

Phase Change Materials (PCMs) for Thermal Management During Permanent Mold Casting

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ABSTRACT

Dynamic casting processes such as permanent mold and die casting require effective thermal management of molds to balance rapid heat absorption from the molten metal and immediate heat recovery to the mold for subsequent casting cycles. Existing thermal technologies like direct flame and coolants have difficulty controlling heat transfer, resulting in thermomechanical fatigue of the mold due to excessive heating and cooling. Controlling the heat transfer in molds is paramount to ensuring the production of high-quality castings and reducing production cycle times. An innovative approach to controlling thermal gradients in molds involves incorporating phase change materials (PCMs) inside the molds. With their thermal energy storage capability and high latent heat, PCMs embedded in molds facilitate mold temperature self-regulation for heating and cooling as the PCM undergoes solid-liquid phase transformations during the casting process. In this paper, the feasibility of PCMs in dynamic casting processes is presented.

Keywords: thermal management, heat transfer, phase change material, PCM, permanent mold casting, interfacial heat transfer coefficient, IHTC

INTRODUCTION

Thermal management of permanent molds plays a crucial role in ensuring rapid solidification rates and preventing the formation of defects during solidification. Proper thermal management will also decrease casting cycle time and enhance cast product quality.¹⁻⁴ The inability to control thermal conditions consistently throughout each casting cycle affects not only quality characteristics, such as porosity and shrinkage, but also results in delayed solidification. Thermal management during solidification relies on the use of thermal technologies, such as direct flame and coolants, which have been widely utilized to manipulate thermal gradients in molds.^{5,6} However, use of these current thermal technologies leads to excessive heating and cooling, which exacerbates thermomechanical fatigue of the molds and negatively affects product quality and productivity.⁷ For effective thermal management, it is essential to maintain a *balanced* control of thermal gradients during both the heating and cooling phases of the process.

Phase change material (PCM) has been proposed as a potential heating and cooling strategy to regulate thermal conditions by leveraging its latent heat thermal energy storage capability.⁸ This approach has applications in various fields, including construction, semi-conductor, and renewable power system, in response to evolving environmental standards.⁹⁻¹¹ Essentially, PCMs possess an intrinsic ability to absorb and release thermal energy during phase transformation cycles, leading to both heating and cooling. This latent heat storage capability allows for heat to be stored and released even with minimal temperature variation, offering a storage capacity that is 5 to 14 times greater than that of sensible heat storage.⁶ Consequently, the application of PCM has the potential for manipulating thermal gradients within a system, enabling efficient thermal management. The application of PCMs to manage thermal gradients in casting processes and systems has been studied.^{12,13} In particular, Noohi et al. investigated the efficiency of metallic PCMs as chills for rapid solidification for sand castings.^{14,15} Pure zinc (Zn) was chosen as the PCM chill material for experiments with an Al-4.5 wt.% Cu-0.2 wt.% Fe alloy. As a result, castings using a Zn PCM chill solidified in 380s, whereas those with traditional chills required 440s. The Zn PCM chill dissipated heat up to 60s faster due to its significant latent heat absorption effect. These findings validate the feasibility of metallic PCMs for static casting processes. However, the technology remains nascent for incorporation in dynamic casting processes, such as permanent mold casting and die casting. The challenge is that in dynamic casting processes, one requires not only rapid heat removal but also heat recovery for subsequent casting cycles. Although rapid heat dissipation using PCMs has been validated in static casting processes, i.e., sand casting and investment casting, the literature for the application of PCMs for dynamic casting processes is lacking. Ideally, the reversible exothermic and endothermic phase transitions of PCMs can effectively control thermal gradients in molds, facilitating rapid solidification and heat recovery to the mold by integrating the PCM into the permanent mold casting system during cyclic casting processes. The primary objective of this study is to investigate the potential application and appropriate design of PCMs within permanent molds for thermal management, both experimentally and through finite element (FE) simulation and modeling. Specifically, this work examines the effects of geometrical variables and

heat transfer characteristics of the molds incorporating PCM on the solidification process.

SELECTION OF APPROPRIATE PCMS FOR PERMANENT MOLD CASTING PROCESSES

The selection of a suitable PCM for permanent mold casting needs to consider the following parameters:¹⁶

- (i) Melting temperature (T_m)
 - The melting temperature should be like the typical temperature of the permanent mold during casting to effectively utilize the thermal energy storage ability of the PCM.
- (ii) High latent heat (ΔH_f)
 - A PCM with high latent heat can store thermal energy efficiently and distribute it to the mold.
- (iii) Specific heat capacity (C_p)
 - The specific heat capacity influences the rate at which temperature changes occur within the material.
- (iv) High thermal diffusivity (α)
 - High thermal diffusivity enhances the heat dissipation capacity and reduces heating/cooling response times.

