

SELECTION AND OPTIMIZATION OF REFRACTORY COATINGS AND DRYING REGIMES FOR 3D-PRINTED PLA PATTERNS IN INVESTMENT CASTING OF ALUMINUM ALLOYS

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ABSTRACT

Investment casting using additively manufactured polymer patterns requires refractory coatings tailored to the thermal-decomposition behavior of the pattern material rather than to classical wax-pattern practice. This study evaluates four refractory coating systems for 3D-printed PLA (and ABS/PMMA) patterns used in lost-pattern casting of aluminum alloys: (1) ZrSiO₄ (zircon) with a colloidal SiO₂ binder, (2) SiO₂ with sodium silicate (Na₂SiO₃, liquid glass), (3) Al₂O₃ with a phosphate binder, and (4) MgO- or SiO₂-based compositions with a colloidal binder. Coatings were compared by thermal stability, adhesion, gas permeability, surface roughness (Ra), cost, and drying behavior. The zircon-colloidal-silica system provided the best overall balance: thermal stability up to 1600–1700 °C, adequate gas permeability during polymer burnout (250–450 °C), crack-free behavior, and a surface roughness of Ra 3–6 μm, at the cost of higher raw-material cost and longer drying time (12–24 h). Drying-parameter optimization established that a temperature of 50 ± 5 °C with forced air circulation (0.5–1.5 m/s) minimizes microporosity (from incomplete moisture removal below 40 °C) and pattern deformation (above the PLA glass-transition range of 55–65 °C), with optimal drying times of 2–4 h for coating layers of 0.3–0.6 mm and 5–6 h for 0.6–1.0 mm. These results provide a practical basis for shell-coating protocols in additive-manufacturing-based investment casting of complex-geometry aluminum parts.

INTRODUCTION

Investment (lost-pattern) casting combined with additive manufacturing of sacrificial patterns is increasingly used to produce complex-geometry parts — such as turbocompressor impellers — that are difficult or costly to produce with traditional wax-pattern tooling (Jones & Yuan, 2003; Pattnaik et al., 2012). Fused deposition modeling (FDM) of polylactic acid (PLA) patterns offers an accessible, low-cost route to such models: PLA undergoes near-complete thermal decomposition (residual mass below ~3% at 1000 °C) through a single-stage depolymerization mechanism in the range of 320–380 °C (Farah et al., 2016; Liu et al., 2010), and its use as an FDM investment-casting pattern material for aluminum castings has been demonstrated in our previous work (Merkibayev et al., 2028).



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The performance of the ceramic shell, however, depends as much on the refractory coating system as on the pattern material itself. A shell mold must simultaneously provide sufficient hot strength and dimensional stability, resist thermal shock during pouring, and remain gas-permeable enough to vent air and pattern-decomposition products without pressure build-up; insufficient permeability is a recognized cause of blowholes and gas porosity in the final casting (Amira et al., 2011; Jones & Yuan, 2003; Kanyo et al., 2020; Wiśniewski et al., 2020). Because polymer patterns decompose over a defined, comparatively low-temperature interval and release a substantial volume of gaseous products during burnout, coating selection for FDM/PLA patterns is not a direct transfer of classical wax-pattern practice — the coating must accommodate the specific outgassing profile of the polymer while still reaching adequate strength at firing temperature (Kanyo et al., 2020; Pattnaik et al., 2012).

Colloidal-silica-bonded slurries combined with zircon, mullite, alumina, or fused-silica flours are the most widely used shell systems in modern precision casting, owing to their favorable rheology, environmental profile, and compatibility with a wide range of refractory fillers (Kolczyk & Zych, 2013; Wiśniewski et al., 2020). At the same time, a range of studies have shown that shell permeability can be deliberately tuned — for example by introducing sacrificial organic or fiber additives that burn out during firing to leave a controlled pore network (Huang et al., 2019; Kumar & Karunakar, 2019; Małek et al., 2025; Pattnaik & Sutar, 2020, 2022) — precisely because base ceramic shells made from fine-grained slurries can otherwise be relatively impermeable (Małek et al., 2025; Wiśniewski et al., 2020). Phosphate-bonded systems, meanwhile, offer high thermal stability but are reported to be comparatively impermeable, favoring their use with metallic rather than polymer patterns (Jones & Yuan, 2003). Sodium-silicate-bonded systems are established in sand-mold and core practice for their low cost and rapid cure, but are known to be sensitive to moisture and to provide comparatively lower bond strength than colloidal-silica systems (Jones & Yuan, 2003). Drying of the applied slurry is itself a critical, and frequently under-reported, step: uncontrolled evaporation or excessive drying temperature promotes shell cracking, delamination, or — in the specific case of low-melting-point polymer patterns — deformation of the pattern itself, since common PLA grades have a glass-transition temperature of approximately 55–65 °C (Farah et al., 2016; Suder et al., 2021).

