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Micro-casting using molds with gradient cooling characteristics

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ABSTRACT

The concept of molds with gradient cooling characteristics is introduced to actively control the microstructure and, thereby, the physical properties of micro-castings. Such molds are composed of materials with different thermal properties arranged in different geometric configurations imposing varying cooling rates at each point of the casting. To ascertain the feasibility of this concept, molds made of materials with different thermal conductivities were used and their cooling properties were measured. The changes in the microstructure of the castings depending on their location in relation to the mold's body were evaluated. The results confirm the plausibility of microstructure control with such molds.

1. Introduction and motivation

The most frequently used micro/mesoscale manufacturing methods for miniaturized products and product features are either subtractive or deformation-based. While both satisfy the geometric requirements, they are limited in their ability to alter and control the product's physical properties that are dominated by the material's microstructure [1,2]. The same limitation also applies to micro-casting, which is performed in various forms ranging from investment, through vacuum to centrifugal casting all rooted in conventional mold and casting technologies [3–6].

To overcome the limitation mentioned above and broaden the processing capability of micro-casting, a novel concept, i.e., "molds with gradient cooling characteristics" is proposed. The idea is shown in Fig. 1 where the relation between, e.g., grain size and yield stress is schematically expressed by the graph in the lower part of the figure for a metallic material. The high-accuracy inner layer, constituting the molten metal-mold interface (the orange region) of the mold wall, is a material with a high melting point. The thermal resistance of the mold will be controlled by the outer layer (purple region) by changing its thickness and the materials being used. It is composed of a combination of materials of different layer thicknesses affecting the cooling rate and, thus, the microstructure of the parts. Several existing additive manufacturing technologies directly support the manufacture of such envisioned multi-material gradient mold structures.

2. Experimental methods

Model experiments of one-dimensional solidification were conducted in which the mold properties were varied in the cooling direction, to investigate the effect of the structure and properties of the mold on the local thermal parameters (cooling rate, degree of undercooling, and temperature gradient) and to determine the relationship between these thermal parameters and the formation of solidified structures.

AZX912 (Al – 9.3, Ca – 2.1, Zn – 0.67, Mn – 0.24, wt.%, Mg - balance), a flame-resistant magnesium alloy for casting was selected [7]. The diffusion of solute species in the melt is closely related to the growth rate and instability of the solid–liquid interface, which is essential for discussing the dimensions and morphology of the solidified structure.

Fig. 2(a) and (b) show a view and schematics of the experimental apparatus that consists of a heating device, the mold, a cooling device, and a control and measurement system. The heating apparatus consists of a tube furnace with a quartz core tube and infrared lamps with fast heating and cooling rates as heating elements. To independently control the temperature gradient and cooling rate of the cast specimen, a piston cylinder made of graphite with

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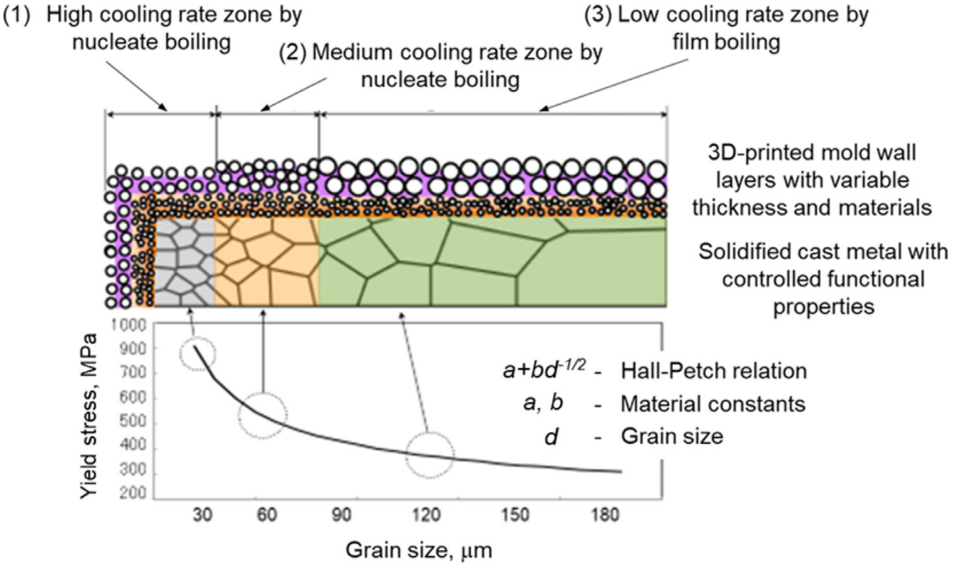


Fig. 1. Conceptual example of controlling the mechanical characteristics and material organization.

a relatively large heat capacity (heat storage block Fig. 2(b)) was placed above the mold, and a heat exchanger for cooling made of hardened steel (cooling block Fig. 2(c)) was placed below the mold. The internal shape of the molds is cylindrical with a diameter of 5 mm and a height of 5 mm.

