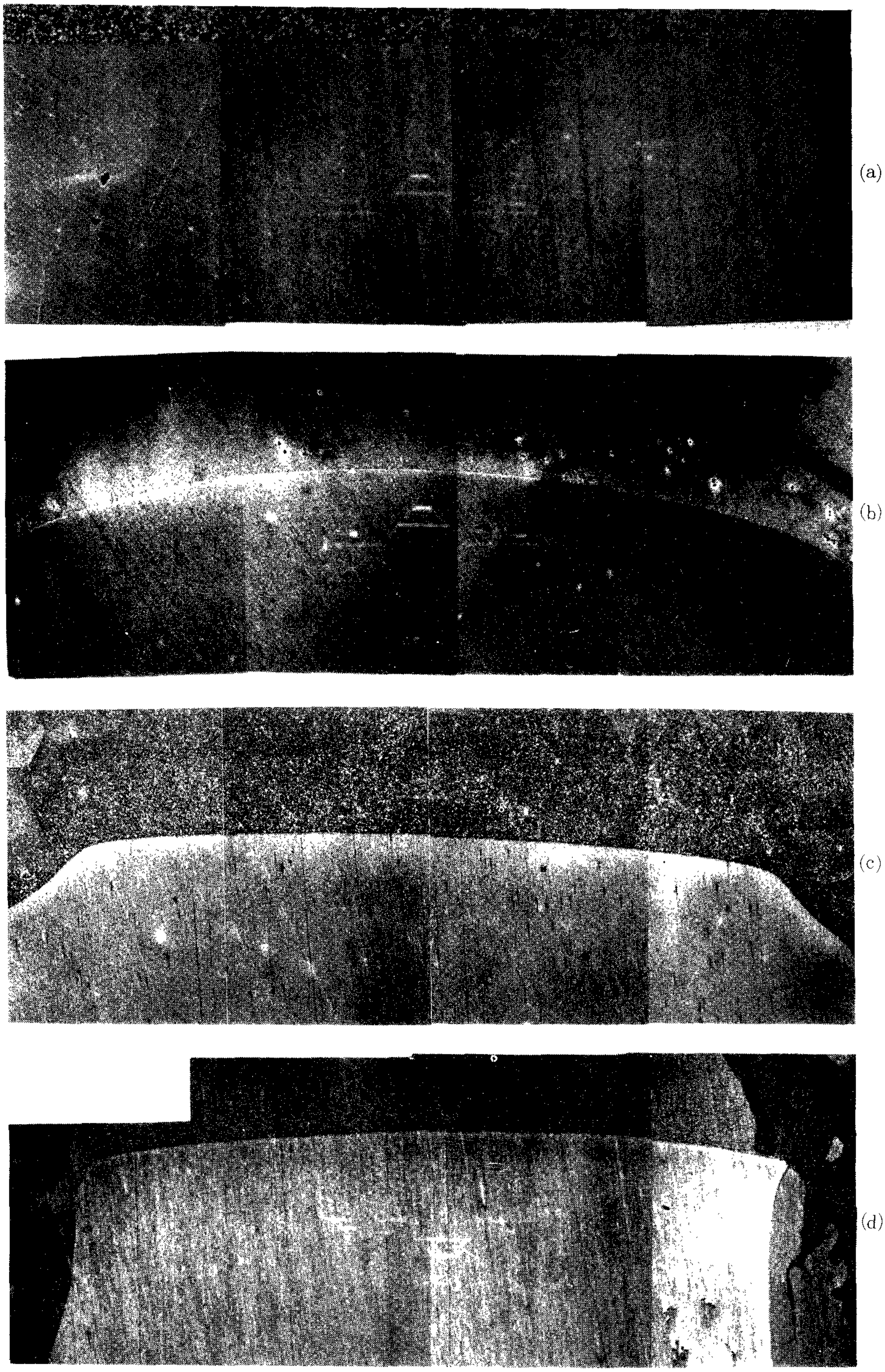


Fig. 2. Interface morphology for various growth velocity under the terrestrial condition. Growth velocity is : (a) 0 (b) 0.2 (c) 0.7 (d) 1.9μm/s.

interface. Interface morphology is determined by this solutal concentration just above it, if equilibrium solidification is provided[9]. Horizontal temperature difference can be estimated from solute concentration data. In case of Fig. 2-(b), temperature difference was about 3.5℃.

