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Three-Dimensional Printing of Metal Parts for Tooling and Other Applications

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Three-Dimensional Printing is a Solid-Freeform Fabrication process that creates parts out of powder by spreading layers into which binder is ink-jet printed to define the part geometry of that layer. By repetition of the process layer-by-layer, three-dimensional components of very complex geometry can be created. This paper describes key aspects of the application of Three-Dimensional Printing to the fabrication of metal tooling where surface finish, dimensional accuracy, wear resistance, and process complexity impose challenging constraints on materials selection and processing.

Keywords : powder metallurgy, three dimensional printing, liquid-metal infiltration, injection molding

1. INTRODUCTION

For over a decade, numerous processes have been developed to enable creation of three-dimensional parts directly from computer-aided design models of those parts. Unlike conventional machining of parts from larger volumes of material, which are *materials subtractive*, a variety of solid-freeform fabrication processes have been devised that create parts by *materials-additive* techniques by assembling smaller bits of material, step-by-step, to build a substantially larger part [1]. The smaller bits can be thin sheets of material such as liquid polymer or paper or thin metal foil, as practiced in stereolithography and laminated object manufacturing. Alternatively, the added material can be particulates such as metal powder or liquid metal droplets that solidify on the surface of the evolving part, as in Three-Dimensional Printing (3DP^{TM}) or Fused Deposition Modelling.

The 3DP process creates a part by spreading thin layers of powder and applying binder with an ink-jet printhead to define the desired cross sectional geometry of the part within each layer [2,3]. The part is made by alternately spreading powder layers and printing the appropriate pattern of binder material, then repeating the process. The process is illustrated schematically in Fig. 1. The part is built at the top of a cylinder containing a piston that can be lowered incrementally, thereby creating a thin volume that is then filled with a layer of powder and smoothed with a roller device. An ink-jet printhead is then rastered over the powder surface, applying binder material in the required pattern. The piston is again lowered incrementally and ready to receive the next powder layer, and the process is repeated until a sufficient number of layers have been created to complete the desired three-dimensional part geometry.

In practice the printing process is speeded up by applying binder through multiple nozzles operating in parallel on a single printhead cartridge. Fig. 2 shows several steps in the printing of a single binder layer using an eight-jet printhead.

At that point, the part consists of a bound geometry of powder that is completely enveloped in loose powder within the cylinder into which powder layers have been spread. By raising the piston the unbound powder falls away from the printed three-dimensional assembly of powder particles. Fig. 3 shows a part emerging from the powder bed in which it was created.

The attributes of three-dimensional printing include:

- The choice of powder material can be suited to the application. Metallic, ceramic, and polymeric powder materials can all be fabricated using 3DP.
- Because the part is produced within a volume that is entirely filled with powder, very complex part geometries can be fabricated, including overhanging structures, trusses, and complex internal passages such as for circulation of a coolant in a molding tool.
- The process of building a "green" part by 3DP is carried out at or very near room temperature and therefore avoids problems associated with residual stresses in the parts.
- The rate at which the part is built is largely a function of

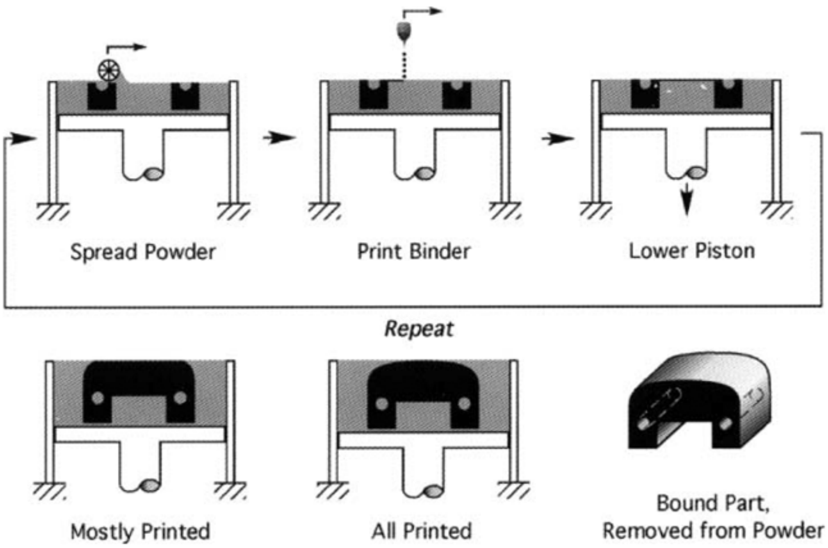


Fig. 1. Illustration of the 3DP process.