To ascertain the feasibility of the concept, two materials were used as mold materials. Fig. 2(d) shows a laminated mold consisting of a 3 mm thick graphite and a 2 mm thick ceramic overlapped plate. Their thermal properties are given in Fig. 2(e). The thermal conductivities of these two materials differ by two orders of magnitude, while their thermal diffusivity (transport coefficient) represents the rate of the process at which a non-equilibrium temperature distribution relaxes and reaches a thermal equilibrium state. The locations of the thermocouples used to measure the temperature of the mold body are also indicated in Fig. 2(d).

Two types of molds were tested to determine the effect of mold structure on cooling rate and thus on the microstructure of the cast parts: Mold A consisted of graphite only; Mold B consisted of the above-mentioned laminated graphite and ceramic plates. Mold B represents an experimental arrangement in which the heat transfer characteristics of the mold are tilted in the direction of heat flow because of laminating graphite and ceramics, two mold materials with different thermal properties. The heat transfer in an unsteady state also shows similar differences. These differences are assumed to cause localized changes in the cooling rate and temperature gradient within the sample, affecting microstructural properties such as the fineness, micro-segregation, and directionality of the solidification layer.

In the experiments, the alloy was first melted in the heat storage block and injected into the mold. Cooling started from an initial temperature of approximately 1,000 K. In the cooling operation, water at about 283 K was passed through the cooling block at a flow rate of 0.14 L/s to exchange heat with the mold containing the molten alloy. Infrared heating was stopped at the same time as the cooling operation.

