Research Square

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Material selection for injection molds of thick-walled PP-R parts: experimental comparison of conventional 316L steel, CuBe alloy, and selective laser melting with conformal cooling: thermal performance, part quality, and financial viability

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Research Article

Keywords: injection molding, conformal cooling, selective laser melting, CuBe alloy, thick-walled parts, mold cost analysis

Posted Date: July 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10360811/v1

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Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on September 22nd, 2026. See the published version at https://doi.org/10.1007/s00170-026-19065-7.

Abstract

Injection molds with conformal cooling channels (CCC) produced by selective laser melting (SLM) are widely reported to reduce cycle time in thin-walled applications, yet their comparative economic performance for thick-walled geometries has not been experimentally quantified. This study presents the first three-way experimental comparison of mold concepts for thick-walled PP-R injection molding (wall thickness up to 8.8 mm): conventional 316L stainless steel, copper-beryllium (CuBe) alloy produced by conventional machining, and 316L with SLM-manufactured CCC incorporating lattice-structure optimization. The evaluation combines two-stage finite element simulation (Moldflow), real-process trials with embedded pressure and temperature sensors, part characterization, and a financial sensitivity analysis based on real ERP cost data. CuBe reduced the injection cycle by 18% and product cost by 12%, at a 10% mold investment premium and an 8-fold demand growth requirement for 3-year payback. The SLM-CCC mold achieved 11% cycle reduction and 7% cost saving, but required 142% longer fabrication time (2.42× the conventional duration), a 46% investment premium, and 18-fold demand growth for equivalent payback. All three mold concepts produced parts meeting full functional qualification for pressurized hot-water hydraulic systems. For this geometry class, CuBe alloy molds outperform SLM-CCC across every economic metric examined. The 18-fold demand growth threshold, rather than the observed 11% thermal gain, constitutes the critical variable for evaluating SLM adoption in thick-walled injection molding.

1 Introduction

Plastic injection molds with conformal cooling channels (CCC) produced by selective laser melting (SLM) can substantially reduce cycle time by bringing coolant closer to the cavity surface, improving heat extraction relative to straight-drilled circuits [1, 2]. Published gains range widely: Park et al. [14] documented reductions exceeding 50% for complex SLM-manufactured molds; Abbès et al. [6] achieved 50–66% with hybrid inserts; and Kuo et al. [15] reached near-89% in rapid-tooling configurations. Tan et al. [4] showed that further improvements in extraction uniformity are attainable through optimized channel geometries. A common limitation across these studies is that thin-walled geometries are the predominant test case, and financial viability is rarely assessed alongside thermal data.

The economic implications change substantially for thick-walled parts. Cooling time scales with the square of wall thickness [11], which amplifies the absolute value of any cycle saving; conversely, thick walls offer less spatial flexibility for conformal channel routing relative to cavity volume, attenuating the geometric advantage of SLM. Beyond thermal considerations, the fabrication premium for SLM inserts, driven by mandatory post-process CNC finishing, must be recovered through incremental contribution margin. Whether this is achievable depends on production volume in a way that has not been quantified for this geometry class.

Copper-beryllium (CuBe) alloys offer an alternative route to faster cooling without the fabrication complexity of SLM. At 156 W/m·°C, CuBe conducts heat roughly ten times faster than conventional 316L

steel [11]. Despite this, no published study has placed CuBe and SLM-CCC in direct experimental competition for the same thick-walled geometry, with financial outcomes quantified alongside thermal and quality data.

This study addresses that gap. Using a PP-R reduction-tee fitting with wall thickness up to 8.8 mm, a geometry class absent from all 25 papers retained in a systematic review of the conformal cooling literature conducted for this work, we report the first experimental three-way comparison of 316L, CuBe, and SLM-CCC molds, integrating thermal, characterization, and financial data within a single industrial case study. The central finding is that the 18-fold demand growth required for SLM-CCC payback, against 8-fold for CuBe, establishes production volume as the primary decision criterion for mold material selection in this geometry class, rather than thermal performance alone. The experimental and financial data originate from a broader investigation reported in Baifus [8].