This study addresses the coating-selection and drying-optimization problem specifically for PLA (and ABS/PMMA) investment-casting patterns. Four candidate refractory coating systems are compared against thermal stability, gas permeability, surface finish, cost, and drying behavior, and optimal drying parameters are established for the best-performing system, as part of a broader research program on the production of complex aluminum castings using 3D-printed patterns and investment casting.

MATERIALS AND METHODS

Preparation of Polymer Models Using FDM Printing

Poly(lactic acid) (PLA) was used as the primary material for manufacturing the experimental specimens. This material was selected for producing polymer prototypes by fused deposition modeling (FDM) due to its good printability, dimensional stability during fabrication, and ability to form complex geometric structures. Before the printing process, the polymer filament was subjected to preliminary drying to remove residual moisture, which can lead to the formation of gas inclusions, deterioration of interlayer bonding, and a reduction in surface quality.

The geometric model of the turbine impeller was developed using CAD software (Fusion 360 and SolidWorks). The design consisted of a central hub and four spiral blades arranged around it at an angle of $\alpha = 30^\circ$. The blade profile was developed considering hydrodynamic performance requirements and subsequent evaluation of the model behavior during the application of refractory coating. The resulting CAD model is shown in Figure 1.

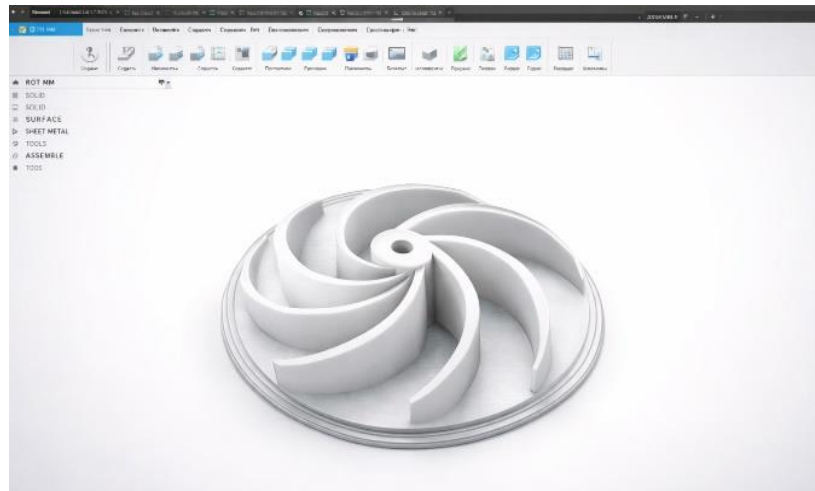


Figure 1. CAD model of the turbine impeller

G-code for 3D printing of the turbine impeller

M104 S205 ; Heat the extruder to 205 °C

M140 S60 ; Heat the build platform to 60 °C

M109 S205 ; Wait until the extruder reaches the set temperature

M190 S60 ; Wait until the build platform reaches the set temperature

G28 ; Home all axes (X, Y, Z)

G92 E0 ; Reset the extruder position

G1 Z0.2 F1200 ; Move to the first layer height

G1 X30 Y30 F1500 ; Move to the starting point

G1 X50 Y30 E1.5 ; Extrusion during movement

G1 X50 Y50 E3.0

G1 X30 Y50 E4.5

G1 X30 Y30 E6.0 ; Close the contour; Layer formation

G1 Z0.4

G1 X32 Y32 E6.5

G1 X48 Y32 E7.5

G1 Z0.6

G1 X34 Y34 E8.5

M104 S0 ; Turn off the extruder heater

M140 S0 ; Turn off the build platform heater

M84 ; Disable stepper motors

M-codes — temperature control

G-codes — printer movement control

E — filament extrusion (plastic feed)

G28 — homing and axis zeroing

G1 — linear movement and layer printing

A turbine impeller is a rotating component designed in a CAD environment for pumps and turbines. It consists of a central hub and blades that control the movement of liquid or gas flow.

