# Freeform Extrusion of High Solids Loading Ceramic Slurries, Part II: Extrusion Process Control

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**ABSTRACT**

Part I of this paper provided a detailed description of a novel fabrication machine for high solids loading ceramic slurry extrusion and presented an empirical model of the ceramic extrusion process, with ram velocity as the input and extrusion force as the output. A constant force is desirable in freeform extrusion processes as it correlates with a constant material deposition rate and, thus, good part quality. The experimental results in Part I demonstrated that a constant ram velocity will produce a transient extrusion force. In some instances the extrusion force increased until ram motor skipping occurred. Further, process disturbances, such as air bubble release and nozzle clogging that cause sudden changes in extrusion force, were often present. In this paper a feedback controller for the ceramic extrusion process is designed and experimentally implemented. The controller intelligently adjusts the ram motor velocity to maintain a constant extrusion force. Since there is tremendous variability in the extrusion process characteristics, an on-off controller is utilized in this paper. Comparisons are made between parts fabricated with and without the feedback control. It is demonstrated that the use of the feedback control reduces the effect of process disturbances (i.e., air bubble release and nozzle clogging) and dramatically improves part quality.

## 1. INTRODUCTION

As described in Part I of this paper the material flowrate of high solids loading ceramic slurry extrusion is slow when compared to other incompressible fluid flows such as water [1]. Therefore a long period of time is required to reach the desired extrusion force. Applying a high ram velocity increases the extrusion force rapidly; however, due to compression effects, the extrusion force increases at an exponential rate eventually causing the motor to "skip." This is an undesirable effect due to inconsistent deposition and possible ram motor damage. In this study a ram motor that can apply forces up to 2.2 *kN* before skipping occurs was utilized. An encoder, which is integrated into the motor, allows for position and velocity feedback data.

From the literature reviewed by the authors, a feedback control system has never been implemented in a ceramic extrusion process during the deposition stage. Feedback control was implemented prior to deposition during the mixing stage, by adding organic binder, acidic, or basic chemicals to change the ceramic slurry properties such as density and viscosity, thereby modifying deposition results [2]. Russell [3] did a significant amount of testing examining effects of process parameters and applying statistical process control (SPC) with plans to implement it towards feedback control. Pressure predication has also been an area of interest towards the future implementation of feedback control. Application of neural networks has been applied for a range of materials in order to produce a good model predictor [4].

The authors have taken a different approach towards feedback control of the ceramic extrusion process. In order to obtain good material deposition and avoid a large period of time necessary to reach the steady-state extrusion force, an on/off controller has been implemented into the Freeze-form Extrusion Fabrication (FEF) system. Deposition tests are conducted and force data is analyzed for effects of constant ram velocity versus variable ram velocity. Parts that have been fabricated with and without the extrusion force controller are examined, comparing material deposition and surface roughness.

## 2. EXTRUSION FORCE CONTROLLER DESIGN

The goal for material deposition in high solids loading ceramic extrusion processes is for smooth, constant material flow. Material flowrate was determined to be directly related to the extrusion force (see Part I of this paper). For a constant ram velocity, the flowrate is transient. To achieve more consistent material extrusion a flowrate controller was designed and implemented. The feedback controller uses the extrusion force reading from a load cell to automatically adjust the ram velocity and maintain a constant extrusion force.

The flowrate response of a high solids loading ceramic extrusion process is slow. It is undesirable to wait for the system to reach a steady-state extrusion force by applying a low ram velocity. Since extrusion force is directly related to ram velocity, a larger ram velocity will increase the extrusion force. However, the ram extrusion motor can only apply forces up to 2.2 *kN* before it "skips" in order to reduce the torque being applied by the motor. After skipping, there is a drastic decrease in extrusion force, and a period of time is required to recompress the material and achieve the desired extrusion force. Due to this hardware limitation, a force limit must be set where the ram velocity is reduced before the motor reaches the skipping level.

