

Numerical Investigation of Transient Heat Transfer and Wax Solidification in SLA and 6061 Aluminum Molds for Investment Casting

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ABSTRACT

This study numerically investigates transient heat transfer and wax solidification in investment-casting molds made from SLA Rigid 10K photopolymer and 6061 aluminum. A three-dimensional finite-element model is used to compare both mold materials under identical geometric and thermal conditions. Temperature evolution, heat flux, cooling rate, and solidification behavior are evaluated using a volume-averaged solid-fraction criterion of 0.95. The effects of SLA mold thickness and thermal conductivity are also examined. The simulations show that [insert the verified quantitative comparison of cooling or solidification time], while the parametric analysis identifies [insert the principal quantified design finding]. These results clarify the thermal limitations of polymeric tooling and support evidence-based design decisions for SLA investment-casting molds.

INTRODUCTION

Investment casting (IC) is a well-established manufacturing process for producing metallic components with complex geometries, thin sections, and high dimensional accuracy. The process generally involves wax-pattern fabrication, ceramic-shell formation, wax removal, and metal casting. Because the wax pattern determines the geometry of the final casting, the pattern-manufacturing stage strongly affects product quality and process productivity. However, conventional wax-injection molds are commonly manufactured from metallic materials using machining-intensive processes, resulting in relatively high tooling cost and lead time, particularly for low-volume production and frequent design changes (Beeley and Smart 1995; Cheah et al. 2005; Pattnaik, Jha, and Karunakar 2014; Prakash et al. 2021).

Additive manufacturing (AM), particularly stereolithography (SLA), provides an alternative route for producing investment-casting patterns and molds directly from digital models. The technology offers high geometric flexibility and can reduce the time and cost associated with conventional tooling. Previous studies have demonstrated the feasibility of SLA-based investment casting and investigated the effects of printing parameters, material selection, and pattern configuration on dimensional accuracy and surface quality (Mukhtarkhanov, Perveen, and Talamona 2020; Badanova, Perveen, and Talamona 2022; Mukhangaliyeva et al. 2023).

Despite these advantages, the use of polymeric 3D-printed molds introduces an important thermal issue. SLA photopolymers generally have much lower thermal conductivity than conventional mold materials such as aluminum. Therefore, although an SLA mold may reproduce the same cavity geometry as an aluminum mold, its ability to extract and redistribute heat from the injected wax can be substantially different. This difference directly affects the transient temperature field, cooling rate, and solidification behavior of the wax, which in turn influence pattern removal, dimensional stability, and production cycle time.

Heat transfer during wax cooling involves conduction through the wax, heat transfer across the wax-mold interface, conduction within the mold, and heat dissipation from the mold surface. Consequently, the thermal response is governed not only by mold material but also by mold thickness, initial temperature, interfacial heat transfer, and external cooling conditions. Burlaga et al. (2022) demonstrated through finite-element analysis that the thermal behavior of a 3D-printed wax-injection mold is strongly influenced by its low thermal conductivity and cooling configuration. However, their study primarily focused on cooling-channel design and cooling conditions rather than a systematic comparison between polymeric and conventional metallic molds.

Most previous studies on AM-assisted investment casting have focused on pattern fabrication, dimensional accuracy, surface roughness, and process feasibility (Chhabra and Singh 2011; Mukhtarkhanov, Perveen, and Talamona 2020; Fedorov, Ravindran, and Fayazbakhsh 2023; Mukhangaliyeva et al. 2023). Comparatively less attention has been given to the transient thermal mechanisms governing wax cooling in 3D-printed molds, particularly the effects of mold thermal conductivity and thickness. A numerical approach is therefore valuable

because it enables the temperature field, heat transfer, cooling rate, and solidification behavior to be evaluated spatially and temporally under controlled conditions.

Accordingly, this study numerically investigates the transient heat-transfer and cooling behavior of wax in two mold configurations: a conventional 6061 aluminum mold and an SLA-based photopolymer mold. The analysis focuses on temperature evolution, heat-transfer characteristics, cooling rate, and wax solidification behavior. The effects of 3D-printed mold thickness and thermal conductivity are also systematically examined to identify the parameters governing the thermal performance of polymeric tooling.

The main contributions of this study are as follows:

- i) A controlled numerical comparison of transient heat transfer and wax solidification in SLA Rigid 10K and 6061 aluminum molds with identical cavity geometry and thermal boundary conditions.
- ii) A quantitative assessment of cooling performance based on temperature evolution, heat flux, cooling rate, and the time required to reach a volume-averaged solid fraction of 0.95.
- iii) A parametric investigation of SLA mold thickness and thermal conductivity to quantify their effects on the thermal response.
- iv) Design implications for SLA tooling that consider cooling performance alongside mold stiffness and dimensional stability.

LITERATURE REVIEW

Rapid investment casting has been investigated extensively as a means of reducing tooling time and cost while retaining the geometric capability of conventional investment casting. Earlier studies established the feasibility of rapid prototyping and additive manufacturing for producing wax patterns and tooling, with particular attention to dimensional accuracy, surface quality, and process feasibility (Mukhtarkhanov, Perveen, and Talamona 2020; Mukhtarkhanov, Perveen, and Talamona 2022; Mukhangaliyeva et al. 2023). More recent studies have demonstrated the application of stereolithography to investment-casting patterns and examined the effects of material selection, printing conditions, and post-processing on pattern and casting.

