Heat Transfer Manipulation for Precision Droplet Manufacturing: Simulation and Experiment

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Abstract

The solid free-form fabrication (SFF) of arbitrary metallic components is accomplished with controlled deposition of nano-liter molten droplets generated by capillary stream break-up and deposited at rates on the order of 10,000 drops/second. By varying the droplet arrival temperature, deposition rate, and substrate temperature in both the simulation and experiment, we seek to obtain a thorough understanding of the heat transfer phenomena that governs the SFF component quality. Of specific interest is the removal of inter-splat boundaries in order to achieve a high quality component, characterized by a uniform and fine microstructure, by having newly arriving drops remelt a thin layer of the previously deposited and solidified material. A numerical model, which simulates the heat transfer manipulation, is used to understand and guide the process development.

Introduction

The ability to build arbitrary 3D objects directly from CAD data without the need for molds, a process often referred to as rapid prototyping (RP), has been around for a number of years[1]. Precision droplet manufacturing (PDM) is a molten metal droplet based RP technique being developed at UCI that differs from many other metal RP technologies. Specifically, it is capable of producing near net-shape metal components that exhibit high accuracy, improved material properties, fast build times, and virtually no warpage. Additionally, since PDM produces fully dense components, no secondary operations such as post firing or infiltration are required.

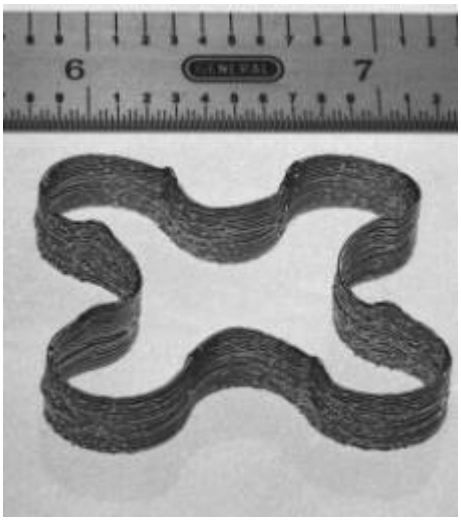
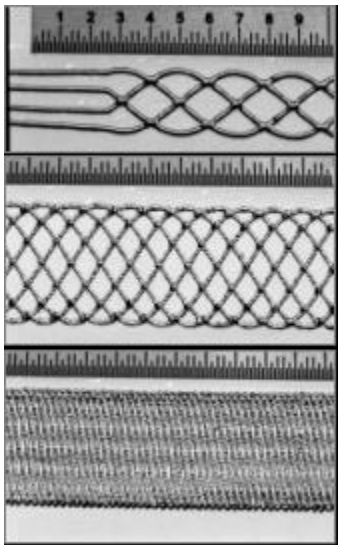


Figure 1 Thin wall clover built with PDM

The PDM process utilizes a capillary stream of molten metal that is broken up into highly uniform drops, which can be individually manipulated via electrostatic deflection on a drop-to-drop basis . Electrostatic droplet deflection in combination with xyz substrate motion is used to build arbitrary 3D objects.[2] Components can be grown at rates up to 40 mm^3 per second since the 200 μm diameter droplets are generated at a rate on the order of 10,000 droplets per second. At this rate, a solid 1.0 cm^3 cube can be produced in 24 seconds. Accuracy and surface roughness are determined by the stream stability and splat characteristics of the drops. Figures 1 and 2 are photographs of components that were processed with PDM.

