Steel-Based Sprayed Metal Tooling

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1. Abstract

A strategy for building sprayed steel tooling by arc spray deposition is discussed in this paper. Depositing steel is crucial for moving sprayed metal tooling from prototype applications to superior prototype and production-quality tooling. Tooling is fabricated by spraying onto substrates that define the tooling shell shape. In particular, two process issues are addressed: deposition of thick metal shells, and control of oxide content by atomization with inert gases.

2. Rapid Tooling

Current solid free form (SFF) systems, economically produce one or, at most, a few parts; in volumes beyond these the systems typically loose their economic advantage. Our work is directed toward quickly making tooling from SFF patterns; the tooling can then be used to make tens to thousands of parts in limited production runs.

The process of manufacturing tooling from arc and flame sprayed materials has been in the literature for over 25 years [MOGUL63, Garner71]. Previous work, however, has been limited to prototype molds and dies made from low melting point materials such as zinc and zinc-aluminum alloys. Previous work has also been limited by the types of patterns available for spraying; the time and expense to manufacture and prove the pattern has prevented the wide-spread use of this technique. The work described here speaks to these limitations. Building upon a concept of rapid manufacture of prototype tooling [Weiss90], this work is directed to solve the difficulties of making thick shelled, sprayed-steel tooling.

The system for rapidly making prototype tools uses a geometric modeling system (NOODLES [Gursoz90]) to describe a part and the patterns required to make the part's molds or dies. A rapid prototyping tool, a stereolithography apparatus (SLA) in our case, creates the patterns in a matter of one to two days. Finally, the patterns are sprayed, using an arc-spray device, with zinc or a zinc alloy [Weiss90] (see figure 1).

The spray applies metal until the built-up shell is thick enough to support itself separately from the underlying pattern. The pattern and shell are separated, and the shell is back filled with a backing material (a ceramic or epoxy, for example). The process is then repeated to make the second half of the mold or die.

The shell wall provides two important functions: form (or shape) of the die or mold, and wear resistance. The shell need not be thick enough to directly support the direct, or normal, loading of the manufacturing process. This

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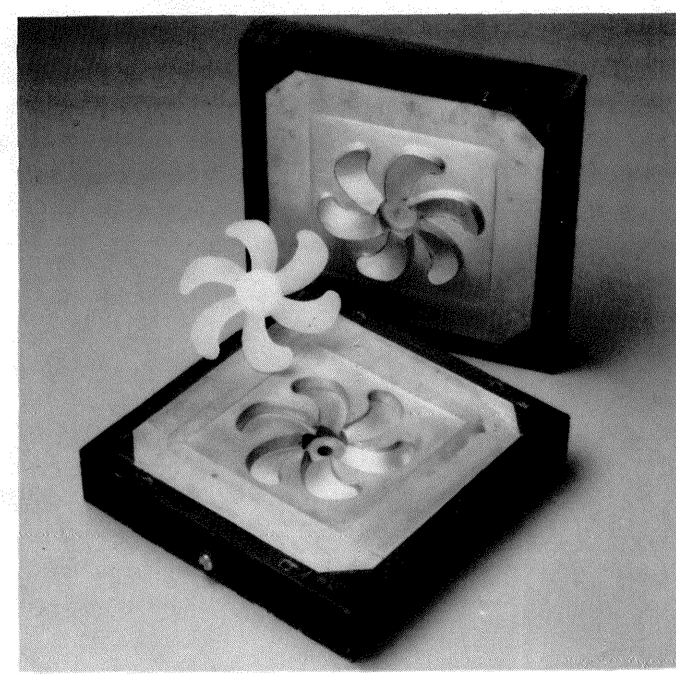


Figure 1: Zinc Molding die for a fan blade

loading will be transferred through the shell and carried by the backing material. The shell will have to support the hoop, or tangential, loading. Simple shells for injection molding, for example, need to support the hoop stresses induced in the shell by the pressurized volume. Typically, these sprayed structures are brittle, and therefore strong in compression, but weak in bending and tension.