An on/off controller was implemented in order to maintain a constant extrusion force. The controller adds an extra initial level for feedback checks as compared with just two levels in a regular on/off controller. Three force levels and three ram velocities are used in the control algorithm. Figure 1 illustrates the on/off control algorithm. The three levels of the force controller are ramp force $F_r$, lower-bound force $F_l$, and upper-bound force $F_u$. The ram velocities are ramp velocity $v_r$, lower-bound velocity $v_l$, and upper-bound velocity $v_h$. The ramp force ($F_r$) is fixed during operation at a level approximately 90 *N* below the desired force ($F_d$), but can be changed to different values. Deposition during this time period is inconsistent and slow when compared to deposition when the extrusion force is at the desired value. Section I of Figure 1 shows the ramp force ($F_r$) and the ramp velocity ($v_r$). The extrusion process begins with the ram velocity set to $v_r$. After the ramp force is reached the extrusion force is still not at the desired level; however, it is still undesirable to operate the ram at a constant velocity to achieve the desired extrusion force. An extrusion force range (i.e., upper and lower force bounds) is chosen that corresponds to an acceptable flowrate variation. This level is set to +/- $\delta$ *N* of the desired force. This force range can be changed, which is necessary due to variations in slurry viscosity from batch to batch. Due to variations in slurry preparation by different individuals there is a variation in slurry viscosity from "thinner" to "thicker." The thinner slurries should have a lower $\delta$ value due to a faster response to the ram velocity. The thicker slurry tends to flow at a slower rate thereby reacting to the ram velocity at a slower rate allowing for a larger $\delta$ value. The lower-bound ram velocity ($v_l$), which is slower than the ramp velocity, is applied when the ramp force ($F_r$) is reached. This lower velocity allows for the ram to reach the desired force without causing the ram motor to skip. The implementation of these force limits and varying ram velocities reduce the time required to reach steady-state to 15–30 seconds, depending on the desired force, as compared to 13–60 minutes necessary when using a constant ram velocity.

The last two ranges of operation are the acceptable material deposition range and the upper range in which the material flowrate is too fast for good deposition. The acceptable deposition range is when the extrusion force is between the lower and upper limits. If the extrusion force goes above the upper force ($F_u$), the ram velocity changes to $v_h$ in order to reduce the extrusion force, by allowing the material to decompress while continuing to flow through the nozzle. Depending upon several factors such as slurry viscosity and desired force, $v_h$ does not have to be 0. As was shown in Part I, depending upon the desired extrusion force a value of 0 for $v_h$ may cause the extrusion force to decrease too quickly. In situations such as this a higher $v_h$ value is chosen so that the extrusion force decreases at a slower rate. Sections III-V in Figure 1 show how the controller chatters between the upper and lower bounds of the extrusion force. There is a delay in the flowrate due to the slow system response to ram velocity inputs.

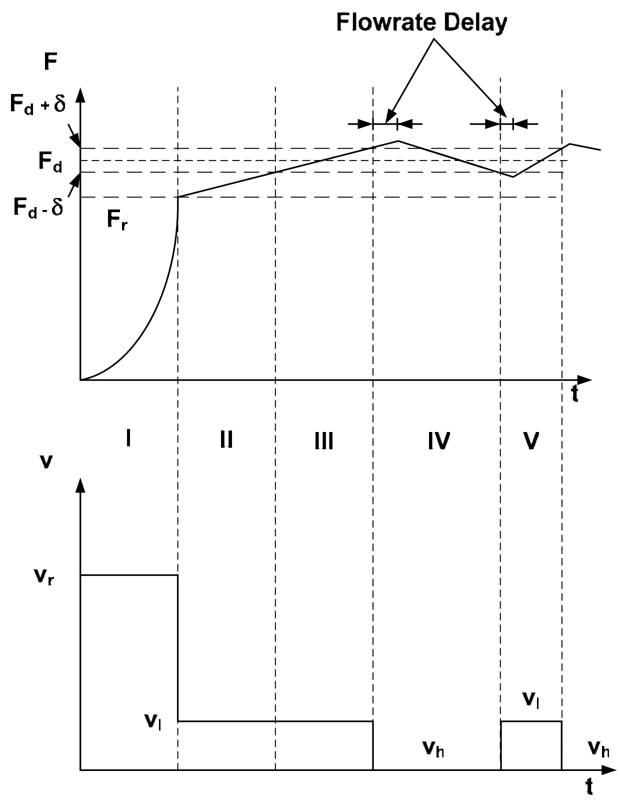


**Figure 1: Flowrate controller force levels with corresponding ram velocities.**

The controller operates at a user defined rate, but is generally chosen to be 5 *Hz*. This is faster than the system is able to react, as previously discussed. This rate was chosen to speed up the reaction to the internal system disturbances (i.e., air bubble release and agglomerate breakdown). Depending on the nozzle diameter, the air bubble release can cause large force reductions between 25 *N* for the 190 $\mu m$ diameter nozzle and up to 450 *N* for the 580 $\mu m$

