Solid Freeform Fabrication of Stainless Steel Using Fab@Home

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ABSTRACT

Metal or ceramic parts can be solid freeform fabricated (SFF) using powdered material processing techniques. A slurry of the powdered material is deposited in a layer-by-layer fashion, and then sintered. We demonstrate this process using a 17-4 PH stainless steel slurry deposited via robotically controlled syringe in the low-cost Fab@Home rapid prototyper. Completed parts had densities as high as 90% volume fraction and tensile strength as high as 35% of the pure solid. Details of the process as well as a number of samples of different geometries are shown.

Introduction

Solid freeform fabrication of metal, ceramic, and composite parts is desirable for accurate prototyping and fabrication of intricate geometries impossible through other methods. One process that has achieved commercialization and wide-usage is Selective Laser Sintering (SLS). This process has been demonstrated with a variety of metals and ceramics including steels, titanium alloys, alumina, hydroxyapatite, etc. It has demonstrated very good resolutions, mechanical properties, and compatibility with a wide range of post-processing techniques. A good summary of the process is available from Kumar [1].

As with all powder bed techniques, SLS of metals and ceramics is not readily adaptable to multi-material SFF. Also, these techniques requires significantly greater amounts of powder to be prepared than will be consumed by the final part. SLS, specifically, requires expensive, high-powered lasers which may not be suitable for all environments.

A method that avoids these issues, compatible with a wide range of materials and multimaterial combinations is the Robocasting process. This process deposits powdered material in a slurry form and then sinters them afterwards to create solid parts with high densities. It was demonstrated first with alumina [3] and the expanded to a range of other ceramics [4,5]. Multimaterial deposition including graded materials produced by variable mixing of slurries has also been demonstrated [4]. Finally, ceramic-metal (Ni) composites have been demonstrated in simple period structures [7].

Much of the work to date on the Robocasting process has focused on modeling and controlling slurry rheology as the slurries used did not rapidly solidify upon deposition as they required significant drying to become solid. A slurry with low binder concentration (for ease of sintering) but an easily controllable liquid-solid transition is desirable and efforts towards this goal have been made. Here, we demonstrate such a slurry ideal for SFF and the first parts printed from a mechanically robust material, 17-4 PH Stainless Steel.

Process

Feedstock Preparation

The feedstock was prepared at United Materials Technologies, LLC in a proprietary process. It contains 45-55% by volume of 17-4 PH powder with a mean size of 12μm, a polysaccharide binder, silicate or borate compounds and water. The materials are combined in a high-shear mixer at 90°C and mixed for about 30 minutes. Extra care is also taken to prevent air from being stirred into the mixture as this negatively affects print quality and final part density. The feedstock becomes liquid at approximately 85°C and is a wet, clay-like solid at room temperature. Finally, it is cooled and pelletized.

The pellets are loaded into a 10cc syringe and compressed to remove air. The syringe is heated to liquefy the feedstock. We attempted several different techniques to remove the air including letting the syringe sit for extended periods and vibrating. Both of these techniques are not effective because the slurry is too viscous for bubbles to travel.

Two effective techniques for air removal that were tried include centrifuging and brief exposure to vacuum. Centrifuging is somewhat effective but is limited because extended centrifuging at high g-forces causes the slurry to separate. An effective centrifuging program was 3 minutes at about 1000 g force.

Another effective method is to extrude the feedstock from the syringe into an open container while the container is under vacuum. This causes bubbles of gas to expand and burst out of the bead of slurry that is created. The slurry cannot sustain extended exposure to low pressure as the water will boil out changing the composition of the slurry.

Printing

The Fab@Home, shown in Figure 1, with a mount for a custom-built syringe heater was used to print the slurry. The standard Fab@Home software was used for machine control and path planning. A 22 gauge (0.016 in diameter) tapered plastic nozzle from EFD, Inc. was used for all of the example parts shown it is possible to print through smaller nozzles. The syringe is loaded into a custom built heater with thermocouple and mounted in the Fab@Home. Several geometries were attempted including thin walls, tensile-test bars, gears, and parts with small lettering.

To achieve greater control over starting and stopping the flow from the deposition tool, the Fab@Home software has several parameters concerning the length and timing of “push-out” or “suck-back” operations that actuate the deposition tool before or after the flow is meant to occur. Careful calibration of these parameters was performed by repeated printing of simple test objects.