The precise geometry of the impeller is developed using CAD software such as Fusion 360 and SolidWorks. The blades are positioned at a specific angle, for example 30°, and their shape directly influences the operating efficiency of the device. Parametric modeling allows the main dimensions and design parameters to be modified easily. After completing the design, the model

is exported in STL format for further processing and 3D printing. Impellers are widely used in pumps and turbines, where they provide fluid acceleration and flow transfer. CAD-based modeling improves the accuracy, repeatability, and overall quality of the developed design.

Preparation and Testing of Refractory Coatings on Polymer Models, Including Drying and Burnout Processes

Refractory coatings are widely used to protect polymer prototypes from high-temperature exposure during investment casting processes. The performance of a coating system is evaluated based on its chemical composition, thermal stability, adhesion strength, and gas permeability. The main coating systems investigated in this study were:

ZrSiO₄ + colloidal SiO₂; SiO₂ + Na₂SiO₃; Al₂O₃ + phosphate binder and MgO or SiO₂ + colloidal binder systems.

1. ZrSiO₄ + colloidal SiO₂ system

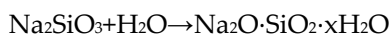
This coating combination demonstrated the highest suitability for PLA and ABS polymer patterns. Zirconium silicate (ZrSiO₄) provides a highly thermally stable ceramic layer capable of withstanding temperatures of 1600–1700 °C, while colloidal silica forms a solid silicate network through dehydration:



The resulting coating provides sufficient gas permeability, prevents cracking during polymer burnout, and produces a smooth surface finish. The main disadvantages of this system are its relatively high material cost and extended drying time; however, these limitations are acceptable for complex geometries and long-term investment-casting applications.

2. SiO₂ + Na₂SiO₃ (sodium silicate) system

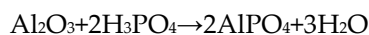
This coating system is characterized by low cost and rapid hardening. The hydration reaction can be represented as:



The reaction produces an amorphous silicate layer. However, the main limitations are reduced adhesion to polymer surfaces and sensitivity to moisture, which may cause degradation of the coating. Therefore, this system is more suitable for short-term experiments and simple geometrical components.

3. Al₂O₃ + phosphate binder system

The alumina-phosphate coating forms a strong and thermally stable ceramic layer. The main chemical reaction is:



The resulting coating possesses high mechanical strength and temperature resistance. However, its low gas permeability may cause pressure accumulation during polymer burnout due to insufficient removal of gaseous decomposition products. Therefore, this type of coating is more suitable for metallic pattern investment casting rather than polymer-based patterns.

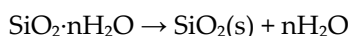
4. MgO or SiO₂ + colloidal binder system

The main advantages of this coating are low cost and relatively high gas permeability. However, the system demonstrates lower layer stability and a less uniform surface structure, which reduces its effectiveness for high-precision polymer models. It is mainly applicable for lightweight castings or preliminary testing.

Development of Optimal Drying Parameters

The quality and durability of refractory coatings for polymer prototypes directly depend on the parameters of the drying process. The main objectives of drying are complete solvent

evaporation, achievement of maximum adhesion, and preservation of a uniform coating structure. For PLA, ABS, and PMMA thermoplastic patterns coated with zircon (ZrSiO_4) and colloidal SiO_2 (silica sol), this stage is particularly important due to the limited thermal stability of polymers and the risk of deformation. To optimize the drying process, the temperature regime must first be determined. Experimental studies showed that the effective drying temperature range for PLA samples is 40–60 °C. The optimum temperature was established as 50 ± 5 °C: at lower temperatures, incomplete solvent evaporation occurs, leading to the formation of micropores within the coating layer; at higher temperatures, thermal deformation of the polymer pattern may occur. During drying, dehydration of colloidal SiO_2 takes place:



As a result, a strong silica-based bonding structure is formed, providing chemical and mechanical compatibility with the high-temperature zircon layer.

