A Sprayed Steel Tool for Permanent Mold Casting of Aluminum[†]

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Abstract

A new application of steel sprayed tooling for the manufacture of prototype permanent molds for aluminum casting is discussed in this paper. The prototype tooling is quickly made by spraying onto substrates that define the tooling shell shape. The shell material, structure, and geometry are adequate to withstand, for a limited number of pours, the demands placed on an aluminum permanent mold. An initial demonstration shows the promise of this method.

1 Rapid Tooling

For several years, our work has been directed toward quickly manufacturing tooling by spraying metal onto patterns [Prinz88, Weiss90]. Tooling made in this way can be quickly made, on the order of days, and have adequate dimensional quality and lifetime for many prototype applications. We believe we will improve the process to the point of also making tooling suitable for limited production, as well.

The method of making zinc tooling has been extant for years [MOGUL63, Garner71], yet the time and cost of making the pattern has prevented the process from being commercially exciting. We are making the patterns quickly; in a competitive world where time is paramount, quickly made patterns has greatly increased the attractiveness of the approach.

The tool face geometry is defined by the pattern, and is formed during the metal spraying operation. The tool is completed with the addition of appropriate supports and backing. The pattern is then discarded.

The patterns are manufactured by one of a variety of solid free form (SFF) systems, for example, stereolithography[‡] (SLA).

We model the part geometry and the tool geometry in a solid modeling environment [Gursoz90], and manufacture the pattern directly from these geometries; pattern manufacture is typically a matter of one to three days.

Metal spraying for the purpose of coating was devised at the beginning of the century [Schoop10]. Using the process to deposit and build up solid bodies was apparently first attempted in 1924 [Turner24] — the goal was to build up enough material to permit mechanical testing of the sprayed materials. We are spraying with an arc spray device, where an arc is established between two consumable electrodes made of wires of the metal being sprayed. The

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[‡] Stereolithography has been commercialized by 3D Systems, Inc., of Valencia, California.

[†] This work has been supported by the Aluminum Company of America, by Carnegie Mellon University under a DARPA contract for Shaping by Deposition, by the Engineering Design Research Center, an NSF Engineering Research Center, and by the Edison Materials Technology Center.

metal is melted, and then atomized and carried to the substrate by a column of moving gas.

The metals sprayed in commercial practice for making tools are zinc and various zinc alloys. These materials have relatively low melting points (pure zinc melts at 693 K) and are also relatively soft. This combination makes them suitable for easy spraying onto patterns, but also limits them from higher temperature or higher pressure applications.

Our most recent efforts are directed toward using steel (T_m ~1800 K), and other high melting point alloys, as the material we spray [Fussell90]. Using a transfer material in the process of making the sprayed shell from the pattern, we have demonstrated prototype tools made of stainless steel.

The application area for our work has been in the injection molding domain. Other commercial work has been done in the areas of low pressure injection molding and composite layup dies; these processes have exclusively been in the relatively low temperature and low pressure domains.

With our initial success making steel shells, we became interested in extending the application area to a higher temperature process; we chose the manufacture of a permanent mold suitable for casting aluminum.

2 Tooling for Permanent Mold Aluminum Casting

The permanent mold casting process uses a material with a measure of permanence to form the cavity of the mold. Typical mold materials include cast iron, steel, graphite or refractory metal alloys. During casting, the surfaces of the mold are generally coated with a refractory slurry or sprayed with graphite; this promotes a long tool-surface life. The coating also acts as a release agent and a thermal barrier.

Conventional wisdom suggests permanent mold casting is not economical for small production runs; the cost of manufacturing the mold is too great. The cost comes making the mold. The machining time to create the mold is generally long; typical industrial experience suggests that two to six months elapse from the completion of the mold drawings to the time the completed mold is delivered. If the mold is manufactured by electro-discharge machining, as might be the case for complex internal surfaces, time is also required to manufacture the EDM electrodes.

