METAL PARTS GENERATION BY THREE DIMENSIONAL PRINTING

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Abstract

Three Dimensional Printing is a rapid prototyping process in which powdered materials are deposited in layers and selectively joined with binder from an ink-jet style printhead. Unbound powder is removed upon process completion, leaving a three dimensional part. Stainless steel and tungsten parts have been created from metal powder with the 3DP process. The parts have green properties similar to those produced by metal injection molding. A tooling insert made from 316L stainless steel powder was used to injection mold a polypropylene part. The 3DP process is easily adaptable to a variety of materials systems, allowing the production of metallic/ceramic parts with novel compositions. This paper will discuss the use of the 3DP process to produce injection molding tooling and end-use parts.

Introduction

Metal parts to be used as end-use parts and injection molding tooling inserts have been made using the 3DP process. This paper describes a process where 316L stainless steel powder is selectively bound with a latex emulsion binder using the 3DP process, producing a green part with strength comparable to parts produced by metal injection molding (MIM). A series of post-processing steps similar to those found in powder metallurgy processing were used to obtain an all-metal part which was then used as a tooling insert to injection mold a polypropylene part.

The 3DP Process

Three Dimensional Printing (3DP) is a process for the rapid fabrication of three dimensional parts directly from computer models [1] . A solid object is created by printing a sequence of two-dimensional layers. The creation of each layer involves the spreading of a thin layer of powdered material followed by the selective joining of powder in the layer by ink-jet printing of a binder material. A continuous-jet printhead is raster scanned over each layer of powder using a computer controlled stepper motor driven x-y table. Individual lines are stitched together to form 2D layers, and the layers are stitched together to form a 3D part. The printing nozzle has a circular opening 46 μm in diameter. The nozzle is stimulated by a piezoelectric transducer vibrating at 60 kHz to break the stream into droplets 80 μm in diameter. Commands to modulate the binder stream are derived from CAD data. The powder bed is lowered at the completion of each layer by lowering the bottom of the rectangular cylinder which contains the bed. Figure 1 is a drawing of the 3DP system. Unbound powder temporarily supports unconnected portions of the component, allowing overhangs, undercuts and internal volumes to be created. The unbound powder is removed upon process completion, leaving the finished part.

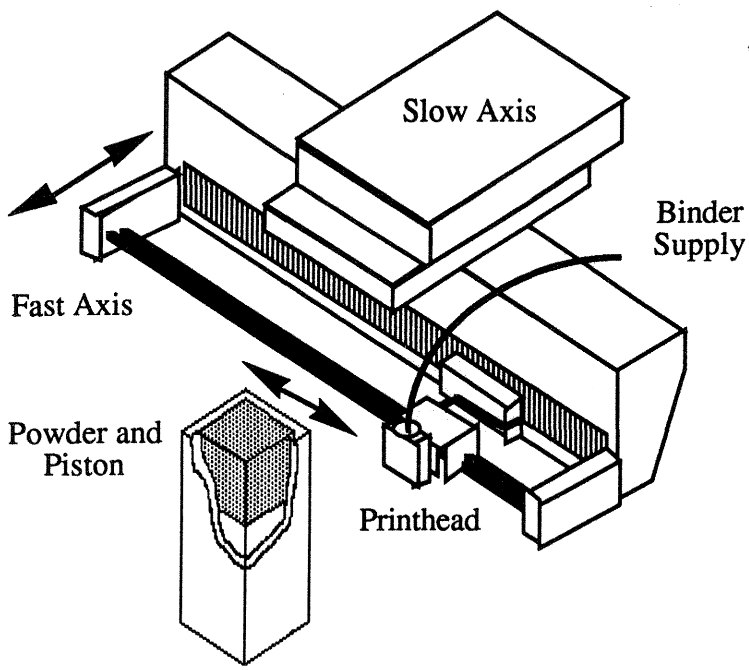

Figure 1. The 3DP System.

