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# Arc-Sprayed Steel-Faced Tooling

*L.E. Weiss, D.G. Thuel, L. Schultz, and F.B. Prinz*

**A process for building arc-sprayed steel-faced tooling is described. Strategies to create matched die sets for injection molding applications are presented, and the issues involving backing materials, spray conditions, and wear resistance are discussed. Examples of stainless steel tools built with this process demonstrate improved durability over more conventional sprayed zinc-faced tools.**

## 1. Background

A SPRAYED metal-faced tool is a composite structure consisting of a sprayed metal coating, or shell, backed by a castable support material. The shell is fabricated by thermally spraying metal onto a preformed pattern made from plastic, wood, or wax, for example. "Soft" tooling can be made relatively quickly with this process for applications such as building prototype and low-volume injection mold dies. While the concept of sprayed tooling has been in existence for decades (Ref 1), TAFA, Inc*., has been largely responsible for popularizing and commercializing arc-sprayed zinc-faced tooling. Relative to conventional machining methods, the sprayed metal tooling approach has the potential to more quickly and less expensively produce tools, particularly tools with complex shape contours or large dimensions.

The typical sequence of steps depicted in Fig. 1 for building a zinc-faced mold are:

1. The process begins with a suitable pattern that is the inverse of the topography of the desired mold cavity. A release agent, such as polyvinyl alcohol (PVA), is applied to the pattern surface.
2. A spray frame is clamped in place on the pattern and a metal coating is deposited with electric arc spraying. Typical shell thicknesses for sprayed zinc tools range from 6.0 to 10.0 mm. After the shell has been deposited, cooling channels made from copper tubing bent to shape may be laid in place. An epoxy is then cast into the frame.
3. When the pattern is fully hardened, it is separated from what is now the first mold half.
4. The first mold half is then used as part of the pattern for the second half. A model of the finished mold cavity (i.e., the desired part with accompanying gates and runners) is inserted into the first mold half to complete the second pattern. Again, a coating of release agent is applied and the spray frame is affixed. Metal is sprayed onto the frame and pattern, and the backing material is cast into the frame and allowed to harden.
5. The second mold half is then separated from the first half, completing the tool.

The process outlined above has several limitations. First, making patterns with conventional methods can be a time-consuming task. Solid freeform fabrication processes (Ref 2, 3), such as stereolithography, have been used to address this issue to rapidly make patterns for sprayed tooling applications (Ref 4). Computer-aided design process planners, such as automated parting surface model generators (Ref 5, 6), have also been created.

Another limitation of sprayed tooling is the inability to form geometric features with high aspect ratios, such as tall, thin walls. These shapes cannot be directly created with spraying because spraying is a line-of-sight operation (e.g., it is difficult to spray into a deep hole in the pattern). This remains a fundamental problem. In some cases, preformed metal inserts are sprayed in place to form these features.

Yet another process limitation is that only low-melting, ductile metals, such as zinc and zinc alloys, can be sprayed in the fashion outlined above. It would be desirable to create steel-faced tooling that would be more durable and useful for a broader range of applications. Higher-strength materials, such as sprayed steel coatings, crack and peel away from patterns due to thermally induced internal stresses. One challenge, therefore, for building sprayed steel tooling is to identify a release agent or