Additionally, non-toxicity, non-flammability, and non-chemical reactivity are vital considerations for safe use of PCMs.

Among the various types of PCMs, metallic PCMs were chosen due to their high thermal conductivity, rapid thermal response, high storage density, and excellent thermal repeatability and reliability compared to other PCM types, such as molten salts and organic PCMs. In particular, pure Zn was selected as the suitable PCM to design the PCM mold in this study, considering its

appropriate phase transformation temperature, high latent heat, and high thermal diffusivity, as shown in Table 1. Specifically, the phase transformation temperature of the PCM must align with the general temperature of the mold during the casting process to effectively utilize thermal energy storage capabilities and latent heat for heat absorption and release. Typically, the mold temperature ranges from 662F(350C) to 932F(500C) during cyclic casting processes.^{17,18}

DESIGN OF EXPERIMENTS

MATERIALS

AISI 1016 carbon steel was utilized for the steel mold for both the inner and outer mold. AISI 1016 is easier to machine than the commonly used H13 tool steel.¹⁹ The chemical composition of the AISI 1016 steel, analyzed using Optical Emission Spectroscopy (OES), [AS01, Spectro Ametek], was found to be 0.15 wt.% C, 0.87 wt.% Mn, 0.02 wt.% P, 0.21 wt.% Si, 0.01 wt.% S, and the balance consisting of Fe. Table 1 provides their thermophysical properties.

Table 1. Thermophysical Properties of AISI 1016 Carbon Steel, Pure Zn, and A356 Alloy²⁰⁻²²
(T_m : Melting Temperature, ΔH_f : Latent Heat of Fusion, and α : Thermal Diffusivity)

	T_m [°F(°C)]	ΔH_f (kJ/kg)	α ($\times 10^{-5} m^2/s$)
A356	716 to 732 (380 to 389)	398	5.92
AISI 1016	2660 (1460)	-	1.51
Pure Zn	787.1 (419.5)	113	4.19

Table 2. Variables Utilized in FE Simulations
(Mold Material Types, Geometrical Parameters, Initial Temperatures of Mold & Casting, Ambient Convective Heat Transfer Coefficient (h), & Interfacial Heat Transfer Coefficients (IHTCs) for Mold-casting & PCM-inner Steel Mold interfaces)

	Mold material		Mold thickness [mm(inch)]		Casting thickness [mm(inch)]	Pre-heated temperature [°F(°C)]	Casting temperature [°F(°C)]	Ambient h (W/m ² ·K)	IHTC (W/m ² ·K)	
	Steel	PCM	Inner mold	PCM					Inner mold/ Casting	PCM / Inner mold
Steel mold (No PCM)	AISI 1016	-	82.55 (3¼)	-	6.35 (¼) 12.7 (½) 25.4 (1)	662 (350)	1328 (720)	20	1500	-
			101.6 (4)	-						
PCM mold	AISI 1016	Pure Zn	6.35 (¼)	76.2 (3)	6.35 (¼) 12.7 (½) 25.4 (1)	662 (350)	1328 (720)	20	1500	1500
			25.4 (1)	76.2 (3)						2000 3000 4000 5000

In addition, pure Zn was selected as the appropriate PCM for designing the PCM mold. The pure Zn, supplied by Rotometals (USA), was confirmed to have a chemical composition of 99.9 wt.% Zn, with other elements (Fe, Cu, Al, and Pb) present at levels less than 0.002 wt.%.

The A356 melt was heated to 1328F(720C) prior to the start of solidification. Three different thicknesses were considered for the A356 that was solidified – 1/4, 1/2, and 1 inch (6.35, 12.7 and 25.4mm) (Table 2).

FINITE ELEMENT (FE) SIMULATIONS

To validate the advantages of the Zn PCM mold for rapid solidification, modeling and FE simulations were conducted prior to the construction of the PCM molds and conducting casting trials. These simulations were performed using the transient heat transfer module in COMSOL Multiphysics. The FE simulations investigated not only the geometrical effects of the mold and casting on heat transfer but also the influence of the PCM mold on solidification. Detailed information regarding the FE simulation, including materials, geometrical parameters, initial conditions (ICs), and boundary conditions (BCs), is given in Table 2.

Typically, permanent mold cast components have thicknesses ranging from 0.1 to 2 inch (2.54 to 50.8mm).²³⁻²⁵ Accordingly, casting thicknesses of 1/4, 1/2 and 1 inch (6.35, 12.7 and 25.4mm) were selected for the FE simulations. Minimizing the inner mold thickness in PCM molds can significantly enhance heat transfer by reducing the impact of the relatively low thermal diffusivity of the steel, as shown in Table 1. As the quantitative effect of inner mold thickness on heat transfer in PCM molds has yet to be determined, the simulations were conducted with the inner mold thickness set to match the casting thickness at 1/4 inch and 1 inch (6.35 mm and 25.4 mm).