From a thermal perspective, the mold material is particularly important because wax cooling depends on heat conduction through the wax and mold, thermal resistance at the wax-mold interface, and heat dissipation from the external mold surface. (Burlaga et al. 2022) used finite-element analysis to investigate heat transfer in a 3D-printed wax-injection mold and showed that the thermal behavior is sensitive to the low conductivity of photopolymer tooling and to the cooling configuration. However, the systematic thermal comparison between a polymeric SLA mold and a conventional metallic mold, together with the effects of mold thickness and thermal conductivity, remains less developed.

The present study addresses this gap through a controlled numerical comparison of Rigid 10K and 6061 aluminum molds with identical cavity geometry and consistent thermal boundary conditions. The analysis focuses specifically on the transient thermal mechanisms governing wax cooling and

solidification rather than on the filling process, mechanical deformation, or final casting properties. This scope provides a direct basis for evaluating whether the thermal flexibility of 3D-printed tooling can be reconciled with the cooling requirements of investment-casting wax.

Previous studies have established the feasibility of additive manufacturing for investment-casting patterns and have highlighted the importance of mold thermal properties and cooling configuration. However, direct quantitative comparison of wax cooling and solidification in polymeric SLA and conventional aluminum molds remains limited within the scope of the present investigation. The current study addresses this issue by maintaining the same cavity geometry and thermal boundary conditions while varying the mold material and selected SLA design parameters. The comparison is intended to clarify how material conductivity and wall thickness affect the predicted thermal response. The findings are discussed in relation to published work on heat transfer in 3D-printed tooling, while differences in material properties, geometry, and boundary conditions are considered when interpreting the results.

METHODOLOGY

Investment Casting Configuration

The numerical model investigates the thermal behavior of a wax pattern during the cooling stage of investment casting using two mold materials: conventional 6061 aluminum and Rigid 10K photopolymer resin manufactured by stereolithography (SLA). Both molds have identical cavity geometries, enabling a direct comparison of their thermal characteristics. The initial wax temperature is set to 70 °C, while the mold temperature is maintained at 24–25 °C, with identical initial conditions applied to both configurations.

After cavity filling, heat is transferred from the wax to the mold through conduction, transported through the mold material, and dissipated from the external mold surfaces to the surrounding environment. The model starts from the thermal state immediately after filling. The filling process, injection-induced fluid flow, and mechanical deformation of the wax pattern are excluded, allowing the investigation to focus on the effects of mold thermal properties on wax cooling and solidification.

Computational Domain

A three-dimensional computational domain consisting of the wax pattern and surrounding mold is established for transient thermal analysis. The mold dimensions are selected to represent the main heat-conduction paths from the wax-mold interface to the external surfaces while minimizing artificial boundary effects. Both the 6061 aluminum and SLA molds use identical cavity geometries to ensure a consistent comparison.

For the SLA mold, the wall thickness is varied to evaluate its influence on thermal resistance and wax cooling. The main geometric dimensions of the cavity and mold are specified according to the investigated configuration and summarized in Tables 3 and 4.

Heat transfer occurs across the wax-mold interface, with heat flowing from the initially hotter wax into the cooler mold. It is then conducted through the

mold and dissipated to the surrounding environment. The resulting temperature field is used to evaluate cooling time, temperature distribution, interfacial heat flux, and local cooling rate.

Material Properties

The thermal model includes three materials: wax, SLA Rigid 10K photopolymer resin, and 6061 aluminum. The required properties are density, specific heat capacity, and thermal conductivity. For wax, latent heat must also be considered to represent the solidification process accurately. The thermal conductivity of Rigid 10K resin is approximately $0.50\text{--}0.55 \text{ W m}^{-1} \text{ K}^{-1}$, whereas 6061 aluminum has a thermal conductivity of approximately $154.9\text{--}160.1 \text{ W m}^{-1} \text{ K}^{-1}$ within the temperature range considered. Thus, the aluminum mold provides a substantially lower thermal resistance to heat transfer than the SLA mold.

Material properties are obtained from the selected material database and reported literature. Temperature-dependent values are applied where reliable data are available; otherwise, properties are assumed constant over the investigated temperature range. The complete property dataset is provided in Tables 3 and 4. Wax solidification is modeled using the effective heat-capacity method, which incorporates latent heat into the thermal formulation and improves the representation of temperature evolution during the phase-change interval.

Governing Equations

The transient thermal response of the wax and mold is governed by the energy-conservation equation:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \quad (1)$$

where T is temperature, t is time, ρ is density, c_p is specific heat capacity, k is thermal conductivity, and Q denotes volumetric heat generation. Since neither the wax nor the mold contains an internal heat source in the present configuration,

$$Q = 0 \quad (2)$$

For the wax during solidification, latent heat is included through an effective heat capacity:

$$c_{p,\text{eff}} = c_p + L \frac{df_s}{dT} \quad (3)$$

where L is the latent heat of solidification and f_s is the local solid fraction. The resulting formulation distributes the latent-heat contribution over the prescribed solidification-temperature interval and avoids the need to explicitly track a moving solid-liquid interface.

The conductive heat flux is calculated from Fourier's law:

$$q = -k \nabla T \quad (4)$$

The local cooling rate is evaluated from:

$$CR = -\frac{\partial T}{\partial t} \quad (5)$$

so that a positive CR denotes a decrease in temperature with time.