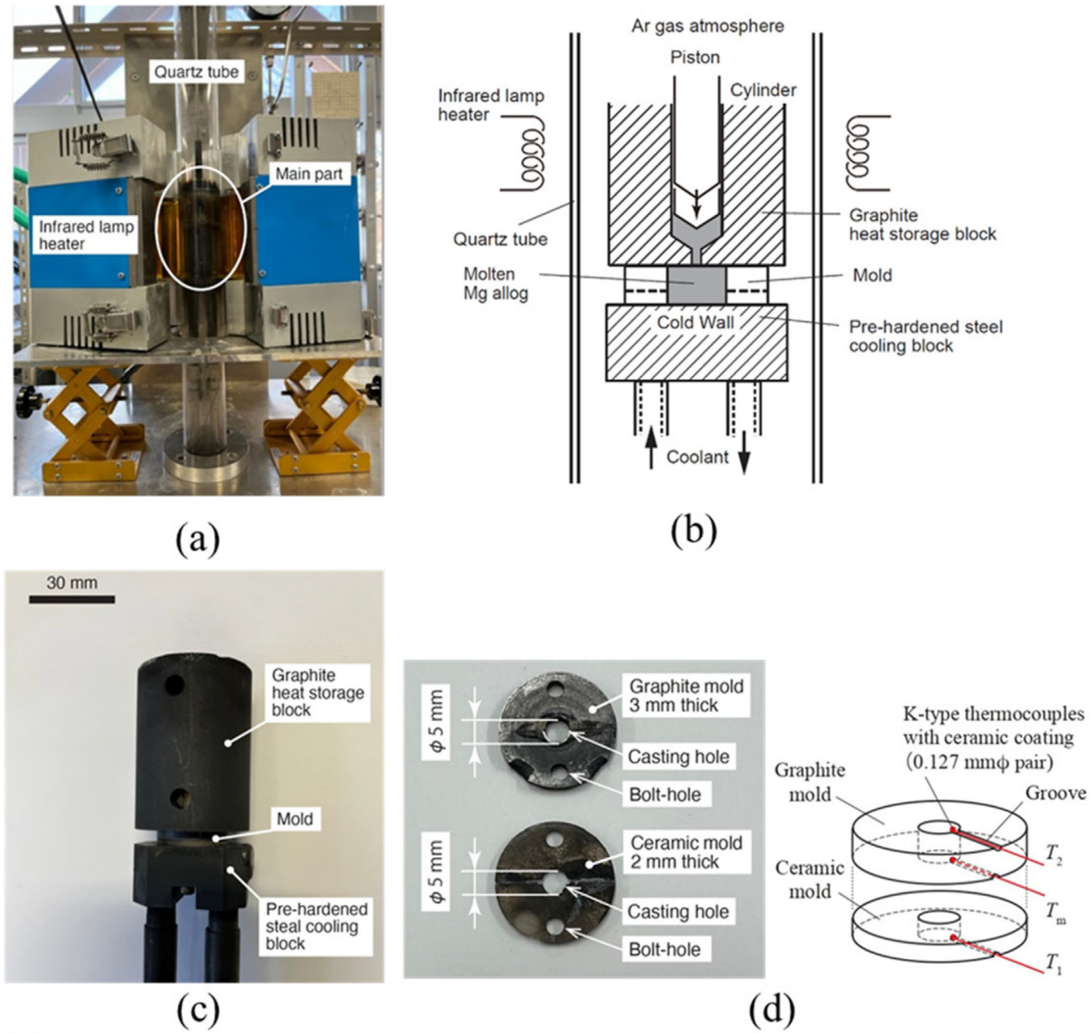
3. Experimental results and discussion

Fig. 3 shows the time variation of temperatures for Mold A and B. For Mold A (Fig. 3(a)), cooling started at about 46 s. After cooling, the temperature decreased from the cooling surface side, and after about 53.5 s, the entire sample area was below the liquidus temperature of about 870 K. The temperature difference between the low-temperature side T_1 and the high-temperature side T_2 was about 155 K (average temperature gradient 31 K/mm). For Mold B (Fig. 3 (b)), cooling started about 49.5 s after the molten Mg alloy was injected into the mold, and the entire sample area fell below the liquidus temperature at about 68 s. The temperature difference between the low-temperature side T_1 and the high-temperature side T_2 was about 218 K (average temperature gradient 43.6 K/mm). The temperature difference between T_1 and T_m was about 180 K at a distance of 2 mm between the sensors and between T_m and T_2 about 38 K at 3 mm. The temperature gradient between the sensors is about 90 K/mm for the ceramic and 12.7 K/mm for the graphite component. Larger temperature gradients were obtained near the wall.

The difference in local cooling rate between Mold A and Mold B is caused by the heterogeneity in the thermophysical properties of the mold. The ceramic used in Mold B has a relatively high thermal resistance (proportional to the reciprocal of thermal conductivity), which suppresses the inflow of heat from the high-temperature side into the melt near the cooling surface. This results in a large cooling rate near the cooling surface. Furthermore, the relatively small thermal resistance of adjacent graphite causes a large temperature difference between T_1 and T_m in Mold B. Overall, thermal diffusivity represents the rate of temperature change until thermal equilibrium is reached, which affects the local cooling rate and temperature gradient.

A temperature increase was observed at about 54 s in Fig. 3 (a) (Mold A) attributable to the latent heat of solidification released due to phase change, so-called recalescence. A similar temperature rise was also observed at about 50.5 s in Fig. 3 (b) (Mold B). These confirm that solidification was initiated by nucleation from a supercooled condition. This recalescence would be due to the primary phase, αMg solid solution. The degree of supercooling, defined as the difference between the liquidus temperature and the nucleation temperature, was approximately 160 K for Mold A and approximately 60 K for Mold B. Thus, supercooling inevitably appears at the initial solidification stage for the crystallization of primary phase.

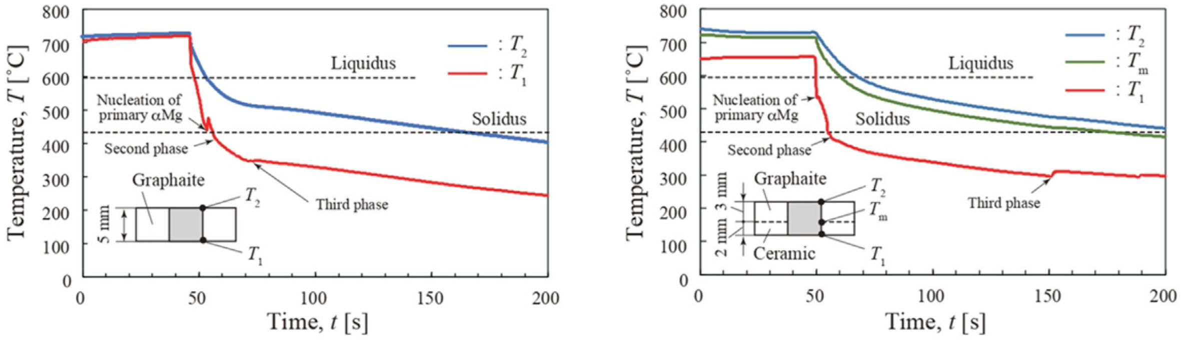
To assess the characteristics of the solidified microstructure, the Mg alloy castings were cut into cross-sections shown in Fig. 4 (a). The solidified microstructure corresponding to the temperature data in Fig. 3 (a) is shown in Fig. 4(b), and that to the temperature data in Fig. 3 (b) in Fig. 4 (c). The structural morphology of Mg



(e)

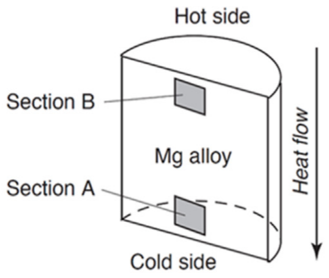
Type	Material	Density kg/m^3	Specific heat J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity ×10^{-6} m^2/s
A	Graphite	1830	710	140	108
B	Machinable ceramics	2520	790	1.46	0.73

Fig. 2. Details of the apparatus: (a) Photo of the testbed, (b) Schematic view of the casting apparatus, (c) Core casting parts, (d) Mold parts and schematic view of temperature measurement method using thermocouples, (e) Thermal properties of the mold materials.