diameter nozzle. The agglomerate breakdown is on a smaller scale and is independent of the nozzle diameter.

Two other inconsistencies occur during material deposition, underfilling and overfilling. Underfilling is internal voids or gaps between points of material deposition. Overfilling is when excess material is deposited. Both of these are undesirable as they produce poor part quality either by creating unacceptable part porosity or poor surface finish. An additional problem with underfilling and overfilling is that they both lead to further problems as deposition continues. With underfilling, the gaps that are created lead to gaps in the following layers that are above the gaps. This leads to overfilling as the material that is not deposited builds up on the nozzle and attaches to the next point where a gap in deposition is not present on the previous layer. Overfilling that occurs at any point during deposition will lead to material buildup on the nozzle during deposition of future layers. With the excess material present on the nozzle, material previously deposited attaches during motion over previous layers. This causes gaps in previously deposited layers. Practical examples of both underfilling and overfilling will be shown later.

## 3. RESULTS

To verify that the described extrusion force controller improves material deposition, several single-line material deposits were made. The lines were 50 *mm* in length, using a table speed ($v_t$) of 25 *mm/s* and a 580 *µm* diameter nozzle. The first set of lines were deposited using a constant ram velocity (Figure 2). The second set of lines were deposited using the extrusion force controller (Figure 3).

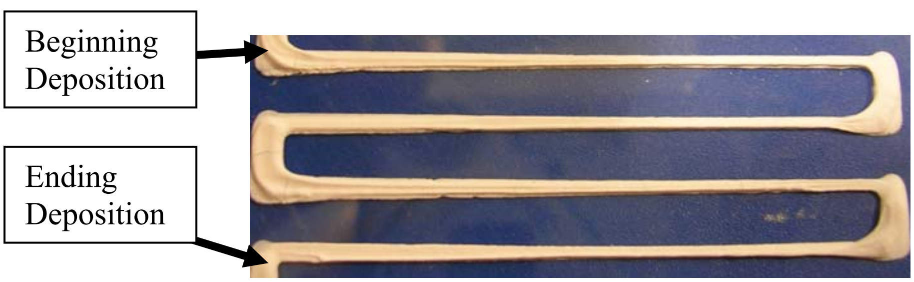


**Figure 2: Deposition lines using constant ram velocity ($v$ = 0.5 *µm/s*). Table speed is 25 *mm/s* and nozzle diameter is 580 *µm*.**

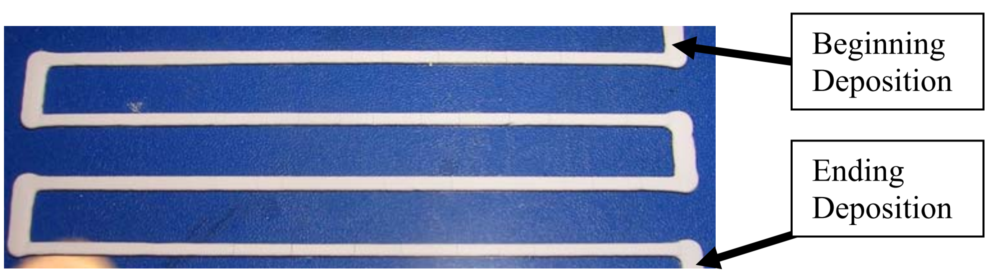


**Figure 3: Deposition lines using the extrusion force controller. Table speed is 25 *mm/s* and nozzle diameter is 580 *µm*.**

By examining Figure 2 it can be seen that the material does not deposit in a constant fashion. The width of the lines varies significantly. Figure 4 shows the ram velocity and extrusion force time history corresponding to the lines deposited in Figure 2. Although the ram velocity is constant the extrusion force continually changes during the entire extrusion process, causing inconsistent line width.