The high cost of tooling manufacture is incurred both for prototype tools and for production tools. Our goal was to prove the utility of sprayed metal tooling to reduce the cost of manufacturing prototype tools, as well as make the prototype tools quickly. If tooling quality needs can be met, this approach for making tools should be appropriate for limited production runs as well.

The prototype mold in permanent mold tooling meets two useful needs: a mold design is tested to determine if the molten metal properly flows and if the mold correctly cools the part; and prototype parts from the actual process are made. The metallurgy and surface condition of a permanent mold part is typically different than a sand cast part; sand casting is the prototyping process more generally used to make prototype parts.

The demands placed on this permanent mold include:

> low pressure — a maximum static pressure of about 5 kPa (0.7 psi)
>
> a mold preheat to, perhaps, 670 K;
>
> the ability to withstand mold surface transient temperatures to roughly 1300 K;
>
> adequate heat transfer rate to remove heat from the molten metal into the mold and mold cooling systems;
>
> and the mold must be robust enough to withstand handling.

Tools made of sprayed steel are able to meet these demands, at least for a limited number of cycles of the tool.

3 Manufacture of Permanent Mold Tool

The geometry of this tool was designed from the geometry of a simple connecting rod. The connecting rod was modeled in NOODLES, a non-manifold geometric modeller being programmed at Carnegie Mellon University. This geometry is shown in Figure 1.

We elected to manufacture, for this experiment, only one of the two mold halves. We simulated the second half with a 3 cm (1.2 inch) steel plate.

Working from the connecting rod geometry, the part which would form the mold cavity was also modeled in NOODLES. Casting process expertise was used here to add appropriate casting features (sprue, runner, gates, well, vent, and overflow), and also to modify the original geometry to make it manufacturable; draft was added, and some holes were removed from the connecting rod to permit a proper flow of metal and subsequent solidification in the mold cavity. The modified geometry is shown in Figure 2.

Figure 1. Solid Model Representation of a Connecting Rod

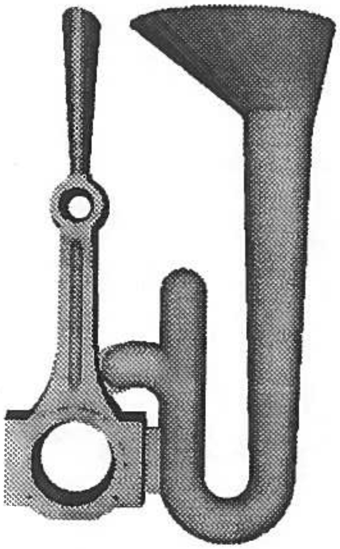

Figure 2. Solid Model Representation of the Connecting Rod Pattern

The connecting rod mold pattern was then made in a stereolithography apparatus. Figure 3 shows a plastic pattern from that process.

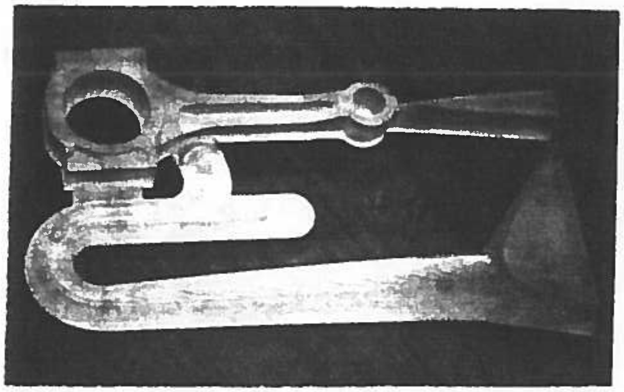

Figure 3. Stereolithography Made Connecting Rod Pattern

Figure 4 schematically shows the development of a sprayed tool. The starting point is the stereolithography made pattern with the same face geometry as the desired tool face geometry. The sequence then follows this scheme:

A frame is placed on the SLA pattern to contain the fusible alloy.

