Three Dimensional Printing: Rapid Tooling and Prototypes Directly from CAD Representation

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ABSTRACT

A process called Three Dimensional Printing is being developed for the direct manufacture of tooling and functional prototypes from computer models. Three Dimensional Printing functions by the deposition of powdered material in thin layers and the selective binding of the powder using a technology similar to ink-jet printing. Following the sequential formation of all layers, unbound powder is removed, leaving a three dimensional part. The initial applications of the process are to the fabrication of ceramic molds and cores for metal casting and to the fabrication of ceramic preforms for infiltration to become metal matrix composites.

Equipment has been built which transports a modulated single nozzle printhead over a powder bed in a raster scan using a computer controlled x-y transport. The powder bed is contained in a stepper motor driven piston and cylinder. Ceramic parts have been printed using alumina powder and colloidal silica as the binder material. Printed geometries include vertical walls which are approximately 200 μm wide and 6 mm high, rectilinear solids with overall dimensions of approximately 40 mm x 40 mm x 15 mm, and airfoil shaped parts which have contoured surfaces and internal geometry. Parts of both the rectilinear solid type and the airfoil type have been used as cores for the investment casting of nickel super-alloy parts.

Part strength is in a range (maximum bending stress 12.3 to 18.7 MPa) suitable for investment casting. Part to part dimensional control was ± 20 μm on a dimension of 38 mm, and dimensional variation along the length of an individual part was approximately ± 13 μm on a 38 mm dimension.

INTRODUCTION

Industrial productivity and competitive success depend on fast, efficient product development technologies. The flexible manufacture of tooling and mechanical prototypes can greatly reduce the time required for bringing a product to market. Tooling frequently dominates manufacturing time and cost, thereby determining the minimum economic batch size for a given process. Tooling can be extremely complex and is generally one-of-a-kind, requiring much human attention to detail. As a result, fabrication of tooling for such processes as injection molding or lost wax casting, commonly requires several months of work. Three Dimensional Printing offers an alternative to conventional options which do not adequately answer the demands for rapid prototyping and speedy, low-cost production of tooling.

Process Description

Three Dimensional Printing is a manufacturing process for the rapid production of three-dimensional parts directly from computer models. This process creates an solid object by printing sequential two-dimensional layers. Each layer begins with a thin distribution of powder spread over a the surface of a powder bed. From a computer model of the desired part, a slicing algorithm draws detailed information for every layer. Using a technology similar to ink-jet printing, selective application of a binder material joins particles where the object is to be formed. An piston that supports the powder bed and the part in progress lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed. Following a heat treatment, unbound powder is removed, leaving the fabricated part. The sequence of operations is depicted in Figure 1.

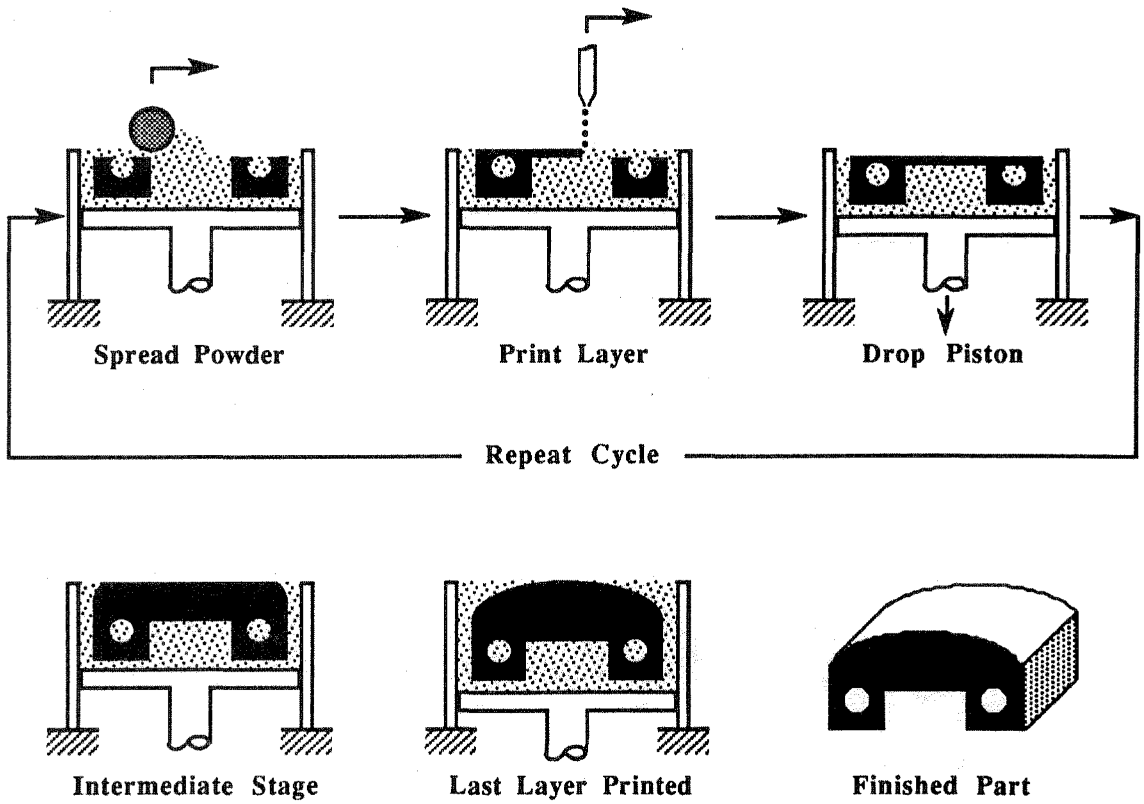

Figure 1. Three Dimensional Printing Process.