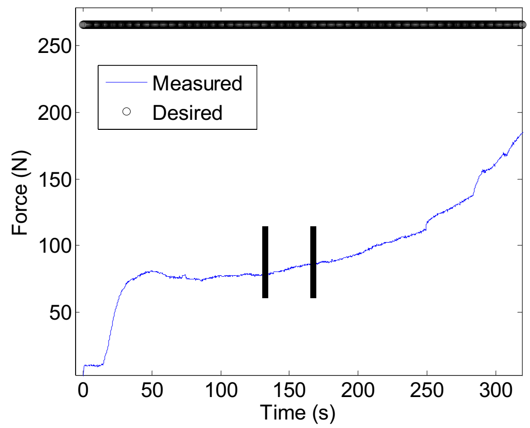


**Figure 4: Extrusion force time history for lines deposited in Figure 2 ($v$ = 0.5 $\mu m/s$). Vertical lines indicate the beginning and ending of line deposition shown in Figure 2.**

By repeating the same deposition test but using the flowrate controller it can be seen from Figure 3 that the material deposition is much more consistent. In order to keep the test comparison as objective as possible the same environmental conditions (temperature, humidity, etc.) were maintained in both experiments as well as nearly the same amount of ceramic slurry left in the material reservoir. A reference force of 613 $N$ and a $\delta$ value of 0 were given for the on/off controller. The reference force of 613 $N$ was chosen to show the ability of the controller to reach a desired extrusion force rapidly as compared to the application of a constant ram velocity. The $\delta$ value of 0 was chosen because it causes the most rapid reaction to a change in the extrusion force, thereby keeping the most constant extrusion force. Figures 5 and 6 show the ram velocity and extrusion force time history corresponding to the lines deposited in Figure 3. It should be noted that the extrusion force controller commands a ram velocity based on the extrusion force measured from the previous time period. Figure 6 shows this more clearly by zooming in on the portion between 114 and 120 seconds.

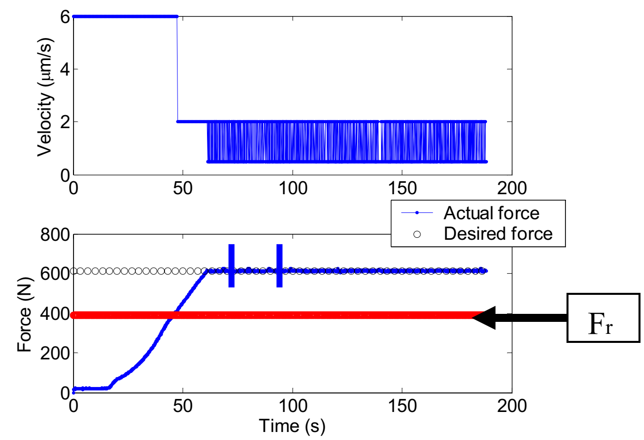


**Figure 5: Ram velocity and extrusion force time history for lines deposited in Figure 3. Vertical lines indicate the beginning and ending of line deposition shown in Figure 3.**