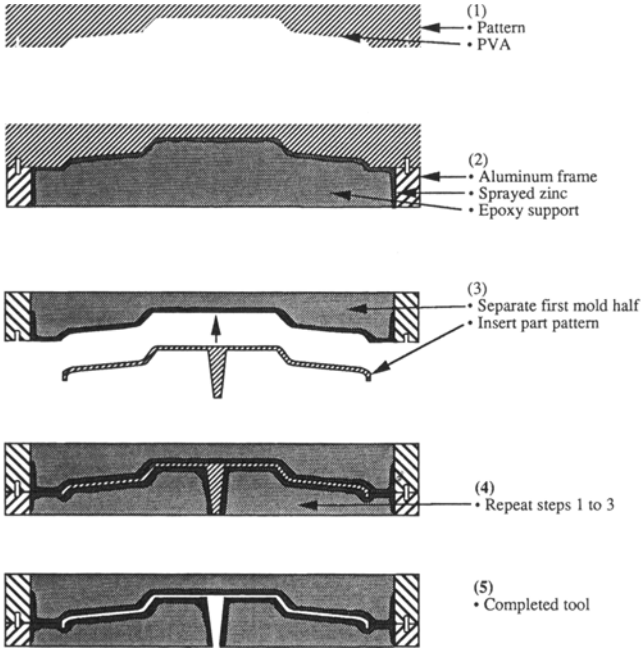

**Fig. 1** Sprayed zinc-faced tool making process

**Key Words:** arc-sprayed coatings, molds, rapid prototyping, tooling application

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pattern to which a thick sprayed steel shell will adhere, without cracking or peeling, and that will later release the shell. The use of patterns made from low-melting point tin alloys have been investigated for this purpose. Sprayed steel adheres to these alloys by superficially melting and abrading the surface. Tin alloy patterns can be made by spray-casting the alloy against stereolithography patterns in complementary shapes (Ref 7). After the steel shell is deposited and backed up with a castable support material, the tin alloy is melted away. To demonstrate this concept a 410 stainless-steel-faced sculpture (Fig. 2) was built (Ref 8). The process for building the sculpture is depicted in Fig. 3 and detailed in following sections.

Several issues need to be addressed in order to incorporate this approach into a process for making steel-faced tooling:

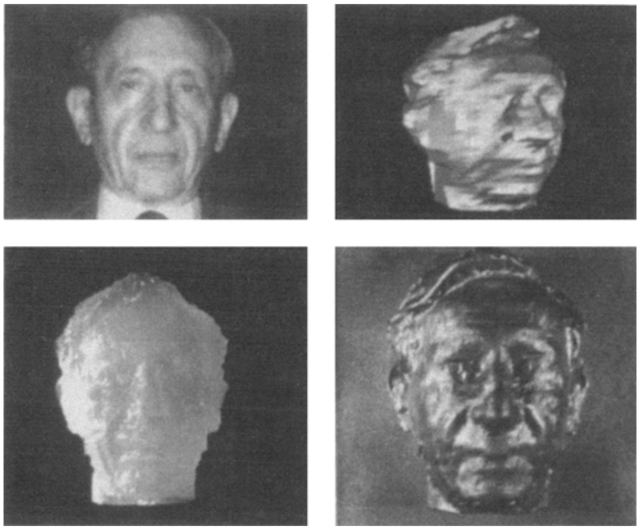

**Fig. 2** Video image of subject (upper left). Computer-aided design (CAD) model of subject created from depth measurements from a range scanning system (upper right). Stereolithography pattern created from CAD data (lower left). Sprayed 410 stainless-steel-faced sculpture (lower right)

- Matched die halves: Molding tools consist of matched sets of cavity and core dies. Poor matching can lead to excessive flash and can reduce the accuracy of the molded part. In the zinc-faced tooling process (Fig. 1), proper alignment and mating is ensured by using the first mold half as part of the pattern for the second mold half. This strategy is not directly applicable to the steel-spraying strategy in Fig. 2 because steel cannot be directly sprayed onto the first steel half.
- Backing material: The backing material should exhibit a coefficient of thermal expansion (CTE) that closely matches that of the sprayed steel. It should have a high stiffness to maintain the steel shell's geometry, in particular during melt-out of the tin alloy.
- Spray parameters: It is important to deposit a uniform thickness of metal to avoid areas of localized stress concentrations. A coating that is too thick can warp or delaminate due to larger internal stresses. A coating that is too thin can easily fail under load. It is also important to minimize heat transfer to the tin pattern during spraying to minimize pattern deformation due to the high CTE of tin alloys.
- Wear resistance: Initial experimentation with sprayed steel shells has demonstrated that while they are more durable than zinc shells, the steel surface can wear quickly.