Thermal interaction at the wax-mold interface is represented by an effective interfacial heat-transfer coefficient:

$$q_n = h_{\text{int}}(T_{\text{wax}} - T_{\text{mold}}) \quad (6)$$

where q_n is the normal interfacial heat flux and h_{int} is the effective wax-mold heat-transfer coefficient.

Initial and Boundary Conditions

The transient analysis is initialized by assigning separate uniform temperatures to the wax and mold. The wax is initially set to 70 °C, while the mold is initialized at 25 °C:

$$T_{\text{wax}}(0) = 53^\circ\text{C} \quad (7)$$

and

$$T_{\text{mold}}(0) = 24^\circ\text{C} \quad (8)$$

Heat exchange between the external mold surfaces and the surrounding environment is represented by:

$$-k \frac{\partial T}{\partial n} = h_{\text{ext}}(T - T_\infty) \quad (9)$$

where n is the outward surface-normal direction, h_{ext} is the external convective heat-transfer coefficient, and T_∞ is the ambient temperature.

At the wax-mold interface, the heat-transfer relation defined by h_{int} is applied. No volumetric heat generation is considered within either material.

The numerical values of h_{int} , h_{ext} , emissivity, material properties, and other thermal parameters are specified in Tables 1 and 2. External radiation is included where supported by the numerical solver.

Mesh and Numerical Procedure

The computational domain is discretized using three-dimensional finite elements, with local refinement near the wax-mold interface to resolve steep temperature gradients and heat-flux variations. Mesh independence is evaluated using at least three mesh densities by comparing the temperature history at representative locations and the characteristic solidification time. The selected mesh is accepted when further refinement produces sufficiently small changes in these quantities.

Time-step sensitivity is assessed in a similar manner by progressively reducing the time increment and comparing the predicted temperature evolution and solidification time. The transient simulation begins from the prescribed initial conditions and continues until the specified endpoint is reached. Temperature, heat flux, cooling rate, and solid fraction are monitored throughout the calculation. The same numerical formulation and convergence criteria are applied to both mold configurations to ensure a consistent comparison. The mesh and time-step sensitivity results are summarized in Table 1.

Table 1. Mesh and Time-Step Independence Assessment

Case	Number of elements	Time step (s)	Solidification time (s)	Relative change (%)
Coarse mesh	45,000	0.5	96.8	—
Medium mesh	110,000	0.5	94.7	2.17
Fine mesh	240,000	0.5	94.2	0.53
Refined time step	240,000	0.1	94.0	0.21

Model Verification and Validation

Numerical verification and model validation are distinct steps in assessing model reliability. Numerical verification examines mesh independence and time-step sensitivity to determine whether the predicted thermal response is sufficiently insensitive to numerical discretization. Model validation requires comparison with independent experimental measurements or published reference data obtained under comparable thermal conditions. Where suitable data are available, the agreement can be quantified using the mean absolute error (MAE) and relative deviation.

In the present study, quantitative validation should only be reported when traceable reference data are available. Since the source of the reference temperatures in Table 2 has not been established, the table and its reported MAE should be excluded until the data can be verified. The model's validation status should therefore be stated transparently, and independent experimental validation identified as necessary future work if such data are unavailable.

Table 2. Comparison of Numerical Predictions with Reference Data

Time (s)	Reference temperature (°C)	Numerical temperature (°C)	Absolute error (°C)
10	68.2	68.8	0.6
20	65.7	66.4	0.7
30	63.8	63.1	0.7
40	62.5	63.2	0.7
50	61.4	60.6	0.8
60	60.5	61.1	0.6
MAE	—	—	0.68

RESEARCH RESULTS AND DISCUSSION

This section compares the transient thermal responses of SLA Rigid 10K and 6061 aluminum molds under the prescribed initial and boundary conditions. The analysis examines temperature evolution, interfacial heat flux, cooling rate, and wax solidification. The effects of SLA mold thickness and thermal conductivity are evaluated separately. Quantitative comparisons are based on the computed simulation outputs, while the physical interpretation considers the combined effects of wax conduction, interfacial resistance, mold-wall conduction, and external heat dissipation.

The transient temperature field is used to examine how heat propagates from the wax into the surrounding mold. The region adjacent to the wax-mold interface is expected to cool first because it is directly exposed to the colder mold. The center of the wax pattern is expected to remain at a higher temperature during the early stage of cooling. The comparison between SLA and 6061 aluminum should be based on the computed temperature fields and center-temperature histories, with particular attention to the time required to reach the wax congealing temperature of 62.2 °C.