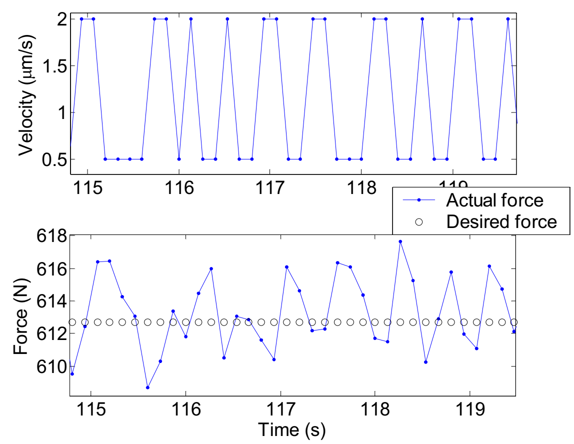


**Figure 6: Zoomed in portion of Figure 5.**

In another experiment, two bars were fabricated, one with a constant ram velocity and the other with the extrusion force control. Figures 7 and 8 show pictures of the fabricated bars. As can be seen the deposition is very poor when a constant ram velocity is utilized. Figure 9 shows the extrusion force time history for the fabricated part with a constant ram velocity. The extrusion force is very inconsistent during the part building process due to system disturbances as mentioned in Part I of this paper such as agglomerate breakdown. The same bar was fabricated in a separate experiment using the same input parameters (e.g., standoff distance, table velocity, horizontal and vertical shifts) except that the extrusion force controller was implemented instead of a constant ram velocity. By comparing the test bars in Figures 7 and 8 it can be seen that the fabrication process is dramatically improved when the extrusion force controller is implemented. Figures 9-11 show the ram velocity and extrusion force time history for the bar fabricated with the extrusion force controller. A reference force of 266 *N* was chosen due to successful results in previously fabricated parts. The δ was once again chosen as 0 for a quick reaction to disturbances during the extrusion process. As discussed in Part I of this paper the nozzle tends to clog if a constant ram velocity is used for an extended period of time. The cause of this is material drying in the die length of the nozzle, thereby reducing the nozzle diameter and eventually causing clogging. By constantly changing the ram velocity the nozzle does not clog. This is believed to be due to variational forcing of the material in the die length of the nozzle. This variation loosens any dried material attached to the nozzle allowing for it to be extruded. This phenomenon is similar to dithering applied to motion systems to overcome the effects of static friction.

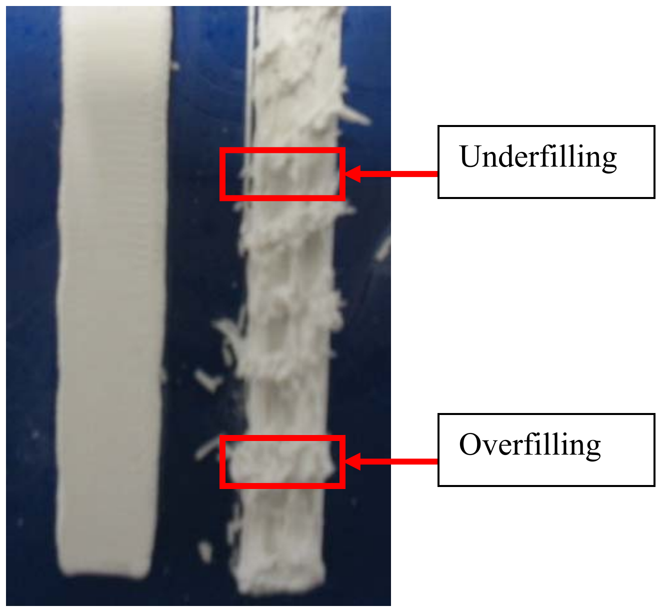


**Figure 7: Top view of bars fabricated using extrusion force controller (left) and constant ram velocity (right, $v = 2\ \mu m/sec$).**

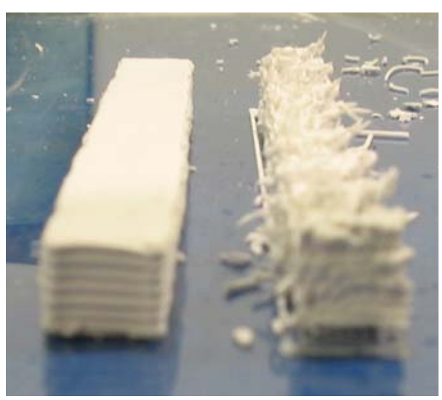

**Figure 8: Side view of bars fabricated using extrusion force controller (left) and constant ram velocity (right, $v = 2\ \mu m/sec$).**

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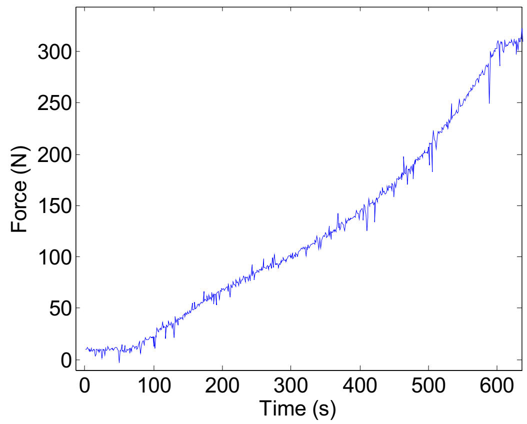