The fusible alloy is added to the pattern, creating a negative impression of the pattern, and the form is backed up with some mass castable epoxy. This step is a transfer step from SLA pattern to the steel sprayed tool.

The SLA pattern is removed, and the tool frame is placed on the fusible alloy transfer pattern. Steel is sprayed onto the fusible alloy to form the face of the tool. This tool was made with 410 stainless steel sprayed to a thickness of about 0.75 mm (0.03 inches). Figure 5 shows the as-sprayed surface as it was applied to the fusible alloy.

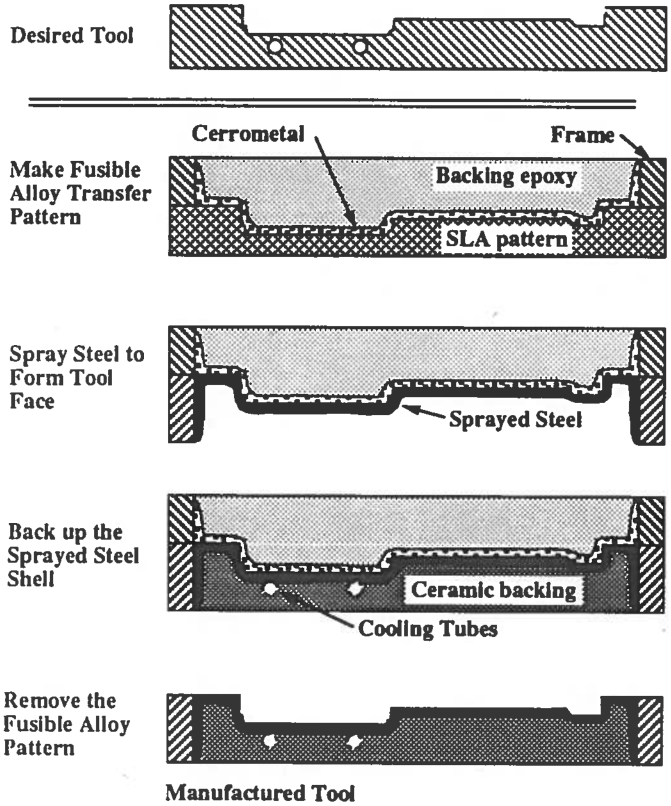

Figure 4. Schematic Sequence for Manufacture of Sprayed Tool

The steel sprayed shell is backed with material that supports the shell. In this application, it is important to have a backing material that will withstand the temperatures of the process, carry heat from the mold face, and reasonably match the co-efficient of thermal expansion of the mold face material. Alternatively, a material that does not match the mold face's expansion coefficient is acceptable if it is strong in compression and weak in shear; thus it will support the clamping loads on the mold face, but not add stress to the mold face during the processes' temperature excursions.

Finally, the fusible alloy transfer pattern is removed, leaving the completed mold. Figure 6 is a photograph of the mold's working face before casting.

In this experiment, the sprayed shell acceptably matched the intended dimensions. A portion of the tool face warped from the intended flat surface about +0.6 mm (0.025 inches); this was the result of stress residually left in the shell from the spraying process. This curvature was eliminated by the clamping forces which closed the mold.

The surface appearance of the sprayed shell was uniform, with a roughness of about 3 to 10 microns RMS average (120 to 400 µinch).