Drying time is also an important technological parameter. For coating thicknesses of 0.3–0.6 mm, the optimal drying time is 2–4 h. For thicker coatings, the drying time increases to 5–6 h, because solvent diffusion requires additional time for complete evaporation. Thickening agents such as bentonite and CMC (carboxymethyl cellulose) increase slurry viscosity, improve coating uniformity, and require controlled drying conditions. The coating application method also affects drying efficiency. The dipping method provides a more uniform coating layer, whereas spraying requires intermediate pauses between layers to allow solvent evaporation. Air circulation in the drying chamber is necessary because stagnant conditions may cause condensation, reducing adhesion and negatively affecting surface quality.

Under optimized drying conditions, the ZrSiO_4 + colloidal SiO_2 coating demonstrates the following properties:

- uniform and smooth surface;
- preventing coating failure during polymer burnout;
- high adhesion and mechanical strength;
- thermal stability up to 1600–1700 °C and chemical resistance.

Therefore, from an engineering perspective, the optimal drying parameters for PLA and ABS samples are: temperature 50 ± 5 °C, drying time 2–4 h, forced air circulation, and coating thickness of 0.3–0.6 mm. These parameters provide maximum adhesion, coating uniformity, and thermal stability. The relationship between chemical reactions, coating thickness, and application method represents a key factor in controlling the process and maintaining the dimensional accuracy and functional properties of polymer prototypes.

RESULTS AND DISCUSSION

Comparison of Coating Systems

The experimental comparison (Table 1, Figure 2) showed that the most suitable coating system for polymer samples was the ZrSiO_4 + colloidal SiO_2 system. It provided high thermal stability, sufficient gas permeability, excellent adhesion, and a smooth surface finish. The SiO_2 + Na_2SiO_3 coating demonstrated advantages in terms of lower cost and shorter drying time; however, its reduced durability and moisture resistance limited its application. The Al_2O_3 + phosphate binder system showed high thermal stability and strength but was less suitable for polymer patterns due to its low gas permeability, which may restrict the removal of gaseous decomposition products during polymer burnout. The MgO or SiO_2 + colloidal binder system provided lower cost and acceptable gas permeability, but its reduced layer stability and surface quality limited its effectiveness.

Table 1. Comparative properties of the four refractory coating systems evaluated for polymer (PLA/ABS/PMMA) investment-casting patterns

Coating	Thermal stability	Gas permeability	Ra (μm)	Drying time	Rel. cost	Notes
ZrSiO ₄ + colloidal SiO ₂	1600–1700 °C	High	3–6	12–24 h	High	Crack-free through polymer burnout (250–450 °C); best overall balance
SiO ₂ + Na ₂ SiO ₃	1000–1100 °C	Moderate	—	2–6 h	Low	Adhesion ~20–30% lower; moisture-sensitive (Jones & Yuan, 2003); short-term tests / simple geometries
Al ₂ O ₃ + phosphate binder	1400–1600 °C	Low (40–50% lower)	—	—	Mode rate	Reduced permeability risks pressure build-up; historically favored for metallic patterns (Jones & Yuan, 2003)
MgO/SiO ₂ + colloidal binder	Not characterized	—	10–20	—	Low	30–50% cheaper than zircon; reduced layer stability, higher roughness

Note – compiled by the authors based on project monitoring data (grant AP26198529).

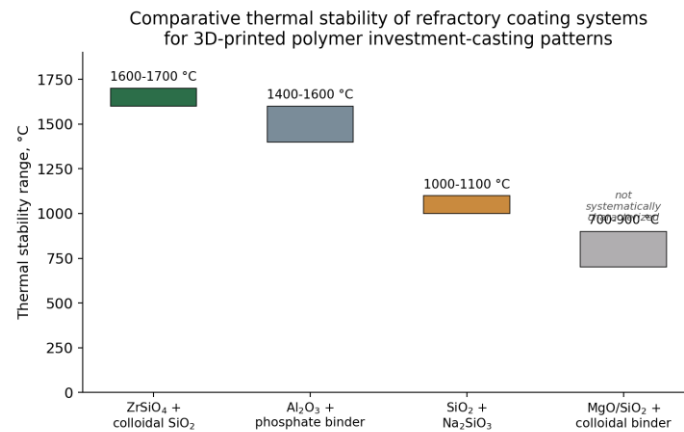


Figure 2. Comparative thermal stability of refractory coating systems for 3D-printed polymer investment-casting patterns

Note – compiled by the authors based on project monitoring data (grant AP26198529)

Therefore, based on the obtained results, the ZrSiO₄ + colloidal SiO₂ coating system was selected as the optimal solution for PLA, ABS, and PMMA polymer patterns. This system provided high thermal resistance, sufficient gas permeability, compatibility with polymer substrates, and preservation of prototype geometry during burnout. Other coating systems were considered suitable only for limited conditions or short-term experimental applications.