**Figure 9: Extrusion force time history for test bar made with constant ram velocity (2 *μm/sec*).**

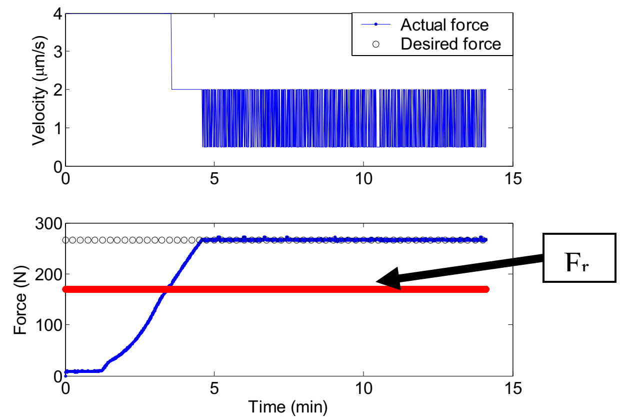


**Figure 10: Ram velocity and extrusion force time history for bar fabricated with extrusion force controller.**

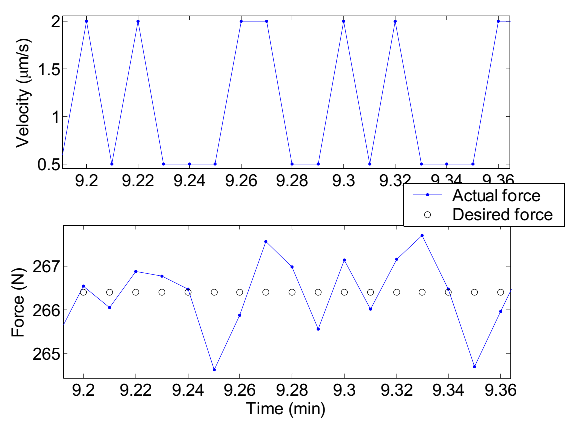


**Figure 11: Zoomed-in portion of Figure 10.**

## 4. PART FABRICATION

Several parts have been fabricated to demonstrate the feasibility of the developed FEF process and the utility of the extrusion force controller. Figures 12–15 show examples of some of the built parts and illustrate the feasibility of the FEF process to make ceramic parts of varying geometries. Figure 12 shows hollow cone and cylindrical geometries. The cones have a sloped wall build angle of $60^o$. The two unfinished cone pairs show the ability of the FEF process to build geometries with sloped walls without the use of support material. This is possible due to the high solids loading of the ceramic slurry (50 vol.% >). Figure 13 shows two different thin-wall (i.e., single-line) polygonal shapes. There is a buildup of material at the corners due to acceleration/deceleration effects. Tests have been run building thin-wall (single-line) deposited geometries up to a height of 180 *mm* without the part collapsing. The material has the ability to build taller geometries but, due to limitations of the Z-axis motion, 180 *mm* is currently the machine's maximum build height. Figure 14 shows ogive hollow cones after freeze drying. The fabrication of all of these parts was made possible by the utilization of the extrusion force controller, without which good consistent material deposition is not possible.

