Indirect Rapid Molds for Prototype Lost-Foam Pattern Production

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Abstract

Lost-foam (also known as Expendable Pattern Casting, EPC) is an ever-growing metal casting technique, capable of producing complex metal components without parting lines. Mold preparation for lost-foam casting is typically accurate, but expensive and slow. The goal of this research was to develop a new approach for producing rapid lost-foam molds. With this new approach, patterns generated by SFF technology are used to form indirect composite lost-foam molds. Ultimately, our objective is to produce these molds quickly, accurately, and inexpensively. This new approach to lost-foam mold-making will be explained as well as the results of one trial.

Introduction

Lost-foam casting is an increasingly popular method for producing complex metal parts. The process starts by molding simple, low-density, foam segments with minimal undercuts. Next, segments are adhered together, to form elaborate lost-foam patterns (figure 1) --*often with intricate features, such as cooling channels and oil passages.* Then, foam patterns are attached to a sprue and runners to form a tree, and coated lightly with a refractory coating. Next, assembled trees are placed in a flask and loose, unbonded sand is vibrated around the tree. The top of the sprue is exposed at the surface of the sand. Finally, molten metal is poured directly into the exposed portion of the tree, replacing the tree and its foam patterns, with exceptional accuracy (figure 2). This process, first used to produce bronze figurines, has advanced considerably over the years. Today, many lost-foam patterns are produced for many applications, including automotive engines, valve bodies, and electric motor housings. Foam patterns are also used for investment casting, replicast [1], and packaging applications.

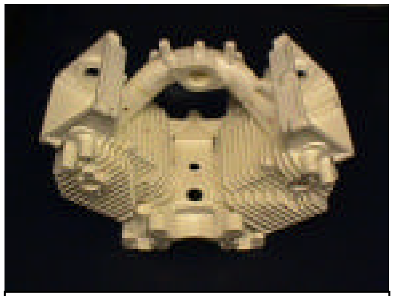


Figure 1. Polystyrene Pattern

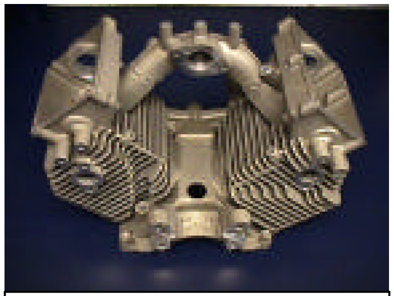


Figure 2. Lost-Foam Casting

Foam patterns are produced using a polystyrene-foam injection molding machine and specialized tooling. The lost-foam injection molding machine consists of several main components including:

- Bead hopper --from which polystyrene bead is continually supplied to the fill-gun.
- Steam chests --stationary steam-chest and movable steam-chest.
- Mold halves --mold halves are mounted on and closed between the two steam chests, to form the mold cavity.

- Steam vents & fill guns --molds are equipped with numerous steam vents and several fill-gun holes. Fill-gun tips, attached through the stationary steam-chest, are positioned flush with the surface of the mold cavity, through the access holes.
- Ports & drains --each steam chest is equipped with a steam inlet port, a compressed air inlet port, a water-cooling sprinkler system, and a drain.

The fundamental process used to form a polystyrene pattern can be described using five main steps as follows:

Step 1. The drains on both steam chests are opened and partially-expanded polystyrene bead is carried into the mold cavity by a stream of compressed air. Excess air within the mold cavity is vented through steam-venting while the bead is packed within the mold cavity. Steam venting, located in the mold wall, communicates with the lower pressure steam chests and drains.

Step 2. Drains are closed and steam (250 F, 15-25 psi) is applied to the bead through the steam-venting. Thermally expanding pentane gas within the bead causes it to expand until the mold cavity is filled. The fine slits on the steam-venting prevent the bead from expanding into the steam chest through the mold wall. The steam venting also allows steam to heat the bead and induce bead expansion and fusion, forming the final polystyrene pattern.

Step 3. Steam is turned off and the drains are opened. The water sprinklers spray water on the mold posteriors, cooling them rather quickly. The polystyrene pattern cools through the mold-wall to a temperature where it can be ejected.

Step 4. Finally, the moveable steam chest retracts, opening the mold for pattern ejection, and the process is repeated.

Step 5. Families of pattern segments are joined with adhesive to form complex patterns.

This is a simplified description, several common steps such as pre-expansion of bead, pre-heating, steam-through, and vacuum-assisted filling have been omitted in this simplified explanation. The lost-foam molding process does not experience the pressures common with injection-molding, lost-foam molds are designed to handle 50psi.