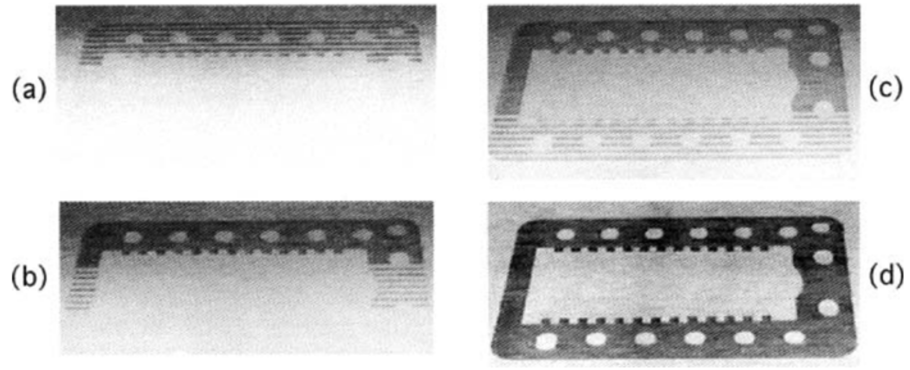


Fig. 2. The four images (a)-(d) show progressive stages of the binder pattern delivered by an eight-jet printhead during the creation of a single layer of a tool. The tool is approximately 20 cm in length. Circular areas where no binder was printed will become coolant passages in the finished tool.

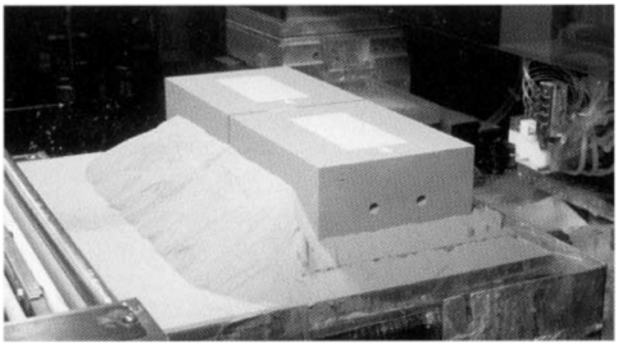


Fig. 3. Parts being removed from powder bed after printing.

the binder printing rate, so, by using multiple binder nozzles, the process can be scaled to print very large parts in a reasonable time.

- Because the printhead delivers material into the part at precisely controlled locations, it is possible to deliver more than one material to the part during the build process. Thus the process has the capability of producing parts with local composition control. This capability could be exploited to produce functionally graded metal parts such as dies with wear-resistant compositions only where needed.

2. IMPLEMENTATION OF 3DP PROCESS TO MAKE INJECTION MOLDING TOOLS

There are two major process components for using three-dimensional printing to make an injection molding tool. First, the tool geometry must be built from powder and binder as described in the previous section. A typical metal part resulting from this stage of the process consists of approximately 60% (by volume) of metal powder, 10% of binder material, and 30% is open porosity. At this stage, we describe the resulting product as a "green part." Typical binders produce green parts with sufficient strength to allow handling the part as required for subsequent processing steps without damaging the part. After removal from the powder bed, the green part is given appropriate thermal treatments to remove any undesirable components of the binder and to allow the formation of interparticle necks that add strength to the part while minimizing dimensional changes. Finally, the part is made fully dense either by sintering or by liquid-metal infiltration.

2.1. Printing metal tools

To fabricate tools with good hardness and wear resistance, we have used gas-atomized 420 stainless steel spherical powder with typical powder diameter of 50 µm. Each layer of powder is spread to 170 µm thickness, and a colloidal latex binder, "Acrysol," is printed to define the part geometry. Binder droplets approximately 80 µm in diameter are formed continuously at a rate of approximately 50 kHz by a printhead nozzle, and the binder droplet trajectory is actively controlled using an electrostatic charging and deflection method. Droplets are placed within 10 µm of the target location. These parameters result in green parts having a minimum feature size of about 100 µm. With an eight-nozzle printhead, a part that is 20 cm×20 cm×10 cm can be built in approximately 8 hours under these conditions.