When growth velocity was over than $V=0.7\mu m/s$(Fig. 2-(c)), central part of solid-liquid interface became nearly flat and, on the other hand, periphery of interface was concave toward liquid along oblique direction to growing axis. It is infered that morphological change occured near this velocity by transition of convection mode related to growth velocity. Calculating critical growth velocity from Jamgotchian'approximation and thermal properties[10,11], it is $8\times10^{-5}\mu m/s$, which is over exaggerated value.

At growth velocity $V=1.85\mu m/s$(Fig. 2-(d)), partial morphological instability appeared on the periphery of interface. It was related to the critical velocity for morphological instability theory.

3.3 UPWARD UNIDIRECTIONAL SOLIDIFICATION OF Al-1wt.%Mg UNDER CENTRIFUGAL FORCES

Shapes of solid-liquid interfaces were shown in Fig. 3 when the centrifugal forces were 5G, 15G and 20G respectively at velocity $V=0.2\mu m/s$. From Fig. 3 together with Fig. 2-(c), it was shown that curvature of interface was increased with increasing centrifugal force but there were not any transition from thresholdless convection to threshold convection.

At $V=0.7\mu m/s$, which the velocity that thermosolutal convection was dominant under terrestrial condition, shape of interface for centrifugal force 20G was shown in Fig. 4. Comparing Fig. 4 with Fig. 2-(b), interface shape for centrifugal force 20G was similar to that for terrestrial condition, however flatness of central part on interface is increased with increasing centrifugal force. It was considered that increasing flatness of interface with centrifugal accelerating was due to the enhanced convection. we could not still found any drastic change in morphology with increasing centrifugal force in the range between 1G∼20G in the range of growth velocity 0.7∼1.85$\mu m/s$.

3.4 Mg SEGEREGATION AND FLOW PATTERN

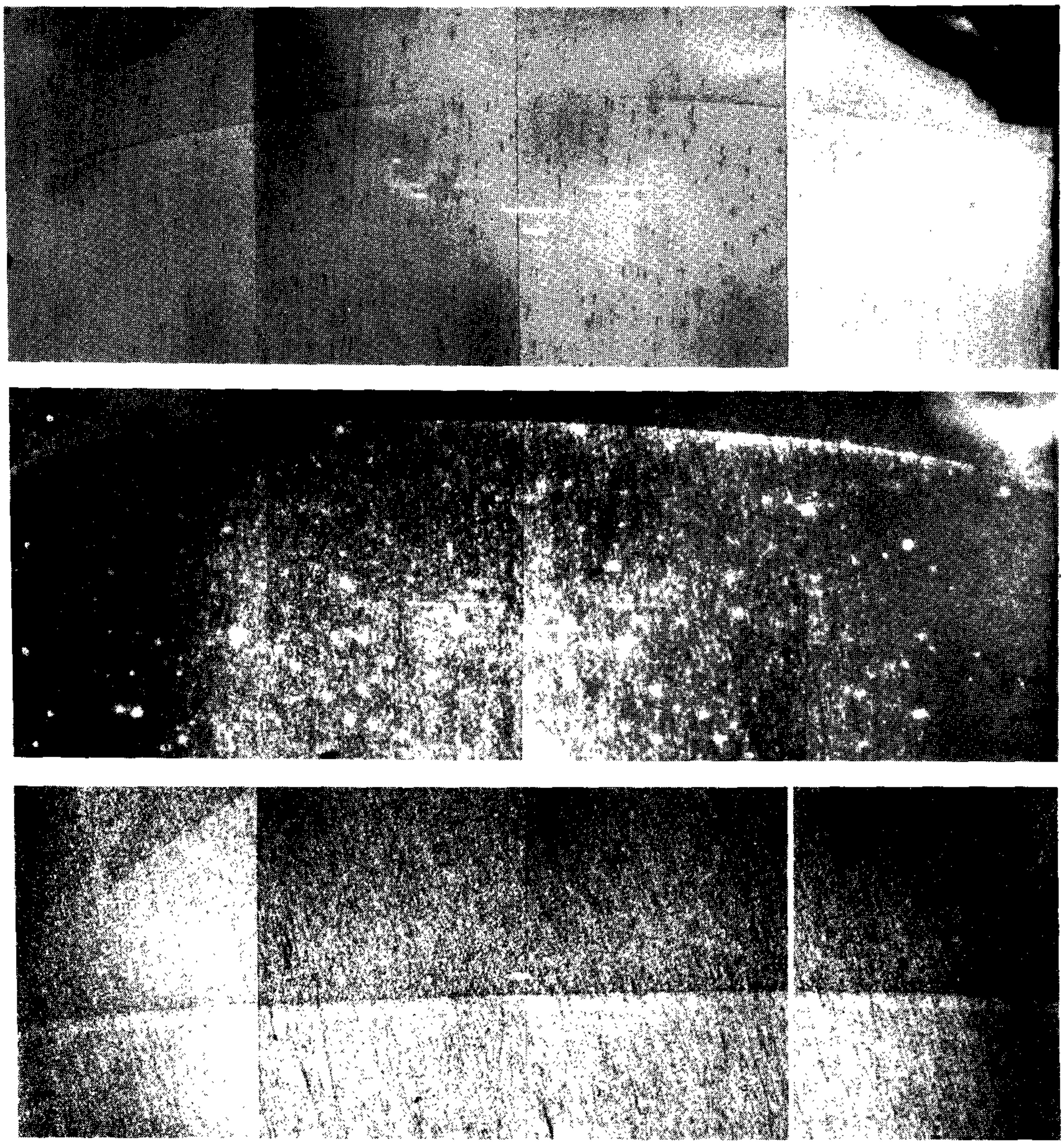
Effective distribution coefficients(K_E) related to the growth velocity at 1G and 20G were shown in Fig. 5. In both cases, 1G and 20G, K_E were approching to K_0 when growth velocity was over than $V=0.7\mu m/s$. This mean that convection is dominant mechanism as mass transfer.