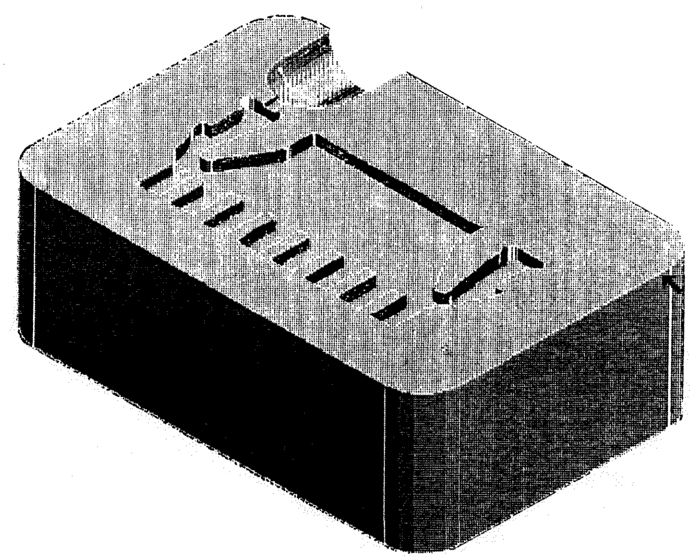

Figure 2. CAD Rendering of an Injection Molding Tooling Insert.

Printing a Stainless Steel Part

The overall process to create a metal part can be divided into several steps. First, the green part is printed using the 3DP system by using a temporary organic binder. The part is processed using techniques similar to those used in MIM. The organic binder thermally decomposes in an inert gas furnace. Subsequent firing at high temperature sinters the part and increases its strength. Firing schedules can be devised to densify the component or increase the particle-particle bonding without densification. Figure 2 is a CAD drawing of the part printed in these experiments. Only the top portion of this part was printed in order to reduce printing time.

3D Printing

The powder used in these experiments was a 316L spherical stainless steel powder with a size range of 15 - 30 μm [2]. This powder exhibited a typical packing density of 57% when spread into layers during the 3DP process. The thickness of each layer was 175 μm in all the experiments.

An aqueous acrylic copolymer emulsion was used as the binder [3]. This emulsion is self-crosslinking and cures by drying in air to form a high durometer solid. The binder was diluted with water to 25% acrylic solids by weight. The binder was filtered through 1.2 μm capsule filters under pressure before then passing through the printhead. Total flowrate was 1.2 cc/minute. The individual printed lines which are stitched together to form each layer were spaced 175 μm apart. Preliminary experiments showed that proper choice of flowrate and binder dilution yielded parts with high strength and stiffness while still being easy to print.

Initial attempts at printing with this combination of powder and binder were unsuccessful because of significant particle rearrangement. The binder stream cut a large trench into the powder surface upon impact and capillary action would then draw the powder up into large agglomerates. Figure 3 is a strobe photograph of this impact effect. The printhead, not visible in the photograph, is traveling right to left. Ejected powder can be observed on the powder surface over an area as wide as 5 mm.

Several methods were tried to give the powder surface enough cohesive strength to resist deformation during printing. First, the entire powder layer surface was sprayed with water from an ultrasonic sprayer prior to printing in order to bind the layer together via capillary tension. The desired cohesive strength was obtained, but the presence of moisture in the top layer of powder greatly enhanced transport of the binder material in the powder bed. The resulting binder "bleeding" caused a complete loss of edge definition in each printed layer and produced an unacceptable part.

The final solution was to pretreat the metal powder with a thin coating of metal salt. A slurry composed of metal powder and dilute aqueous salt solution was blended, dried and sieved to create the coated powder. During the printing process, a layer of treated powder was spread, misted with ultrasonic water mist and dried with forced hot air. The presence of the metal salt significantly increased the cohesive strength of the layer. Presumably, the metal salt on the powder surface recrystallized during wetting and drying, forming interparticle bonds which were strong enough to resist binder stream impact and the subsequent interparticle capillary forces. Less than 0.05 weight % salt (based on final part weight) was required to achieve this cohesive effect. Figure 4 shows the dramatic improvement which the powder surface locking process has on the printing process.

The entire powder bed was placed in an oven after completion of the printing process and fired at 100°C for one hour to completely cure the acrylic binder. The green part was then removed from the powder bed. Salt bonded material is extremely weak compared to the polymer bonds in the green part. Thus, the remaining attached powder was easily blown off with compressed air. Excess powder was sieved and reused.