2 Methods

In accordance with journal policy on the use of generative AI tools, the authors disclose that an AI assistant (Claude, Anthropic) was used to support the drafting, restructuring, and language formatting of this manuscript, based exclusively on the authors' own experimental data and analyses; no scientific content, data, or conclusions were generated by the tool. Full disclosure details are provided in the Declarations section.

2.1 Mold concepts and insert fabrication

A PP-R reduction-tee fitting (32×20 mm, wall thickness up to 8.8 mm, for pressurized hot-water hydraulic systems) was modeled in Creo Parametric and used as the test workpiece. A standard two-plate mold holder (Polimold Classic 25.30, 296×296 mm) accommodated interchangeable inserts fabricated in three configurations: (i) conventional 316L stainless steel by 3-axis CNC milling (Maple ME-1055); (ii) CuBe alloy BM 172HT by the same machining route; (iii) 316L with SLM-manufactured CCC (Concept Laser CL50WS, 400 W fiber YAG, 100 µm spot, 1070 nm). Material properties are listed in Table 1.

Table 1
Main properties of the insert materials and the PP-R workpiece material

Parameter	316L	CuBe alloy	PP-R RA140-E
Density (g/cm³)	7.95	8.0	0.905
Hardness (HB)	80	370	—
Thermal conductivity (W/m·°C at 20°C)	17	156	0.24

SLM inserts required CNC milling and polishing after printing to meet dimensional and surface-finish tolerances for direct contact with molded parts. A honeycomb lattice structure [12] was applied to the solid regions of larger SLM cavities (Fig. 1), reducing cavity mass by up to 28% and print time by up to

39% relative to a fully solid insert, with smaller gains (4–17%) for narrower core inserts. Despite this optimization, total SLM fabrication time remained 142% longer than conventional machining, i.e. 2.42 times the conventional duration (Table 2), which directly accounts for the 46% mold acquisition cost premium reported in Section 3.4.

Figure 1 SLM-printed 316L inserts: (a) solid-region core; (b) lattice-optimized upper cavity; (c) lattice-optimized lower cavity. The honeycomb lattice reduced cavity mass by up to 28% and print time by up to 39%

Table 2
Fabrication time by mold concept

Mold component	316L (h)	CuBe (h)	316L CCC (h)
Upper cavity	47	47	94
Lower cavity	47	47	94
Core insert (118 mm)	11	11	40
Core insert (115 mm)	11	11	40
Core insert (105 mm)	11	11	40
Total fabrication time	127	127	308

2.2 CAE simulation

Thermal simulation used Moldflow in two FEM stages. The first mapped temperature-gradient behaviour across successive injection cycles, identifying the boundary between the transient heating phase and the permanent thermal regime for each mold concept. The second stage simulated the complete cycle (filling, packing, cooling, deformation), with minimum cooling time set to 45% part solidification, the threshold for ejection without permanent deformation [8]. Coolant conditions were constant throughout: 25°C water at 10 l/min.

2.3 Experimental injection trials

Trials ran on a ROMI Primax 150R injection molding machine using PP-R Borstar RA140-E (density 0.905 g/cm³, MFI 0.30 g/min). Kistler 6157C piezoelectric sensors in the movable cavity and K-type thermocouples in the fixed cavity recorded pressure and temperature throughout each cycle. Figure 2 shows the three mold configurations mounted during the experiments.