For ICs, the temperatures of the mold and casting were set to 662F (350C) and 1328F (720C), respectively.

A constant ambient convective heat transfer coefficient (h) of 20 W/m²·°C was applied as a BC on the surroundings. Furthermore, the interfacial heat transfer coefficient (IHTC) between the A356 alloy and the inner mold was set to an average value of 1500 W/m²·°C.^{26,27} The IHTC between the inner mold and the Zn PCM was ranged from 1500 to 5000 W/m²·°C.

CASTING TRIALS

A schematic diagram of the Zn PCM mold is shown in Fig. 1. Specific geometrical details, including depth and width, of the thermocouples (TC) are shown in Fig. 1(b). To obtain temperature profiles of the inner mold, Zn PCM, and A356 alloy during solidification, seven thermocouples (TCs) were inserted at various depths, Fig. 1(b). A minimum of three TCs were placed in both the Zn PCM and the inner mold to obtain the interface temperature through extrapolation, facilitating the calculation of IHTC between the Zn and steel.

The thickness of the inner mold must be minimized to ensure rapid heat transfer, considering the thermal properties of both the steel and pure Zn (Table 1). However, it was necessary to drill at least three holes at different locations within the inner mold. Consequently, the inner mold was designed with a thickness of 1/2 inch (12.7mm) as a compromise between effective heat transfer and structural integrity.

To construct the PCM molds, pure Zn was melted at 1112F(600C) in a muffle furnace. After pre-heating the outer and inner molds to 662F(350C) in a forced convection chamber furnace, the molten Zn was poured between the molds and allowed to solidify directly. During the pouring process, temperature profiles were recorded. In addition, Ca₂O₄Si insulation, with a thermal conductivity of 0.08 W/m·°C, was applied to the sides of the PCM, the casting, and the bottom of the PCM mold to ensure uni-directional solidification of the casting as shown in Fig 1(a).²⁸

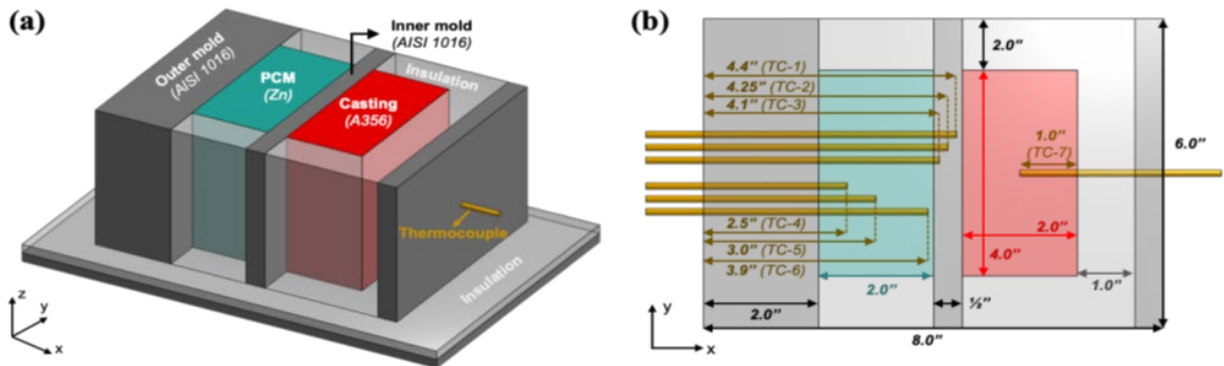


Figure 1. (a) A schematic of the Zn PCM mold utilized for casting trials and (b) a 2D configuration illustrating the geometric dimensions of the mold, Zn PCM, casting, and specific locations of thermocouple (TC) used.

After completing the construction of the Zn PCM mold, the A356 alloy was melted at 1328F(720C) in a muffle furnace. The PCM mold was preheated to 662F(350C) for 3 hours in a forced convection chamber furnace. Following this, seven TCs were inserted into designated holes to collect temperature data after the mold was removed from the furnace. The molten metal was then poured into the inner of the PCM mold. Subsequently, an additional Ca₂O₄Si insulation sheet was placed on top of the Zn PCM mold to ensure unidirectional solidification and to prevent convective heat transfer from the top during solidification.

RESULTS AND DISCUSSION

EFFECTS OF GEOMETRICAL VARIABLES AND INTERFACIAL HEAT TRANSFER COEFFICIENT DURING SOLIDIFICATION USING PCM MOLD

Figure 2 is a schematic of the temperature distribution and the resistances that exist at each interface when a PCM is embedded in the steel mold. The melting point T_m of A356 and the PCM are also shown in Fig 2.