Drying-Parameter Optimization

Table 2. Optimal drying parameters as a function of coating layer thickness.

Layer thickness	Optimal drying time	Temperature	Air circulation
0.3–0.6 mm	2–4 h	50 ± 5 °C	0.5–1.5 m/s (forced)
0.6–1.0 mm	5–6 h	50 ± 5 °C	0.5–1.5 m/s (forced)

Note – compiled by the authors based on project monitoring data (grant AP26198529)

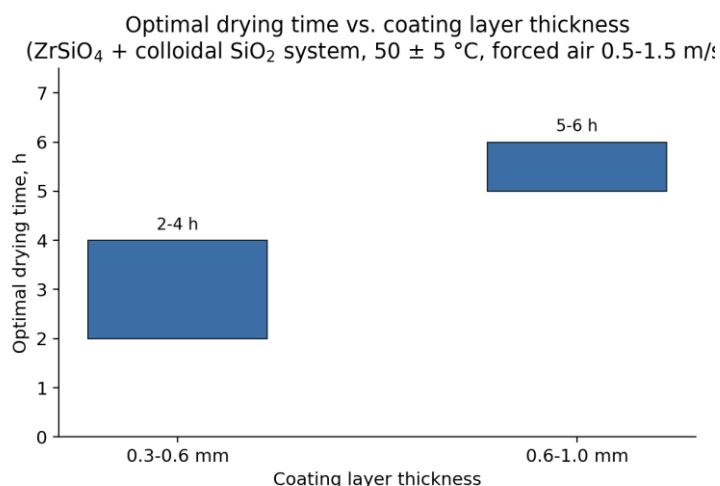


Figure 3. Optimal drying time vs. coating layer thickness
(ZrSiO₄ + colloidal SiO₂ system, 50 ± 5 °C, forced air 0.5–1.5 m/s)

Note – compiled by the authors based on project monitoring data (grant AP26198529)

Drying time is also an important engineering parameter (Table 2, Figure 3). For a coating thickness of 0.3–0.6 mm, the optimal drying time was 2–4 h. For thicker layers, the drying time increased to 5–6 h, since solvent diffusion requires additional time for complete evaporation. Thickeners such as bentonite or CMC (carboxymethyl cellulose) increase slurry viscosity, improve layer uniformity, and require controlled reduction of the drying rate. The coating application method also affects drying efficiency. The dipping method provides a more uniform coating layer, whereas spraying requires pauses between individual layers to allow solvent evaporation. The drying chamber should provide air circulation, since stagnant conditions may lead to condensation formation, reducing adhesion and deteriorating surface quality. Under optimized drying conditions, the ZrSiO₄ + colloidal SiO₂ coating system demonstrates the following properties:

- uniform and smooth surface;
- high gas permeability, preventing coating failure during polymer burnout;
- high adhesion and mechanical strength;
- thermal stability up to 1600–1700 °C and chemical stability.

Therefore, from an engineering perspective, the optimal drying parameters for PLA and ABS samples were determined as a temperature of 50 ± 5 °C, circulation, and a coating thickness of 0.3–0.6 mm. These parameters ensure maximum adhesion, coating uniformity, and thermal resistance. The relationship between chemical reactions, coating thickness, and application method is a key factor in process control and allows preservation of the geometric stability and functional properties of polymer prototypes.

The narrow optimal window (50 ± 5 °C; Figure 4) therefore reflects a genuine material constraint specific to low-melting polymer patterns, rather than an arbitrary process choice: unlike wax or metallic patterns, PLA begins to soften well below typical ceramic-shell curing temperatures, so drying must be bounded on both sides — by moisture removal on the low side and by pattern integrity on the high side (Farah et al., 2016; Suder et al., 2021). Forced air circulation (0.5–1.5 m/s) was found necessary to prevent condensation at the coating surface and to promote uniform, adhesive layer formation; this is particularly relevant when coatings are applied by spraying, where inter-layer solvent evaporation (10–20 min pauses) is also required to avoid trapped moisture (Jones & Yuan, 2003; Wiśniewski et al., 2020).

