Real Time Video Microscopy for the Fused Deposition Method

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1. ABSTRACT:

Fused deposition is a layered manufacturing technology, which is being investigated for fabrication of functional parts. Defects and voids in the build process affect the quality and level of accuracy of components. These occur due to several factors, such as the toolpath contours in a layer, material(s) deposited, and the environmental conditions. For a functional part to be constructed, a perfect green part is critical. To further understand this process, a visualization of the deposition is needed. Therefore, we have developed a real-time video microscopy system. The hardware has been constructed and mounted on the existing liquifier. Real time deposition of layered manufacturing is being recorded. Three materials being investigated are: PZT, silicon nitride, and wax. The contrast in wax layering is not as strong, which makes visual observation extremely hard. However, interaction between the roads of PZT and silicone nitride parts has been successfully quantified. Using the current set up and software, the raod width and height have been quantified.

2. INTRODUCTION:

The Fused Deposition Method has been employed as a rapid prototyping technique. Many different materials are being tested, including silicon nitride, lead zirconate titinate (PZT), and metals. Rutgers, The State University of New Jersey is currently developing a multi-material fused deposition fabrication hardware, which could use combinations of different materials[1].

One critical area in the effort of producing a perfect part is that of quality control. Parts produced using FDM which contain voids and imperfections will have a much higher probability of failure. Thus, it is of the utmost importance that the layered deposition is properly understood so weaknesses in the fabrication process can be corrected. A visualization technique is imperative as an aid in understanding the deposition method. The goal has been to create a system by which we could visually observe and then quantify certain aspects of the layering process. This would produce information not only about how the machine was creating the part, but also how different materials behave.

3. MOTIVATION:

At Rutgers University, under ONR (Office of Navy Research) funded MURI program [1], An intelligent layered manufacturing (LM) system for fabrication of multiphase electromechanical parts has been developed. To achieve this multi-materials LM software system, one of the necessary requirements is to perform the virtual simulation of the of the multi-material LM process[2]. In order to make this simulation realistic, the information on layer deposition is needed. In the present project, a real time video microscopy system is developed. This system provides geometric information on deposited roads and layers which will be used in the virtual simulation.

4. PROCEDURE

4.1 HARDWARE CONSIDERATIONS:

The initial setup included the COHU CCD camera, microscope attachment, and Trinitron monitor. The task was to create a non-obtrusive way to observe the deposition at high magnification without effecting or disturbing the normal build process or environment. This required the equipment to fit into the existing closed FDM chamber and have it mounted in a way that would allow as normal a build as possible.

The choice of hardware was carefully thought out. It was assumed that going from our initial video microscope to a different setup would provide the performance enhancements which were sought since the original hardware was not designed for this task. AEI was selected as a good choice because of the variety of hardware which they carried. The two choices which had to be considered again, were either the boroscope or the fiberscope. Both provided integrated lighting and reduced size. The advantage that the fiberscope seemed to have was that it would be the most flexible in terms of positioning. However, after a sample was sent to AEI for analysis with several of their packages, they strongly suggested the boroscope as a solution for our imaging needs. They felt that the magnification we required would result in compromising image degradation. This degradation was due to the fact that the image would be carried by a bundle of fiberoptic cables. As magnification is increased, each of these cables becomes more visible and the image is fragmented into partitioned areas defined by the individual fibers. This would make analysis virtually impossible. So, based upon the advice from AEI we selected an industrial boroscope.

4.2 ATTACHMENT TO THE EXISTING FDM SYSTEM

The next step attempted was a physical mount to the liquifier head. Again, it was considered imperative to maintain the isolated nature of the build chamber. By mounting an extra piece to the extrusion head, several new problems had to be faced. Since the head would be in motion, the possibility of vibration existed. At such a high level of magnification, even a small vibration can be enough to completely blur the image. In addition, problems of lighting and depth of field were of similar nature to those experienced in the previous static experiments.

The camera attachment to the liquifier head was considered carefully. Two possible locations to attach the camera are: to the carriage in which it rides on, and, to the cooling assembly. To preserve normal function of the machine, the second option of attaching the camera from the top surface of the cooling chamber was chosen. Primarily, this allowed an attachment which changed nothing in the existing FDM system when it was connected, Figure 1. It also gave easy access so the camera assembly could be quickly removed and replaced. Another benefit which was gained was the ability to remove the liquifier and replace it without changing anything of the video setup.

The physical implementation of the mount was two L shaped metal pieces, Figure 1. Sliding channels were left instead of simple screw holes to allow adjustment in the X, Y, and Z directions. This helps to avoiding precise measurements and calculations that would have had to be done in order to place the centerline of the camera exactly along the centerline of the nozzle. Finally, the camera is held firmly in a u-clamp which is mounted to the protruding L bracket (see Figure 1).