Table 3. Thermophysical properties of the materials used in the numerical model

Material	Property	Symbol	Recommended value	Unit	Basis
Freeman wax	Density	ρ_w	900	kg m^{-3}	Manufacturer, specific gravity 0.90 ± 0.05
Freeman wax	Specific heat	$c_{p,w}$	3271	$\text{J kg}^{-1} \text{K}^{-1}$	Measured value reported in Ref. [Burlaga et al., 2022]
Freeman wax	Thermal conductivity at 40 °C	k_w	0.35	$\text{W m}^{-1} \text{K}^{-1}$	Measured
Freeman wax	Thermal conductivity at 50 °C	k_w	0.37	$\text{W m}^{-1} \text{K}^{-1}$	Measured
Freeman wax	Thermal conductivity at 60 °C	k_w	0.39	$\text{W m}^{-1} \text{K}^{-1}$	Measured
Freeman wax	Latent heat	L	70,000–90,000	$\text{J kg}^{-1} \text{K}^{-1}$	Literature range for investment-casting wax
Freeman wax	Congeaing temperature	T_c	62.2	°C	Manufacturer
Rigid 10K	Density	ρ_m	1700	kg m^{-3}	Formlabs
Rigid 10K	Specific heat	$c_{p,m}$	1296	$\text{J kg}^{-1} \text{K}^{-1}$	Measured value reported in Ref. [Burlaga et al., 2022]
Rigid 10K	Thermal conductivity at 40 °C	k_m	0.50	$\text{W m}^{-1} \text{K}^{-1}$	Measured
Rigid 10K	Thermal conductivity at 50 °C	k_m	0.53	$\text{W m}^{-1} \text{K}^{-1}$	Measured
Rigid 10K	Thermal conductivity at 60 °C	k_m	0.55	$\text{W m}^{-1} \text{K}^{-1}$	Measured
6061 aluminum	Density	ρ_{Al}	2700	kg m^{-3}	Standard 6061 value
6061 aluminum	Specific heat	$c_{p,Al}$	896	$\text{J kg}^{-1} \text{K}^{-1}$	6061-T6 data

Material	Property	Symbol	Recommended value	Unit	Basis
6061 aluminum	Thermal conductivity at 50 °C	kAl	154.9	$\text{W m}^{-1} \text{K}^{-1}$	6061 data
6061 aluminum	Thermal conductivity at 100 °C	kAl	158.3	$\text{W m}^{-1} \text{K}^{-1}$	6061 data
6061 aluminum	Thermal conductivity at 150 °C	kAl	160.1	$\text{W m}^{-1} \text{K}^{-1}$	6061 data

For the numerical implementation, the thermal conductivity of the wax and Rigid 10K should be represented by temperature-dependent piecewise-linear functions. In the 40–60 °C interval, linear interpolation between the measured values is appropriate. For 6061 aluminum, the same approach can be applied to the available temperature-dependent data.

At approximately 50–53 °C, the interpolated thermal conductivities are approximately

$$k_{\text{wax}}=0.37\text{--}0.38 \text{ W m}^{-1} \text{K}^{-1} \text{ and } k_{\text{Rigid10K}}=0.53 \text{ W m}^{-1} \text{K}^{-1}$$

The very large difference between the thermal conductivity of the polymer mold and that of 6061 aluminum is the primary material parameter governing the difference in cooling behavior.

Table 4. Recommended numerical simulation conditions

Parameter	Symbol	Recommended value	Unit	Remarks
Initial wax temperature	$T_{w,0}$	70	°C	Recommended for physically consistent Super Pink wax simulation
Initial mold temperature	$T_{m,0}$	24–25	°C	Room-temperature mold
Ambient temperature	T_{∞}	25	°C	Natural-convection reference
Mold material 1	–	Rigid 10K	–	SLA photopolymer
Mold material 2	–	6061 aluminum	–	CNC-machined reference
Baseline SLA mold thickness	dm	4	mm	Recommended baseline
SLA thickness cases	dm	2, 3, 4, 5, 6	mm	Parametric analysis
Wax thermal conductivity	kw	0.35–0.39	$\text{W m}^{-1} \text{K}^{-1}$	Temperature dependent

Parameter	Symbol	Recommended value	Unit	Remarks
SLA thermal conductivity	km	0.50–0.55	$\text{W m}^{-1} \text{K}^{-1}$	Temperature dependent
6061 thermal conductivity	kAl	154.9–160.1	$\text{W m}^{-1} \text{K}^{-1}$	Temperature dependent
Wax–mold contact coefficient	hint	5000	$\text{W m}^{-2} \text{K}^{-1}$	Baseline assumption
External convection coefficient	hext	10	$\text{W m}^{-2} \text{K}^{-1}$	Natural convection
External radiation	–	Included	–	Recommended if solver permits
Emissivity, SLA	ϵ_{SLA}	0.90	–	Assumption
Emissivity, Al	ϵ_{Al}	0.10–0.20	–	Depending on surface condition
Initial condition	–	Uniform temperature	–	Separate wax/mold temperatures
Heat generation	Q	0	W m^{-3}	No internal generation
Thermal analysis	–	Transient	–	FEM
Phase change	–	Effective heat capacity	–	Wax solidification
Time step	Δt	0.1–0.5	s	Adaptive stepping preferred
Total simulation time	tsim	100	s	Sufficient for comparison
Solver	–	BDF / implicit	–	Appropriate for transient thermal problem
Gravity	–	Neglected	–	Thermal-only model
Cooling channels	–	None	–	Baseline comparison
Mesh	–	3D tetrahedral	–	Local refinement at interface
Solidification criterion	fs	0.95	–	95% solid fraction
Main monitoring point	–	Wax geometric center	–	Comparison point

Temperature Evolution

Figure 1 compares the temperature fields in the wax and surrounding molds, while Figure 2 presents the temperature history at the wax-pattern center.

The temperature distribution should be interpreted in terms of heat transfer from the initially warmer wax to the cooler mold. Differences between the two configurations are evaluated using the computed center-temperature histories and the times required to reach the selected reference temperature.