Related Work

Recently there has been much interest in the direct fabrication of three-dimensional parts from CAD files without part-specific tooling. Such processes are often referred to as desktop manufacturing, in analogy to desktop publishing. Examples of different approaches include directed photo-chemical alteration of a liquid, powder sintering, and selective addition of material to an existing surface.

Stereolithography is the most commercially advanced desktop manufacturing process [1]. In stereolithography, a focused UV laser vector-scans the top of a liquid polymer bath. The laser polymerizes selected areas on the liquid surface, resulting in the addition of a solid layer to the top of the part being created. The part is lowered into the bath so that the most recently created layer is slightly below the surface of the liquid. The liquid environment requires that overhangs and undercuts be accommodated by support structures, which must be removed later by machining. In order to minimize total process time, only a fraction of the part interior is hardened by the laser and the remainder is post-cured in a UV "oven", resulting in some part warpage. A fundamental limitation is that stereolithography only applies to polymers that may be photopolymerized.

A system called Solider [2] also uses a photopolymerizable liquid. A high-power mercury lamp is used instead of a laser, allowing the part interior to be fully cured during the process, and a photomask determines which portions of each layer is hardened. The non-cured regions of binder are wiped off, and the layer is filled and machined flat in preparation for a new layer.

Selective Laser Sintering (SLS) uses a high-powered laser to sinter chosen regions of a powder layer [3]. Plastic powders are being used initially, but wax, metal, and ceramic powders are also being investigated as candidate materials.

Laminated Object Manufacturing is a material-additive approach that cuts foils or sheets using a laser and stacks them to form a three-dimensional part [4, 5]. The layers are either glued or welded together. In a material-additive system known as Ballistic Particle Manufacturing, ink-jet printed particles build up an object from a central seed [6]. This process is different than the others described in that it does not use sequential flat layers.

APPLICATIONS

Three Dimensional Printing technology applies to a wide variety of substances, including ceramic, metal, metal-ceramic composite and polymeric materials. Investigation to date has focused on the use of ceramic powders for the following applications:

- Direct fabrication of ceramic cores and shells for metal casting.
- Direct fabrication of porous ceramic preforms, which when infiltrated by liquid metal will form metal-ceramic composite parts.

Metal Casting

In current practice, complex, high precision castings are made by lost-wax (also called investment) casting [7]. The process begins with the fabrication of an aluminum die (usually made by electric discharge machining), which is used to mold wax positives of the part to be cast. The wax positives are then made by a process resembling transfer molding. If the part is to have internal voids, a second tool must be made to mold ceramic cores. The cores are inserted into the wax positives as they are molded. The positives with cores are then connected by hand with wax runner branches to form a tree. The tree is then dipped repeatedly into ceramic slurries with a drying cycle between each dipping operation. Following a final dry, the wax is melted and burned out of the shell mold, which is then finally ready for casting.

Production of the dies used for making cores and wax positives is extremely costly and time-consuming. The dies must be fabricated from many parts and require side actions in order to mold undercuts and other complex features. The dies for the wax positives can be made from aluminum, but those used for the abrasive ceramic cores must be made of hard materials such as metal carbide. The cost for any die set is dependent on the size and complexity of the part, but a typical range would be $5,000 to $50,000. The one-of-a-kind nature of the dies also results in long lead times from 4 to 20 weeks.

Three Dimensional Printing can have a significant impact on the economics of small and moderate scale production of cast parts. By printing cores and shells directly, 3D Printing virtually eliminates initial tooling costs, thus making prototyping and small production runs economically feasible. Furthermore, 3D Printing bypasses the long time delay in waiting for die sets to be produced.

Parts fabricated by 3D Printing can be applied to metal casting in a variety of ways. Directly printed cores can be insert molded into conventional wax patterns followed by conventional shell building and casting. Ceramic shell molds can be fabricated directly to final shape without the need for wax positives. Printing integral shells and cores would provide the greatest cost and time savings, as illustrated in Figure 2.

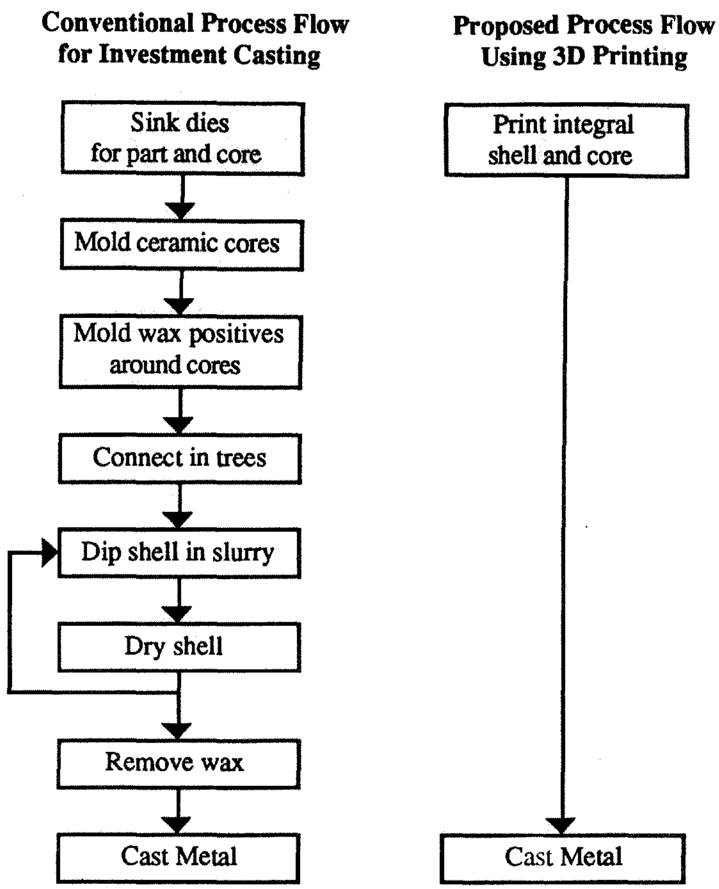

Figure 2. 3D Printing Process Savings for Metal Casting

Metal Matrix Composite Preforms

A particularly attractive method for the manufacture of metal matrix composite parts is "pressure infiltration". The process begins with the manufacture of a porous ceramic preform of the desired final shape. The preform is then infiltrated by liquid metal under a pressure gradient to form the composite part. Compared to other composite fabrication techniques, pressure infiltration offers the advantage of good control over the uniformity and placement of the ceramic particles.