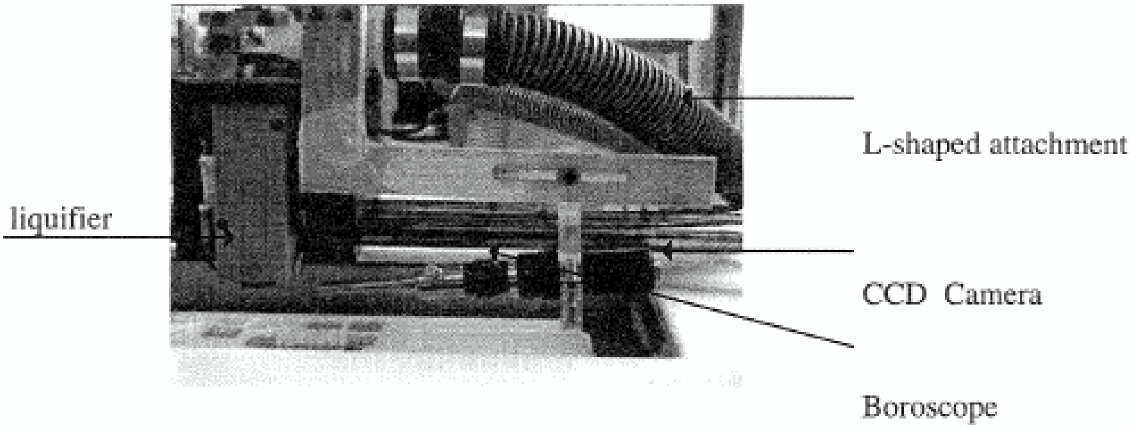


Figure 1: L-shaped mounting bracket with CCD camera

This setup provided a workable solution. One problem with this setup is that there is no way to focus the camera except by manually moving it towards or away from the object. With the small depth of field, this was extremely difficult. Another problem is that the camera and microscope combined are so long that they just barely fit into the confines of the build chamber. This left us only enough room for a quarter inch wide part at the very corner of the build platform. Since the part was so small, the inner contours were such as to require sharp and rapid turning. The vibration induced from this repeated cornering was too much. As shown later on the videos taken, all of the sequences were blurry. Long roads parallel to the camera, however, could be observed.

With minor modifications to the existing implementation, we were able to adapt it to the new hardware, with an attachment that reduced significantly the vibration problem (see Figure 2). The benefits which the boroscope had over our previous equipment was its reduced size, a focusing ring, and an integrated fiber-optic lighting system. This allows a direct beam of high intensity light to be focused on our area of interest.

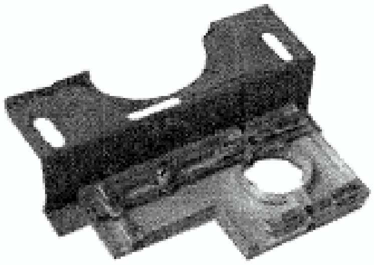


Figure 2: L-shape mounting bracket with camera

The modified set up (see Figure 3) proved to be more efficient and exhibited less vibration than the previous set up.

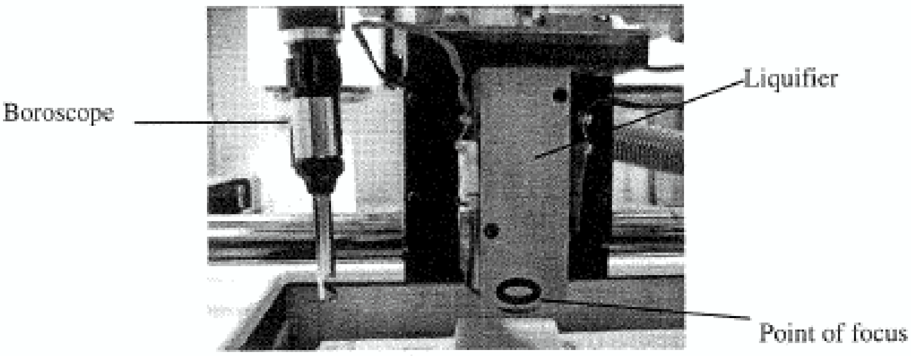


Figure 3: Final set up with attachment #2

As far as calibration, it is impractical to place a scale at the point of focus during operation allowing us to have every frame calibrated automatically by the software on hand. Therefore, another method was sought. The problem was expected to be solved by using the nozzle as a reference. Because the nozzle size is known exactly, it would be an easy reference point to look at in each frame. However, in most of the videos the nozzle is obscured by material build up. It is unclear whether or not the entire bottom of the nozzle is visible, or if some is being obscured by material. What is being done to overcome this is to capture visual data on the nozzle size before the build begins. These initial frames can then be used to calibrate the ones that will follow. In addition, a ruler with 1/16" markers were recorded and the scale factor was computed. These markers were quantified within 5% error. This calibration scheme implies that the results are accurate to ±75 μm.