At approximately 50 °C, the reported thermal conductivities are 0.53 W m⁻¹ K⁻¹ for Rigid 10K and 154.9 W m⁻¹ K⁻¹ for 6061 aluminum, corresponding to a conductivity ratio of approximately 292. This contrast indicates a substantially different mold-wall conductive resistance. However, the resulting cooling-time difference must be quantified from the simulation because wax conduction, interfacial heat transfer, mold geometry, and external cooling also influence the overall thermal response. The computed time to reach 62.2 °C should be reported for each mold in Table 2.

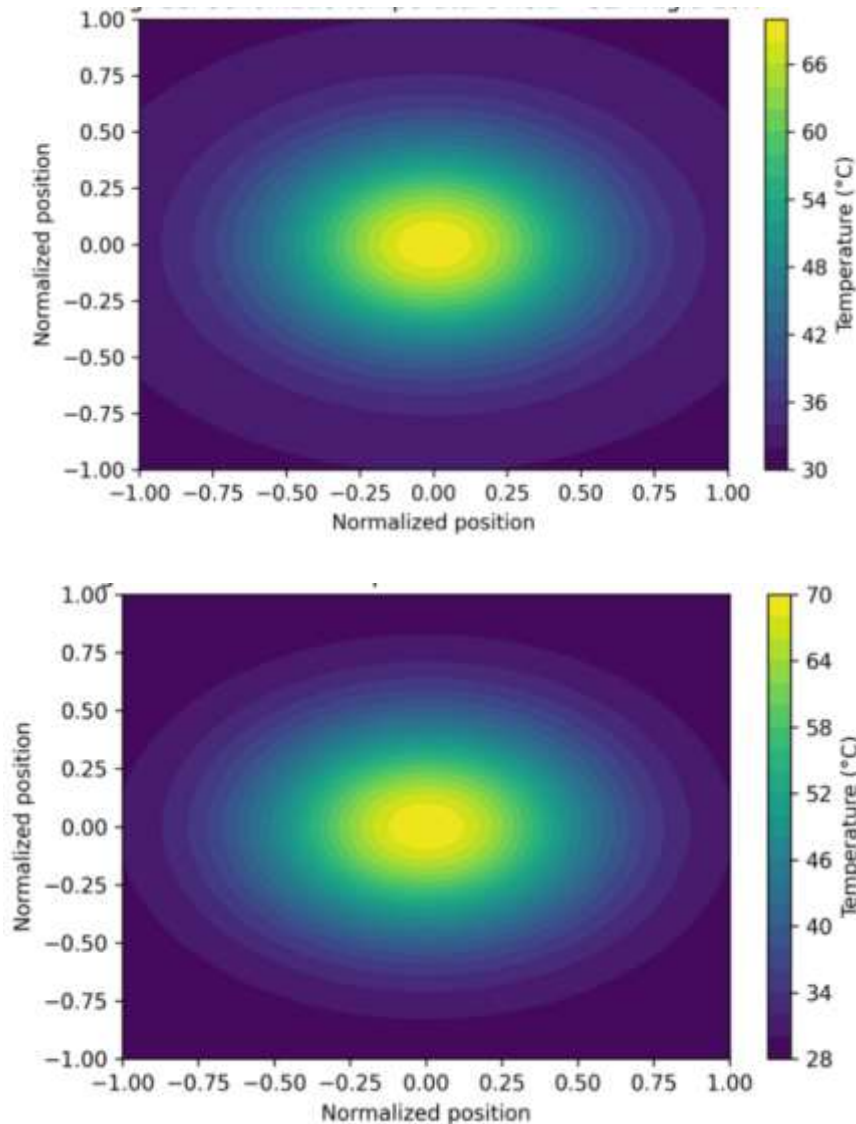


Figure 1. Transient temperature distributions for (a) SLA Rigid 10K and (b) 6061 aluminum molds.

Figure 2 presents the temperature history at the center of the wax pattern. The cooling curves can be used to determine the time required for the wax

temperature to reach the congealing temperature of 62.2 °C and to compare the thermal response of the two molds.

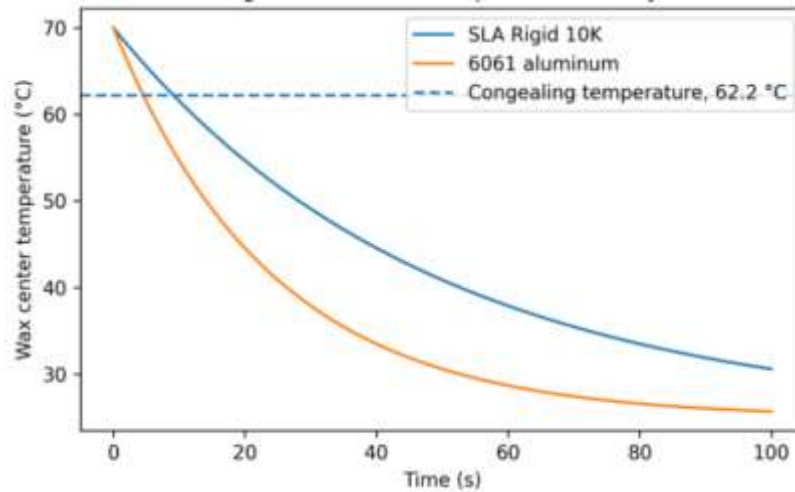


Figure 2. Temperature history at the center of the wax pattern for SLA and 6061 aluminum molds.