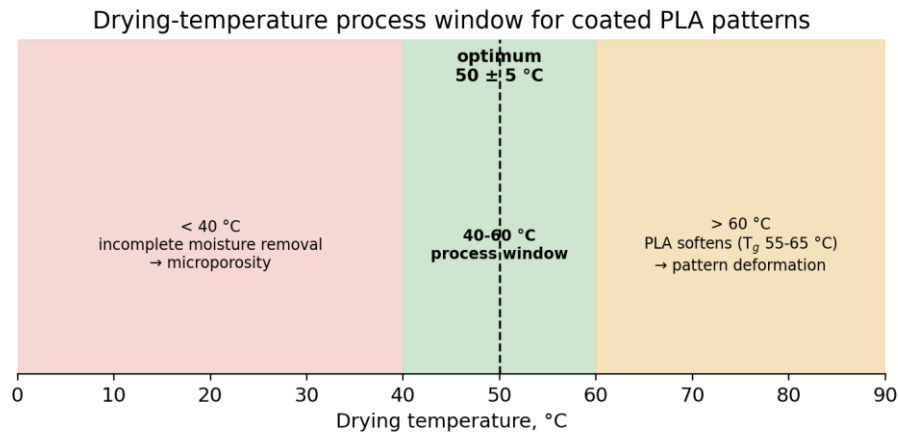


Figure 4. Drying-temperature process window for coated PLA patterns.

Note: compiled by the authors based on project monitoring data (grant AP26198529).

Under these optimized conditions (50 ± 5 °C, 2–4 h for 0.3–0.6 mm layers, forced circulation), the resulting coating exhibited a surface roughness of R_a 3–6 μm and thermal stability up to 1600–1700 °C, consistent with the values reported for the zircon–colloidal-silica system in Table 1 and comparable to surface-finish values reported for zircon/colloidal-silica face coats used with 3D-printed patterns in other investment-casting studies (Nguyen et al., 2025).

CONCLUSIONS

The experimental study demonstrated the effectiveness of combining FDM-printed polymer patterns with optimized refractory coating technology for investment-casting applications. PLA was selected as the primary pattern material due to its stable printing behavior, suitable thermomechanical properties, and ability to reproduce complex geometries with high dimensional accuracy using additive manufacturing. The developed turbine impeller prototype was successfully fabricated by FDM printing, confirming the suitability of polymer patterns for further coating and burnout processes.

The investigation of refractory coating systems showed that the ZrSiO_4 + colloidal SiO_2 coating provided the required performance for PLA, ABS, and PMMA polymer patterns. The coating demonstrated high thermal stability up to 1600–1700 °C, sufficient gas permeability for the removal of polymer decomposition products, good adhesion to the polymer surface, and the ability to maintain the geometric accuracy of the prototype during thermal treatment.

The drying parameters of the selected zircon–silica coating system were optimized. The most effective drying conditions were determined as a temperature of 50 ± 5 °C, a drying time of 2–4 h for coating thicknesses of 0.3–0.6 mm, and forced air circulation of 0.5–1.5 m/s. These parameters ensured uniform coating formation, complete moisture removal, prevention of cracking, and preservation of polymer pattern integrity.

Under optimized conditions, the developed coating system provided a smooth surface finish with a roughness of R_a 3–6 μm , high thermal resistance, and stable behavior during polymer burnout. The obtained results confirm that the combination of additive manufacturing and zircon-based refractory coating technology is suitable for producing complex investment-casting patterns from polymer materials. The established coating and drying parameters provide practical guidelines for the preparation of FDM-produced polymer patterns used in precision casting of complex components and can be applied for further optimization of casting processes involving additively manufactured models.

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STATEMENT ON INSTITUTIONAL ETHICS COMMITTEE (IRB) APPROVAL: Not applicable. This study is a materials and process-engineering investigation of refractory coatings and drying regimes for 3D-printed casting patterns; it did not involve human participants or animal subjects, and therefore did not require review or approval by an Institutional Ethics Committee.

INFORMED CONSENT STATEMENT: Not applicable, as this study did not involve human participants.

DATA AVAILABILITY STATEMENT: The data supporting the results of this study (coating-system comparison and drying-parameter measurements, compiled from project monitoring records under grant AP26198529) can be provided by the corresponding author upon reasonable request.

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