This technique for making low-volume tooling is appealing for two major reasons: the time required to manufacture such a prototype tool can be of the order of one week; and the cost of making this prototype tool is substantially less than a conventionally made one-of-a-kind mold or die.

Elements of this technology have been extant for a quarter century, yet there remain several major hurdles in the manufacture of tooling made from sprayed high temperature alloys:

- Thick Shells -- the metal spray process builds up the shell on the pattern by a layering process. As each new layer is added it solidifies, cools, and contracts. This imposes a strain field onto the top surface of the shell. Generally, this stress added with each layer eventually causes the shell to peel up and thus fail. This effect is pronounced with the higher temperature, stronger materials. This catastrophic failure of the shell during manufacture is the reason that steel shells are not sprayed in industrial practice today.
- Shell Material -- the shells must resist wear and be sufficiently strong to produce good parts. Unfortunately, the spraying processes have the side-effect of oxidizing the sprayed material. The oxides dominate the mechanical characteristics of the sprayed shell to their considerable detriment.
- Backing Material -- the material behind the shell must carry compressive loads and be matched to the shell's coefficient of thermal expansion (if the tool is to operate at elevated temperatures). Current materials used in prototype tools (zinc or aluminum filled epoxy) are not suitable for use with steel tooling.
- Integration -- cost effectiveness is only assured by easily progressing from geometry to tool. This implies a simple progression from the CAD design tool, through pattern creation and shell creation, to

the proving of the tool. This is still the subject of research.

- Dimensional Control -- today's tooling must be dimensionally precise. Our goal is to minimally meet the expectations from a vacuum die casting technology (tolerances of order +- 0.5 mm (+- 0.025 inch)) The dimensional quality of rapid prototyping technologies when built up with the tolerances of the spraying process does not yet seem to support the need in tooling.
- Geometry, small aspect holes -- The spray process is not able to deposit sound material into small aspect ratio holes and channels.

These challenges must be met to make successful tooling.

3. Metal Spraying

There are several metal spraying processes. The OSPREY process [Mathur89] and [Lavernia88] provides large deposition rates (of the order of 1000 kg hr^{-1}) by atomizing a molten stream of liquid drawn from a pool of liquid metal. There is typically a contiguous molten surface present on the substrate. Cooling rates are reported at 10 K sec^{-1}.

Plasma systems, at the other end of the spectrum, deposit material at a rate from 0.1 kg hr^{-1} to 5 kg hr^{-1}. These systems function by propelling powdered material in a stream of gas heated by an electrical arc. Gas temperatures are reported to be as high as 20 000 K [Safai81]. Deposition rates of a few kg hr^{-1} are problematical for typically the powder materials are not entirely melted.

Flame systems, similar in concept to oxy-acetylene cutting and heating torches, melt a powder, wire, or stick of material in the flame and then use the combustion gases to blow the molten particles to the substrate. The deposition rates vary between 4 kg hr^{-1} and 20 kg hr^{-1}. As this processes essentially uses a heating torch, the substrate is heated, while the particles are conveyed in a gas stream of combustion products.

High velocity variants of flame and plasma systems greatly increase the kinetic energy of the particles in order to reduce the porosity of the sprayed material. The high speed flow of molten material also serves as a harsh abrasive to the substrate.

Our system uses an arc-spray system. It is as low cost as a flame system wile avoiding the inherent products of combustion, it is easy to use, and it uses widely available materials (any conductive material that can be drawn into a wire, and welding electrode wire is easily obtained).

The arc-spray gun is arranged as in Figure 2. Two consumable electrode wires are fed through contact tips to the area of the arc. A D.C. power supply establishes an arc between the wires, melting them in the arc. A column of atomizing gas, ranging from 480 kPa to 690 kPa (70 psi to 100 psi) atomizes the molten droplets and carries them, in a spray, to the substrate. For steel systems, the arc is typically at a temperature of 10^4 K [Safai81]. Deposition rates for an arc-spray system range from 1 kg hr^{-1} to 20 kg hr^{-1}.