In Fig. 6, it was shown that solute segregation profiles in radial direction for growth velocity $0.7\mu m/s$ and $0.1\mu m/s$ respectively under the terrestrial condition. Although we could not estimate distincively the effect of centrifugal force on the solute segregation in radial direction because of small content of solute in this expriment, there might be some tendency that solute distribution profiles for thermosolutal convection dominant regime were having 5 nodes which were symmetrically located to sample axis contrasting that those for thermal convection dominant regime were near flat.

Fluid flow pattern on solid-liquid interface can be infered from solute distribution profile[9].

Flow pattern on solid-liquid interface for thermosolutal convection dominant regime would be the mode composed of 5 solute concentrated nodes.

In order to get more detailed information on the effect of centrifugal force on fluid flow in upward unidirectional solidification, it is necessary to take highter solute concentration system than this experiment. Numerical analysis is also recommended.

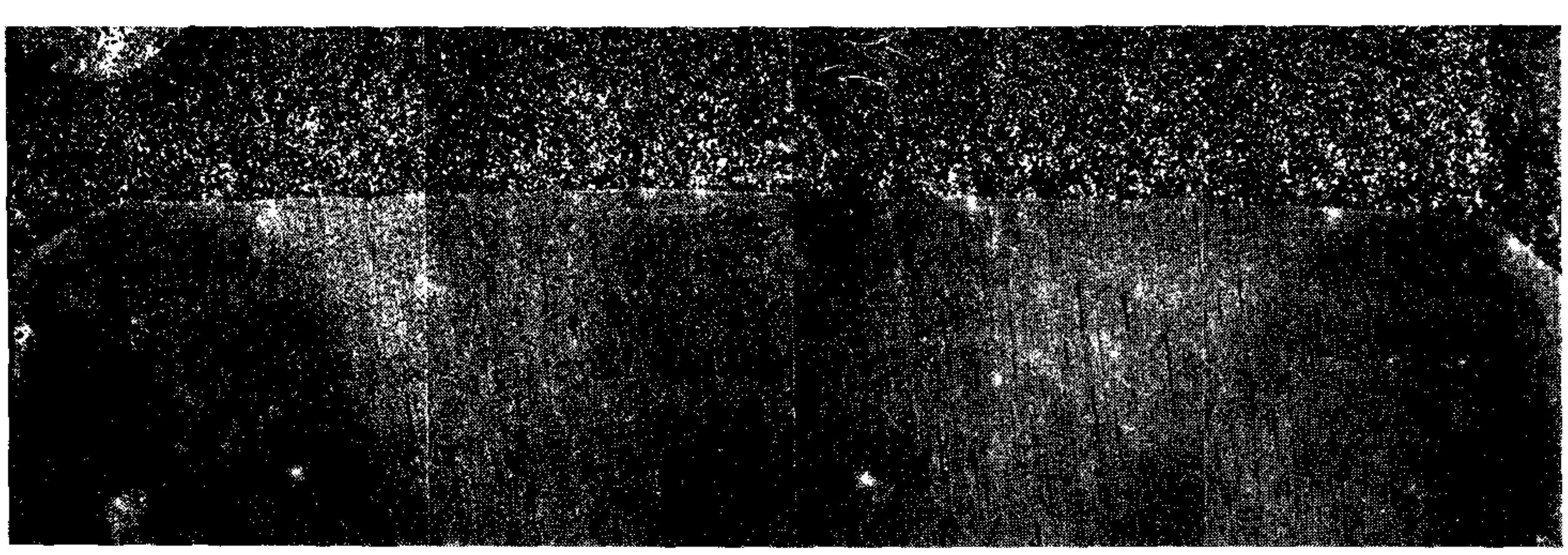


(a)