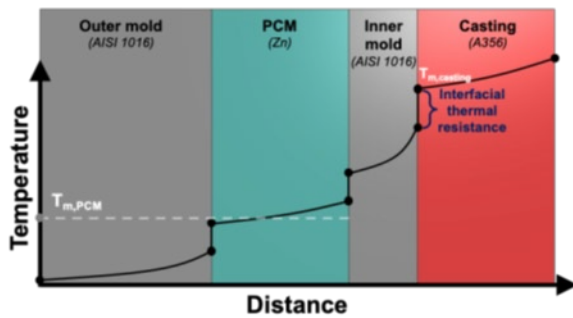


Figure 2. A schematic of the temperature distribution and the interfacial thermal resistances with PCM embedded in the steel mold.

Figure 3 illustrates the concept of a PCM mold highlighting enthalpy and temperature profiles in comparison to a conventional steel mold. When heat is transferred as molten metal is poured in, both enthalpy and temperature rise. Moving farther from the A356

casting, the temperature and enthalpy progressively decrease. This behavior exemplifies the typical energy and temperature gradients present during the casting process, Fig. 3(a).

In contrast, the PCM mold concept differs significantly from conventional molds due to its unique energy management properties. When molten A356 is poured, the PCM mold absorbs heat rapidly. However, unlike the conventional mold, the temperature of the PCM does not spike upon absorbing energy. Instead, during the phase transformation, the PCM stores thermal energy by transitioning from solid to liquid, maintaining a consistent temperature throughout this period.

This steady temperature creates a pronounced thermal gradient within the inner mold, enabling rapid heat dissipation from the casting. This storage capability can be utilized to promote faster solidification while also allowing the stored energy to reheat the mold once the PCM re-solidifies after the casting product has been completed and ejected. Ultimately, the PCM embedded in the mold enables effective management of the thermal gradient and temperature by self-heating and self-cooling throughout the dynamic casting process.

A key advantage of using PCM is its ability to control the thermal gradient by selecting materials with specific melting points. By adjusting the melting temperature of the PCM, the thermal gradient within the mold can be tailored to suit different casting objectives. In this study, pure Zn was selected for reasons previously discussed. Furthermore, the specific design of the PCM mold and the interfacial thermal resistance are critical factors that must be considered to assess the efficiency of the PCM mold in comparison to a conventional steel mold.

The FE simulation was performed to evaluate the effect of the Zn PCM mold on solidification, comparing its performance with that of a conventional steel mold. The analysis of geometrical variables and interfacial heat transfer coefficient (IHTC) for various inner mold thicknesses evaluated by the efficiency of the PCM mold on solidification time is shown in Fig. 4.

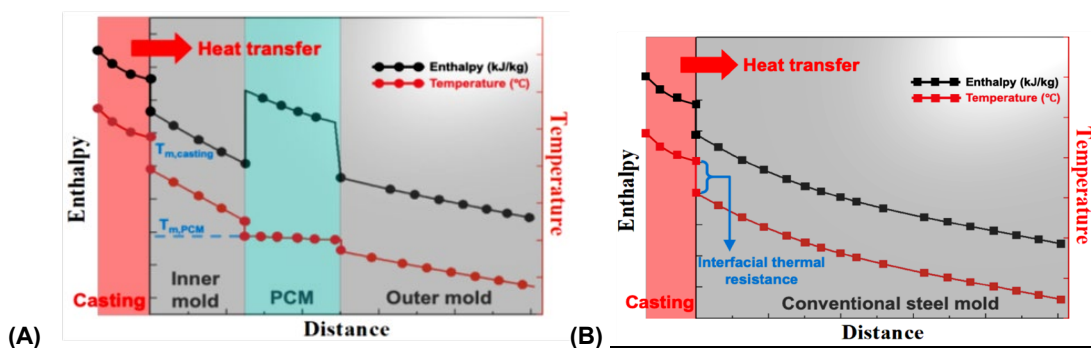


Figure 3. Enthalpy and temperature profiles of (a) the convective steel mold and (b) PCM mold.

As a result, in the conventional steel mold, the molten metal solidified in 31.6s for a casting thickness of 1/4 inch (6.35mm), 75.9s for 1/2 inch (12.7mm), and 206.3s for 1 inch (25.4mm). Utilizing these results as a reference, the effect of the PCM mold was investigated based on various IHTCs with different mold and casting thicknesses.

As can be seen in Fig. 4 (a), for a casting thickness of 1/4 inch (6.35mm), there were a few advantages to using the PCM mold compared to the steel mold in terms of solidification; in fact, the PCM mold delayed solidification by 17.7% when the IHTCs were both 1500 and 2000 W/m²·K. As the IHTC exceeded 4000 W/m²·K, the casting solidified up to 1s faster. However, with a casting thickness of 1/2 inch (12.7mm), the efficiency of the PCM mold became apparent, depending on the IHTC. When the IHTC exceeded 3000 W/m²·K, the casting solidified more rapidly in the PCM mold than in the steel mold, resulting in a maximum reduction of 12% in solidification time. Significantly, regardless of the IHTC, the Zn PCM mold always facilitated faster solidification up to 45s compared to the steel mold for the larger casting thickness of 1 inch (25.4mm).