4.3 QUANTIFICATION:

For analysis and quantification, we are using HL Image software which has several useful capabilities. First and foremost, images can be calibrated using a scale image. Thus, we are able to measure distances and feature sizes directly from the images with good accuracy. It also has a "blob analysis" function, which discerns areas of different coloration. In images of high contrast, this can be very helpful since voids can be "automatically" detected and quantified.

5.0 EXPERIMENTATION:

Experiments were conducted with the modified hardware in an attempt to quantify several aspects of the tool path parameters such as the road shape and road interaction. In these experiments, the voids were intentionally created by using positive offsets. We held the nozzle size constant at 15 mil, the road width at 20 mil, the height at 10 mil and the build speed at ½" per second. Then, video sequences of builds being performed with offsets of 0 mil, -4 mil, and +4 mil were recorded. Experiments were conducted with silicon nitride, PZT and wax materials.

An experiment with 5 mil road height on PZT material was for the same set of tool path parameters.

6.0 ANALYSIS:

6.1 GENERAL OBSERVATIONS:

Various experiments were conducted with wax, silicon nitride and PZT materials. Due to the natural shine of wax, it is very difficult to distinguish each layer under a light source.

To investigate the vibration problem, the machine was allowed to build two parts without the camera. These were compared with the images obtained with the ones produced while recording with the video camera mounted on the machine. Direct visual comparison and inspection revealed that the set up was not disturbing the normal building process. Stacking of the rows and inclination angle was almost identical in both image. Under the light of a micro-camera set up interesting information can are gathered. Several factors were evaluated. They are road shape, bead shape, nozzle location, voids recurrence and alignment of the beads.

6.2 SILICON NITRIDE EXPERIMENTS:

Initially, the frames captured from the video on Silicon Nitride revealed rows slightly inclined. The location of the deposited road was changing from layer to layer. The adjacent road shape was altered as new road was deposited for negative offset. Using HL Image software, a point of reference was drawn in one of the frames at the beginning of the process. Looking at successive frames with respect to the point drawn, the nozzle appeared to be in a different location each time it deposited a bead on top of a previous one, creating the alignment problem (Figure 4).

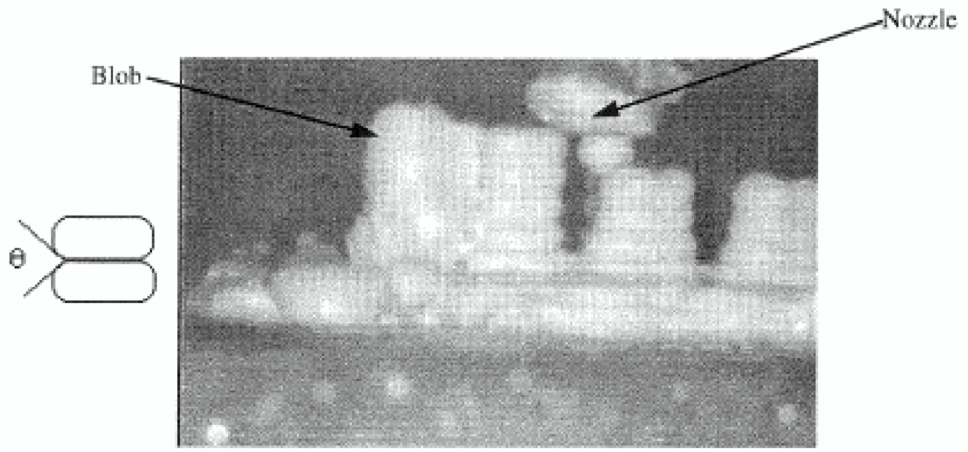


Figure 4: Silicon Nitride +4 mil Offset Layered Fabrication
(Inclination is due to camera misalignment)

When the deposition process begins, in the current set-up a blob of material is deposited for approximately 3 seconds before the nozzle moves, Figure 4. This blob corresponds to a start error in the process. However, at the end of each layer there is no blob. The nozzle finishes up clean.

An enlarged image of the stack of 10 rows was analyzed to determine the inclination angle θ between the adjacent layers. This angle of inclination θ was computed to be 80 ± 1.2°. In a parallel study, direct measurements were obtained (on cross-sections of 2-2 plates of PZT fabricated by some hardware) using optical micrograph[3]. The inclination angles for PZT under the similar set-up were 80±13°. These two results are in agreement, and they are hardware dependent & independent of material properties.