Metal matrix composites often offer superior cost and performance over materials uses in many current applications. However, the difficulty of fabricating prototypes and small production runs often results in the dismissal of composites, in spite of their favorable performance. A typical example is in the area of packages for electronic devices. Electronic packaging materials are required to allow thermal dissipation, to minimize the thermal geometric stresses, and to be lightweight (especially for avionic applications). Kovar, the traditional material of choice, is far from ideal because it has low thermal conductivity and high mass density. Metal matrix composites offer tremendous potential for this application. Aluminum/silicon carbide composites can be tailored nearly match the coefficients of thermal expansion of gallium-arsenic and alumina substrates while having a higher thermal conductivity, lower density, and lower materials cost than Kovar.

Using Three Dimensional Printing to fabricate metal matrix composite preforms, prototypes and small-scale production runs can be made with application-specific geometry and material properties, such as particle density and coefficient of thermal expansion. This flexibility should allow for metal matrix composites to displace inferior materials and to penetrate new markets.

OBJECTIVE

Central goals of Three Dimensional Printing which have directed research in the areas of engineering design, sample part fabrication, and physical properties analysis, are as follows:

- Developing the technologies required to fabricate parts at the production level.
- Demonstrating the utility of the process for industrial application, especially in the areas of metal casting and metal-matrix composite pre-forms
- Understanding and controlling the physical and chemical parameters that produce parts suitable for intended applications.

EQUIPMENT

Parts are printed using the system illustrated in Figure 3.

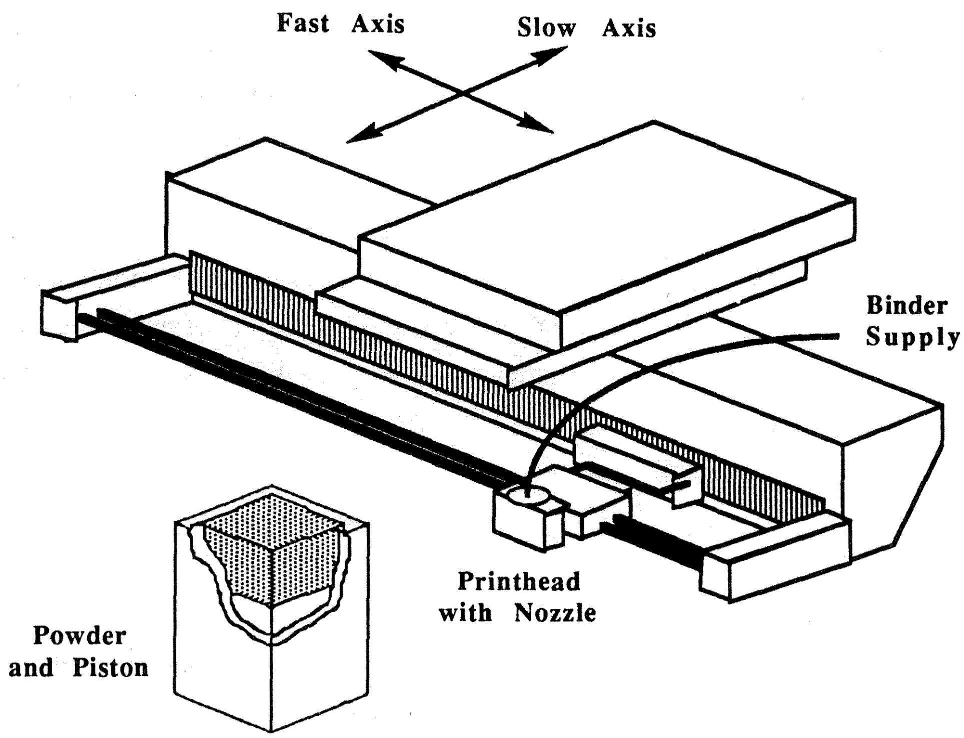

Figure 3. Three Dimensional Printing Machine

Positioning

A positioning mechanism has been implemented which makes possible a computer-controlled raster-scan over the powder bed. The system includes a linear stepper motor (Northern Magnetics, Inc., Van Nuys, CA), a lead-screw table and rotary stepper (D.C.I., Franklin, MA), and a two-axis controller (DCI-1000). The printing nozzle is mounted on a linear bearing carriage driven by a linear stepper motor, which travels on an air bearing along a 0.81 m long platen. The platen is mounted on its side on a stiff aluminum bracket which is bolted to the lead-screw table. The table is referenced to the fixed position of the powder bed.

The design of the linear stepper or "fast axis" was chosen to provide speeds of 2.5 m/s over a 0.30 m x 0.30 m work space. The step size of 13 μm corresponds to the feature resolution we can expect along this axis, since position information from the controller will be used to turn the stream on and off at the correct location during each sweep past the part. The "slow axis" was designed to accommodate 0.30 m wide parts and support the weight of the bracket. It has a repeatability of 1.3 μm and a lead error of 25 μm per meter. The advantage of interfacing to a linear stepper motor is that a linear encoder is not required, since reliable position information is obtained from the controller itself.