In contrast, the solidification behavior of the PCM mold changed significantly with a mold thickness of 4 inches (101.6mm), consisting of a 3-inch (76.2mm) PCM and a 1-inch (25.4mm) inner mold thickness, as shown in Fig. 4(b). For the casting thickness of 1/4 inch (6.35mm), the solidification rate remained consistent regardless of the mold type. The relatively thicker inner mold was able to absorb sufficient thermal energy from the casting to achieve complete solidification, preventing heat from reaching the PCM during the process. As a result, the excellent thermophysical properties and thermal storage capacity of the PCM were not fully utilized. Similarly, with the casting thickness of 1/2 inch (12.7mm), some advantages were observed when the IHTC reached values

above 4000 W/m²·K, leading to a rapid solidification in the PCM mold, up to 9s faster than in the steel mold. Moreover, when the casting thickness increased to 1 inch (25.4mm), solidification occurred more rapidly in the PCM mold compared to the steel mold under certain IHTC conditions exceeding 3000 W/m²·K.

Ultimately, the inefficiency of the Zn PCM mold is evident when the inner mold is thicker than the casting, resulting in either similar or delayed solidification rates compared to the conventional steel mold without any PCM. Moreover, it is crucial to thoroughly investigate the IHTC between the inner mold and pure Zn to clearly validate the advantages of the PCM mold during the casting process.

TEMPERATURE PROFILES OF PCM MOLD

The casting experiment was conducted utilizing the Zn PCM mold (Fig. 1) to obtain temperature profiles for the Zn, inner mold, and the casting. This allowed for an investigation of the IHTC between the inner mold and the Zn (Fig. 2). While three TCs were placed in the PCM and the inner mold, only two temperature profiles are shown in Fig. 5 for the sake of clarity.

As shown in Fig. 5, the A356 melt completely solidified within 610s in the Zn PCM mold. In addition, the temperature profile of the casting exhibited a plateau during its phase transformation, which occurred between 200s and 400s. At the same time, temperatures of both the inner mold and the Zn PCM initially increased rapidly as they absorbed significant amounts of heat from the casting. During the phase transformation of the casting, latent heat was released to the inner mold, causing its temperature to gradually rise to a peak of 786.2°F(419°C). While the temperature of the Zn PCM also increased slowly, it remained solid throughout the casting process due to the relatively low pre-heating temperature used in the experiment.

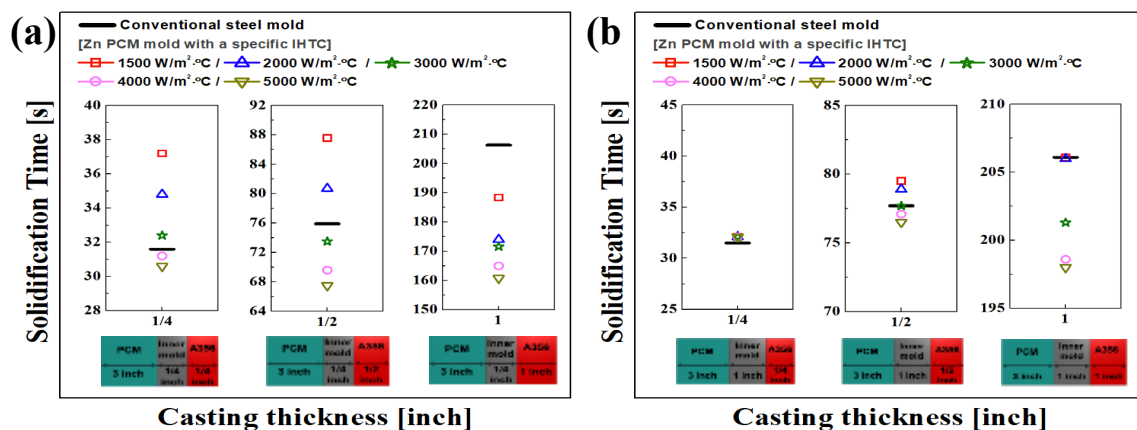


Figure 4. Solidification times of conventional steel molds and Zn PCM molds with varying interfacial heat transfer coefficients (IHTCs) between the inner mold and pure Zn. These results are presented for casting thicknesses of 1/4, 1/2 and 1 inch (6.35, 12.7 and 25.4mm), with mold thicknesses of (a) 3 1/4 inch (82.55mm) and (b) 4 inch (101.6mm).