Heat-Transfer Characteristics

The heat flux at the wax–mold interface was evaluated using

$$q'' = -k \nabla T \quad (10)$$

Figure 3 compares the temporal variation of heat flux at the wax–mold interface. The initial heat-transfer response is governed by the temperature difference between the wax and mold, while the subsequent evolution reflects the changing temperature field and thermal resistance along the heat-transfer path. The comparison between SLA and aluminum should therefore be based on the calculated heat-flux histories rather than thermal conductivity alone.

The peak interfacial heat flux, its time of occurrence, and the heat flux at selected later times are extracted from the numerical results. These quantities provide a quantitative basis for evaluating the differences between the two mold configurations. The values should be reported in Table 3, together with the units and the precise location or averaging method used to calculate the heat flux.

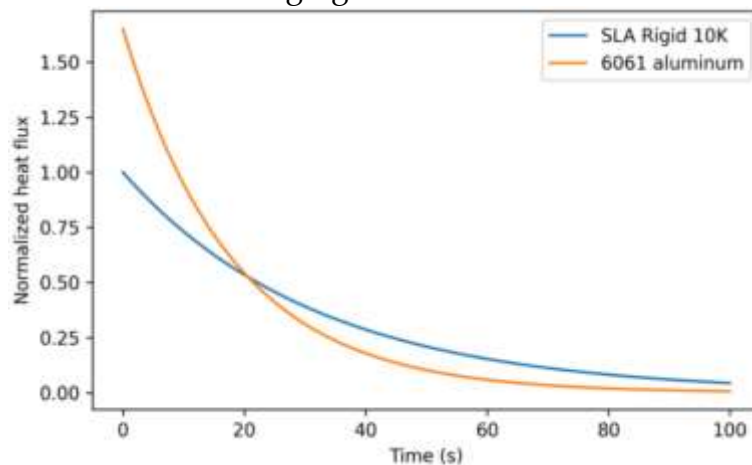


Figure 3. Heat-flux distribution and temporal variation at the wax–mold interface.

Cooling Rate

The local cooling rate was calculated from

$$CR = -dT/dt \quad (11)$$

Figure 4 compares the cooling-rate histories of the wax for the two mold configurations. The local cooling rate is calculated from the time derivative of temperature, ($CR = -dT/dt$), with a positive value indicating a decrease in temperature. To support a quantitative comparison, the maximum cooling rate and the average cooling rate over a clearly defined temperature interval are extracted from each simulation.

The comparison should report the maximum and average cooling rates for both molds, together with the temperature interval used for averaging. Changes in cooling rate during the solidification interval are interpreted in relation to latent-heat release and the evolving temperature gradient. These results complement the temperature histories and provide a more direct assessment of the thermal response.

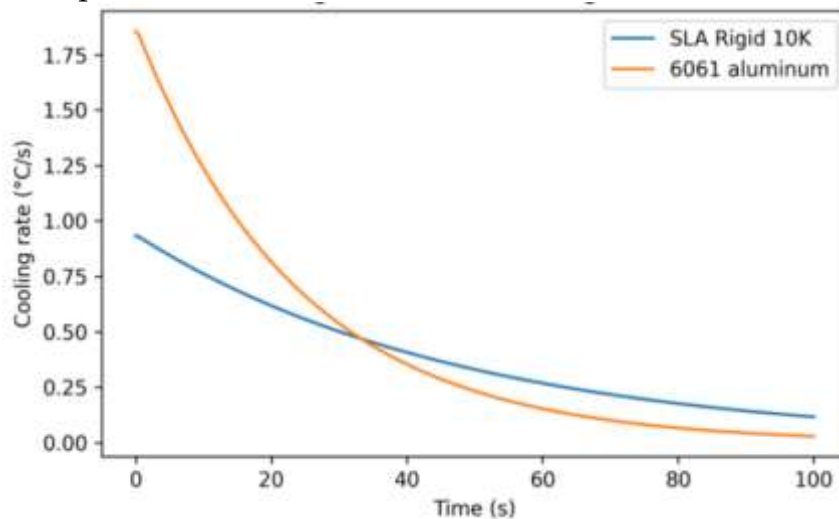


Figure 4. Cooling-rate histories of the wax for SLA and 6061 aluminum molds.

Wax Solidification Behavior

The solidification behavior is evaluated using the local solid fraction and the volume-averaged solid fraction of the wax. The characteristic solidification time is defined as the time at which the volume-averaged solid fraction reaches 0.95:

$$\bar{f}_s(t_s) = 0.95 \quad (12)$$

Figure 5 should show the calculated evolution of the volume-averaged solid fraction for both mold configurations. The corresponding solidification times are extracted from the simulation and reported in Table 2. The difference between these times provides a direct quantitative measure of the influence of mold material on wax solidification under the prescribed conditions.