2.2. Densification of green parts

Parts produced from 3DP have about 40 volume percent open porosity after "burnout" of the polymeric binder. If such parts are sintered to full density they will undergo severe dimensional change (approximately 15% linear shrinkage in each dimension). Because typical tooling demands very high dimensional accuracy, often better than 0.1%, sintering to full density is problematical for densification of large green parts. A better route to densification is liquid-metal infiltration, as the dimensional changes are much smaller.

Liquid-metal infiltration of a porous body places significant constraints on the infiltrant. First, the infiltrant's melting temperature must be below that of the powder material. Second, the components of the powder material cannot be soluble in the infiltrant. Third, the infiltrant should have sufficient strength for the desired application, particularly in tooling applications.

Prior to infiltration, a green part must be heat treated to remove the polymeric binder material and to impart sufficient strength to the part so that gravitational forces and forces arising from the infiltration itself do not lead to distortion of the part geometry. A high-temperature treatment in a reducing atmosphere is used to break down the binder and simultaneously lightly sinter the metal particles together. For 420 stainless steel powder this treatment consisted of heating to 1250°C for 45 minutes in 95% Ar/5% H_2 forming gas, resulting in approximately 2% linear shrinkage and satisfactory strength for subsequent infiltration with liquid metal infiltrant.

A suitable infiltrant for green parts made from 420 stainless steel powder is Cu-10 wt. pct. Sn bronze. This alloy has only a small solubility for Fe and our results show very good retention of powder integrity after infiltration treatment for 5 to 30 minutes at an infiltration temperature of 1110°C in forming gas. There is some indication of grain boundary grooving of powder particles, however, and electron microprobe analysis of the infiltrated regions indicates an iron content of about 3 wt. pct., consistent with iron saturation of the infiltrant.

2.3. 420/10% Sn bronze properties

The 420 steel/10% Sn bronze material processed as described above results in tools comprised of very hard steel particles (Vickers microhardness values HV of approximately 700) in a relatively soft bronze matrix (HV approximately 150). Rockwell hardness of the material after furnace cooling from the infiltration temperature is approximately 30 (R_C). Room temperature tensile strength and elongation is typically 700 MPa and 5%, respectively. In spite of the relatively low macrohardness compared with typical tool steels (R_C 40 and above), the wear performance of the 420 steel/10% Sn bronze tools is excellent. The infiltrated 3DP parts are weldable and can be electroplated.

3. DIMENSIONAL ACCURACY FOR TOOLING

Because of the extremely high binder droplet placement accuracy that can be achieved with 3DP, the as-printed dimensions of the green parts can be held to very high tolerances. Additional processing is needed to bring a part to full density, and these subsequent processing steps lead to dimensional inaccuracies. These processing steps typically result in approximately 2% linear shrinkage in the debinding/sintering step, and about 0.3% linear expansion during infiltration. The resulting total dimensional change of about 1.7% linear shrinkage is easily compensated by adjustment of the printing process to make the green part 1.7% larger than the target finish dimensions. Thus, the principal obstacle for dimensional accuracy in the final tool is the *variation* of dimensional changes, not the magnitude of the overall changes.

Through careful documentation of our experience in printing and infiltrating 18 tools of varying geometries, we have demonstrated that the 3DP process described here is capable of consistently making tooling parts to within about 0.2% of the desired dimensions. Our accumulated results for these 18 tools are shown in Fig. 4.