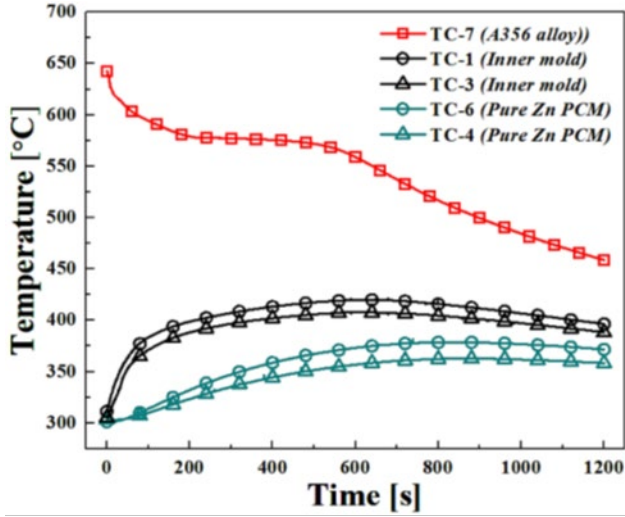


Figure 5. Temperature profiles of A356 casting alloy (red) recorded by TC-7, inner mold (black) obtained by TC-1 and TC-3, and pure Zn PCM (teal) attained by TC-4 and TC-6 over time. The specific thermocouple (TC) locations are shown in Fig. 1 (b).

The temperature differences observed between TC-1 and TC-3 in the inner mold, as well as TC-4 and TC-6 in the pure Zn, were attributed to the thermal conductivity of each material. Although TC-3 and TC-6 were positioned close to each other, just 0.2 inch (5.08mm) apart (Fig. 1(b)), the temperature differences became significant, with an average difference of 35°C (63°F). It was deduced that the interfacial heat transfer resistance between the Zn and the inner mold was substantial, impeding effective heat transfer from the inner mold to the Zn PCM.

INTERFACIAL HEAT TRANSFER COEFFICIENT (IHTC) BETWEEN PCM AND INNER MOLD

In general, the interfacial thermal resistance between two dissimilar materials can be evaluated by examining the IHTC. The experimentally measured temperatures in both the inner mold and the Zn PCM were extrapolated to estimate the interfacial temperatures at each section. Prior to calculating the IHTC, the heat flux of the inner mold was determined using Eqn. 1. Following this, the IHTC between the inner mold and the Zn was computed using Eqn. 2.²⁹

$$Q = \left[\rho \cdot C_p \cdot V \cdot \left(\frac{\partial T}{\partial t} \right) \right] \div A \quad \text{Eqn. 1}$$

$$IHTC = Q / (T_{\text{Inner mold}} - T_{\text{pure Zn}}) \quad \text{Eqn. 2}$$

Where: Q refers to the heat flux, ρ is the density, C_p is the specific heat, V denotes the volume, and A refers to the surface area.

Figure 6 depicts the IHTC between the inner mold and the Zn PCM as a function of the Zn PCM temperature. Specifically, when the Zn PCM was in the liquid phase (above 786.2F(419C)), the average IHTC was approximately 1850 W/m²·K. However, this value gradually dropped to an average of 500 W/m²·K as the Zn PCM completely solidified. The IHTC experienced a sharp decline during the solidification process of the Zn. Similar to the general behavior of IHTC between the casting and the mold,^{26,30} it is likely that the solid Zn partially detached from the surface of the inner mold due to its shrinkage during phase transformation.

Consequently, this separation would create air gaps at the interface between the Zn and the inner mold, which significantly increases the interfacial heat transfer resistance.

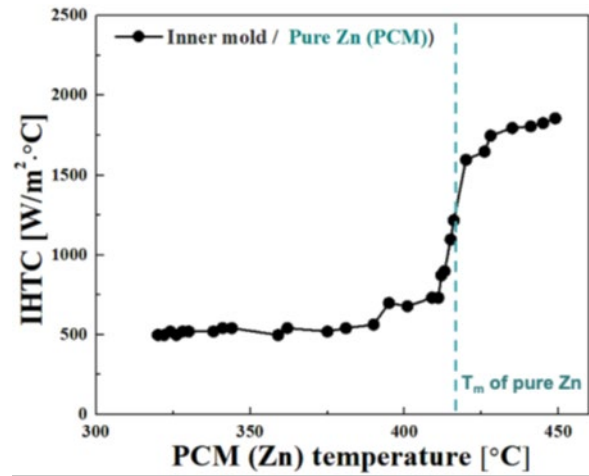


Figure 6. Interfacial heat transfer coefficient (IHTC) between the Zn and the inner mold as a function of Zn PCM temperature.

Building on the results from the previous FE simulation, few benefits of the PCM mold can be demonstrated by incorporating the experimentally determined IHTCs between the inner mold and Zn. Therefore, ensuring a tight contact between the Zn PCM and the inner mold is crucial to facilitate efficient heat transfer for both absorption and release in the PCM mold during casting.