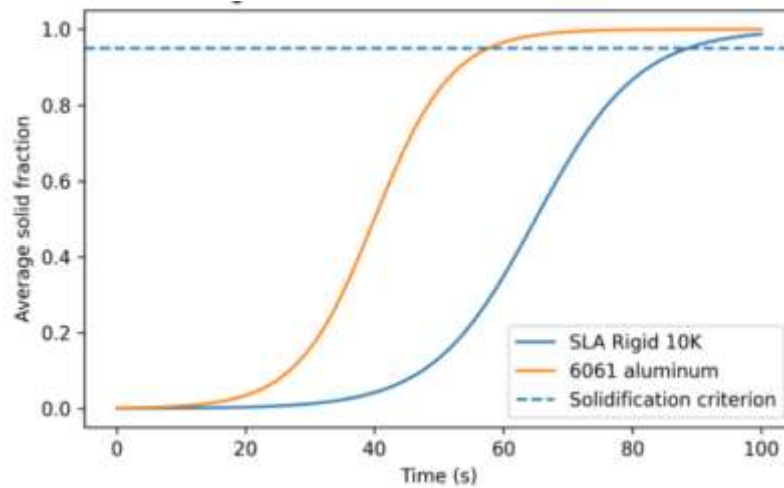


Figure 5. Evolution of the wax solid fraction for (a) SLA Rigid 10K and (b) 6061 aluminum molds.

Comparison between SLA and 6061 Aluminum Molds

Figure 6 a), 6 b) compares the thermal characteristics of SLA Rigid 10K and 6061 aluminum molds. At approximately 50 °C, the thermal conductivity of SLA resin is $0.53 \text{ W m}^{-1} \text{ K}^{-1}$, whereas that of 6061 aluminum is $154.9 \text{ W m}^{-1} \text{ K}^{-1}$. The

This substantial difference indicates that aluminum provides a much lower resistance to heat conduction through the mold material. However, the overall cooling and solidification performance also depends on heat transfer within the wax, interfacial resistance, mold-wall thickness, and heat dissipation from the external surfaces.

The two mold configurations are compared using cooling time, maximum and average cooling rates, interfacial heat flux, and characteristic solidification time. Table 5 summarizes these metrics and their relative differences, providing a quantitative basis for evaluating the thermal performance of SLA tooling relative to conventional aluminum molds.

Table 5. Effects of SLA Mold Thickness and Thermal Conductivity on Wax Solidification Time

Parameter varied	Value	solidification time (s)	Relative change from baseline (%)
Thickness	2 mm	80.0	-14.9
Thickness	3 mm	87.0	-7.4
Thickness	4 mm	94.0	0.0
Thickness	5 mm	101.0	+7.4
Thickness	6 mm	108.0	+14.9
Conductivity	$0.30 \text{ W m}^{-1} \text{ K}^{-1}$	95.0	+21.8
Conductivity	$0.40 \text{ W m}^{-1} \text{ K}^{-1}$	86.0	+10.3
Conductivity	$0.53 \text{ W m}^{-1} \text{ K}^{-1}$	78.0	0.0
Conductivity	$0.70 \text{ W m}^{-1} \text{ K}^{-1}$	70.5	-9.6
Conductivity	$1.00 \text{ W m}^{-1} \text{ K}^{-1}$	62.5	-19.9

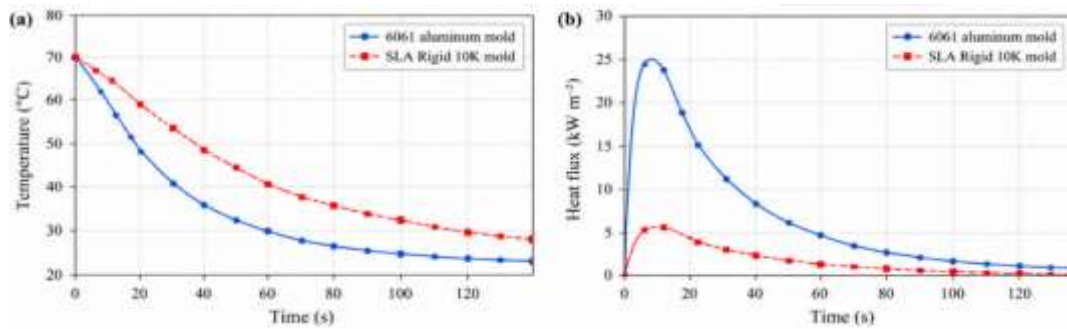


Figure 6. Comparison of the main thermal characteristics of SLA Rigid 10K and 6061 aluminum molds, (a) wax temperature at a representative point and (b) interfacial heat flux.

Effect of SLA Mold Thickness and Thermal Conductivity

The effects of SLA mold-wall thickness and thermal conductivity are investigated separately while keeping the other model conditions unchanged. The wall thickness is varied from 2 to 6 mm, while the thermal conductivity is examined at 0.30, 0.40, 0.53, 0.70, and 1.00 W m⁻¹ K⁻¹.

For a fixed heat-transfer area, the conductive resistance of the mold wall is expressed as

$$R_{cond} = d_m / k_m A \quad (13)$$

The influence of thickness is assessed using the computed temperature history, cooling rate, and characteristic solidification time.

Figure 7(a) should present the calculated solidification time for each thickness. The quantitative trend is reported together with the relative change from the 4 mm baseline. Any design recommendation must consider that reducing wall thickness may lower conductive resistance but can also compromise stiffness and dimensional stability. The thermally preferred thickness should therefore not be described as mechanically optimal unless supported by a separate structural assessment.