Powder Distribution

Powder is deposited along one edge of the powder bed perimeter. The piston platform lowers the surface of the powder by a specified distance (for example, 0.15 mm). At a fixed level across this sunken surface, a cylindrical rod is used to spread the supply powder, forming a new layer for printing. The rod is counter rotated against its traverse direction to prevent disturbance of lower layers. DTM, a company that develops Selective Laser Sintering, had found this method of spreading most effective.

The powder bed is designed for parts as large as a 75 mm cube. A 76 mm x 76 mm x 154 mm piston is actuated by a stepper motor with a resolution of 7.9 μm per step. The walls around the piston form the powder bed with outer dimensions of 102 mm x 102 mm x 229 mm. The piston is spring loaded against two of the piston walls and rides on brass bearings. A strip of ceramic felt at the interface prevents powder from falling through the 0.25 mm gap between the piston and its walls.

An alumina substrate is placed underneath the first layer of powder. After a part has been completely printed, the piston is raised to the surface so that the part in its green state (still on the substrate) may be transported for curing.

Print Modulation

The modulation of very small binder droplets at high rates is controlled by the implementation of continuous-jet inkjet printing. A continuous stream of liquid breaks into droplets and the droplets can selectively charged and deflected in an electric field. The continuous-jet print modulation principle is illustrated in Figure 4.

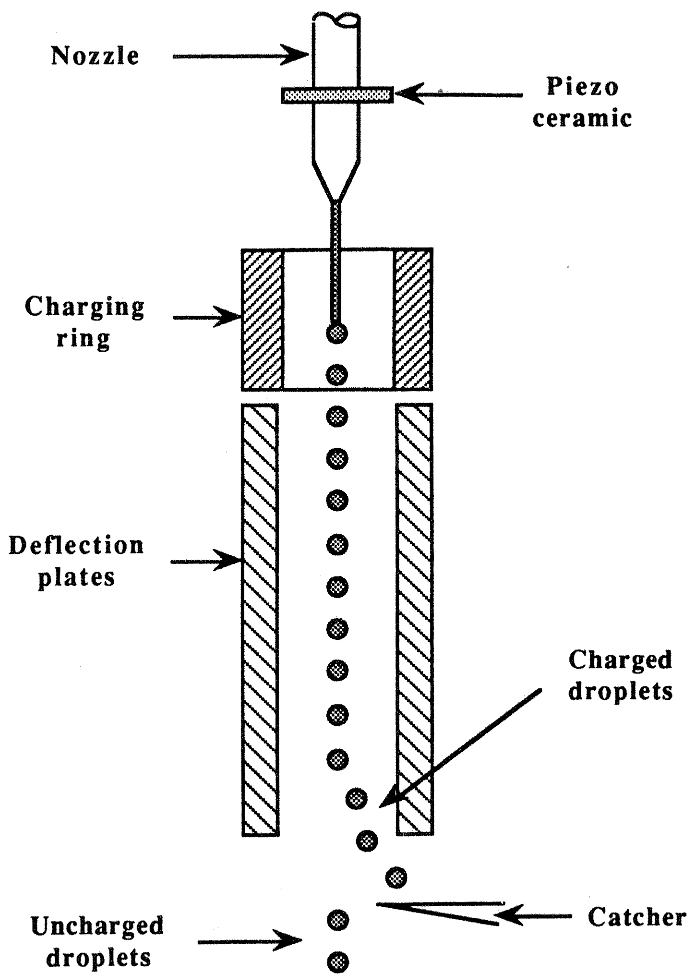

Figure 4. Print Modulation Schematic

The jet passes through a 0.34 mm cylindrical orifice where it forms the center conductor of a cylindrical capacitor. At the moment a droplet breaks off from the stream, its charge may be controlled by switching the charging voltage on or off. Droplets emerge into a transverse deflection field created by parallel plates spaced 1.6 mm apart. Charged droplets impinge on the surface of the plates, and uncharged droplets continue on a straight-line path. Thus, droplets may be controlled in a binary fashion at their formation rate, which is about 50 kHz.

Stream breakup occurs because spherical droplets possess less surface area than a cylindrical stream of equivalent volume. Infinitesimal disturbances grow exponentially on the surface of the stream, eventually separating it into droplets at a characteristic frequency that is a function of jet diameter and drop velocity [8]. A piezoelectric disk (Piezo Kinetics, Inc. in Bellefonte, PA) is mounted near the jet exit and vibrated at a frequency near the spontaneous breakup frequency (50 kHz) to insure repeatable drop formation. The piezo crystal is 4.76 mm in diameter and 0.5 mm thick.

A prototype printhead with on-off capability has been built and tested for reliable electrostatic deflection. Parts like the ones illustrated in Figure 12 have been printed for demonstration of functionality and for preliminary geometrical studies.

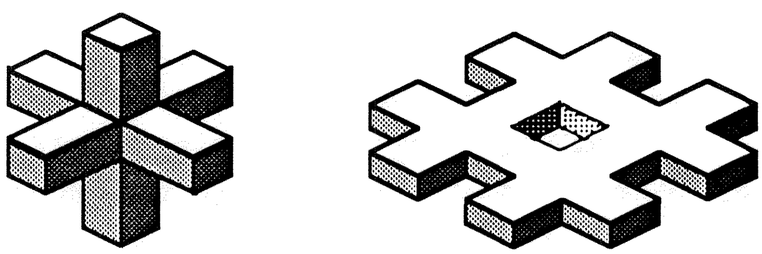

Figure 12. Sample Parts to Test Control of Print Modulation

Droplet deflection operated most reliably when using a charging voltage of about 100 volts and an deflection field of 4.0 volt-meters, corresponding to plates charged to a 2500 volt potential difference separated by 1.6 mm.