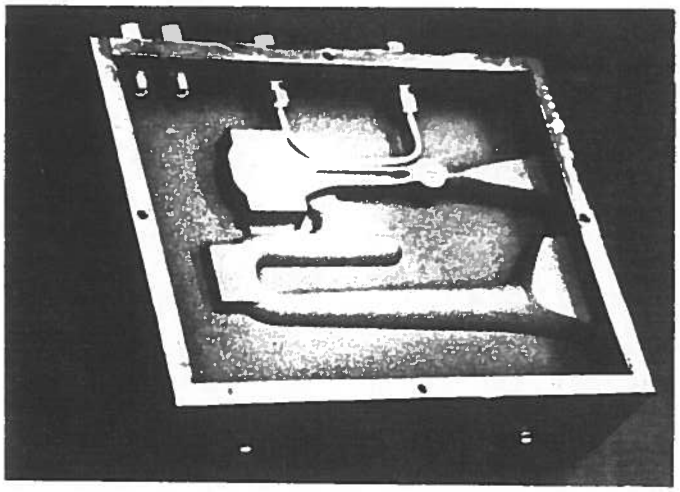

Figure 5. Connecting Rod Casting Tool — Back of Sprayed Shell

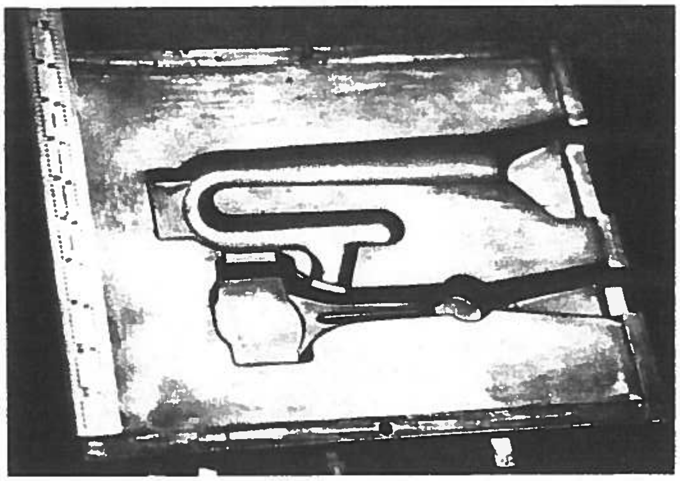

Figure 6. Connecting Rod Casting Tool — Face of Sprayed Shell

The mold's sprayed surface was not robust; a thickness of only 0.75 mm was not adequate for the mechanical handling we gave it. During final processing, a small portion of the shell was chipped. This particular failure would be unexpected in a mold made of wrought material; a similar load would have only scratched the wrought tool's surface.

4 Microstructure of the Sprayed Metal Shell

Shells which have been built up from sprayed materials do not have the microstructure of shells made from wrought materials [Fussell91]. Figure 7 shows a typical scanning electron microscope photomicrograph of sprayed material. There are three types of regions in the photograph:

Solidified droplets of metal; these are structurally either formed into flattened lamella, or retain some spherical quality. The lamella arrived at the substrate in either molten or mushy condition, and flattened upon splatting onto the surface. The more spherical droplets arrived at the substrate relatively solid, and did not flatten.

Regions of oxide; these are slightly darker regions in figure7. The oxides are formed at the arc and in transit from the arc to the substrate. They appear both as lines between the lamella and as larger, misformed, oxide droplets themselves. Systems sprayed using air typically range from 30% to 50% volume oxide. The sample shown in figure 7 was sprayed using Argon as an atomizing gas; this typically reduces the oxide levels to 10% to 15% volume. The casting tool shell was sprayed using inert gas to reduce oxide levels.