CONCLUSIONS AND SUGGESTED FUTURE WORK

This work aims to explore the potential application and strategic design of phase change materials (PCMs) within permanent molds for efficient thermal management during dynamic casting processes. Ideally, PCMs can effectively regulate thermal gradients in molds, serving as both heating and cooling mechanisms. This is mainly achieved utilizing the latent heat thermal energy storage

capability of the PCM through reversible exothermic and endothermic phase transitions consistently during the permanent mold casting process.

Prior to designing the PCM mold, selecting an appropriate PCM is crucial for improving the overall performance of the casting process. In this study, pure Zn was selected as the suitable PCM in this system due to its phase transformation temperature being close to the general mold temperatures during the casting process. This compatibility facilitates the reversible phase transformation of Zn, which is critical for effective thermal management within the mold. In addition, Zn exhibits high thermal diffusivity and excellent latent heat capacity, making it ideal for thermal energy storage. Therefore, the PCM mold was constructed using pure Zn for the casting trials.

The effects of geometrical variables and interfacial heat transfer characteristics on the solidification of the PCM mold were examined through FE simulations to assess the efficiency of the PCM mold before conducting casting experiments. The results indicated that when the inner mold thickness in the Zn PCM mold exceeded that of the casting, few significant advantages were observed, regardless of the IHTC between the Zn and the inner mold, compared to the conventional steel mold without PCM in terms of rapid solidification. Specifically, the PCM mold led to either similar or delayed solidification times, with up to a 17.7% increase compared to the steel mold. Therefore, the inner mold thickness must be minimized to ensure efficient heat transfer and rapid solidification during the casting process.

In addition, the efficiency of the PCM mold was significantly dependent on the IHTC between the Zn and the inner mold. For instance, with a Zn PCM mold thickness of 4 inch (101.6mm) and a casting thickness of 1 inch (25.4mm), the PCM mold facilitated rapid heat dissipation and solidification under specific IHTC conditions above $3000 \text{ W/m}^2\cdot\text{K}$, compared to conventional steel mold. However, when the casting thickness was relatively larger than the thickness of the inner mold, the casting solidified faster with the PCM mold compared to the traditional steel mold. Ultimately, the IHTC must be experimentally investigated to clearly validate the advantages of using the PCM mold.

Following the casting trials with Zn PCM molds, significant temperature differences were observed between TC-3 and TC-6, averaging 35°C , despite their proximity. It was shown that while the average IHTC between the liquid Zn and the inner mold was approximately $1850 \text{ W/m}^2\cdot\text{K}$, this value drastically decreased as the Zn transitioned from liquid to solid, dropping to an average of $500 \text{ W/m}^2\cdot\text{K}$. The high thermal resistance at the interface between the Zn and the steel

inner mold significantly reduced the efficiency of the PCM mold. It is likely that solid Zn partially detached from the inner mold surface due to shrinkage during phase transformation, creating an air gap that severely hindered effective heat transfer at the interface.

To ensure the efficiency of the PCM mold in rapid heat transfer, future research should focus on eliminating the interfacial air gap between the PCM and the mold by tightly bonding the dissimilar material, while also exploring strategic methods to enhance heat transfer in molds during the casting process. Although this work primarily focused on heat dissipation using PCMs, future work should address heat recovery through the exothermic phase transformation of the PCM during the casting cycle. The relatively low value of IHTC in the solid state of the PCM helps maintain a higher mold temperature by limiting heat transfer, compared to the higher IHTC value in the liquid state of the PCM. Leveraging this solid-liquid phase regulation of the PCM enables efficient control of both heat removal and subsequent heat recovery processes. Future work will focus on validating solutions for efficient heat removal/recovery and demonstrating the advantages of PCM molds during casting. This study could lay the foundation for the development of a self-regulating permanent mold that incorporates PCMs, enabling both the heating and cooling of molds through the reversible phase transformations of the PCM during dynamic casting processes.

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REFERENCES

1. Yang, T., Hu, H., Chen, X., Chu, Y.-I. & Cheng, P. "Thermal analysis of casting dies with local temperature controller," *The International Journal of Advanced Manufacturing Technology* **33**, 277-284 (2007).
2. Ahn, D., & Kim, H., "Study on the manufacture of a thermal management mould with three different materials using a direct metal tooling rapid tooling process," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* **224**, 385-402 (2010).
3. Wylonis, E.M., "Production of injection molding tooling with conformal cooling channels using the