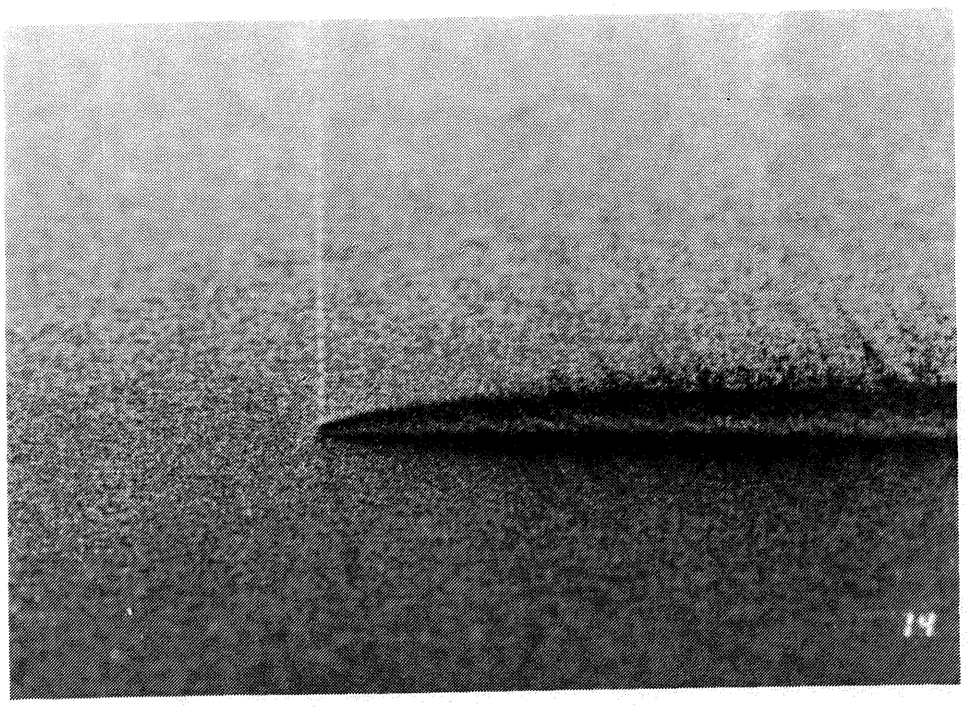

Figure 3. Printing Into Untreated Stainless Steel Powder.

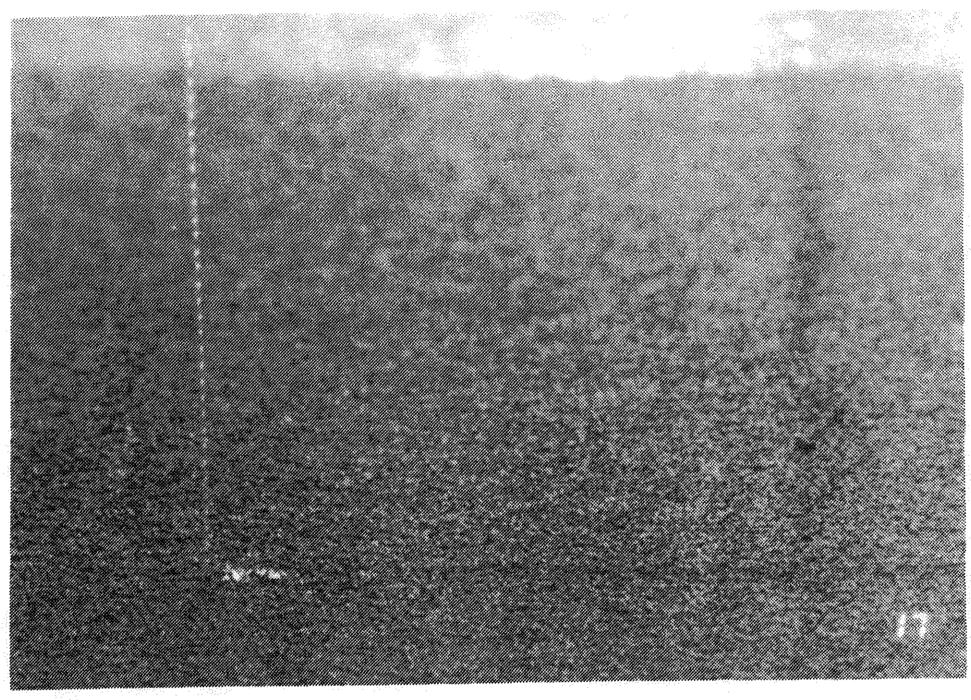

Figure 4. Printing Into Stainless Steel Powder Treated with Metal Salt.