This paper discusses these issues and work in progress toward creating a practical sprayed steel-faced tooling process. To evaluate the concepts presented here, several iterations of the 410 stainless-steel-faced injection molds in Fig. 4 and 5 were built. The "Frisbee" tool in Fig. 4 was selected because its flat surfaces were challenging to create since warpage from internal stresses is readily manifested here. The fan blade tool in Fig. 5 represented a demanding application for injection molding glass-filled nylon.

## 2. Building Strategies

To build matched sprayed-steel tooling sets, such as single-pull injection molds, there are two basic strategies. First, each mold half can be made independently using individual patterns.

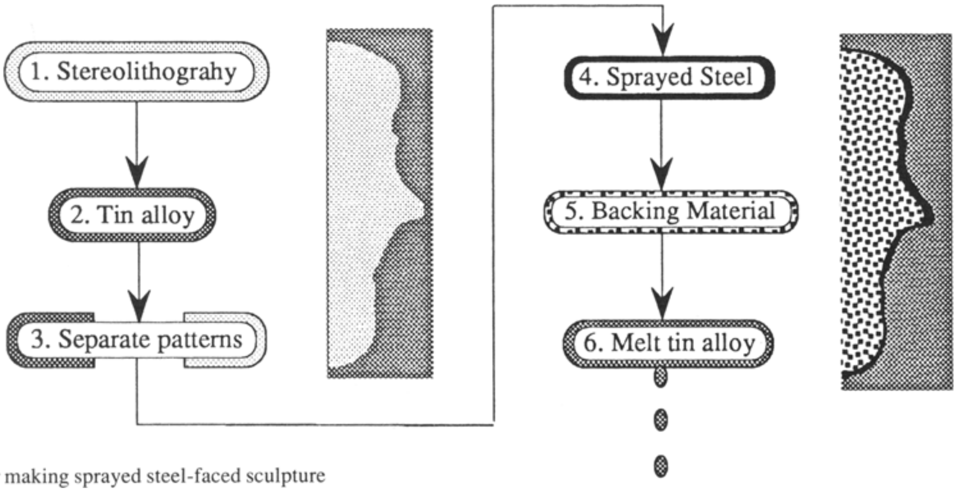

**Fig. 3** Process for making sprayed steel-faced sculpture

In this parallel approach, not only must the patterns be closely matched, but the sprayed tooling process must also be capable of producing very accurate replications of these patterns. A second approach, based on a sequential strategy, uses a pattern transfer from the first half to build the second half of the tool. These two strategies are depicted in Fig. 6 and 7 for constructing the "Frisbee" tool in Fig. 4. The benefit of the parallel approach is overall building speed. The sequential approach takes longer, but it can produce better matching.

Each building strategy requires the creation of patterns made from low-melting point tin alloys. It is feasible to create these patterns directly by milling bulk stock or by direct deposition of tin onto three-dimensional shapes created with solid freeform fabrication. In general, however, it is assumed that the tin patterns are created by a pattern-transferring process using master patterns in wood, plastic, or wax. The approach is to spray deposit a thin coating of the tin alloy onto the master pattern and then back the tin shell with a low-shrinkage castable epoxy. This approach results in very accurate replications. A suitable tin alloy for this application is Cerrocast from Cerro Metal Products Co. ($T_{melt} \cong 138$ °C).