- three dimensional printing process," Massachusetts Institute of Technology (1995).
4. Wang, G., Zhao, G., Li, H., & Guan, Y., "Research of thermal response simulation and mold structure optimization for rapid heat cycle molding processes, respectively, with steam heating and electric heating," *Materials & Design* **31**, 382-395 (2010).
 5. Hariram, V., *et al.*, "FEA based approach on replacing the metal cast wheel into thermoset plastic wheel," *Materials Today: Proceedings* **33**, 3420-3425 (2020).
 6. Oppelt, T., Schulze, J., Stein, H. & Platzer, B., "Comparison of methods for mould surface heating–Part 1," *International Polymer Science and Technology* **39**, 1-8 (2012).
 7. Hu, H., Chen, F., Chen, X., Chu, Y.-L. & Cheng, P. in *EPD Congress 2003, as held at the 2003 TMS Annual Meeting*, 439-451.
 8. Reddy, V. J., Ghazali, M. F. & Kumarasamy, S., "Innovations in phase change materials for diverse industrial applications: A comprehensive review," *Results in Chemistry*, 101552 (2024).
 9. Marani, A. & Nehdi, M. L., "Integrating phase change materials in construction materials: Critical review," *Construction and Building Materials*, **217**, 36-49 (2019).
 10. Song, W. *et al.*, "Thermal management of standby battery for outdoor base station based on the semiconductor thermoelectric device and phase change materials," *Appl Therm Eng*, **137**, 203-217 (2018).
 11. Wei, G. *et al.*, "Selection principles and thermophysical properties of high temperature phase change materials for thermal energy storage: A review," *Renewable and Sustainable Energy Reviews* **81**, 1771-1786 (2018).
 12. Chadha, U. *et al.*, "Phase change materials in metal casting processes: a critical review and future possibilities," *Adv Mater Sci Eng* **2022**, 7520308 (2022).
 13. Wang, S. & Millogo, J.D., "Phase changing material used with RP technology in quick wax molding for investment casting," *Computer-Aided Design and Applications* **9**, 409-418 (2012).
 14. Noohi, Z., Niroumand, B. & Timelli, G., "Numerical simulation of the effects of a Phase Change Material (PCM) on solidification path of gravity sand cast Al-Cu alloy," *La Metallurgia Italiana*, 25-30 (2021).
 15. Noohi, Z., Niroumand, B., Panjepour, M. & Timelli, G., "A new generation of metal chillers to control the solidification structure of Al-4.5 wt% Cu alloy," *Journal of Materials Research and Technology* **28**, 2488-2503 (2024).
 16. Sharma, A., Chouhan, A., Pavithran, L., Chadha, U. & Selvaraj, S. K., "Implementation of LSS framework in automotive component manufacturing: a review, current scenario and future directions," *Materials Today: Proceedings* **46**, 7815-7824 (2021).
 17. Ayabe, M. *et al.*, "Effect of high thermal conductivity die steel in aluminum casting," *International Journal of Metalcasting* **2**, 47-55 (2008).
 18. Roorda, S., *Influence of Mold Coating Wear on Heat Transfer Coefficient in Aluminum Permanent Molds*, Worcester Polytechnic Institute, (2021).
 19. Thompson, S., *Handbook of mould, tool and die repair welding*, (Elsevier, 1999).
 20. McBride, B. J., *Thermodynamic data for fifty reference elements*, (National Aeronautics and Space Administration, Glenn Research Center (2001).
 21. Miettinen, J., "Calculation of solidification-related thermophysical properties for steels," *Metallurgical and Materials Transactions B* **28**, 281-297 (1997).
 22. Kolahdooz, A. & Dehkordi, S.A., "Effects of important parameters in the production of Al-A356 alloy by semi-solid forming process," *Journal of Materials Research and Technology* **8**, 189-198 (2019).
 23. Hajas, G., (Google Patents, 2017).
 24. Grosselle, F., Timelli, G., Bonollo, F. & Della Corte, E., "Correlation between microstructure and mechanical properties of Al-Si cast alloys," *la metallurgia italiana* (2009).
 25. Stefanescu, D., Davis, J. & Destefani, J., "Metals Handbook," Vol. 15-Casting, *ASM International*, 937 (1988).
 26. Ho, K. & Pehlke, R.D., "Metal-mold interfacial heat transfer," *Metallurgical Transactions B* **16**, 585-594 (1985).
 27. Bazhenov, V., Tselovalnik, Y.V., Koltygin, A. & Belov, V., "Investigation of the Interfacial Heat Transfer Coefficient at the Metal–Mold Interface During Casting of an A356 Aluminum Alloy and AZ81 Magnesium Alloy into Steel and Graphite Molds," *International Journal of Metalcasting* **15**, 625-637 (2021).
 28. Ebert, H.-P. & Hemberger, F., "Intercomparison of thermal conductivity measurements on a calcium silicate insulation material," *International journal of thermal sciences*, **50**, 1838-1844 (2011).
 29. Dhodare, A., Ravanani, P. & Dodiya, N., "A review on interfacial heat transfer coefficient during solidification in casting," *IJERT* **6**, 464-467 (2017).
 30. Poirier, D.R. & Poirier, E.J., "Heat transfer fundamentals for metal casting," *The Minerals, Metals & Materials Society* (1994).