Figure 2 Three mold concepts on the ROMI Primax 150R injection molding machine: (a) conventional 316L stainless steel; (b) CuBe alloy with gold-colored inserts; (c) 316L CCC with SLM-manufactured conformal cooling and more complex coolant circuit

2.4 Part characterization

Characterization of molded parts (Fig. 3) covered six properties: dimensional deviation (Mitutoyo digital caliper, 0.01 mm); crystallinity by DSC (TA Instruments Q20, 10°C/min, 20–300°C, inert atmosphere; reference enthalpy 209 J/g, Eq. 1); frozen-layer morphology by backscattered electron imaging (Hitachi TM 3000, 2500×, 10 µm microtome sections); tensile strength per ASTM D638 [13] (EMIC DL2000); short-duration hydrostatic pressure resistance (PHI) at 6.03 MPa, 20°C, 1 h; and long-duration PHI at 1.32 MPa, 95°C, 1000 h, plus pigment dispersion per NBR ISO 18553.

$$\%C = (\Delta H / \Delta H_0) \times 100 \quad \text{(Eq. 1)}$$

Figure 3 PP-R reduction-tee parts produced during experimental trials. All three mold concepts produced parts meeting PHI qualification for pressurized hot-water hydraulic systems

2.5 Financial analysis

Financial data came from the manufacturer's ERP system, with the conventional 316L mold as the baseline. A sensitivity analysis converted the incremental contribution margin from each cycle-time reduction into the demand growth required for 3-year payback on the incremental mold investment. Mold acquisition values, originally recorded in Brazilian reais (R$), are expressed here in USD using an exchange rate of R$/USD = 5.68 (commercial dollar closing rate on 7 November 2024, Banco Central do Brasil); product cost and margin values are normalized to 316L = 1.00 at the manufacturer's request.

3 Results and Discussion

3.1 FEM simulation

In Stage 1, CuBe reached thermal steady state in the fewest cycles, followed by 316L CCC, with conventional 316L requiring the longest transient phase. The number of pre-stabilization cycles determines the set-up time after a mold change and the associated scrap rate during warm-up, representing a cost that per-unit cycle analysis does not capture. Stage 2 results are summarized in Table 3; no significant cavity pressure difference was found between mold materials, since polymer pressure was evaluated independently of mold surface temperature.

Table 3
Second-stage FEM simulation results

Parameter	316L	CuBe	316L CCC
Cooling time — FEM (s)	17.2	12.3	13.3
Injection cycle — FEM (s)	38.4	33.5	34.5
Cooling time reduction	—	−28%	−23%
Cycle reduction	—	−13%	−10%

3.2 Experimental injection trials

Experimental cycle times (Table 4) confirmed the directional ranking from simulation but differed in magnitude. CuBe required a longer injection phase (3.0 s vs. 2.2 s for 316L and 316L CCC), attributed to a lower initial mold surface temperature (~ 28°C vs. 35°C for 316L), which increased melt resistance during filling. Because this effect partially offsets the cooling-time advantage, total cycle time is the appropriate metric for economic comparison.

Table 4
Real injection molding process parameters

Parameter	316L	CuBe	316L CCC
Injection time (s)	2.2	3.0	2.2
Cooling time (s)	28.0	18.0	22.5
Full cycle time (s)	50.7	41.5	45.2
Cooling time reduction	—	−36%	−20%
Cycle reduction	—	−18%	−11%

Cavity pressure was highest in the 316L mold, consistent with the higher polymer melt temperature resulting from slower cooling: greater fluidity facilitated additional mass transfer during packing, producing heavier parts and higher sensor readings. Comparing 316L and 316L CCC (same material, different channel geometry), conformal cooling alone reduced cooling time by 20%, isolating the contribution of channel routing geometry from conductivity effects.

3.3 Part characterization

Table 5 summarizes characterization data. Crystallinity varied little across mold concepts (316L: 42.9%; CuBe: 41.9%; 316L CCC: 42.6%), with differences statistically inconclusive and directionally consistent with the expected inverse relationship between cooling rate and crystallinity. CuBe produced the thickest frozen skin (7.43 μm, 18% above 316L), attributable to rapid surface chilling that shortened the time available for polymer chain relaxation. The 316L CCC result ran counter to this pattern: the thinnest skin (4.72 μm) and highest tensile strength (105.7 kgf), a combination inconsistent with conductivity-based predictions and not mechanistically explained by the present dataset. Dimensional scatter was lowest for CuBe (0.40%), followed by 316L CCC (0.53%) and 316L (0.65%), which tracks thermal efficiency ranking.