Debinding

Binder was removed from the green part by thermal decomposition in an inert gas tube furnace [4] . The binder polymer chains are broken by heating during thermal decomposition and the binder is evolved as a gaseous product. Binder removal from 3DP parts is similar to debinding of MIM parts but is inherently faster because less binder is required in the 3DP process. A typical 3DP green part is 10% by volume binder, leaving approximately 30% open porosity. MIM parts, being solid metal/binder composites with little open porosity, must be debound very slowly to prevent the formation of internal gas pockets which can rupture the part. No such limitation exists for 3D Printed parts.

Debinding was done in an argon atmosphere tube furnace. Parts were heated to 400°C to burn out the acrylic binder, followed by firing at 1000°C to provide the skeleton with sufficient strength to be handled after debinding. A typical debinding process requires six hours. Upon completion of the debinding process, parts exhibited dimensional change of +/- 0.2% along the x and y axes and up to +2% in the z axis. (The x axis is along the printed line, the y axis is across the printed line, and the z axis is across the printed layers.)

Sintering

Metal skeletons have sufficient strength to be handled after the debinding step described above. Tooling inserts were, however, sintered to higher density. Various firing schedules were used to obtain parts with final densities between 65% and 92% of theoretical. Figure 5 is a photograph of a green and sintered part. In this case, the part had been sintered to 78% of theoretical density, resulting in obvious shrinkage.

Injection Molding

A 3DP part was used to demonstrate plastic injection molding from a SFF generated die. The 3DP part was machined to fit into an aluminum runner assembly block and installed into an Engel EC88, 25 ton injection molding machine located at MIT. The mating half of the mold was a simple cavity cut into an aluminum block which gave the injection molded part additional thickness and strength.

Approximately 40 polypropylene parts were injection molded. Melt temperature and pressure were 230°C and 1200 psi, respectively. Figure 6 is a photograph of the tooling insert and injection molded part. Part removal from the 3D printed mold was made difficult due to the absence of knockout pins in the mold, the lack of draft angle in the mold features, and the relatively rough finish of the infiltrated mold surface. These factors contributed to the rough finish on the plastic parts.

Economics

The green parts produced by the 3DP process can be compared directly to those produced by metal injection molding. In both cases, green parts are approximately 60 vol. % metal, held together with a polymeric binder. The most important cost associated with MIM is that of the hard tooling required for each part. The analogous cost in 3D printing is the 3D printing machine itself. The 3DP machine is, however, a universal tool capable of producing any shape. A calculation of the tooling cost associated with 3D printing reveals the economic feasibility of producing end-use 3D printed metal parts. A production capacity 3D printing machine has an estimated price of $200,000. Over a 20,000 hour service life, an additional $50,000 would be spent on maintenance and operating costs. The powder printing surface on such a machine might typically measure 30 cm x 30 cm. The vertical build rate for a 32 nozzle printhead would be 2.5 cm per hour. Many small parts distributed throughout the powder bed could be printed simultaneously. Over 140 green parts with overall dimensions of 2.5 cm x 2.5 cm x 2.5 cm could be