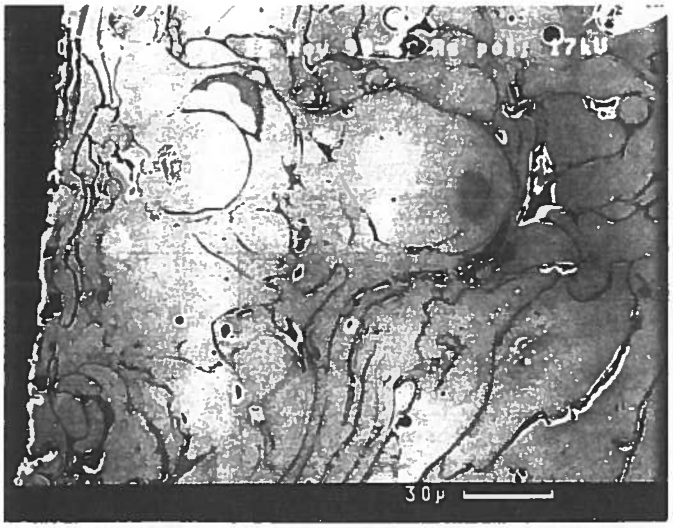

Figure 7. SEM Photomicrograph of Typical Sprayed Shell

Voids; these are structural holes in the sprayed material. They appear singly and also grouped together; the voids are artifacts of the rapidly solidified spray process where the droplets periodically arrive. Some of the dark lines between metal lamella may also be micro-voids, very small in scale compared to the resolution of this SEM. The shells sprayed with this style of arc-spray apparatus generally show a volume void content from 3% to 8%.

The surface in figure 7 is an as-sprayed surface, showing a typical surface morphology and surface roughness.

The quality of the shell, and particularly the void fraction of the material, is heavily influenced by the spraying parameters. For this shell, the single most important variable is the angle of incidence of the particles as they arrive on the substrate; arriving perpendicular to the surface is best, with even angles from 10 to 25 degrees away from perpendicular greatly degrading the material quality. Under these conditions, void content increases, and the void morphology is altered: the voids tend to appear in clusters. This factor plays a strong role in sprayed tool manufacture. The vertical walls of the connecting rod mold (*e. g.*, at the base of the connecting rod in figure 5) were difficult to spray; the sprayed material was not optimally deposited. The failure in the tool during preparation and the during the tool's use occurred in these regions.

A gross structure composed of metal lamella which are generally separated by thin layers of oxide and shot through with voids can not be as strong or as robust as structures made from wrought materials. None-the-less, the sprayed structure is adequate for the needs of a prototype tool, and the sprayed system can be formed quickly. In fact, the forming time is independent, within limits, of the complexity of the substrate pattern; this is not true for conventionally manufactured tools.

Alternative spraying processes can produce materials that are competitive with wrought materials [Lavernia88, Mathur89, Safai81], at the loss of rapidly making the final tool shape.

5 Aluminum Casting using the Tool

The tool was tested by casting an aluminum part at Alcoa Laboratories. This tool was pre-heated to about 700 K and poured with an aluminum alloy. The part from the first pour is shown in figure 8.

Permanent molds are typically cycled several times (*i. e.*, several parts are made) before the mold produces good parts. The first part made in this tool showed promise; it was better than that typically made by a first cycle mold. The tool failed to an extent after this first part and we elected to not continue using the tool. Yet even one part showed that the basic pattern was adequately designed to make parts; one purpose of the experimental prototype mold was met.

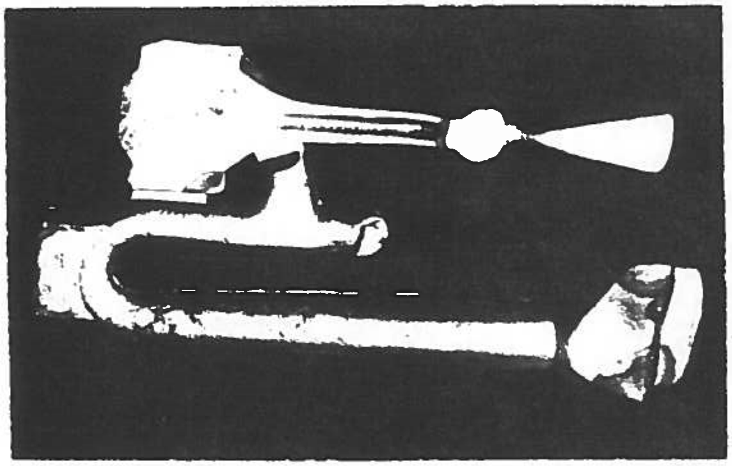

Figure 8. First Aluminum Part from the Sprayed Steel Permanent Mold

The part showed reasonable, but not excellent, surface quality and dimensional quality. The cooling of the connecting rod, in this first pour, was not optimal for producing the best part. This is due to both the mold's internal design, and our lack of use of the tool.