Table 5
Part characterization results

Property	316L	CuBe	316L CCC
Crystallinity (%)	42.9	41.9	42.6
Tensile strength (kgf)	90.3	78.3	105.7
Skin layer thickness (μm)	6.05	7.43	4.72
Average part weight (g)	47.2	45.2	46.0
Dimensional variation (%)	0.65	0.40	0.53

All three mold concepts produced parts that cleared both hydrostatic pressure qualification and NBR ISO 18553 pigment dispersion requirements. Manufacturers can therefore capture the cycle savings in Table 4 without triggering product re-qualification.

3.4 Financial analysis

Table 6 traces the full cost chain from mold investment through cycle reduction to margin outcome. CuBe outperformed SLM-CCC on every metric: 18% versus 11% cycle reduction, 12% versus 7% cost saving, and a 10% versus 46% investment premium. The asymmetry is driven by fabrication time: 127 h for CuBe (identical to 316L) against 308 h for SLM, a gap that lattice optimization partially but not fully closed. At demand levels representative of Brazilian PP-R fittings production, the 18-fold demand requirement for SLM payback is unlikely to be met near-term, whereas CuBe reaches break-even at 8-fold growth — a more attainable threshold.

Table 6
Comparative financial analysis. Product costs normalized (316L = 1.00); mold investment in USD (R$/USD = 5.68, commercial closing rate on 7 November 2024, Banco Central do Brasil)

Financial metric	316L	CuBe	316L CCC
Full cycle reduction	—	−18%	−11%
Transformation cost (norm.)	0.68	0.56	0.60
Product cost (normalized)	1.00	0.88	0.93
Cost reduction	—	−12%	−7%
Gross margin increment	—	+ 10%	+ 6%
Mold investment (USD)	7,593	8,315	11,121
Investment premium vs. 316L	—	+ 10%	+ 46%
Annual payback payment (USD)	—	2,772	3,707
Demand growth for 3-yr payback	—	8×	18×

Table 6

Cycle reductions of 11–18% are modest by conformal cooling standards: Park et al. [14] exceeded 50%, Abbès et al. [6] reached 50–66%, and Kuo et al. [15] approached 89%. The discrepancy reflects a geometry-class effect specific to thick-walled parts, where conformal channels serve proportionally less cavity surface area relative to wall volume. The resulting thermal gain per unit of fabrication investment is lower, which shifts the financial calculus against SLM at the demand levels examined here. A hybrid machining/SLM route, shown by Marin et al. [5] to cut SLM fabrication cost by 53%, would proportionally reduce the 18-fold demand threshold and represents the clearest engineering pathway to broader adoption of CCC in this geometry class.

3.5 Mold material selection framework

Table 7 translates the experimental and financial data into a structured decision framework for practitioners. The three mold concepts occupy distinct positions in the cost-performance space, and the appropriate choice depends primarily on production volume relative to the payback thresholds quantified in Table 6.

Table 7
Mold material selection framework for thick-walled PP-R injection molding

Decision dimension	**316L (baseline)**	**CuBe**	**316L CCC (SLM)**
Fabrication route	CNC milling (127 h)	CNC milling (127 h)	SLM + CNC finish (308 h; +142%)
Thermal outcome	Baseline (28 s cooling)	−36% cooling (18 s)	−20% cooling (22.5 s)
Cycle outcome	Baseline (50.7 s)	−18% (41.5 s)	−11% (45.2 s)
Cost outcome	Reference (1.00)	−12% cost; +10% margin	−7% cost; +6% margin
Investment	USD 7,593	USD 8,315 (+ 10%)	USD 11,121 (+ 46%)
Payback threshold	—	8× demand growth	18× demand growth
Recommended when	Low volume; cost control	Moderate-to-high volume	Very high volume; or with hybrid SLM route