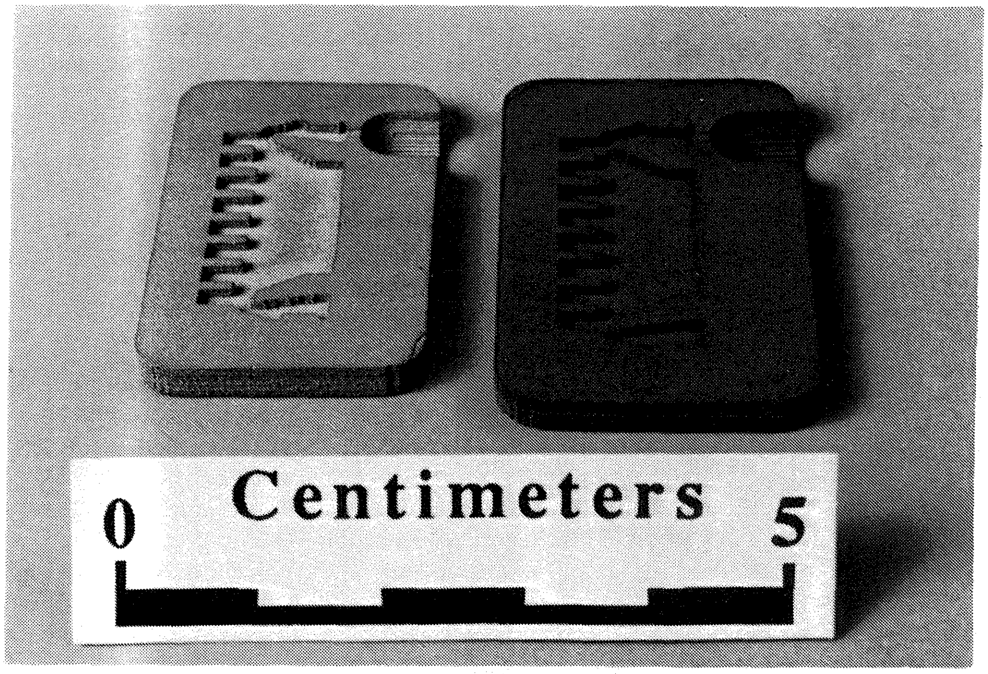

Figure 5. A 3D Printed Part Sintered to 78% Density (left) and a Green Part (right).

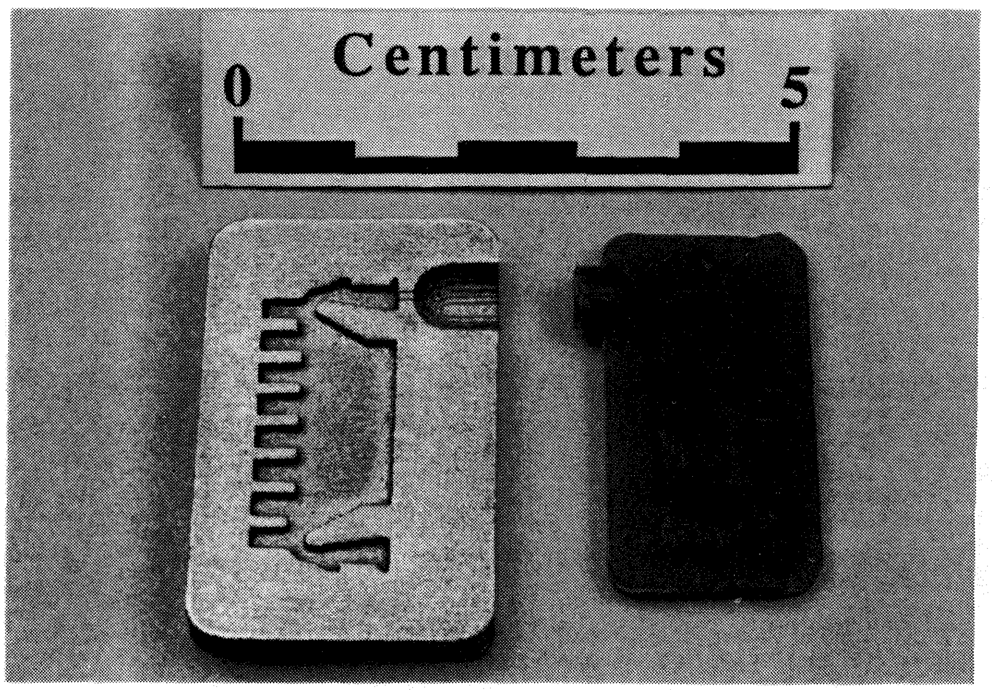

Figure 6. A Tooling Insert and an Injection Molded Polypropylene Part.

printed together, requiring an hour to produce one "layer" of parts. The associated tooling cost per part would be $ 0.09. A MIM mold to produce the same part would cost approximately $50,000. In this case, 3D printing can economically compete with metal injection molding in batch sizes of up to 500,000 parts.

The rough estimate above demonstrates that the 3DP process is a viable method for metal part production. An important aspect of this analysis, however, is that there is no minimum batch size associated with the 3DP process. Batches of 10 or 10,000 all have the same tooling cost . Most importantly, the "tool" can be redesigned as quickly as new CAD information can be downloaded.

Conclusions

3D printing has the capability to produce a wide variety of complex metal parts to be used as tooling and end-use parts. In addition, nearly any material system which can be provided in powder form can be used in the 3DP process to produce parts with novel material compositions. To date, green parts have been printed with iron, stainless steel, tungsten, tungsten/nickel alloy, tungsten carbide and tungsten carbide/cobalt alloy.

Areas of future work include an investigation of the parameters related to part dimensional accuracy, surface finish and material properties. Methods for increasing the green density of as-printed parts need to be in investigated. A better understanding of the ballistic interaction of the binder stream and the powder layer is needed, as well as new methods for preventing powder rearrangement during the printing process.

References

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