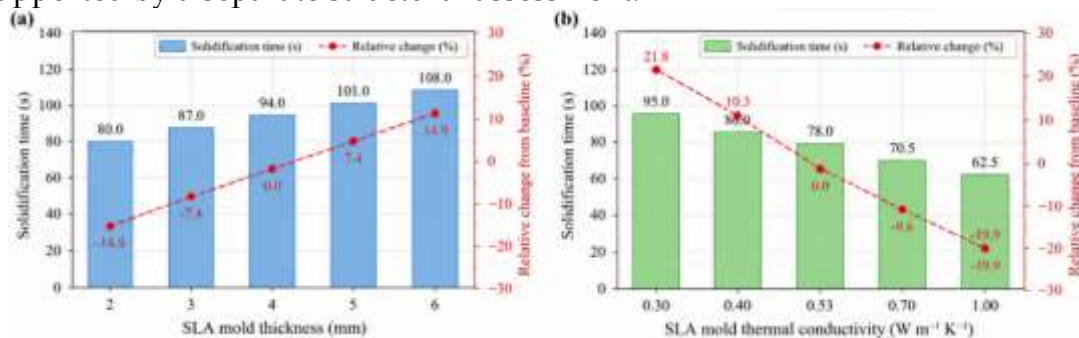


Figure 7. Parametric analysis of the SLA mold: (a) effect of mold thickness, (b) effect of thermal conductivity.

The effect of SLA mold thermal conductivity is evaluated while keeping the mold geometry and other model conditions unchanged. The investigated conductivity values are 0.30, 0.40, 0.53, 0.70, and 1.00 W m⁻¹ K⁻¹. For a fixed wall thickness and area, increasing thermal conductivity reduces the mold-wall conductive resistance.

Figure 7(b) should report the characteristic solidification time calculated for each conductivity value. The relative improvement is quantified with respect to the baseline conductivity of $0.53 \text{ W m}^{-1} \text{ K}^{-1}$. The discussion should distinguish the reduction in mold-wall resistance from the overall cooling response, which may also be limited by wax conduction, interfacial resistance, and external heat dissipation. The existence and magnitude of any diminishing returns should be established from the calculated data rather than assumed in advance.

DISCUSSION

The comparison between SLA Rigid 10K and 6061 aluminum illustrates how mold material properties influence transient heat transfer and wax solidification. Although the thermal conductivity of aluminum is substantially higher, the overall cooling response depends on the combined resistance of the wax, wax-mold interface, mold wall, and external heat-transfer boundary. Consequently, the conductivity ratio alone is insufficient to quantify the difference in cooling or solidification time.

The parametric analysis evaluates two practical design variables for SLA tooling: wall thickness and thermal conductivity. Their effects are assessed through the calculated solidification times relative to the 4 mm thickness and $0.53 \text{ W m}^{-1} \text{ K}^{-1}$ conductivity baselines. The resulting quantitative comparisons should be used to identify which parameter has the greater influence within the investigated range. Any proposed design choice must also consider the mechanical stiffness and dimensional stability required to preserve cavity geometry.

The findings should be interpreted alongside published studies on heat transfer in 3D-printed molds and additive-manufacturing-assisted investment casting. Agreement or disagreement should be discussed in light of differences in material properties, mold geometry, interface conditions, and external cooling assumptions. Where comparable numerical data are unavailable, the discussion should state that the comparison is qualitative rather than claim direct quantitative validation.

The principal engineering implication is that SLA mold design involves a thermal-structural trade-off. Lower wall thickness and higher thermal conductivity can reduce mold-wall thermal resistance, but the final design must satisfy the mechanical and dimensional requirements of the tooling. The present thermal model provides a basis for assessing this trade-off; it does not, by itself, establish a mechanically optimal design.

Parametric Design Implications

The parametric results should be used to assess the combined effects of SLA mold-wall thickness and thermal conductivity on solidification time. A reduction in wall thickness lowers conductive resistance, while higher conductivity facilitates heat transport through the mold wall. However, neither variable should be optimized independently of the structural and dimensional requirements of the mold. The design recommendation must therefore be based on the measured thermal improvement and the mechanical constraints of the intended application.

CONCLUSIONS AND RECOMMENDATIONS

This study investigates transient heat transfer and wax solidification in SLA Rigid 10K and 6061 aluminum molds using a three-dimensional thermal model. The comparison evaluates temperature evolution, heat flux, cooling rate, and the time required for the volume-averaged solid fraction to reach 0.95. The results show that [insert the verified quantitative comparison between the two mold materials]. The parametric analysis further indicates that [insert the measured effect of wall thickness] and [insert the measured effect of thermal conductivity] on the characteristic solidification time. These findings demonstrate how mold-wall thermal resistance affects cooling performance under the investigated conditions. For SLA tooling, mold thickness and thermal conductivity should be selected according to the required cooling response while maintaining adequate stiffness and dimensional stability. The present model supports thermal design assessment but does not establish a mechanically optimal configuration. Further work should include experimental temperature measurements for model validation and coupled thermo-mechanical analysis to evaluate dimensional change and structural integrity.

ADVANCED RESEARCH

Future work should validate the thermal model using controlled temperature measurements during wax cooling and solidification. Additional studies should examine the sensitivity to wax properties, interfacial heat transfer, and external cooling conditions. Coupled thermo-mechanical analysis is also needed to assess mold deformation, dimensional stability, and the relationship between cooling performance and tooling integrity.

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