4. OPPORTUNITIES FOR THERMAL MANAGEMENT IN TOOLING MADE BY 3DP

Thermal management in tooling is often the factor that lim-

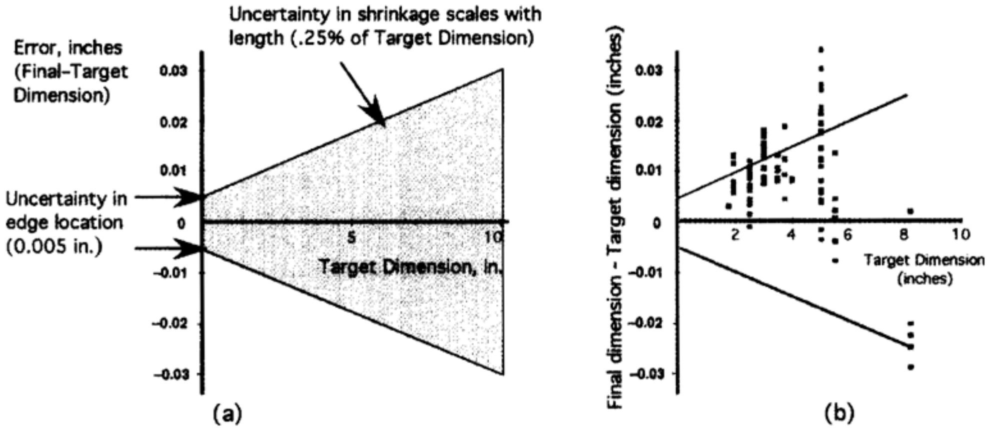


Fig. 4. (a) Predicted scatter band on 3DP tooling dimensional accuracy. (b) Comparison of actual dimension with target dimension for 18 tools fabricated by 3DP. Band shown is for ±0.25% variation. 81 of 107 measurements are within the target band.

its the production rates that can be achieved with the tool. The conventional method of thermal management in a complex tool is to add cylindrical cooling channels to the tool by drilling intersecting through-holes and plugging them appropriately so as to result in a continuous circuit for the flow of coolant through the passageway. Because the 3DP process is materials additive, it is possible to incorporate continuous passageways of highly complex form into the part while it is being built. Because the passageways do not need to be comprised of discrete straight segments, it is possible to locate the cooling passages so as to optimize the thermal performance of the tool. Thus it is possible to design the number, cross section, and precise placement of each cooling channel appropriate to the cavity geometry in the tool. In complex tools, the most ideal placement can maintain a specified distance from the tool cavity, thus leading to smoothly curved trajectories of the cooling circuits. An example of a conformal cooling design in an industrial tool with relatively simple geometry is shown in Fig. 5.

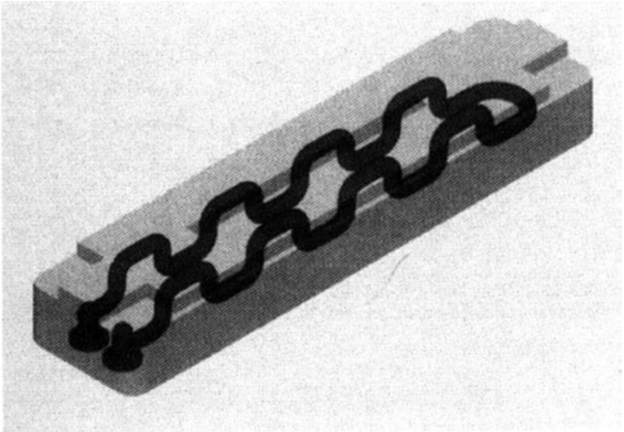


Fig. 5. Conformal cooling design for a manufacturer's production injection molding tool. 3DP was used to create a tool with the conformal cooling channel and its performance was compared with the production tool.

Such *conformal cooling* designs have proven to result in significant enhancements of the performance of production tooling. Conformal cooling reduced part distortion by 37% in the tool shown in Fig. 5. When the tool with conformal cooling was run with a 15% decrease in cycle time, it still showed a 9% reduction in distortion of plastic parts molded from the tool.

5. DEVELOPMENT OF ALTERNATIVE MATERIALS SYSTEMS FOR METAL PARTS

The powder material, binder, and infiltrant comprise a *materials system* for 3DP tooling. Each component of the materials system must work together to produce parts with the desired properties. Higher dimensional accuracy, higher strength, and the potential for compositional homogeneity in the final parts can be achieved by developing alternative materials systems.

5.1. Binders

The Acrysol polymeric binder used to bind 420 stainless steel powder is "burned out" of the green part as the powder begins to sinter. Because the infiltration process relies on having strong interparticle joints, sintering is essential to the success of the process. Sintering is the process step that produces the majority of the dimensional change during processing to full density. We have developed alternative binder materials, called *reactive binders*, that can virtually eliminate the large shrinkage required to gain sufficient strength by sintering. A variety of metal salt solutions have been studied, with the objective of printing an aqueous solution of the salt into the powder bed, then using a low-temperature treatment of the entire powder bed (containing the printed part) in a reducing atmosphere, such that the salt solution is reduced and leaves behind reduced metal that forms interparticle necks. In this