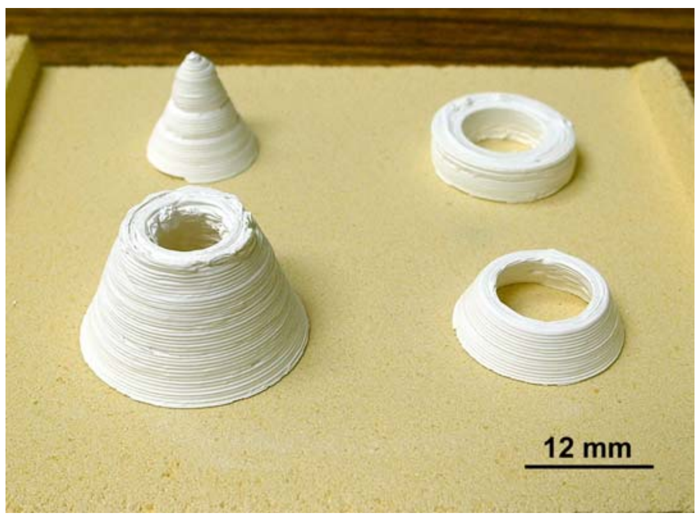


**Figure 12: Hollow cones and cylinder (after sintering) fabricated with the extrusion force controller.**

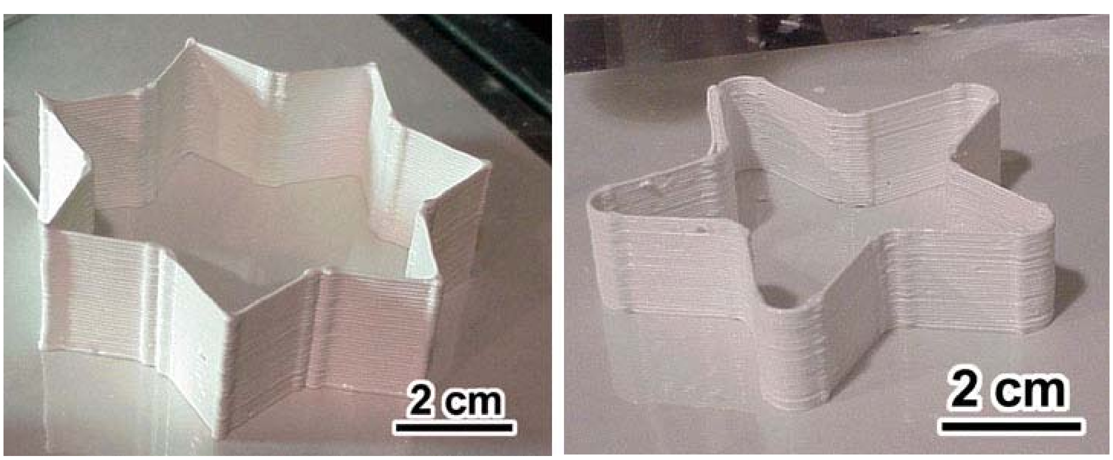


**Figure 13: Thin wall polygonal parts (before binder burnout and sintering) fabricated with the extrusion force controller.**

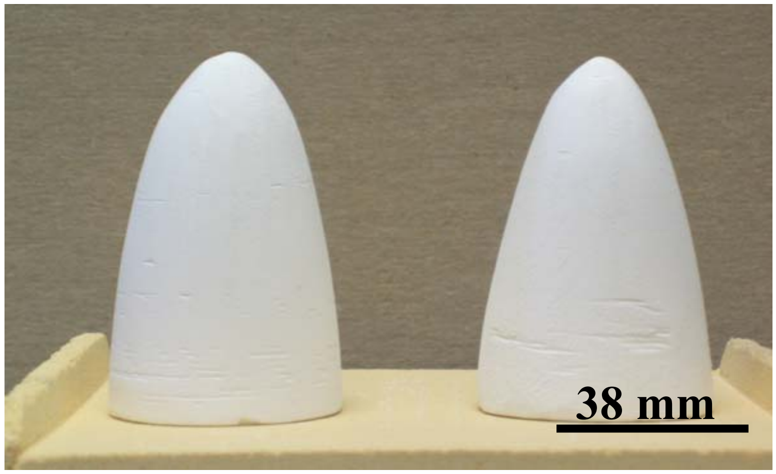


**Figure 14: Hollow ogive cones (after surface finishing) fabricated with the extrusion force controller.**

## 5. SUMMARY AND CONCLUSIONS

An on/off feedback controller was designed for improved material deposition. Deposition tests were conducted comparing the deposition consistency and extrusion force with and without the extrusion force controller. Several parts were made with and without the extrusion force controller and the surface finish of these parts was compared.

Successful fabrication of parts is not possible without the use of an extrusion force controller. The implementation of the extrusion force controller allows for quick compensation of system disturbances that cause changes in extrusion force. Without the use of feedback control, periodic poor material deposition leads to future deposition problems. Application of a constant ram velocity for material deposition leads to a continuous increase in extrusion force.

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