3.6 Limitations

Several limitations bound the generalizability of these findings: the study covers one product geometry, one PP-R grade, and a single manufacturer's cost structure. The mechanical anomaly for 316L CCC parts (highest tensile strength at the lowest conductivity) remains without mechanistic explanation. Four areas warrant follow-on investigation: the cost-efficiency cascade for polymers with markedly different

processing requirements, such as PVC; hybrid machining/SLM fabrication routes [5] as a route to reducing the SLM investment premium; mold wear over extended production runs; and a financial model that incorporates set-up time and downtime costs, where faster thermal stabilization for CuBe and SLM-CCC may provide an additional advantage not captured in per-unit cycle analysis.

4 Conclusions

Four conclusions follow from the experimental comparison of 316L, CuBe, and SLM-CCC molds for thick-walled PP-R injection molding.

CuBe alloy molds delivered the best financial result: 18% cycle reduction, 12% cost saving, and a 10% margin gain at a 10% investment premium. With 8-fold demand growth required for 3-year payback, CuBe is the accessible route to cycle-time improvement for this geometry class at current Brazilian production volumes.

SLM-CCC molds achieved 11% cycle reduction and 7% cost saving, but the 142% fabrication time penalty (2.42× the conventional duration) produced a 46% investment premium and raised the payback threshold to 18-fold demand growth. Lattice optimization partially offset this burden; the more substantial reduction would come from hybrid machining/SLM routes, which Marin et al. [5] showed can cut SLM fabrication cost by up to 53%.

Parts from all three mold concepts passed full functional qualification, including 1000-hour hydrostatic pressure testing at 95°C and NBR ISO 18553 pigment dispersion. The cycle-time improvements are available to manufacturers without triggering re-qualification.

A geometry-class effect on SLM economics is documented here: cycle reductions that exceed 50% in thin-walled applications contract to 11% for thick-walled PP-R parts, where conformal channels cover less cavity area relative to wall volume. In this context, the 18-fold payback threshold is the decisive variable for SLM adoption decisions, not the thermal gain itself.

For practitioners evaluating tooling investments in thick-walled injection molding, the financial break-even volume is the primary criterion; thermal performance becomes the relevant differentiator only once that threshold is met.

Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethical Approval

Not applicable. This study did not involve human participants or animals.

Consent to Participate

Not applicable.

Consent to Publish

All authors have read and agreed to the published version of the manuscript.

Generative AI and AI-Assisted Technologies Disclosure

During the preparation of this manuscript, the authors used an AI assistant (Claude, Anthropic) to support drafting, restructuring, and language formatting based on content and data provided by the authors. All data, results, analyses, arguments, and references originate entirely from the authors' original experimental research [8]. No scientific content was generated, invented, or supplemented by the AI tool. The authors reviewed and edited all content and take full responsibility for the accuracy and integrity of the published article. This disclosure is also referenced in Section 2 (Methods), per journal policy on the documentation of LLM/AI tool use.

Funding

This work received financial support from Amanco Wavin Pipes and Fittings, the Brazilian National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the Santa Catarina State Research and Innovation Support Foundation (FAPESC). No grant numbers are available for these sources.

Author Contributions

All authors contributed to the study conception and design. Experimental work, data collection, and analysis were performed by J.C.T. Baifus. Financial modeling was carried out by J.C.T. Baifus and P.P. de Andrade Júnior. The first draft was written by J.C.T. Baifus. P.P. de Andrade Júnior and A.F. de Souza reviewed and edited previous versions. All authors read and approved the final manuscript.

Availability of Data and Materials

The processed results underlying this study are presented within the article and its tables. Mold investment values reported in Table 6 are disclosed with the manufacturer's authorization. The manufacturer did not authorize disclosure of the underlying itemized cost data (e.g., detailed manufacturing and material cost breakdowns); accordingly, only the normalized product-cost and margin

values reported in the article are available. Additional processed data supporting these findings are presented in the corresponding dissertation [8].