(b)

(c)

Fig. 3. Interface morphology at constant growth velocity V=0.2μm/s for various centrifugal forces : (a) 5G (b) 15G (c) 20G.



(d)

Fig. 4. Interface morphology at the growth velocity V=0.7μm/s for centrifugal forces 20G.

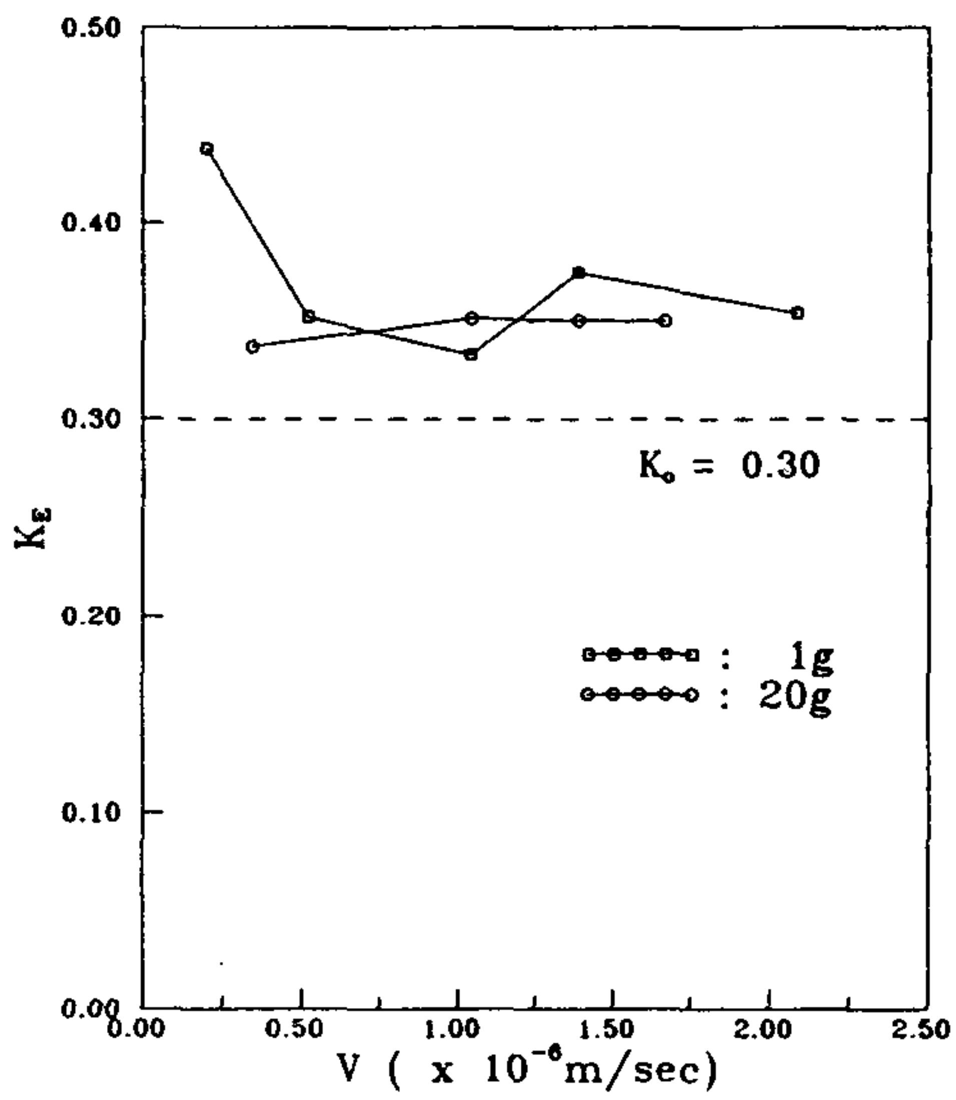


Fig. 5. Variation of the effective distribution coefficient K_E versus the growth velocity for terestrial (1G) and centrifugal forced(20G) condition.