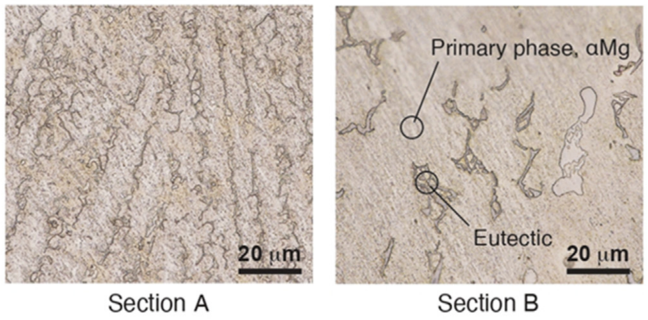


(a) Mold A (b) Mold B

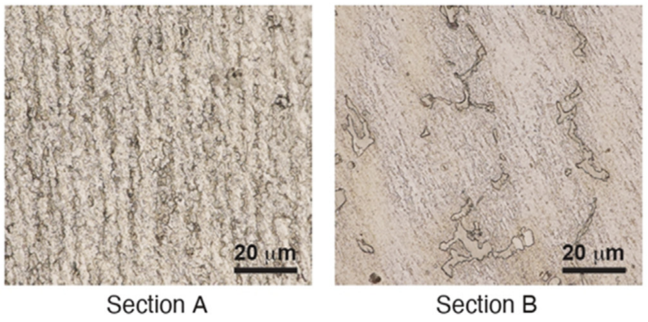
Fig. 3. Temperature change after solidification in each die.



(a) Heat flow of specimen



(b) Solidification structure of AZX912 (Mold A)



(c) Solidification structure of AZX912 (Mold B)

Fig. 4. Casting microstructure of AZX912 in each die.

alloys is well-known in the literature [7]. The phase equilibria in the Mg-Al-Ca system are fundamental to the understanding of the presented solidification phenomenon [8]. The primary phase αMg occupies most of the solidified phase and can be observed as a relatively bright area using an optical microscope. Based on the above metallographic perspective, the phases in the casting were identified. The solidification process can be described as follows. First, free dendrite growth of αMg occurs due to initial supercooling. Next, continued external cooling from the wall caused αMg to grow while discharging solute species (Al, Zn, Mn, Ca, etc.) from the solid–liquid interface, resulting in the crystallization of the second and third phases (αMg + Al_2Ca eutectic and αMg + $Mg_{17}Al_{12}$ eutectic). From the photos in Fig. 4, a small eutectic region is observed in the gap between the primary αMg dendritic crystals. Relatively fine crystals were observed in cross-section A in Fig. 4(c), i.e., in the ceramic mold. These results suggest that the temperature gradient in the mold is closely related to grain refinement.

The above results reveal that the gradient cooling characteristics of the mold are closely related to the casting microstructure. In micro-casting, solidification from a supercooled state may be used to impart the desired micro-characteristics of the castings such as amorphousness, metastable phases, and microstructures. In order to obtain large supercooling for the production of new materials such as amorphous materials, it is necessary to reduce the diameter of manufactured products. For the development of micro-casting technology, a future challenge will be to elucidate the correlation between microscopic supercooling solidification phenomena and macroscopic transport phenomena.

4. Conclusion

The presented experimental evidence on the feasibility of molds with gradient cooling properties aimed at microstructure control of micro-casings allows the following conclusions:

(1) Solidification experiments with non-uniform distribution of mold properties revealed that microstructural changes occur locally due to the influence of non-uniform thermal conditions.
(2) Both mold geometry and material property and arrangement influence the mold's cooling properties.
(3) Items (1) and (2) suggest that additive manufacturing techniques can be used to manufacture molds with varying geometry and material variations to impart the desired cooling properties of the mold.

The proposed technology offers the potential to control the properties of micro-cast products in applications ranging from implants, medical instruments, microelectronic components, micro-sensors/actuators as well as in larger castings with micro-scale functional features.

CRediT authorship contribution statement

Kuniaki Dohda: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Vasudev Aravind:** Writing – review & editing, Formal analysis. **Hideaki Yoshioka:** Writing – review & editing, Methodology, Investigation. **Kornel Ehmann:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Tatsuya Funazuka:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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