The steps for the parallel building strategy in Fig. 6 are:

1. A pattern of the desired mold cavity is created. The pattern can be made from a variety of materials, such as plastic, wax, wood, or metal. This pattern has locating holes for dowel pins to align frames in subsequent steps. A release agent, such as PVA, is sprayed onto the pattern.
2. An aluminum frame is located on the pattern and clamped in place. A thin coating of Cerrocast is sprayed onto the pattern and around the inside of the pattern frame. A coating thickness of approximately 0.1 to 0.2 mm is sufficient. The Cerrocast shell is then backed with castable epoxy. When the epoxy hardens, the Cerrocast/epoxy pattern is separated from the master by submerging the structure in water to dissolve the PVA.
3. A low-profile steel frame with a roughened inner surface is located on the Cerrocast/epoxy pattern and clamped in place. Its low profile allows access to uniformly spray the steep sides of the pattern. Steel is sprayed onto the pattern and the inside of the frame to a thickness of approximately 1.0 mm.
4. A second steel frame is clamped on top of the first frame to create a deeper well into which the backing material is cast.
5. The backing material is fully hardened using a thermal curing cycle, and at the same time the Cerrocast pattern is released by melting out the Cerrocast. The surface of the tool face is polished by wet sanding.

This completes half of the tool. To build the second half of the mold, shown in steps 6 to 8 of Fig. 6, the procedures in steps 1 to 5 are repeated starting with a pattern of the mold core. In addition, a preformed steel sprue insert is also sprayed into place.

The "Frisbee" tool in Fig. 4 was built using this parallel approach. Because several iterations were required to develop the process, the reusable master patterns were machined from steel. The accuracy of these patterns eliminates one possible source of inaccuracy in the final tool and therefore simplifies the analysis of the results. The sprayed tool exhibited a maximum deviation of 75μm warpage, as measured by the deviation from a flat surface. Although the matching of the dies was good enough to prevent flashing using polyethylene, this was not a particularly demanding injection molding application. Therefore, the suitability of this strategy for use with higher injection temperatures, pressures, and other geometries cannot be generalized at this time.

The most time-consuming step of the sprayed steel tooling process is the ~26 h curing of the castable materials. However, the shells for both halves can first be sprayed and then backed with the castable material at the same time. In contrast, the sequential strategy requires that the first half be completely built before proceeding with the second half. It attempts to achieve a better match at the cost of longer building times. After the first mold half is built, using steps 1 to 5 of the parallel approach, the additional steps for building the second mold half in the sequential approach are as shown in Fig. 7. In this sequence, a pattern of the desired part is inserted into the first mold half. A pattern transfer is made by casting a low-shrink compound, such as a silicone rubber, against a pattern to produce the inverse pattern. The transfer is made from the completed sprayed steel mold half with cavity pattern inserted. This method is very much like the