Traditionally, lost-foam tooling is CNC machined from either a billet of aluminum or a near-net casting. Tooling is usually thin-walled (_ to 3/8 inches) to allow steam transfer from the back of the mold to the mold-cavity. Venting is added by drilling holes normal to the surface of the cavity and steam-vents are press-fit until flush with the surface of the mold. Traditional approaches result in a tool with excellent thermal conductivity, accurate features, at a high cost ($10,000 on the low end) and long lead-time (4 weeks on the low end).

Several new processes for producing molds used for lost-foam pattern production have been enabled by SFF. These new processes may someday produce molds at a fraction of the cost and time of existing methods, along with a potential improvement in accuracy and complexity. Several direct and indirect SFF based processes have been explored. Direct approaches include

SLS metal, pro-metal, POM, or Lens and indirect approaches include spray metal or composite casting. When exploring the feasibility of using direct SFF tooling, it was concluded that these processes have much potential in the future, but the materials today are limited. Limitations including high shrink factors, steam-venting problems, high cost, small build envelopes, and low working temperatures (mainly for polymer based SFF) were identified. Indirect methods, such as spray metal and composite casting were also considered, both having advantages and disadvantages. For these two indirect methods, a clay parting line is handcrafted around the positive RP pattern. The first mold-half is spray-metal coated and back-filled with a composite material, followed by clay removal. Next, the second mold-half is spray-metal coated and back-filled. After composite solidification, the pattern is removed and the two mold halves are ready for machining. Although spray metal tooling has good surface characteristics, it becomes limited when deep features are required. The second approach skips the spray-metal step and casts a composite tool from the RP master. Adding steam venting in both methods becomes difficult and weakens the mold. Steam venting placed after mold construction can loosen, reducing part quality, cycle-time, and tool life. These two indirect approaches result in a solid rather than thin-walled mold, further complicating steam vent addition.

Other labor-intensive approaches are used to make thin-walled molds from a positive SFF master, but the drive behind this research was to let current technology minimize human intervention. For this reason attention was focused on combining RTV silicone molding with composite casting to make a mold from an SFF pattern. In addition, a novel cast-in-place steam venting technique was used to reduce machining.

Objective

The main objective of this research was to use a new, indirect composite tooling technique to produce molds for the lost-foam pattern making process. The molds would be tested under near-typical molding conditions to determine if this technique is worthy of further development, and if so, which steps need refinement.

Another objective was to estimate cost and time requirements for this process if it were to be used in an industrial setting.

Approach

The approach used consists of eight main steps starting with CAD model of mold halves and ended with polystyrene injection molding (mold testing in this case). The part geometry chosen for this process is shown in figure 3. The part is a section of a four-cylinder engine block and has dimensions of 17x15x3 inches. The process used to form this part is described in the following eight steps.

CAD Model of Mold Halves

CAD models of both mold halves were designed based on the part geometry. The mold face was approximately 3/8 of an inch thick and supported by a web of ribs. Walls were added around the mold face and ribs.

RP of Mold Patterns

LOM was the SFF process selected for this project due to the large build envelope and relative speed. LOM patterns produced were in the form of the final mold rather than the final part.

Silicone Molding

LOM patterns were mounted in two mold boxes and RTV silicone was poured around each. Specialized mold boxes, a large molding chamber and a silicone injection system were required to fill the large molds under vacuum. After silicone vulcanization, the LOM patterns were removed from the silicone molds.

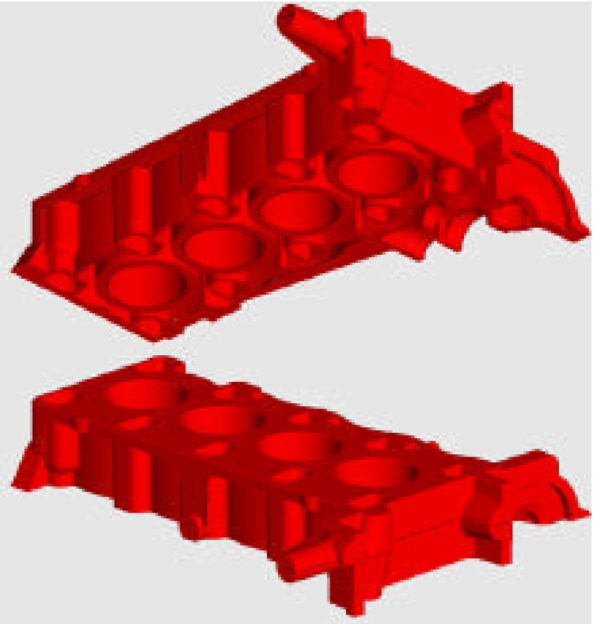


Figure 3. Part Geometry

Steam Vent Placement

With other, indirect mold making processes, steam-venting has a tendency to become loose, and sometimes is driven out by the cyclic bead pressures. For this new approach, Steam-venting was cast-in-place to reduce machining and improve performance. Traditional Steam-vents were modified to prevent the composite slurry from entering the steam passageway and slits. Steam-vent faces were positioned firmly against the silicone surface before silicone mold assembly and composite casting.