When the nozzle assembly with deflection capability is removed from the machine for independent experimentation, a continuous stream nozzle assembly may be used. Without the on-off feature, this simpler assembly prints parts of uniform cross-section (the objects resemble extruded parts). A channel under the printline catches all binder that is not intended to land in the powder bed, and selected lines of binder are permitted to pass through an adjustable window in the channel.

Fluid Delivery

Binder is delivered at a constant flow rate to the print nozzle by a positive-pressure fluid transport system. A water branch flushes the nozzle before and after the use of binder. The nozzle is an alumina wire-bonding tool used in the microelectronics industry (Gaiser Tool Co., Ventura, CA). It has an inner diameter of 46 µm ± 2.5 µm. The nozzle is epoxied to a 26 gauge hypodermic needle, which is attached to a small syringe filter with an adhesive. The syringe filter has a pore size of 5 µm (absolute), and prevents particles introduced during periodic maintenance from entering the nozzle assembly. Microgel and most other particles are captured in a series of in-line capsule filters located between the nozzle assembly and the binder reservoir.

In early printing efforts, nozzle reliability had been very difficult to achieve. The 46 µm exit frequently clogged with binder, thus disabling the entire system. Theories for nozzle failure include insufficient filtering of large particles in the binder, micro-gel behavior along the fluid delivery path, and interaction with contaminants at the nozzle exit. Preventive measures include careful filtering (5 µm, 1.2 µm, .45 µm capsule filters are used in series), a gel-inhibiting additive in the binder, and exhaust exhaust ventilation (near the machine to reduce particles in the immediate printing environment).

Control

A Compaq 386 computer integrates three-dimensional positioning and print modulation. Control of the x-y position of the raster assembly is accomplished by downloading programs to a dedicated motor controller built by DCI. The on-off control of the printhead is accomplished using a counter/timer card from Metrabyte Corp. The on-off control is accomplished by loading on and off vectors into 5 counters on the counter card. The pulses from the fast axis of the x-y raster scan are counted and when the counts pass the values stored in the registers on the card, the state of the printhead is toggled from on to off. The vertical position of the piston is actuated by a stepper motor which is controlled by the computer.

FABRICATED PARTS

Most parts fabricated with the current 3D Printing machine have been built from 320 grit aluminum oxide powder from Norton Co. (Worcester, MA, product number 7307). The binder is colloidal silica from Nyacol, Inc. (Ashland, MA). It contains silica suspended in water in a 30 weight-percent ratio (16 percent by volume), with a viscosity of 8 centipoise. Demonstration parts have been typically fired at 800 °C for one hour.

In addition to aluminum oxide, candidate powder materials for 3D Printing are silica, zirconia, zircon, and silicon carbide. These materials are identical to those currently in use for the fabrication of shells and cores in the investment casting industry.

The first printed objects were simply thin vertical walls on a substrate [9]. The 0.43 mm wall widths demonstrated the potential for fine feature definition. Edge distances intended to be 12.70 mm averaged 12.69 mm in the green state and 12.73 mm after curing. Simple rectangular solids and combinations of rectangular solids were printed at the next level of complexity. Examples include plates, bars and stair-steps.

Several turbine blade prototypes have been printed to demonstrate the ability to fabricate more complex geometries. An example is shown in Figure 6a. It was printed without on-off print modulation, so the shape is that of an extrusion, as evident in Figure 6b. Printed lines were spaced 0.19 mm apart. The part has multiple curvatures and hollow cavities, yet no part-specific tooling was required.