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Figures

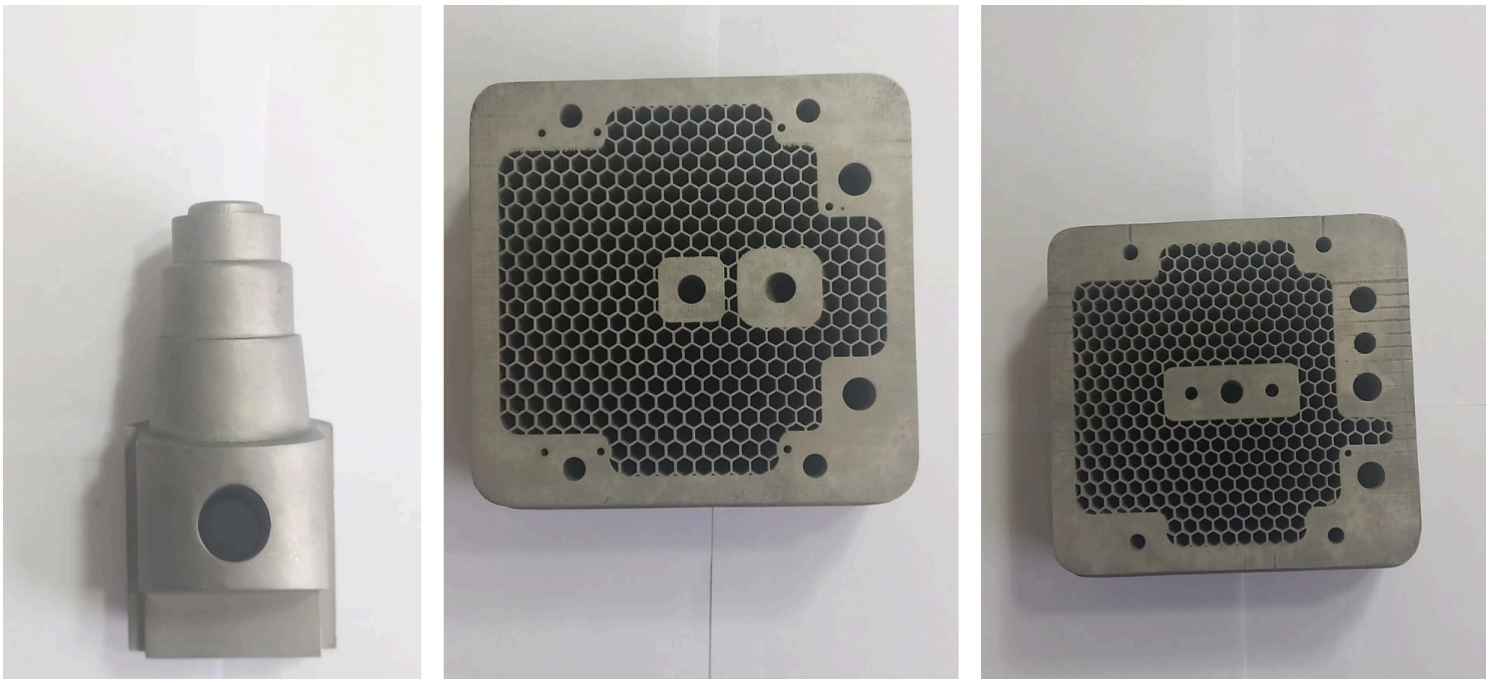


Figure 1

SLM-printed 316L inserts: (a) solid-region core; (b) lattice-optimized upper cavity; (c) lattice-optimized lower cavity. The honeycomb lattice reduced cavity mass by up to 28% and print time by up to 39%