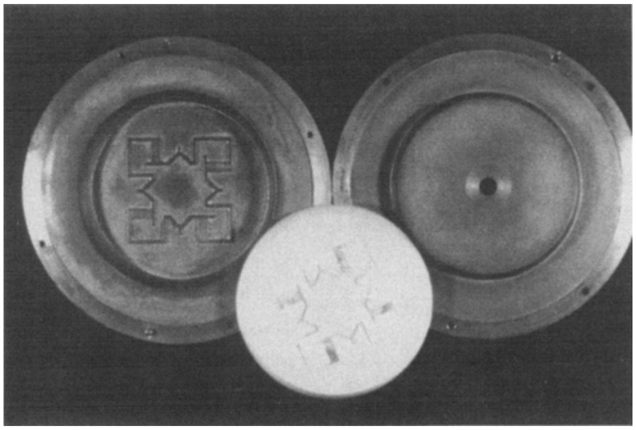

**Fig. 4** "Frisbee" tool

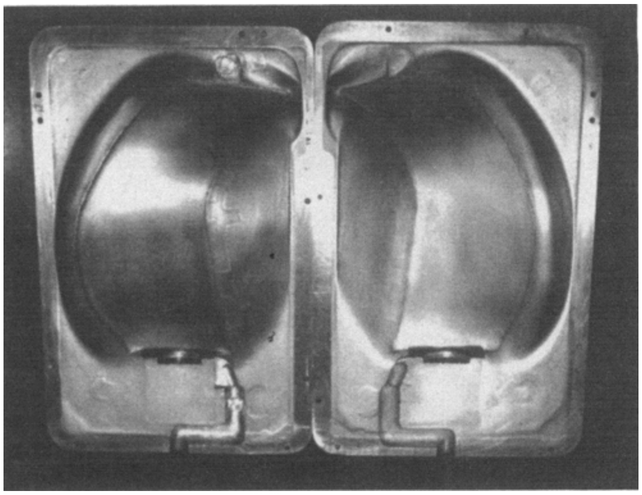

**Fig. 5** Injection mold tool for glass-filled nylon

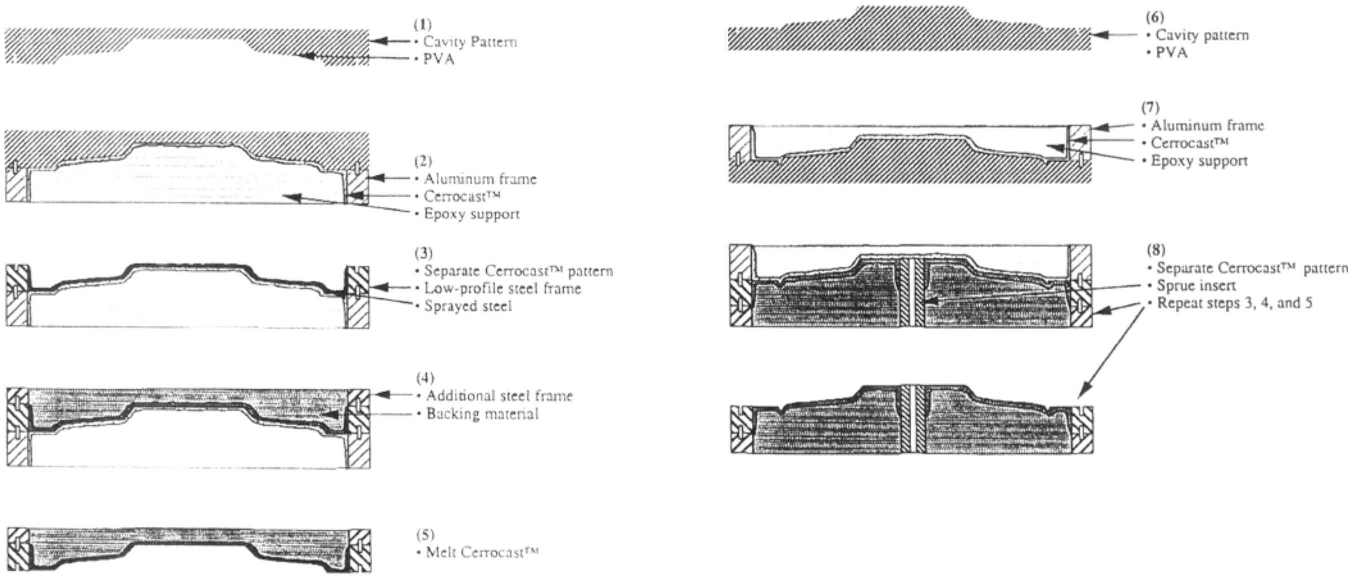

**Fig. 6** Parallel building strategy

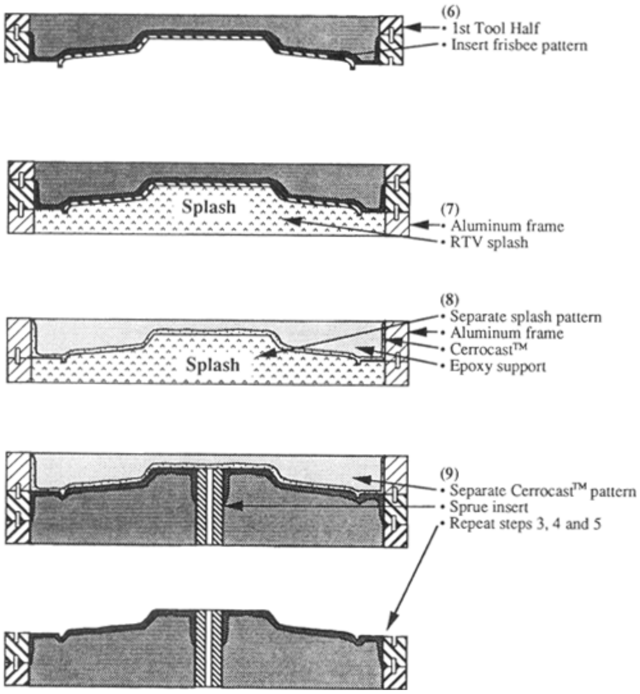

**Fig. 7** Sequential building strategy proceeds from step 5 of the parallel approach (Fig. 6)

sequential zinc process, affording the best topographical compensation between the mold halves.

The fan blade tool in Fig. 5 was built with the sequential strategy. The patterns for this tool were derived from a sprayed zinc-faced tool of the same geometry. One half of the zinc tool was used as the starting pattern (e.g., step 1 in Fig. 6), and a polyurethane fan blade produced with the zinc tool was used as the pattern insert (e.g., step 6 in Fig. 7). The zinc tool was originally created using stereolithography patterns. The test results are discussed in section 5 of this article.

## 3. Backing Material

A suitable backing material must exhibit high tensile strength and stiffness, good adhesion, low shrinkage, and a CTE that closely matches that of the steel shell, to prevent delamination due to differential expansion. This material must also be able to support the steel shell during meltout of the Cerrocast. One backing system that appears to work well for these needs is a close-packed steel-filled epoxy composite. Steel shot and powder are used as fillers for the epoxy to lower the CTE and stiffen the epoxy. A very high volume percentage of filler is used while maintaining a castable consistency of the backing material. The constituents include a low-shrinkage, high-temperature, commercially available tooling epoxy, 1.98 mm (0.078 in.) and 0.28 mm (0.011 in.) diameter carbon steel spherical shot, and 0.025 mm (0.001 in.) diameter 410 stainless steel powder. A volumetric ratio of 67% coarse, 