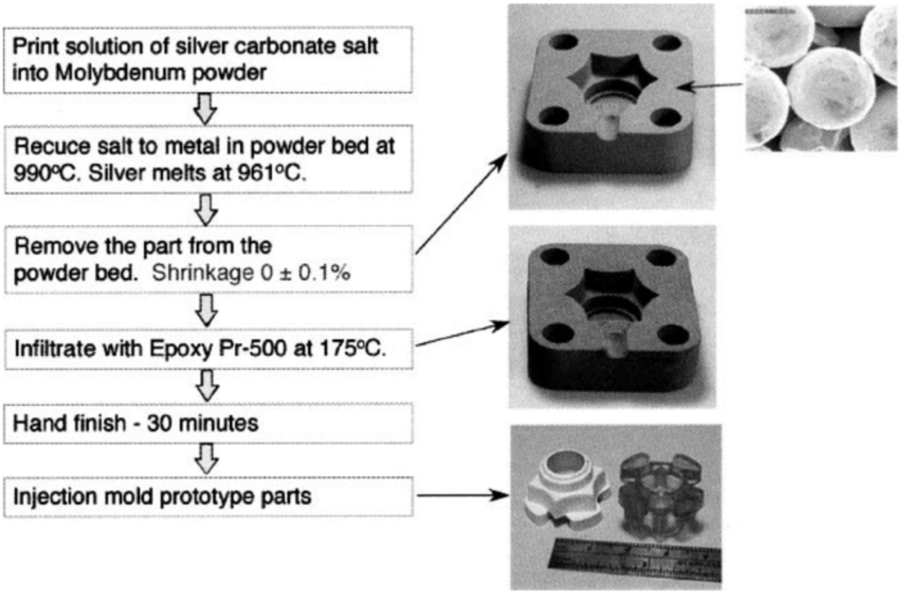


Fig. 6. Processing route for low-shrinkage, high dimensional accuracy tool produced using silver carbonate as a reactive binder for molybdenum powder. The salt was reduced at 990°C, thus melting the silver and having it pulled to the interparticle necks by capillary action. Shrinkage of the part was less than 0.1%.

way the necks gain strength without center-to-center motion of the powder particles and the shrinkage. Fig. 6 details an implementation of the process and shows injection molded prototype parts made from the tool.

The use of reactive binder materials places additional restrictions on the powders and infiltrants that are compatible. The reduction treatment needs to impart sufficient strength to the parts of the powder bed to which binder was applied, but not result in any binding of the remaining powder (so that the printed part can be retrieved from the powder bed after the reduction treatment). Furthermore, the subsequent infiltration treatment must not degrade the strength of the interparticle necks. We have not yet succeeded in finding a suitable metallic infiltrant for silver-bound molybdenum powder parts, but the epoxy infiltrated part shown in Fig. 6 was sufficiently robust to successfully injection mold prototype plastic parts.

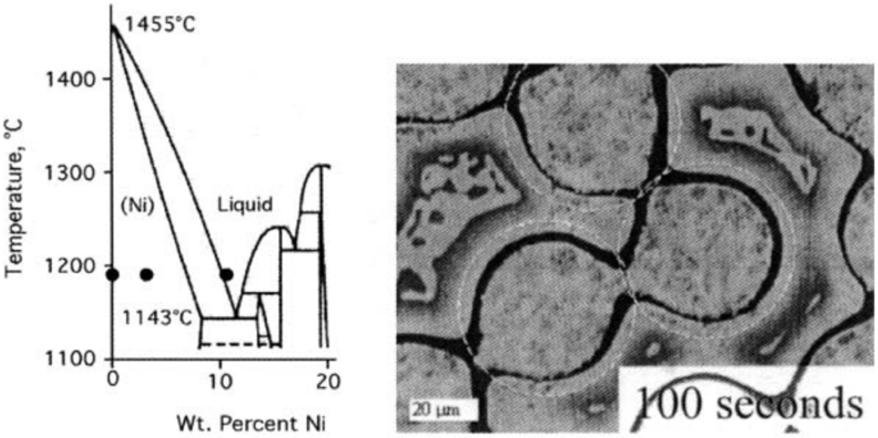
5.2. Powders and infiltrants

The 420/10% Sn bronze materials system has lower hardness than tool steels that are typically used in injection mold tooling, largely because of the relatively low strength of the Sn-bronze infiltrant. Alternative copper-base infiltrants that are age hardenable have been studied using both thermodynamic calculations of phase equilibria and experiments to look at powder/infiltrant interactions. Cu-Ni-Sn spinodal alloys were studied with a wide variety of powder alloys and, although the infiltration performance was adequate, there is a very strong tendency for Ni to diffuse from the infiltrant to the powder particles. The resulting infiltrated regions contained insufficient amounts of Ni to have significant age-hardening response.