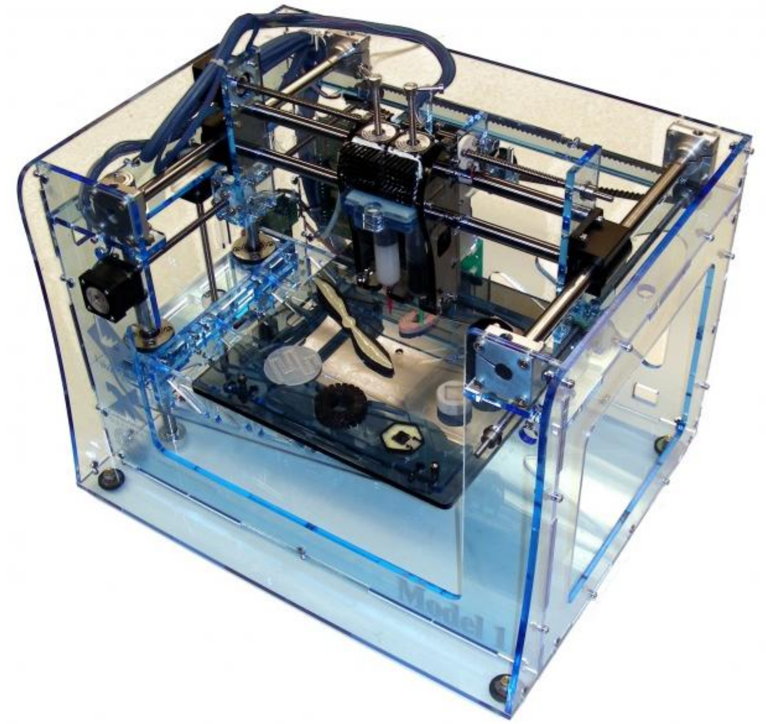

Figure 1: Fab@Home Rapid Prototyper with several example fabricated parts on the stage

Sintering

Before the green part can be sintered, a large fraction of the water must be removed to prevent outgassing during rapid temperature ramping. This can be done at room temperature in ~24 hours or in an oven or under heat gun at ~80°C for about 30 minutes.

After the parts are dried, they are placed in a furnace boat and loaded into a controlled atmosphere furnace. In our process, we used a 1.5 in. I.D. tube furnace with a single ~8 in. hot zone. The furnace is capped and a flow of reducing atmosphere is applied.

A typical heating schedule consists of two main steps. First a 1.5 hr ramp to 550°C followed by a 1 hr hold. This is called the debinding step and it allows all for the majority of the binder to be burned out while the part is still porous. Debinding often takes place in a different oven under a different atmosphere than that required by sintering, but this slurry has a very small binder content so a simple debinding step is possible.

Next, in the main sintering step the furnace is ramped for 1.5 hr to 1350-1400°C and held for 1 hr then allowed to cool. The peak sintering temperature was varied to find the maximum density (as described in the section *Shrinkage and Density* below) without significant deformation to the geometry. This optimum temperature was about 1380°C.

Initially, a 94% nitrogen, 6% hydrogen atmosphere was used, but this created parts with poor final densities. As suggested in [8], switching to a nitrogen free atmosphere, 94% Argon, 6% Hydrogen improved densities significantly.

Results

Print Quality

A variety of printed and sintered parts are shown in Figure 2. All of the parts shown have a bead size of .013 in. Of particular interest is the cup with a thin wall that is two beads thick and about 50 layers tall. No significant sagging was seen while printing and it is likely that the material can sustain even taller structures.

Figure 2: A variety of example parts after sintering

One of the issues encountered while printing is that it is difficult to control starting and stopping the flow from the syringe with the type of deposition tool used in the Fab@Home. As the Fab@Home only controls the height of the plunger, compression in the fluid prevents the system from accurately controlling the amount of fluid leaving the nozzle. Most of this compression is created by air bubbles in the fluid. Without using centrifuging or vacuum degassing, it is very difficult to create good quality parts. Even when great care is taken, the flow does not stop very precisely. This is visible as the small protrusions or holes in the gear or cup seen in Figure 2.