23% medium, and 10% fine filler is used to approximate a ternary packing similar to those studied by McGeary (Ref 9). Because the filler is being mixed into the epoxy rather than being packed in the manner cited in Ref 9, the effective packing density will be lower than the 95% given in the paper. An estimated 60% packing of the steel filler inside the epoxy backing gives good results as far as castability is concerned. The total epoxy volume, including resin and hardener, is calculated by assuming it occupies 40% of the tool volume. The actual volume occupied after settling of the filler is somewhat less, resulting in a greater than 60% packing density of steel. The preparation of the backing material is described below.

The coarse and medium shot is degreased and cleaned in acetone and allowed to air dry. It is then annealed at 700 °C in stainless steel bags for 2 h and allowed to furnace cool to well below 400 °C. This softens the shot sufficiently for it to be machinable, because the backing material structure must be machined flat, after it hardens, to square-up the tool.

The volume of the medium-sized shot can be derived as $(0.23/0.67)V_c$, where $V_c$ is the packed volume of the coarse shot. This is the volume to which the shot would settle if complete settling were to occur. However, weights are much easier and more reliable to work with, so the coarse shot is weighed, and the weight ratios are calculated for the medium and fine shot as follows:

$$M_M = C_M \frac{D_M}{D_C} M_C \qquad \text{(Eq 1)}$$

and

$$M_F = C_F \frac{D_F}{D_C} M_C \qquad \text{(Eq 2)}$$

where $M_C$, $M_M$, and $M_F$ are the mass of the coarse, medium, and fine fillers; $D_C$, $D_M$, and $D_F$ are the material densities of the coarse, medium, and fine fillers; and $C_M$ and $C_F$ are the volumetric ratios of medium to coarse (0.23/0.67) and fine to coarse (0.10/0.67) fillers, respectively.