With the aid of HL Image information on the size and shape of the beads was also obtained. Seven captured frames at random locations and layers, were analyzed and tabulated.

Table-1 Deposited Silicon Nitride Road Width & Height

	CAD	-4 mil Offset	0 mil Offset	+4 mil Offset
Road width(mil)	20	23.29 ± 2.28	21.88 ± 1.35	27.76 ± 1.30
Road height(mil)	10	13.87 ± 0.76	14.06 ± 0.89	17.23 ± 1.65

Table-2 Results of Void Creation in Silicon Nitride Parts

	-4 mil Offset	0 mil Offset
Void Area(mil^2)	0	60.06 ±39.16
Equivalent Diameter(mil)	0	7.74 ± 4.20

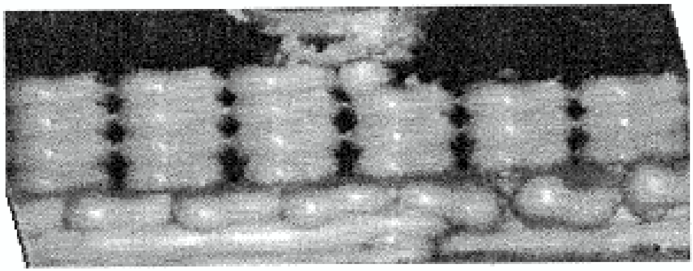


Figure 5: Silicon Nitride 0 mil offset Layered Fabrication

The shape of the deposited road was a truncated ellipse, Figure 5. The width of the deposited roads was slightly larger than what was set by CAD, Table-1. The road height was larger than the set road height, implying that there is a swelling in the vertical direction. Table-2 shows that -4 mil offset eliminated voids, a perfect part was created. With 0 mil offset, the void size was 7.74±4.20 mil diameter.

6.3 PZT EXPERIMENTS:

Again, seven frames were captured for each offset and compared against the values set by the hardware. For each of the PZT off sets, the bead size was quantified with HL Image software and a calibrated image. The results are tabulated below.

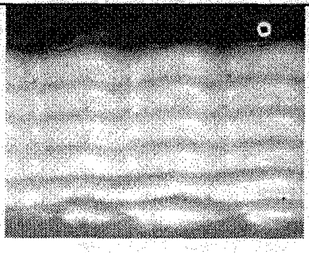
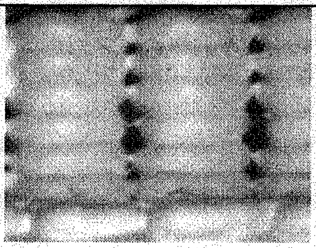
Table 3: Deposited PZT Road Width & Height

CAD Setup		-4 mil Offset	0 mil Offset	+4 mil Offset
Road width(mil)	20.00	19.71 ± 1.20	19.60 ± 1.60	19.94 ± 2.00
Road Height(mil)	10.00	13.71 ± 1.30	14.39 ± 1.35	11.56 ± 0.75

The results from Table-3 indicate that the road width deposited was close to what was set by CAD, with an error of about 10%. Whereas, the road height was always greater than what was set by CAD. This implies that the material was swelling in the vertical direction.

The last aspect to quantify is the voids present in between roads. The entire void area accounts significantly for the defects created in the parts built by the FDM machine. Again, using HL Image software, the void areas were quantified as follows:

Table-4 Results of Voids Creation in PZT Parts

	-4 mil Offset	**0 mil Offset**
Void Area(mil^2)	1.52±2.37	40.58± 23.90
Equivalent Diameter(mil)	1.39	7.19
Video Microscopy Image		

In the case of +4 mil offset the void/gap area is largest as expected. However, this is not an error of the process. This gap area is due to a predetermined offset between roads. When looking at the negative offset, the void area is almost negligible compared to the area of the road width. This makes the negative offset part almost void free. However, the zero off set gives a 7.19 mil diameter void size. For the current PZT processing set-up, it appears that for a 15mil nozzle with 20mil road width & 10mil height and -4 mil offset, void occupied less than 5% of the area. Finally, for both PZT & Silicon Nitride materials, the void sizes are very similar.

7. CONCLUSIONS:

Video microscopy experiments demonstrated that imperfections in the process can be detected, analyzed and quantified. This study demonstrated that we can make void free parts by selecting appropriate toolpath parameters. Plus this investigation helped us quantify how and when the voids can occur, and this data is useful in making virtual layered manufacturing simulation more realistic.

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