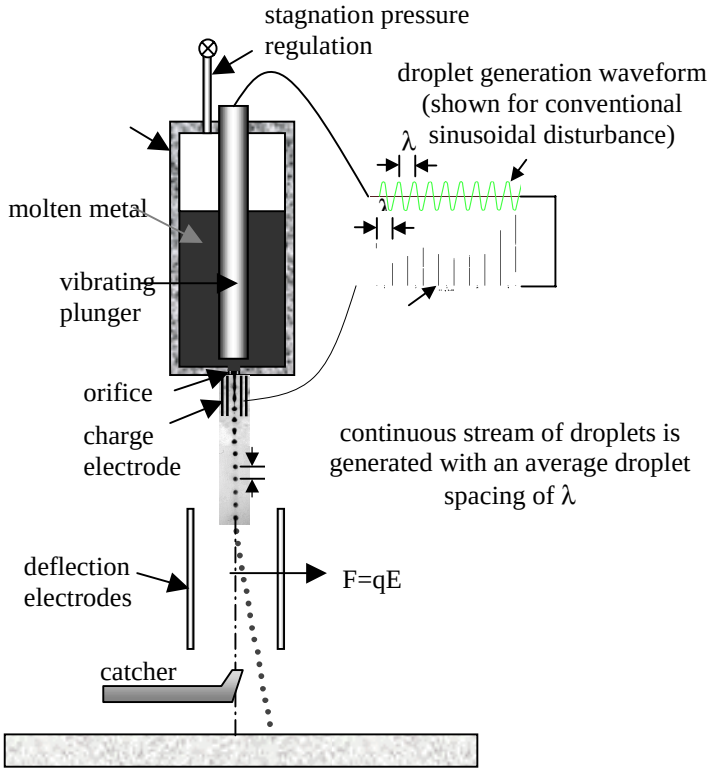
Having previously deposited drops solidify before the next drop arrives is vital so that geometric integrity is maintained. However, enough thermal energy must be delivered with each new drop to remelt a thin layer of the previously deposited material to help remove inter-splat boundaries and thus create a strong inter-splat bond. Remelting promotes inter-droplet adhesion by allowing mixing and therefore should minimize delamination. Therefore, superheated drops in combination with a cool substrate will allow remelting yet pull heat away fast enough that the splat can solidify before the next splat arrives.



To investigate the conditions required to achieve quality components, a numerical simulation is developed and compared with experiments. With these two goals in mind, the model can be used to predict optimum parameters that yield the maximum deposition build height in relation to droplet generation frequency, droplet arrival temperature, and substrate temperature.

Numerical Model

A 1D model is used to simulate the bulk material deposition and heat diffusion process associated with PDM. Heat transfer and solidification are simulated as droplets are added at regular intervals. The first drop lands on a finite substrate and subsequent drops stack on the previous drop. Two moving boundaries are associated with PDM: (1) liquid/solid interface that varies continuously with time and (2) the upper adiabatic boundary that varies discretely as each new drop is added. The model allows re-melting of previous layers, but not the substrate. Thus, the liquid/solid interface is free to move in two directions. A constant temperature boundary condition is applied to the bottom of the substrate and an adiabatic condition is applied to the free droplet surface. A fixed grid Crank-Nicolson numerical scheme is used. The basis for this formulation can be found in detail elsewhere.[3]



The adiabatic boundary condition at

the top surface is valid since the dominating heat transfer mode is conduction through the substrate.[8] Additionally, it is assumed that the droplet deformation will not influence the heat diffusion process. This assumption is reasonable because of the high impact velocities associated with PDM. Besides, modeling the deformation would make the model unwieldy when analyzing hundreds or thousands of droplets (which is very realistic for PDM).[9]

Experimental Apparatus

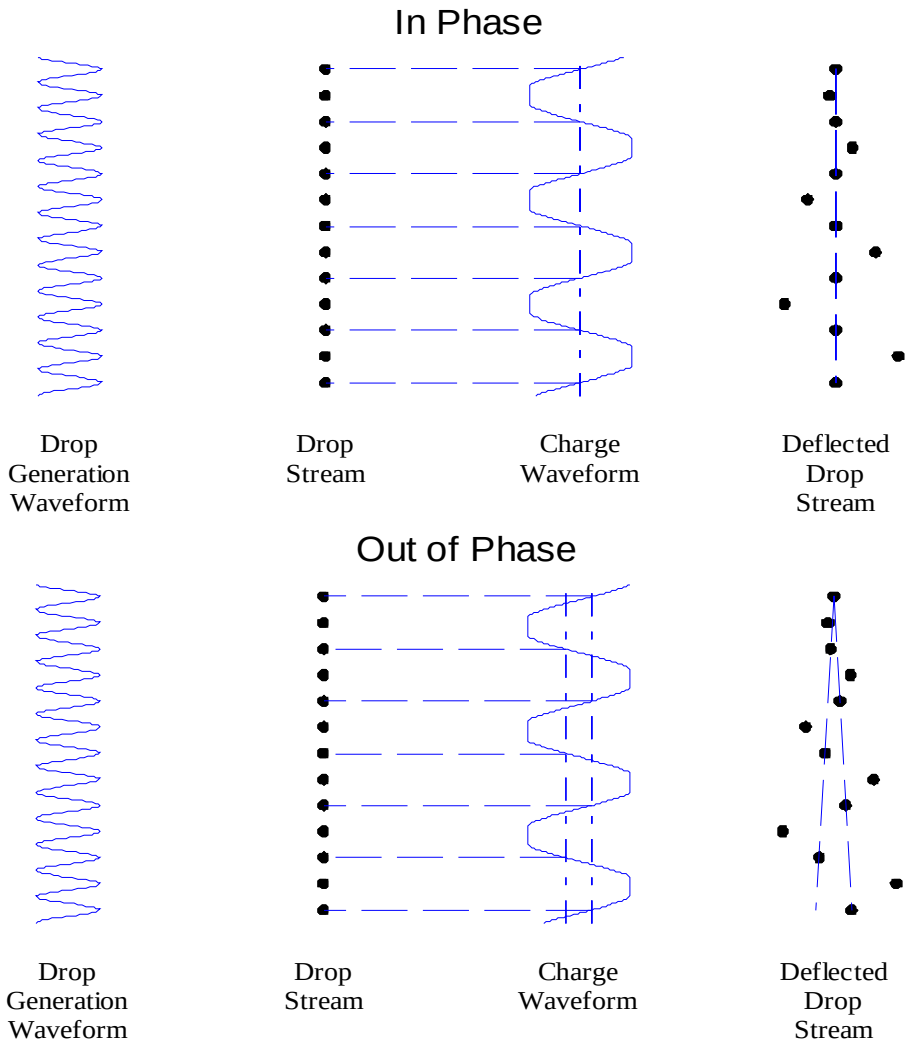
Molten metal is jetted through a small orifice (100 μm) at the base of the liquid metal reservoir as shown in figure 3. This stream is broken into uniform molten metal drops through capillary stream breakup induced with a periodic pressure disturbance to the stream. The entire stream can be given an electrical charge with the charge electrode. When a drop breaks free from the stream, it retains whatever charge was on the stream at the time of separation. Thus, arbitrary charges can be applied to each drop by applying a varying voltage to the charge electrode that is synchronized with the droplet breakup perturbation. The arbitrarily charged drops then pass through deflection plates that generate a constant electric field. Each drop will then be laterally deflected a distance proportional to its charge.