Composite Mold Casting

After the silicone halves were assembled within the mold boxes, they formed a void, which embodied the form of the final mold. Steam-vents remained in position, within the void. The composite material used was a high temperature aluminum filled epoxy. The composite slurry was injected into the silicone molds under vacuum and then room temperature cured at 80 psi. The silicone was stripped from the final molds and the composite molds were trimmed of excess composite.

Post Curing

The composite molds were placed on a flat aluminum plate positioned in an oven. The composite molds were buried in sand to reduce thermal shocks and hold the molds flat. Both molds were incrementally heated to above 300 degrees F through a series of 50 degree steps. After cooling, the molds were cleaned and prepared for final machining.

Final Machining

Machining consisted of opening the backs of the steam vents and fitting the mold into the fixture. The fixture was used to hold the tooling halves in place while foam bead was injected, expanded, and cooled. The fixture was designed to take the brunt of the molding press clamping force while holding the mold-halves in alignment -through a 150°F-temperature range.

The tools expand due to thermal expansion and must be held to expand together. Parting-line alignment is critical to hold accuracy and prevent crashes.

Mold Testing

After the mold halves were fitted into the fixtures and bolted onto the steam-chests of the foam injection machine they were handled like a traditional aluminum mold. Autoclave pressures between 15 and 25 psi were used. After part formation the mold was opened slightly and the pattern was blown to the movable side. Next the mold was opened completely and the part was blown off the cavity using air-eject. The main difference when "tweaking" this mold was the initial steam pressures. After several shots the pressure was increased to 25 psi.

Results & Discussion

The results of this research are best divided into three main categories including: 1) process and testing, 2) process lead time, and 3) composite mold costs.

Process & Testing

This new mold-making approach was able to produce a mold for testing, images from each step are shown in figure 4. CAD modeling of the mold halves was done using Magics RP by Materialize. This was somewhat challenging due to a combination of CAD geometry and .stl quality. As shown, ribs and outer walls were added to a thin-walled mold face. Twenty three shut-offs were required for this part geometry.

A LOM 2030 was used to produce patterns of the mold halves. One pattern was generated and decubed with little to no difficulty. The other mold half was problematic due to bad edges and a shift during the build. The problematic pattern was repaired manually to reduce the undercut, but it was never completely eliminated.

The silicone molding, steam vent placement, and composite casting steps were almost problem free. The greatest difficulty was adding the steam-vents and assembling the silicone halves without knocking a vent out of place. Of the 600 steam vents only one vent shifted. The silicone captured and transferred mold features exceptionally (including undercuts). The vent faces were clearly visible on the mold face with little to no composite blockage.

Post-curing was a step of concern. The molds had the potential to curl, warp, or distort at the elevated temperatures but they did not. The machining took a considerable amount of time, mainly do to the generous composite clearance we added behind the steam vents. All 600 vents were opened from the back of the mold by breaking through the 1/8 inch thick composite barrier that remained. Cutting through with a rotary tool was not the difficulty, but finding the location to start cutting was. Vents were securely cast in place. Machining the mold halves to fit in the fixture was straight-forward and required minimal machining.

The focus of mold testing was on the composite mold integrity and pattern quality. The composite molds were designed to operate in temperatures cycling from 250 deg F down to 60 deg F repeatedly and pressures reaching 60 psi without deflecting or cracking. Ribs were added to support the mold cavity during bead injection and expansion. The molds withstood the harsh conditions for approximately 10 hours with no notable wear or deflection. Twenty three areas of the mold with shut-offs also functioned well, with little to no flash as shown in figure 5. The fixture used, to hold the mold halves together, performed as expected.