4. Ferrous Tooling

The essential difficulty in spraying ferrous alloys, or other high temperature melting point alloys, is getting the sprayed material to adhere to the substrate. During tooling manufacture the sprayed shell must remain rigid and in intimate contact with the substrate to assure good dimensional quality and correct shape. After the shell is complete, however, it is best if it easily separates from the pattern; this ideal is rarely achieved in practice. Current practice aids this process by painting or spraying a thin release agent onto the pattern surface, and then spraying down the shell. The release agent most generally used is polyvinyl alcohol. This material holds zinc and zinc alloys with good

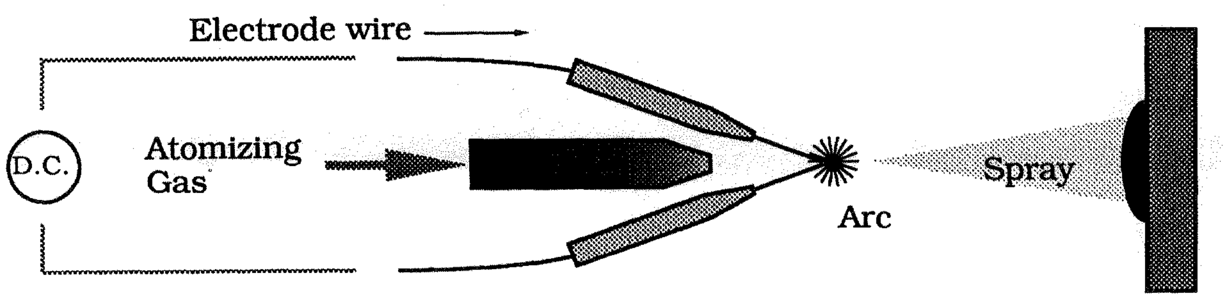


Figure 2: Schematic of Arc-Spray System.

tenacity on a slightly roughened surface, but immediately burns away when sprayed with copper or iron alloys.

Ferrous alloys will initially adhere to ceramic surfaces, graphite surfaces, and a slightly roughened metal surface. After a number of layers have been applied, however, the sprayed material will typically debond from the substrate and peel back. This behavior is different from that of zinc, for low modulus and low melting point of zinc permit thick shells. Induced bending in the sprayed materials is largely, if not completely, driven by thermally induced strain. Each new layer, as it is added to the top surface, changes from a molten state to a solid state and shrinks (for most metals). The layer then cools from the molten point to the ambient temperature. This cooling results in strain. At some point, the induced strain grows to a level that causes failure at the shell-substrate interface.

Finally, the plastic substrates coming from most SFF systems have a substantially larger coefficient of thermal expansion than the sprayed metals. As the temperature rises during spraying, the differential dimension change between substrate and shell causes additional stress at the interface; this promotes debonding.

5. Thick Shells

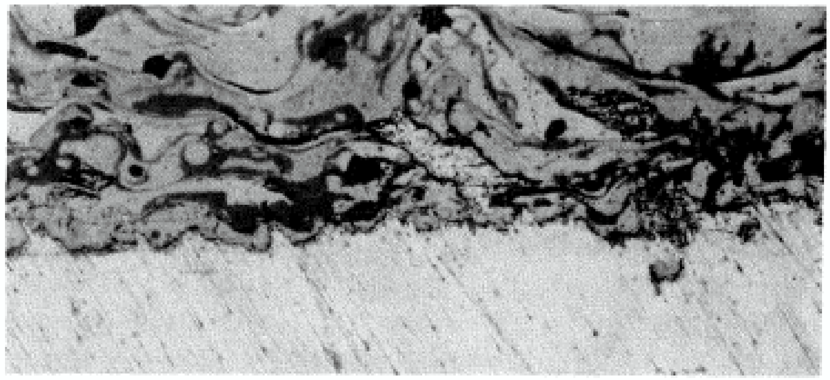
The basic solutions to these problems reported here are centered around finding appropriate substrates with a good surface qualities for adhesion of the sprayed material and a matching coefficient of thermal expansion. Substrate materials which are not currently available with SFF may be transferred from SFF patterns.