Droplet stream phase and deflection calibration

To help guarantee deposition control, it is important that charging pulses be in phase with the droplet generation waveform and that the droplet breakup location is relatively invariant. If neither of these conditions is satisfied, drops may only receive a fraction of their nominal charge value or even no charge at all, resulting in large targeting errors. Therefore, it is desirable to have a visual method so that noncompliance can be easily identified and eliminated. An innovative method has been developed that achieves this goal.

A video camera that is oriented perpendicular to the deflection direction is used to observe the droplet stream. Verification of the droplet formation location invariance, or stability, can be easily accomplished by applying a constant charge voltage and observing if all the drops are deflected the same amount. To verify synchronization between the charging and droplet generation waveforms, a charging waveform that is highly sensitive to phase shifts is used. To this end, a droplet charging waveform with a steep voltage gradient that is centered about zero volts is applied. Thus, when generation and charging are slightly out of phase the trajectory of neighboring drops diverge noticeably. Hence, neighboring drops are aligned only when the generation and charging waveforms are in phase. This method provides a true and readily observable indicator of phase relationship since it examines the final result of the charge input.

Both calibration schemes can be implemented simultaneously by using a clipped sine wave for the charge waveform with a frequency that is 1/4 of the droplet generation frequency. The top of figure 4 shows how the charging waveform relates to the droplet stream when they are in phase. Note that every other drop has zero volts applied to it and is in a steep voltage gradient region as desired. In addition, every other drop is on the flat peak of the clipped sine wave and can be used to observe deflection stability. Since the zero voltage drops are in a steep voltage gradient region, a small phase shift will result in a large change in the charge voltage, resulting in large errors in droplet trajectory and placement as shown in the bottom of figure 4. It is clear that the phase shift causes the center drops to no longer travel in tandem since they were given non-zero charges at the time of droplet generation. The calibration method involves “tuning” the phase



difference between the droplet generation waveform and charge waveform until the center droplets are observed to travel in tandem.

Experiment

For the current experiment, solder (60Sn-40Pb)[7] droplets splat and form a cylindrical bead 450 μm thick on a 3.2mm thick aluminum substrate mounted on a rotating platform. The substrate rotates at a frequency of 1.3 Hz for 15 revolutions to build each component. The bottom surface of the substrate is held at a constant temperature. As the platform rotates, a bead of molten metal is deposited. After one revolution, material is deposited on top of the previously deposited material. In this way a slinky shaped component as shown in figure 5 is built. The bonding between the "rings" of the component is of primary interest.

To evaluate the inter-layer bonding a metallographic study of the specimens is conducted. Droplet arrival temperature is held constant while substrate temperature is varied. The grain structures of a sample is shown in figure 6 (discussed in more detail later). The bottom layers,

which were closest to the substrate, exhibit a fine grain structure that then transitions quickly to larger grain structure further away from the substrate. Towards the top the component looses geometric integrity.