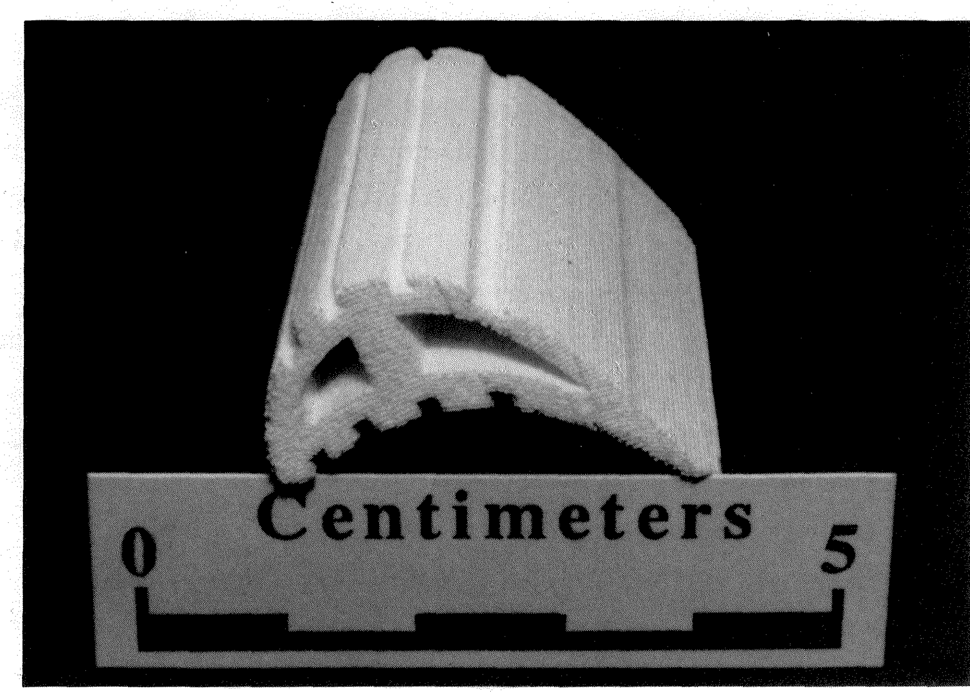

Figure 6a. Turbine Blade Fabricated by 3D Printing

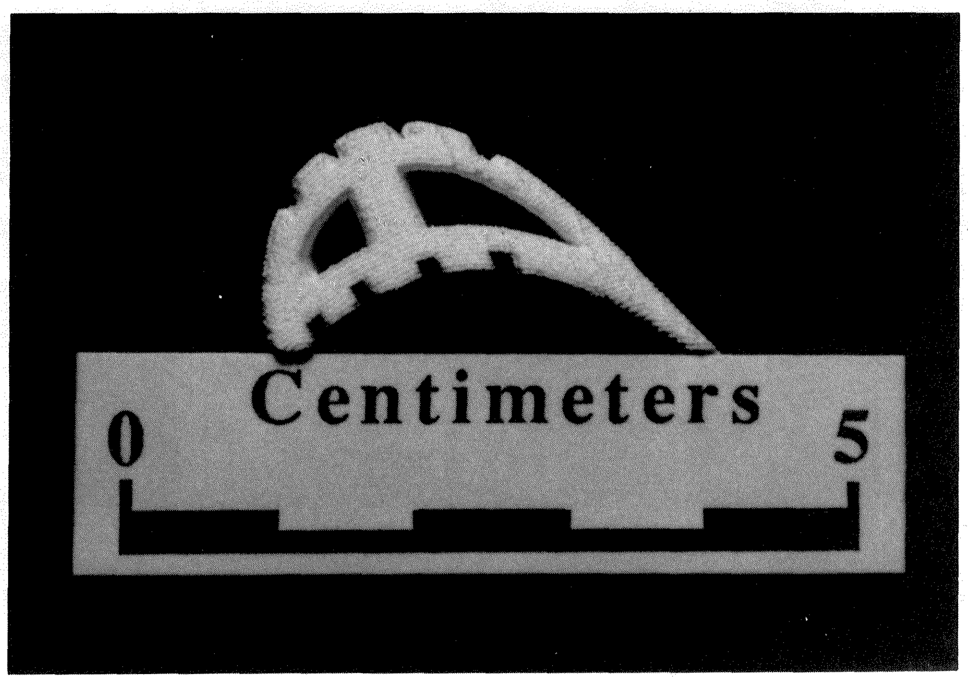

Figure 6b. Turbine Blade Fabricated by 3D Printing, End View

Parts made from 3D Printing were used for metal casting cores by industry collaborator, using procedures identical to those used in conventional casting. The core was wrapped in wax, then dipped in a ceramic slurry to form a shell. After wax was removal, a nickel super-alloy was cast in the shell with the 3D Printed core in place. Finally, the the core was etched out to form the internal detail of the part, shown with its shell in Figure 7.

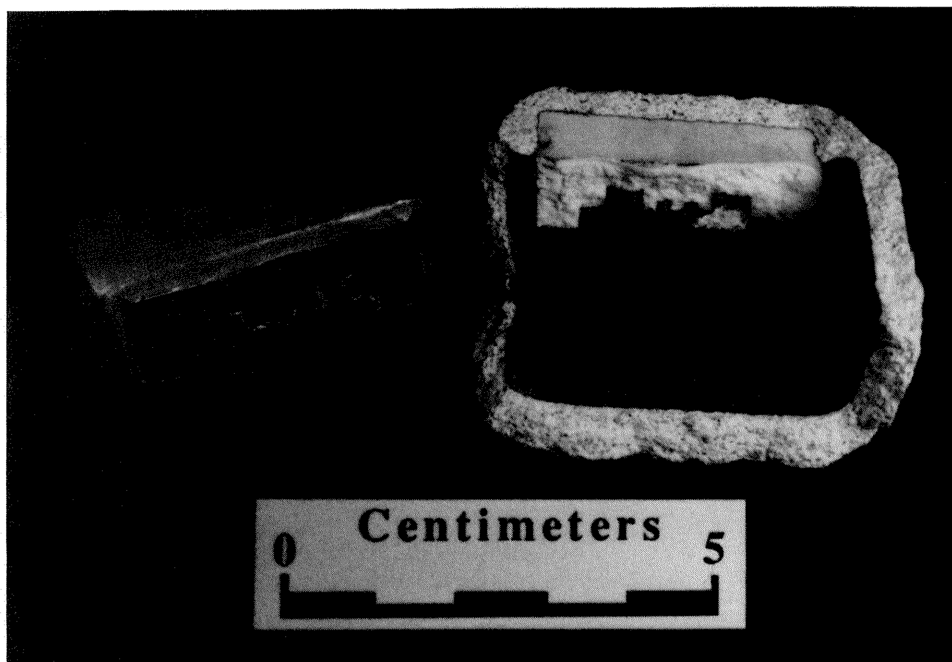

Figure 7. Cast Nickel Super-Alloy, with Internal Detail Made by a Core from 3D Printing; Shell shown adjacent.

PART PROPERTIES

Factorial experimentation has been conducted to quantify the effects of relative binder volume content and printed line spacing on the properties of finished parts. Strength, flatness, surface finish, and dimensional control were characterized using second-order regression models. These models can be used to test process understanding, to design equipment and to design process parameters. Results from the maximum bending stress (before fracture) of square cross-section bars and from the width dimension of flat plates are presented here as typical examples of the studies.

Strength

Four-point bending tests were applied to bars which were fired at 1500 °C. Data points were collected at print line spacings of 0.13 mm, 0.19 mm and 0.25 mm, and at relative binder volumes (with respect to overall part volume) of 40%, 50% and 60%. Four replicate measurements were made at each combination of process parameters. Figure 8 shows a contour plot of the regression model for maximum bending strength against binder volume percentage and print line spacing. Boldface numbers indicate the actual results from which the regression was derived. Predicted values are compared to measured data in Figure 9.