The mass of the epoxy was based on an assumed 60% packing (or settling) density of the filler. The mass of the epoxy is then:

$$M_E = \frac{0.4\,D_E}{\varepsilon_C\,D_C} M_C \qquad \text{(Eq 3)}$$

where $M_E$ and $D_E$ are the mass and density of the uncured epoxy and $\varepsilon_C$ is the dry packing efficiency of the coarse filler, which is equal to:

$$\varepsilon_C = \frac{M_C}{V_C D_C} \qquad \text{(Eq 4)}$$

The mix ratio for the epoxy system used is 100 parts resin to 28 parts hardener by weight. Because the densities of resin and hardener are approximately equal, epoxy components are calculated as:

$$M_R = \frac{M_E}{1.28} \qquad \text{(Eq 5)}$$

and

$$M_H = 0.28\,M_R \qquad \text{(Eq 6)}$$

where $M_R$ is the mass of the resin and $M_H$ is the mass of the hardener.

The epoxy components are weighed and mixed at room temperature. The coarse shot is then added and mixed until thoroughly wetted. Next, the medium shot is added and thoroughly mixed, and then the fine shot is added and mixed. Before the shell is filled, a small amount of epoxy is brushed onto the sprayed surface of the steel coating. This ensures that the epoxy penetrates into the pores of the sprayed material for maximum adhesion at this interface. The backing material is then cast into the mold while the mixture is stirred to reduce settling during the pour.

The epoxy is then thermally cured according to the manufacturer's suggested schedule. The tool is allowed to cool after the cure sequence before proceeding to melt-out the Cerrocast. It is reheated at 1 °C per minute, holding for one h at 120 °C before continuing up to 175 °C. After 1.5 h at 175 °C, the steel tool half can be separated from the now-molten Cerrocast pattern. The tool half is then returned to the 175 °C furnace to maintain heat. After 15 to 20 min of reheating, the tool is removed from the furnace and the residual cerrometal is scraped and brushed off the surface. Cleaning typically requires several iterations of this procedure. The tool is returned to the furnace and allowed to cool below 65 °C.

## 4. Spray Parameters

One key factor in the selection of spray parameters is to minimize heat transfer to the Cerrocast pattern. The pattern has a relatively high CTE. If it gets too hot, the geometry may be significantly affected. In our experience the temperature of the pattern/steel shell should be kept at less than 38 to 45 °C during spraying. To accomplish this it is necessary to spray with minimal power levels while maintaining a stable arc. Acceptable spray settings for 1.6 mm diameter 410 stainless steel wire are:

- Voltage: 25 V using a constant-voltage power supply
- Current: 18 A
- Gas pressure: 100 psig, atomized with nitrogen
- Torch stand-off: 15 to 25 cm

The surface may also be cooled by passing a low-pressure air stream over the pattern. In addition, cooling channels can be cast inside the pattern to regulate the temperature. Using active cooling can speed the deposition, because significant amounts of time are spent waiting for the substrate to cool sufficiently between spray passes.

Not only are the spray parameters important, but also the manner in which the metal is deposited. The metal should be deposited uniformly to maintain a consistent thickness and to help keep the pattern/shell evenly heated to avoid areas of large internal stress concentrations. This is not an easy task, because the pattern geometry affects the effective deposition rate. For example, deposition rates can be quite low in corners and along edges, whereas the metal builds up more rapidly on flatter adjacent areas. Therefore, shielding of flatter regions is sometimes required to prevent buildup on them while spraying into corners.

In general, the torch should be kept in motion to avoid excessive application of heat or material at any one point. It is important to follow surface contours, maintaining normal incidence of the spray stream to the pattern surface. Several shell thickness measurements must be taken during the spray process to gauge uniformity of coverage, and surface temperature must be monitored with a touch probe or infrared pyrometer. The spray technician must use these measurements to adjust the spray sequence as required. Therefore, spraying steel for this tooling application is to a large extent an art that requires practice, skill, and patience on the part of the spray technician. Automatic planning and control of robotic spraying is being investigated as one method to address this problem (Ref 5).