Results and Discussion

Larger grains indicate that the solder is cooling slower than for smaller grains. This occurs since the substrate is being continuously heat by the arriving molten solder. Longer cooling times give a layer more of a chance to bond with the lower layer and a stronger bond results. It is theorized that the transition region show in figure 6 is where strong inter-layer bonding starts to occur. At some point, solidification slows such that a layer is unable to fully solidify before the next layer arrives and geometric integrity is compromised. All of these regions are illustrated in figure 6.

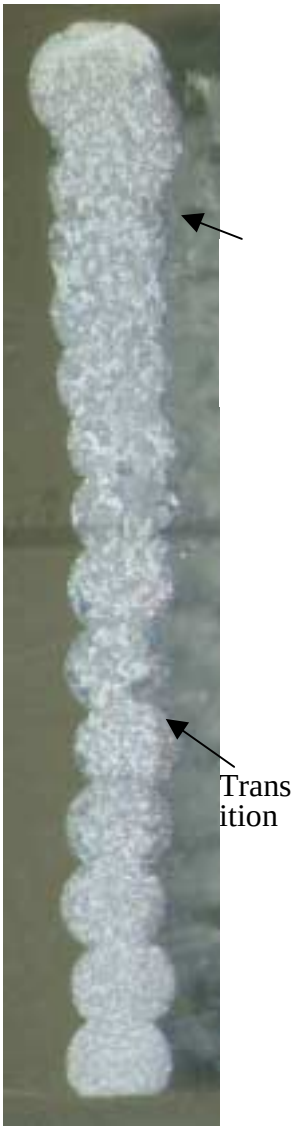


Figure 7 shows the temperature history for the simulation through a succession of 15 layers, where the solid line is the substrate temperature profile and the dashed line is the temperature profile of the top surface of the last droplet deposited. To compare the simulation with the experiment, the last layer to fully solidify before the next layer arrives is examined for the temperature range of interest. This point is indicated in figure 7. This point is chosen since, as shown in the micrograph of figure 6, the point at which the layers are no longer distinct is easily located. The simulation predicts when this point will occur for a certain substrate temperature as shown in figure 7. It can be seen from figure 8, which is a plot comparing the experimental results of the metallographic samples with the predictions, that the simulation is in good agreement with experiment.

Experimental results are presented in figure 8 along with our simulation predictions. Even though there is some variation in the metallographic results the specific downward trend is clearly evident. The slope of the lines is the same within the experimental variations. As shown, the predicted and actual last layer to solidify differ by approximately 3 layers. Since the coil thickness is composed of multiple droplets, material flow may have an effect on heat diffusion and account for some of the discrepancy. It is anticipated that experiments utilizing a single drop layer thickness will more closely agree with the model and allow more control of thermal issues involved with PDM.

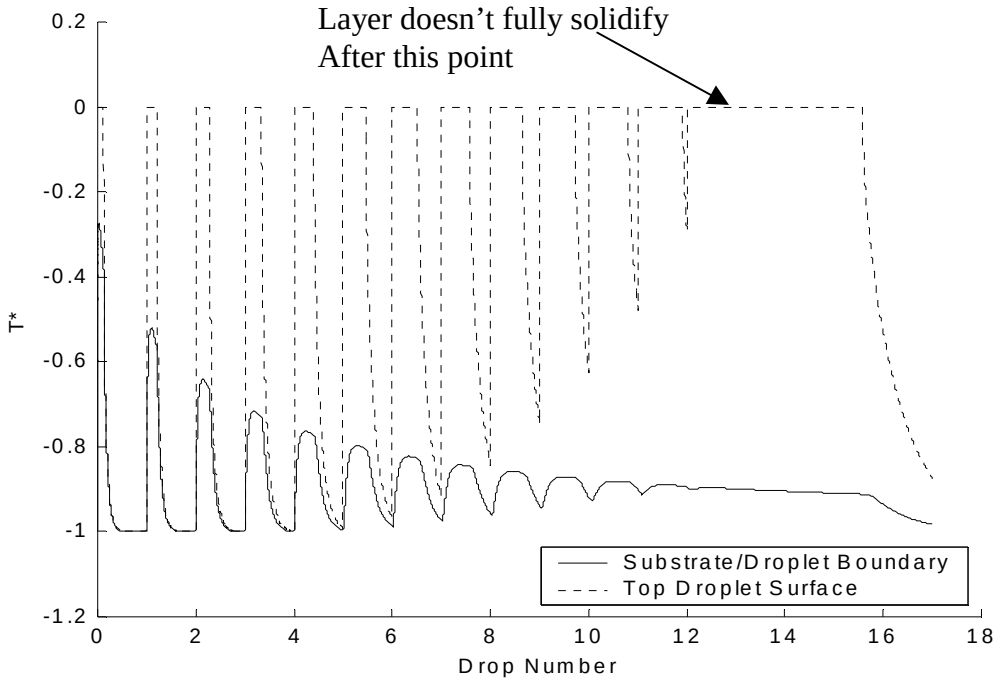


Figure 7 Simulation of temperature history of the substrate and succession of deposited droplets when substrate is 331 °F.

