AFRL-ML-WP-TP-2006-442

FREEFORM EXTRUSION OF HIGH SOLIDS LOADING CERAMIC SLURRIES, PART II: EXTRUSION PROCESS CONTROL (PREPRINT)

Michael S. Mason, Tieshu Huang, Robert G. Landers,
Ming C. Leu, and Gregory E. Hilmas

JULY 2006

Approved for public release; distribution is unlimited.

STINFO COPY

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YY)* July 2006	**2. REPORT TYPE** Conference Paper Preprint	**3. DATES COVERED *(From - To)***

4. TITLE AND SUBTITLE FREEFORM EXTRUSION OF HIGH SOLIDS LOADING CERAMIC SLURRIES, PART II: EXTRUSION PROCESS CONTROL (PREPRINT)	**5a. CONTRACT NUMBER** FA8650-04-C-5704 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 78011F
6. AUTHOR(S) Michael S. Mason, Robert G. Landers, and Ming C. Leu (University of Missouri-Rolla/Department of Mechanical and Aerospace Engineering) Tieshu Huang and Gregory E. Hilmas (University of Missouri-Rolla/Department of Materials Science & Engineering)	**5d. PROJECT NUMBER** 2510 **5e. TASK NUMBER** 00 **5f. WORK UNIT NUMBER** 00
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Materials Science & Engineering, and Department of Mechanical and Aerospace Engineering 1870 Miner Circle University of Missouri-Rolla, Rolla, MO 65409–0050	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Materials and Manufacturing Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson AFB, OH 45433-7750	**10. SPONSORING/MONITORING AGENCY ACRONYM(S)** AFRL-ML-WP **11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)** AFRL-ML-WP-TP-2006-442

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

This work, resulting in whole or in part from Department of the Air Force contract FA8650-04-C-5704, has been submitted for publication in the 2006 Freeform Fabrication Symposium Proceedings. If this work is published, the publisher may assert copyright. The United States has for itself and others acting on its behalf an unlimited, paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the Government. All other rights are reserved by the copyright owner.

PAO Case Number: AFRL/WS 06-1753, 13 Jul 2006. Paper contains color.

14. ABSTRACT

Part I of this paper provided a detailed description of a novel fabrication machine for high solids loading ceramic slurry extrusion processes and presented an empirical model of the ceramic extrusion process, viewing ram velocity as the input and extrusion force as the output. A constant extrusion force is desirable as it correlates with a constant material deposition rate and, thus, good part quality. The experimental results used to construct the model demonstrated that a constant ram velocity will not necessarily produce a constant extrusion force. In some instances the extrusion force increased until ram motor skipping occurred, and process disturbances, such as air bubble release and nozzle clogging, 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 model, an on-off controller is utilized in these studies. Comparisons are made between parts fabricated with and without feedback control. It is demonstrated that the use of intelligent feedback control reduces the effect of process disturbances (i.e., air bubble release and nozzle clogging) and dramatically improves part quality.

15. SUBJECT TERMS Ceramic, slurry, extrusion, freeform

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	18	Mary E. Kinsella
Unclassified	Unclassified	Unclassified			**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

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

Michael S. Mason[1], Tieshu Huang[2], Robert G. Landers[1],
Ming C. Leu[1], and Gregory E. Hilmas[2]

1870 Miner Circle
Department of Mechanical and Aerospace Engineering[1]
Department of Materials Science and Engineering[2]
University of Missouri at Rolla, Rolla, Missouri 65409–0050
{mmason,hts,landersr,mleu,ghilmas}@umr.edu

ABSTRACT

Part I of this paper provided a detailed description of a novel fabrication machine for high solids loading ceramic slurry extrusion processes and presented an empirical model of the ceramic extrusion process, viewing ram velocity as the input and extrusion force as the output. A constant extrusion force is desirable as it correlates with a constant material deposition rate and, thus, good part quality. The experimental results used to construct the model demonstrated that a constant ram velocity will not necessarily produce a constant extrusion force. In some instances the extrusion force increased until ram motor skipping occurred, and process disturbances, such as air bubble release and nozzle clogging, 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 model, an on-off controller is utilized in these studies. Comparisons are made between parts fabricated with and without feedback control. It is demonstrated that the use of intelligent 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 requires a long period of time is required to reach the desired ram extrusion force. Applying a high ram velocity increases the extrusion force rapidly, but 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 part 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, also allows for position and velocity feedback data. Therefore, the data collection is more precise.

From the previous literature reviewed by the authors a feedback control system has never been implemented in a ceramic extrusion process during the deposition stage of the process [2-3]. Feedback control is currently implemented prior to deposition during the mixing stage. By adding organic binder, acidic, or basic chemicals the ceramic slurry properties such as density and viscosity are changed thereby modifying deposition results. Russell [3] did a significant amount of testing examining effects of process parameters and applying statistical process control (SPC) with plans to implement this towards feedback control at a future time. Pressure predication has also been an area of interest towards the future implementation of feedback control. Application of neural networks has been applied over a range of materials in order to produce a good model predictor [4]. The authors have taken a different approach towards feedback control of a ceramic extrusion process. In order to obtain good material deposition and avoid the 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 flowrate controller are examined, visually 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). For a constant ram velocity, the flowrate is not always constant. To achieve more consistent material extrusion a flowrate controller is designed and implemented in this paper. The feedback controller uses the extrusion force reading from a load cell to automatically adjust the ram velocity, to maintain a constant extrusion force.