An approach showing promise uses a fusible alloy as the substrate material upon which the steel is sprayed. We have been using a cerrometal, a 40% bismuth, 60% tin non-eutectic alloy, with a melting range from 138 C to 170 C. The sprayed steel adheres to the substrate with tenacity; the substrate yields in a ductile manner; and the substrates yield strength is 55 MPa (8000 psi) so it plastically yields as the shell is elastically straining during manufacture.

The tool shown in figure 1 was made using this process.

Figure 3 shows the interface between the sprayed steel shell (1080 (0.8% C) steel in this case) and a cerrometal substrate. The molten particles of steel arrive and melt into the cerrometal; this provides the measure of tenacity between substrate and shell. The surface roughness after removing the cerrometal is seen in Figure 3 as 10 to 15 microns; this is fairly rough for a finished die or mold surface.

Using a fusible alloy as the substrate has permitted shell thicknesses from 1.2 mm (0.048 in) to 1.9 mm (0.075 in). The upper limit, however, is now defined by a residual camber in the shell, not by catastrophic failure of the shell during manufacture; we have sprayed shells as thick as 6 mm (0.24 in).



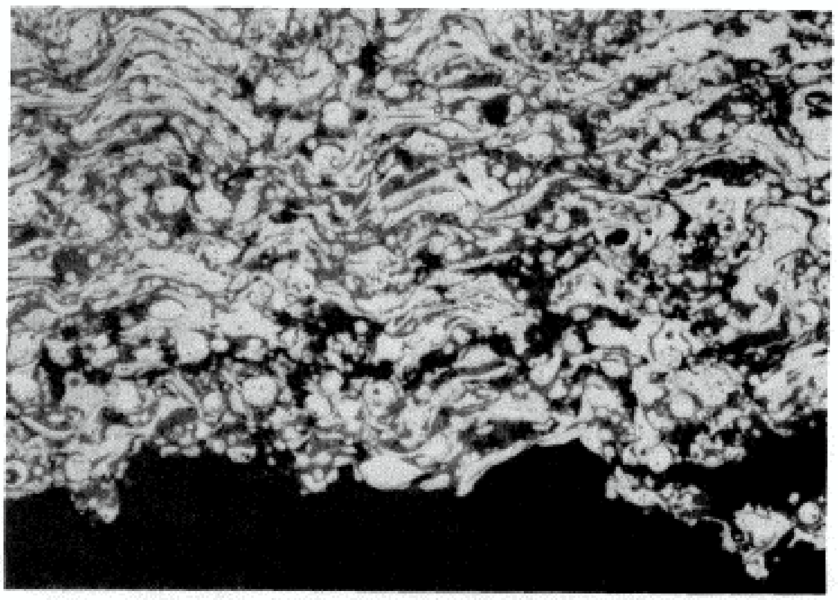
50 μm

Figure 3: Interface between Sprayed Steel and Cerrometal Substrate

After spraying the shell, it is backed with an epoxy or ceramic, and then heated to melt off the cerrometal substrate. The cerrometal and sprayed steel are mechanically bound (as seen in figure 3), so the last film of cerrometal is removed by glass-beading or wicking.

6. Oxide Control

The second principal difficulty in making ferrous tooling is the presence of oxides in the sprayed shell. Molten iron has a high affinity for oxygen and the residence time of the particles in the atomizing air stream is great enough to create considerable oxide. We find the volume oxide levels in sprayed 420 stainless to range from 26% to 31%, when the atomizing gas is air. Figure 4 shows a shell sprayed under these conditions.