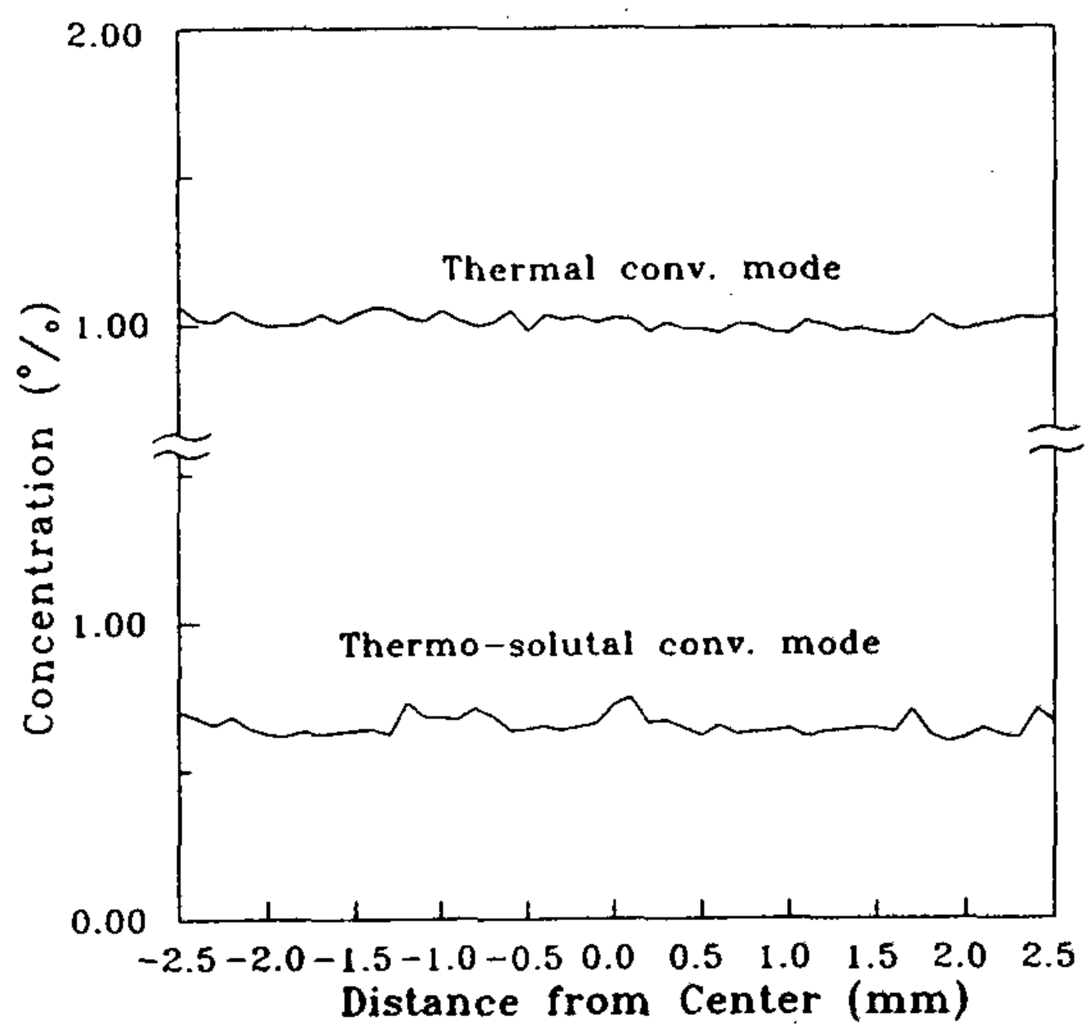


Fig. 6. Solute segregation profile in radial direction for thermal convection mode and thermosolutal convection mode under the terrestrial condition.

4. CONCLUSION

Under terrestrial and centrifugally forced condition, unidirectional upward solidification for Al-1wt.%Mg was performed.

It was confirmed that thermal convection due to the horizontal temperature gradient was dominant when growth velocity was less than V= 0.2μm/s, and thermosolutal convection was dominant when growth velocity was over than V=0.7μm/s in this experiment, this criterion was not altered by centrifugal force in the range from 1G to 20G.

The flatness of solid-liquid interface was increased with centrifugal force acceleration.

ACKNOWLEDGEMENT

Authors want to express their gratitude to the Korea Science and Engineering Foundation for the financial support to accomplish this research.

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