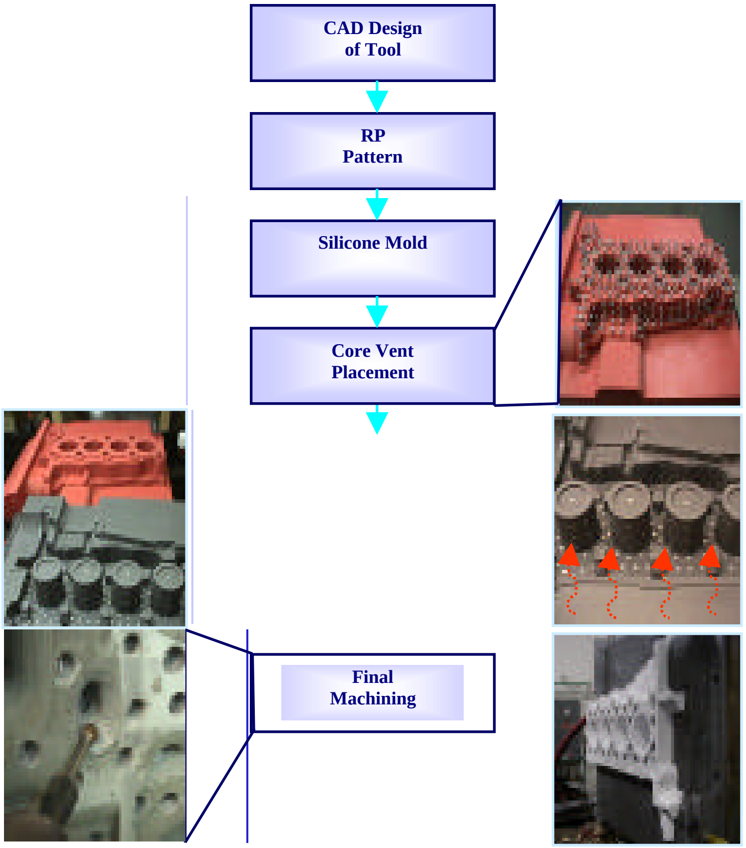


Figure 4. Mold Making Process

None of the patterns produced were of castable quality, although much potential was evident. The mold halves were modified several times during testing to improve bead fusion and fill --*resulting in moderate improvements.* 68 steam-vents were added to one side of the mold, but there was still not enough bead reaching some regions for proper fill and fusion. Also, undercuts due to the poor LOM pattern made part ejection difficult. These undercuts were sanded but could not be removed sufficiently for smooth part ejection. Ejector pins were needed to push the patterns past these undercuts. Better LOM patterns, produced on a newer LOM machine, would have reduced or eliminated these undercuts.

Figure 5. Pattern with shut-offs visible

Cast-in-place steam vents and added steam-vents performed well without any dislocation (approximately 600 steam-vents total). Steam transfer is somewhat limited in this steam-vent design. A new design, providing ease of use and better steam delivery is recommended for this rapid tooling process. The cost of preparing steam-vents was expensive and could be reduced with a new design and automated steam-vent production.

Process lead time

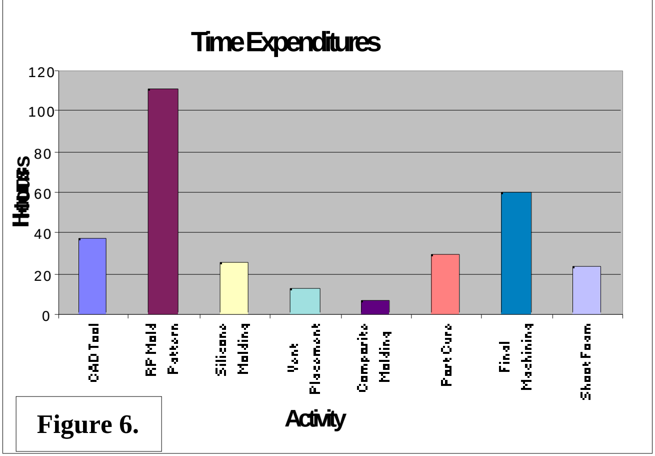
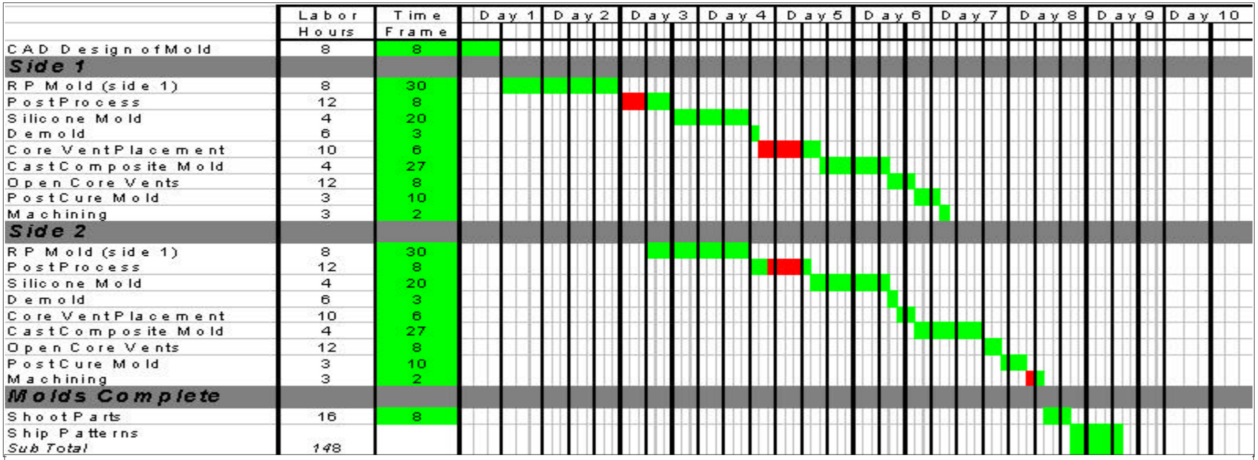