100 μm

Figure 4: Typical air sprayed metal coating; dark areas are oxide.

Changing the atomizing and carrier gas to an inert gas such as nitrogen or argon reduces the availability of oxygen for oxidation. In our experiments, sprayed 420 stainless shells, when made with nitrogen atomizing and carrying gas, shows volume oxide levels of 10% to 13%.

A shell with 10% of its composition in an oxide form is still weak in mechanical properties. A simple shroud, backfilled with nitrogen or argon, further reduces the partial pressure of oxygen in the vicinity of the molten particles resulting in an shell oxide content of about 3%.

The best solution for oxide control is to spray the molten material in a chamber with no oxygen present. Figure 5 shows a cross section of the 420 stainless steel sprayed under these conditions; the chamber was evacuated to 3 torr and then backfilled with argon to 500 torr. The defects remaining in the section are only porosity.

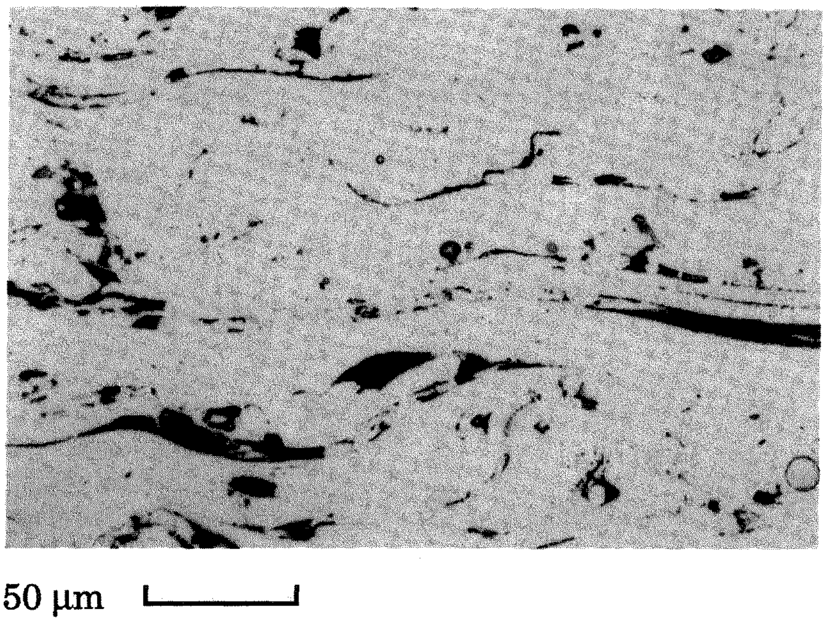


Figure 5: 420 Stainless steel sprayed in Argon atmosphere

We further reduce the oxide level by manipulating the spray process parameters to maximize droplet size (thus reducing the surface to volume ratio). This has the added benefit of increasing the temperature of the molten particles as they arrive at the substrate. An important second order problem (which would become first order if the shell weren't dominated by oxides) is the presence of porosity in the sprayed structure. Our sprayed shells are showing a volume porosity from 1% to 5%. This will affect the shell's performance by greatly reducing their fatigue life. Having particles arrive at the substrate as large molten particles gives them a better chance of splatting out and filling cavities in the surface; this reduces porosity. Complete removal of the porosity, however, will require significant process changes or post process consolidation.

7. Continuing Work

The other challenges in manufacturing successful steel tools are a subject of continuing effort. We are defining our integration environment within a consistent non-manifold geometric modeling system (NOODLES); the environment now includes a primitive design scheme leading to complete process automation including programming of robotic spray torch manipulation. This results in a completely paperless manufacture of tooling.

Dimensional quality is largely driven by the 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 build-up is a subject of keen interest.

Small aspect holes also continue to be a challenge. We are using metal inserts to provide the needed tooling geometries when small aspect holes are mandated by the tool design. More basic research is exploring electrostatic spraying to provide improved flow of the spray into smaller holes and channels.

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