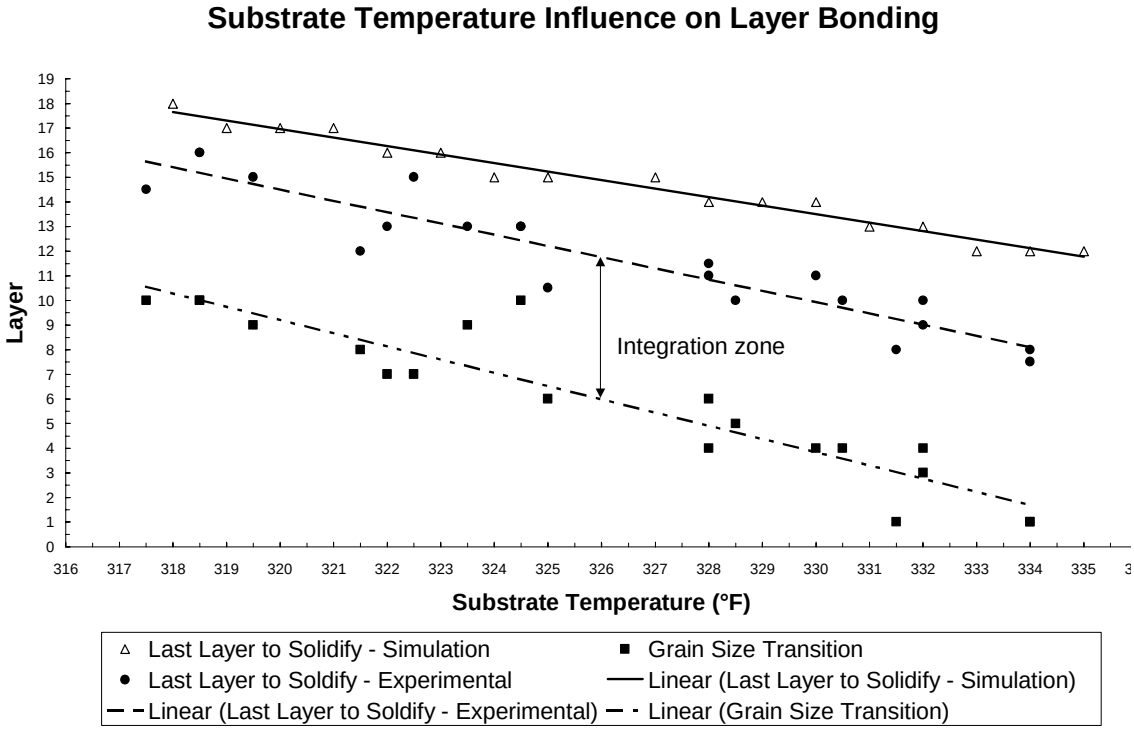


Figure 8 Comparison of experimental and simulation results

The experimentally determined integration zone is also shown, which can be conjectured to be the extent of the region in the direction perpendicular to the substrate of which full bonding occurs. The integration zone is approximately 6 layers thick for our experiments.

Since there is only a small zone of optimally integrated material, it is clear that temperature control is needed to build a fully integrated component. Due to the high deposition rates, arbitrary geometry, and thermal response time, substrate temperature control would be very difficult if not impossible. Thus a larger optimal integration window should be realizable by controlling the drop arrival temperature.

Summary

This work, though still continuing, has demonstrated several important findings. First, a novel calibration scheme for PDM is introduced. Second, we have shown that the bonding characteristics of the fabricated components can be predicted from a 1-D model with good accuracy. Ongoing work is focused on extending the model predictions and experiment to aluminum components.

Acknowledgments

We gratefully acknowledge the generous funding from the National Science Foundation, grant number DMI-0070053, "High-Speed Droplet-Based Manufacturing of High-Precision Structural Components and Photonic BandGap Materials."

The authors are also grateful for the assistance of Mr. Robert Smith and Mr. Tyler Pugh in the success of this project.

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