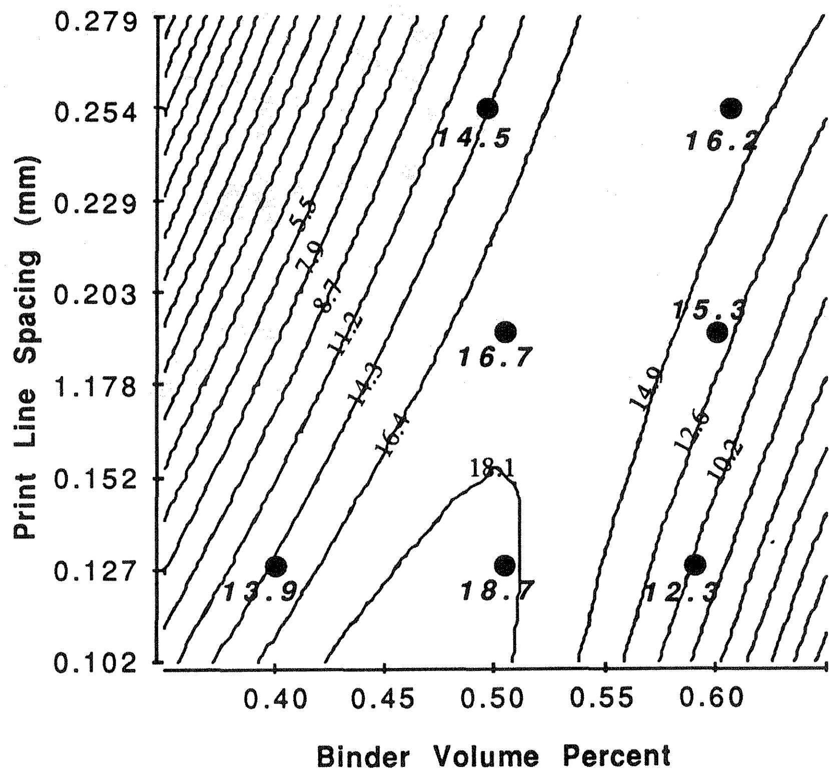

Figure 8. Maximum Bending Stress (in MPa) as a Function of Binder Volume Percentage and Print Line Spacing

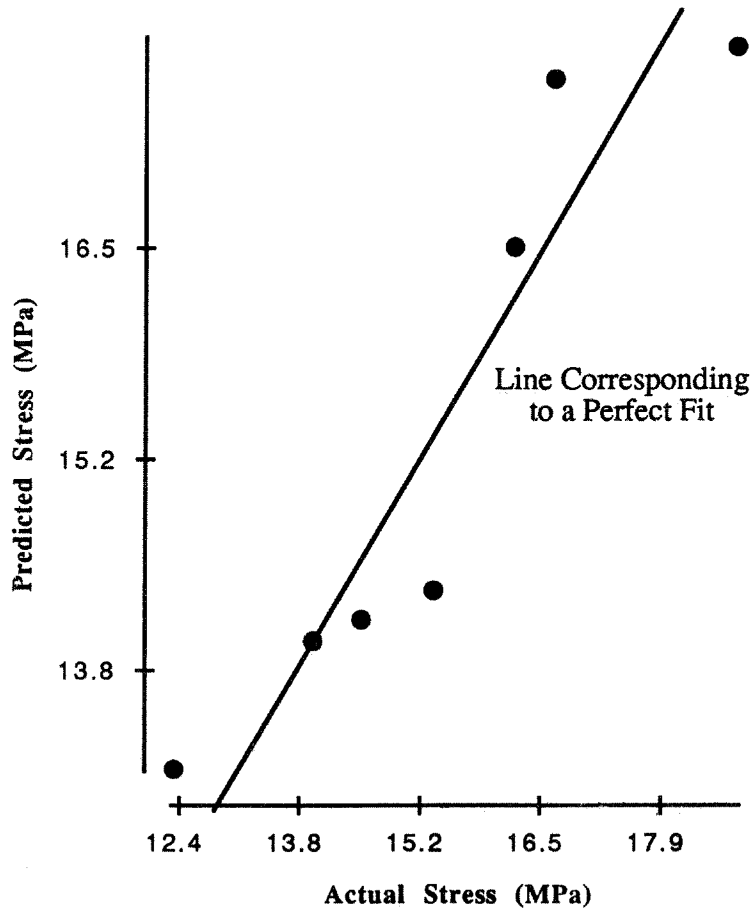

Figure 9. Maximum Bending Stress Regression Fit

The most important point is that the strength is in the range required for investment casting (estimated at about 7 to 16 MPa, based on discussion with individuals in the casting industry). At proper strength levels , the mold and core are strong enough to avoid fracture during handling and pouring, but weak enough to fracture as the poured casting cool and contracts (thus avoiding hot tears in the casting). It is also of interest to note that there is a peak in the strength as a function of the relative binder volume below which there is not enough material between powder particles and above which there is too much.

Dimensional Control

The widths of printed plates fired at 1000 °C were measured with a micrometer with a spring loaded anvil to maintain control over contact force. As with the strength bars, data points were collected at print line spacings of 0.13 mm, 0.19 mm and 0.25 mm, and at relative binder volumes of 40%, 50% and 60%. The width of each part, intended to be 38 mm, was measured in the direction perpendicular to its print lines. Figure 10 shows a contour plot for plate width against binder volume percentage and print line spacing. As with the strength data, boldface numbers indicate the results from which the regression was derived. The regression is compared to actual data in Figure 11.