Another issue encountered is warping caused by non-uniform drying of the part. Some shrinkage occurs while the water evaporates from the part after printing. If the part dries unevenly, this shrinkage will occur unevenly and the part may warp. Additionally, if the slurry binds to the substrate, it may prevent the bottom surface from shrinking uniformly. An example of this type of warping is shown in Figure 3.

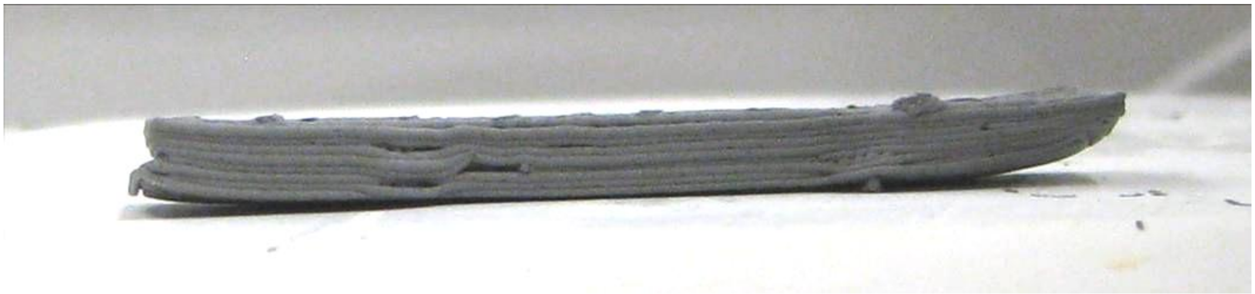

Figure 3: A part deformed after printing by uneven drying.

Shrinkage and Density

One of the key parameters measured for sintered metal materials is the density of the final part as many materials properties are strongly and positively correlated with this property. This process produces gaps within the parts because the bead typically fails to fill the entire volume of the part. To account for this each sintering run included a part produced by extruding a small lump of slurry with no gaps was included to measure the density of the solid portion of the part.

Density was measured using Archimedes method. After optimizing the sintering conditions, a volume fraction density for the solid parts of 94% and a volume fraction for a printed cube was 90%.

Linear shrinkage was measured by taking length measurements with a digital camera within one minute after finishing printing and after sintering. Note that some shrinkage (1-2%) occurs during drying after printing so it is important to take measurements before significant drying occurs. Total linear shrinkage for drying and sintering a printed part was 18%.

These shrinkage and density values are comparable to those for injection-molded stainless steel [8]. Improved path planning and control of slurry rheology may allow for improvements to the densities of printed parts.

Tensile Strength

Note that the tensile strength of arbitrary parts is strongly dependent on the path pattern with which they are printed and the following results should be taken only as an example of typical strengths of printed parts. Tensile strength was measured on printed and sintered tensile bars with final dimensions of the gauge area of approximately 0.212 x 0.100 x 0.550 in. printed with a border/cross-hatch pattern. The bars were strained at a crosshead rate .05 in/min. The measured tensile strength varied widely and all of the specimens broke at the end of the gauge area suggesting that poor print quality or path planning created stress concentrations that led to failure. The best achieved tensile strength was 53000 ksi or 35% of pure 17-4 PH.

As injection-molded stainless steel parts can have tensile strengths of around 80-90% [8] of pure stainless steel, it is likely that further optimization of the sintering process, and more importantly, better print quality and path planning can let this process achieve significantly higher tensile strengths.

Future Work

This process is identical, except for the sintering step, for any metal or ceramic that can be sintered. The sintering process is self contained and can occur in a very controlled furnace instead of happening in a very dynamic fashion in the middle of the printing process as with SLS. Almost all of the well-known powder metallurgy/ceramic processing techniques can be directly applied to processing these parts. These advantages make it easy to develop many materials for use with this process.

The second major advantage of this technique is that it allows for multiple materials to be printed together. Materials may be printed in complex, inter-locking geometries, or even graded together.

Conclusion

A new process for the solid freeform fabrication of steel parts is demonstrated. Example parts were fabricated with features as small as .32 mm out of 17-4 PH stainless steel. Mechanical properties are good with printed parts having densities of up to 90% and tensile strength of up to 35% that of the pure metal. This process can be applied with minimal changes to a wide range of metals, ceramics, composites, and multiple materials in the same part.

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