We elected to not pour a second part in the tool. The tool failed when a ~4 mm^2 portion of the tool surface flaked away in the region of the connecting rod base. The failure was on a near vertical wall and would have acted as a locking catch between part and tool, so the part would have been difficult to remove.

The shell also cracked; the crack in lightly be seen in figure 9 in the sprue. This is almost certainly from the thinness of the shell combined with the temperature cycling of the tool. The crack failure would not have prevented us from making more prototype parts.

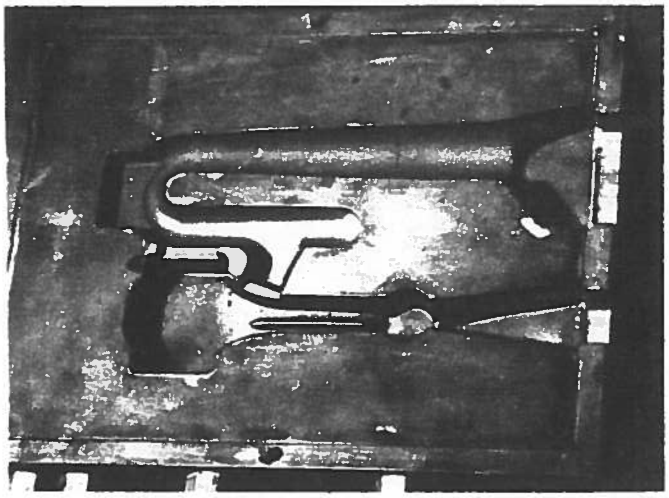

Figure 9. Sprayed Steel Permanent Mold after Pouring

6 Continuing Work

We are pleased that this initial experiment has shown limited success. The survival of the tool and the quality of the part both show enough promise to continue with this effort.

The principal continuing work must concentrate on making a better tool, *i. e.*, the internal structure of the tool must be stronger and more robust to withstand both the preparation work, the thermal cycling the mold experiences, and the mechanical handling of removing the cast part. This aim can probably best be achieved by more carefully spraying the steel shell to prevent regions of poor quality shell, and also by making the shell thicker and thus more robust. The latter approach must be balanced with a need to avoid warpage of the mold face during and after spraying.

The dimensional quality of a tool is also of concern, even in prototype tooling. The prototype process in permanent mold tooling yields two valuable results: a tool design where molten metal properly flows, and prototype parts that come from the casting process. Dimensions are of particular concern for the latter result. The tolerance buildup starts with SFF technologies; the spray process replicates the surface finish with high fidelity, yet the sprayed shell dimensions vary about ± 0.25 mm (± 0.010 inch) from the pattern dimensions. This tolerance buildup is a subject of keen attention.

Our next step is the creation of a mold that meets both goals of a prototype tool. Our hope is to manufacture as many 10 to 20 parts from a prototype mold, excluding the parts used to pre-heat and understand the tool.

In parallel with improving aluminum casting tooling, we also intend to extend the idea of sprayed metal tooling to other domains. One domain of interest is an ambient temperature, higher load application, such as a stamping die tool.

Acknowledgment

This work has been supported by the Aluminum Company of America, by Carnegie Mellon University under a DARPA contract for Shaping by Deposition, by the Engineering Design Research Center, an NSF Engineering Research Center, and by the Edison Materials Technology Center.

We particularly thank Mr. Charles West and his staff at Alcoa Laboratories, Molten Metal Processing Division, for their assistance in specifying the modifications to the mold pattern, and for pouring the mold.

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