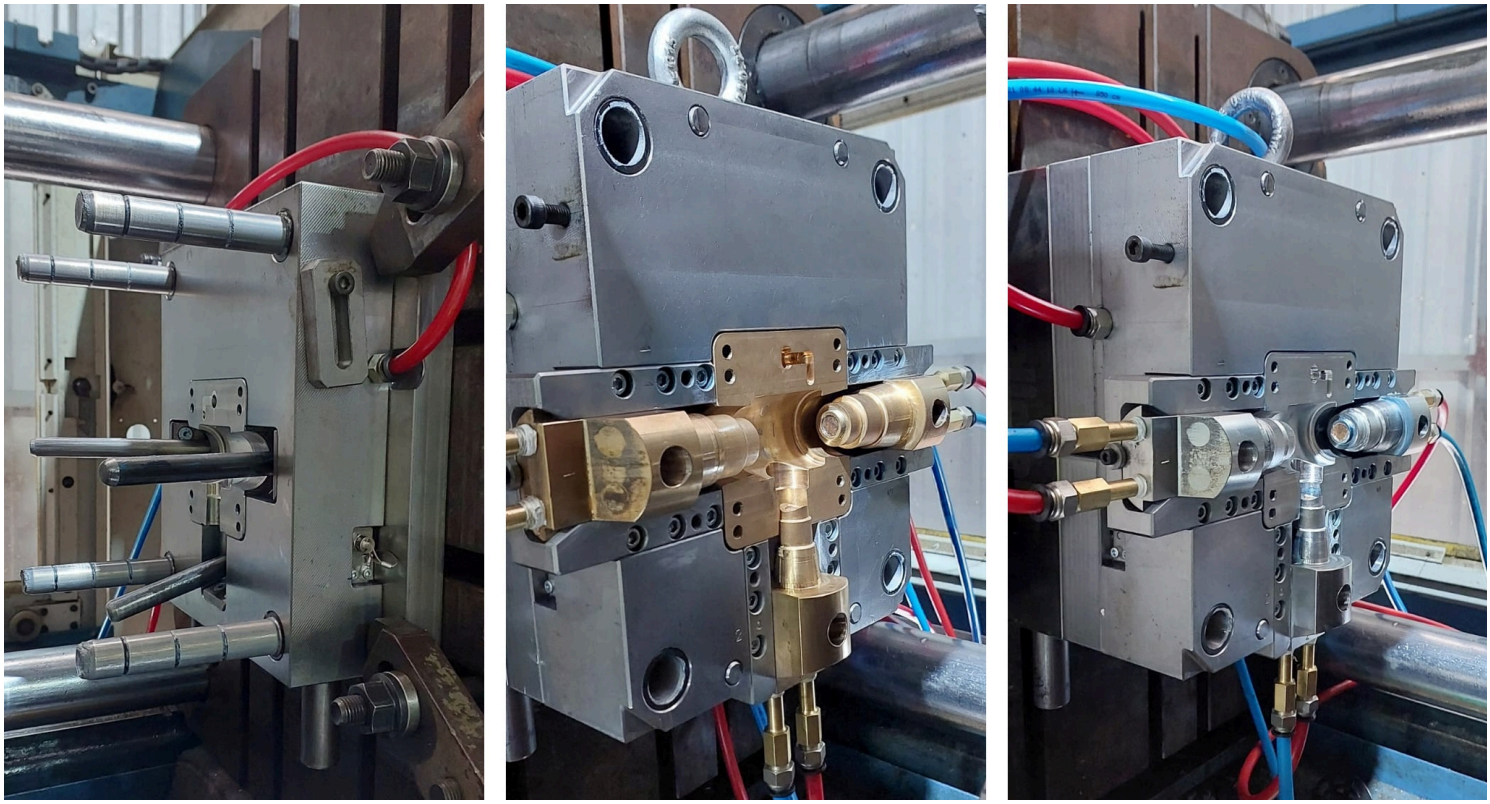


Figure 2

Three mold concepts on the ROMI Primax 150R injection molding machine: (a) conventional 316L stainless steel; (b) CuBe alloy with gold-colored inserts; (c) 316L CCC with SLM-manufactured conformal cooling and more complex coolant circuit



Figure 3

PP-R reduction-tee parts produced during experimental trials. All three mold concepts produced parts meeting PHI qualification for pressurized hot-water hydraulic systems