## 5. Test Results

Several zinc-faced and steel-faced fan blade tools have been evaluated for a demanding injection molding application for Nylon 6 with 38% glass and mineral filler. The injection pressure was 52.38 MPa (7500 psi) at 285 °C. Under these conditions, the steel-faced tools proved to be strong and durable. They have withstood up to 1400 shots without cracking; additional shots have not been made. Zinc-faced tools, under the same conditions, developed hairline cracks after approximately 200 shots and exhibited far more wear around sharp edges. One unexpected result of this testing was the high rate of surface abrasion exhibited by the steel-faced tools in comparison with the zinc tools. Pitting and roughening was predominant in the vicinity of the gate as well as along the curves of the tool in Fig. 5. Small particles from the shell surface were also entrapped in some of the injected parts.

At this time there is no conclusive evidence to determine what causes this pitting. One hypothesis is that the glass and mineral in the nylon chip away at the minute steel "splats" comprising the shell. The steel particles are sufficiently hard that the mineral components in the nylon may catch them on their edges and pull them out of the shell surface. A softer material such as zinc may allow the mineral particles to scrape material from the surface of the splats, deforming them without plucking them out of the shell. A second hypothesis is that the nylon first infiltrates into microscopic pores in the shell. As the plastic hardens and shrinks, the metal particles are bound in the part and ejected out of the shell with the part. By this mechanism, a higher density of pits would form in a steel shell due to the rougher texture of the steel surface relative to that of zinc.

Chrome plating was evaluated as a means for improving the surface wear properties. One of the tools, which had already undergone 680 shots, was plated before additional injections were made. First, it was cleaned with sulfuric acid to rid the shell of any embedded nylon that could adversely affect adhesion of the plating metal. The frame face, sides, and back were masked to ensure that these mounting surfaces would not be affected dimensionally. The surface was then glass bead blasted, which is a standard treatment before plating chrome on steel. An initial coat of electroless nickel was applied, and then one of electrolytic chrome. The resultant plating thickness was between 38 and 50 µm.

After plating, the mold was returned to the injection press and an additional 500 shots were made under the same processing conditions as in the first trial. There was no evidence of any additional surface wear. It is believed that the primary reason for the improvement is not so much an increase in surface hardness, but an increase in the sealing of surface porosity.

Plating appears to be one possibility for solving the surface wear problem of sprayed steel molds. If the wear resistance is actually achieved through the sealing of surface porosity, other surface treatments may be equally successful for this purpose. There already exists a wide assortment of treatments for porous materials that could be investigated.

## 6. Conclusions

The work in progress reported here demonstrates the feasibility of making sprayed steel-faced tooling. A variety of tools, with varying geometries, must still be built and tested to prove the concept. Optimal coating thicknesses and backing material compositions must be determined, and alternative steel alloys should be explored. Applications other than plastics injection molding should also be considered. For example, we have investigated the use of sprayed steel shells for making prototype permanent mold castings of aluminum (Ref 10).

There are several areas to pursue in future research. First, spraying is a tedious operation requiring skill and diligence. To make this a viable process, automating spraying with robotics and computer-aided design is important for repeatability and consistency (Ref 5). Second, it would be beneficial to create a shell that would not require plating or ceiling. Plasma spraying may be a viable option for building denser shells that would be less susceptible to wear. Although even thicker, denser shells could be deposited with high-velocity oxyfuel, the tin alloy patterns are not rugged enough to withstand this process. Perhaps a thin protective layer could first be arc sprayed with subsequent deposition using high-velocity oxyfuel spraying. In the future it is envisioned that tooling might be deposited directly, without requiring preformed patterns, using thermal spray shape deposition processes (Ref 11). With this approach, there would be no geometric limitations.

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