Better results were obtained by infiltrating refractory metal powder with age-hardenable copper alloys. Tools with final macrohardness in the range 35-40 R_C were successfully made using Acrysol binder in molybdenum powder, and infiltrating with a Cu-20 Ni-20 Mn alloy (wt. pct.). After infiltration, tools made from these materials are relatively soft and machinable by conventional methods; full hardness is obtained by solution treatment and ageing after machining. A disadvantage of this materials system (and of any based on refractory metal powder) is the relatively poor machinability characteristics when electro-discharge machining is used.

5.3. Homogenizing infiltration

All of the materials systems and processing described above use powders and infiltrants that are relatively unreactive, and thus the tools made with these materials are necessarily composites. While this may have some benefits for strength and wear resistance, parts with compositions that are homogeneous would be less susceptible to galvanic corrosion, and would be more likely to gain user acceptance as direct replacements for conventional tool steel parts. Sintering a green part to full density would produce a compositionally homogeneous part, but it is unlikely that this could be achieved without loss of dimensional accuracy. An alternative is to use a liquid-metal infiltrant with the same base-metal component as the powder alloy, and including a fast-diffusing melting-point depressant. As long as the infiltration kinetics are rapid relative to the redistribution kinetics of the melting-point depressant, it will be possible to bring the green



(a) (b)

Fig. 7. Homogmizing infiltration of Ni powder can be performed with Ni-10% Si alloy. (a) Phase diagram for Ni-Si alloys, showing compositions of Ni powder (0%), Ni-Si infiltrant (10%) and resulting homogenized composition (4%). (b) Scanning electron micrograph of structure formed after infiltrating 50 µm Ni wires with Ni-10% Si alloy for 100 s. Dashed circles show initial diameter on Ni wires. The specimen was mostly solidified when it was quenched.

part to full density with good dimensional accuracy. By holding the part at the infiltration temperature for a suitable time, the melting-point depressant can diffuse into the powder material and result in a compositionally homogeneous final part.

This process has been demonstrated with nickel powder and a Ni-10% Si infiltrant. Fig. 7(a) shows the Ni-rich portion of the Ni-Si equilibrium diagram. The high liquidus slope for the Si addition is desirable because it results in a large melting point difference between the Ni powder and the Ni-Si alloy infiltrant. If infiltration is carried out at the liquidus temperature of the infiltrant (1190°C in this example), dissolution of the Ni powder can be avoided. Furthermore, because Si is a relatively fast diffuser in Ni, holding the infiltrated sample at the infiltration temperature for sufficient time will result in *isothermal solidification* of the part as the Si diffuses out of the infiltrant and into the Ni powder. The resulting part composition depends on the relative volumes of powder and infiltrant; in the example shown here, the final part composition would be approximately 4% Si.

Cylindrical test specimens of sintered Ni powder have been fully infiltrated with Ni-10% Si at 1190°C to a height in excess of 20 cm using this method. Infiltration, solidification, and homogenization kinetics are under investigation, and mechanical properties of the resulting material are being characterized.

6. CONCLUSIONS

Three-Dimensional Printing of metal tooling for plastic injection molding tools has numerous advantages, including short fabrication time, good dimensional control, and the ability to incorporate complex structural features such as conformal cooling channels. At present, the high dimensional accuracy that is generally required for tooling can only be obtained by liquid-metal infiltration of debound and lightly sintered green parts. This places challenging constraints on powder/binder/infiltrant combinations for 3DP tooling. Very good properties and performance can be obtained using tool steel powder and bronze infiltrants; improved macrohardness can be achieved using refractory metal powders and age-hardenable copper alloy infiltrants. Promising results have been obtained by using infiltrants that contain melting-point depressants that are relatively fast diffusers, because they provide a possible route to producing 3DP tools that are compositionally homogeneous.

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