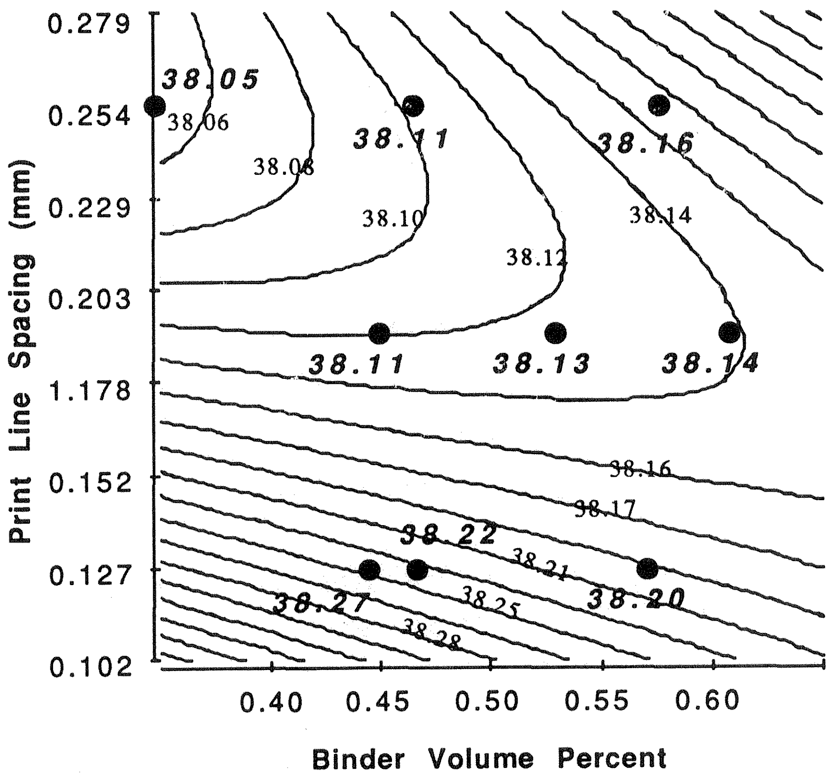

Figure 10. Plate Width as a Function of Binder Volume Percentage and Print Line Spacing

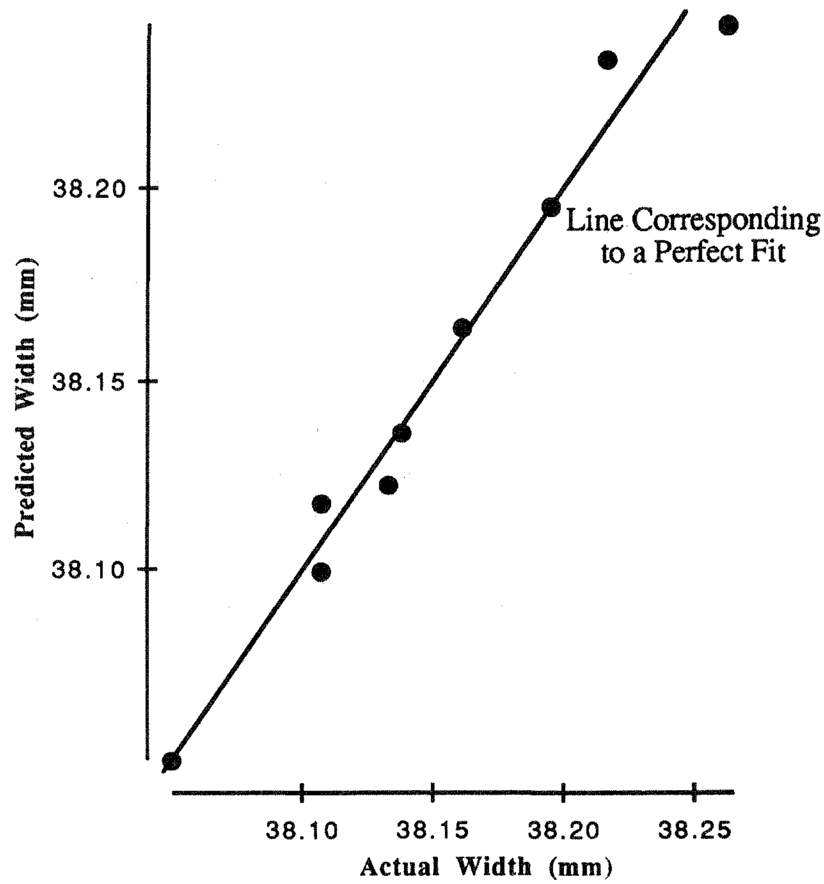

Figure 11. Maximum Bending Stress Regression Fit

Part strength is in a range (maximum bending stress 12.3 to 18.7 MPa) suitable for investment casting. Part to part dimensional control was ± 20 μm on a dimension of 38 mm, and dimensional variation along the length of an individual part was approximately ± 13 μm on a 38 mm dimension.

CONCLUSIONS

Three Dimensional Printing creates solid objects directly from software representation by selectively binding sequential layers of powder. With extreme flexibility, this process has high potential for dramatically increasing manufacturing productivity. 3D Printing can improve the economic feasibility of small batch size tooling and prototype fabrication.

The initial applications of 3D printing are the direct production of cores and shells for metal casting, and the fabrication of porous ceramic preforms for metal-ceramic composites. Part strength and dimensional accuracy results, as well as the success of test molds and cores in metal castings, show great promise for casting applications.

Current research issues for process understanding and equipment design include the interaction of binder and powder, print modulation technology, printhead transport, powder deposition, and automation control.

ACKNOWLEDGEMENT

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