Figure 6.

Figure 6 illustrates the amount of time spent on each step of the process. All steps include training as well as focused work. Portions of the work, RP pattern, silicone molding, composite molding and post curing are unattended activity and continue around the clock. The remainder of the steps would likely take place during a normal work day. Using data from figure 6, figure 7 was created to illustrate the estimated time required for trained lost-foam mold makers to produce polystyrene patterns via this process (given ideal conditions). The time is around two weeks and could be faster if mold halves were produced in parallel using two LOM machines. The time to metal could be reduced if the foundry was included in early planning.



	Labor Hours	Time Frame
CAD Design of Mold	8	8
Side 1		
RP Mold (side 1)	8	30
Post Process	12	8
Silicone Mold	4	20
Demold	6	3
Core Vent Placement	10	6
Cast Composite Mold	4	27
Open Core Vents	12	8
Post Cure Mold	3	10
Machining	3	2
Side 2		
RP Mold (side 1)	8	30
Post Process	12	8
Silicone Mold	4	20
Demold	6	3
Core Vent Placement	10	6
Cast Composite Mold	4	27
Open Core Vents	12	8
Post Cure Mold	3	10
Machining	3	2
Molds Complete		
Shoot Parts	16	8
Ship Patterns		
Sub Total	*148*	

Figure 8. Mold Making Time Estimates

Cost of composite molds

Using this research as a baseline, the cost of producing composite tooling for patterns that are 11”x11”x4” is fairly reasonable. Assuming that mold boxes and fixtures are reusable, and steam vents are both relatively inexpensive and functional, this process could result in prototype tooling for as little as $12,000. For this project, expenses reached almost $20,000, not including equipment development (mold-boxes/fixture/pressure-vessel/experiments). A large portion of these expenses were in RP pattern post-processing (repairs) and steam-vent machining, two tasks that can be easily refined. With trained mold-makers and reduced machining (increased molded-in-place features) the cost in labor would bring total cost down substantially.

Conclusions

This research shows that molds can be produced within a two week time period with acceptable mechanical properties. Steam vents need to be improved and ejector pins should be

incorporated. Quality of patterns produced was not acceptable but very promising. The cost of the molds was reasonable, between $12,000-20,000, depending on geometry and size.
Benefits of using this type of rapid tooling include:

- Cost of tooling is significantly less than production tooling
- Improved time to market
- Improved quality of cast products
- Early patterns can be used to design tree configurations
- Early patterns and castings can be used to set-up and program production equipment
- Early castings can be tested and redesigned several times before production begins
- Composite tooling can potentially act as bridge tooling
- Composite tooling can potentially become production tooling for short runs

Future Recommendations

Although patterns of castable quality did not result from this research, the feasibility of using this approach for polystyrene patterns was apparent. Several portions of this composite tooling process should be refined including:

1. Steam-Vent --*design and production method*
2. Use small scale molds to refine vent design as well as other process parameters
3. Refine basic fixture design for better mold attachment and part ejection
4. Mold box improvements for reduced machining (mounting-holes and datum-planes cast-in-place)
5. Vacuum assist polystyrene bead fill

Acknowledgements

We gratefully acknowledge the support of Ford Motor Company and the Rapid Prototyping Consortium Members.

The authors would also like to thank the MSOE, Rapid Prototyping Center Students for their contribution on this project.

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