The flowrate response of high solids loading ceramic extrusion processes is slow as compared to other non-compressible fluid flows [1]. 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 faster. 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 to 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 keep a constant extrusion force. The controller adds an extra initial level for feedback checks as compared with just the two in a regular on/off controller. Three force levels and three ram velocities are used in the control algorithm. Figure 1 shows a drawing of an example run of the on/off control. 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 initial force limit (F_r) is fixed during operation at a level approximately 90 *N* below the desired force, but can be changed to different values. Deposition during this time period is inconsistent and slow when compared to desirable extrusion force values. 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 limit is reached the extrusion force is still not at the desired level; however, it is still undesirable to operate the ram at the slow steady-state 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 +/- δ *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 from individual to individual there is a variation in slurry viscosity from “thinner” to “thicker.” The thinner slurries must have a much lower δ value due to a much faster response to the ram velocity. The thicker slurry tends to flow at a much slower rate thereby reacting to the ram velocity at a much slower rate allowing for a larger δ value. The lower-bound ram velocity (v_l), which is slower than the initial 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 stepper motor to skip. The implementation of these force limits and varying 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 limit (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 too quick of a force decrease. 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 extrusion force bounds given the keep ram velocities. There is a delay in the flowrate due to the slow system response to ram velocity inputs.

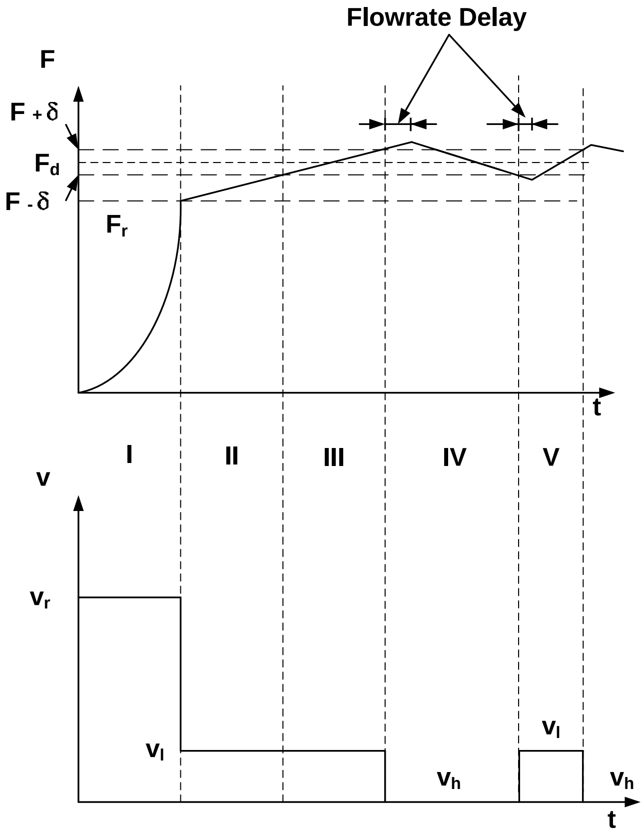

Figure 1: Flowrate controller force levels with corresponding ram velocities.

The controller operates at a user defined rate, but is generally chosen to be 5 *Hz*. This is much 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 μm diameter nozzle up to 450 N for the 580 μm diameter nozzle. The agglomerate breakdown is on a much 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 of 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 attaches to the next point that had proper deposition on the previous layer. Overfilling that occurs at any point during deposition will lead to material buildup on the nozzle during future layers of deposition. With the excess material present on the nozzle, material previously deposited attaches during motion over previous layers. This causes gaps in previously deposited layers. Examples of both underfilling and overfilling will be seen later in Figures 7 and 8.

3. RESULTS

To verify the extrusion force controller improves material deposition, several single line material deposits were made. The lines were 50 mm in length using a table speed of (v_t) 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).

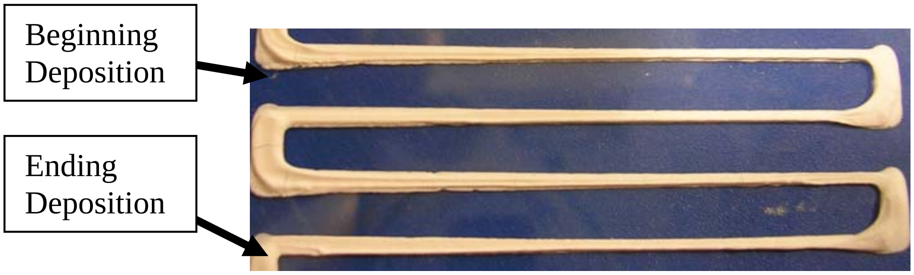

Figure 2: Deposition lines using constant ram velocity ($v = 0.5\ \mu m/s$).

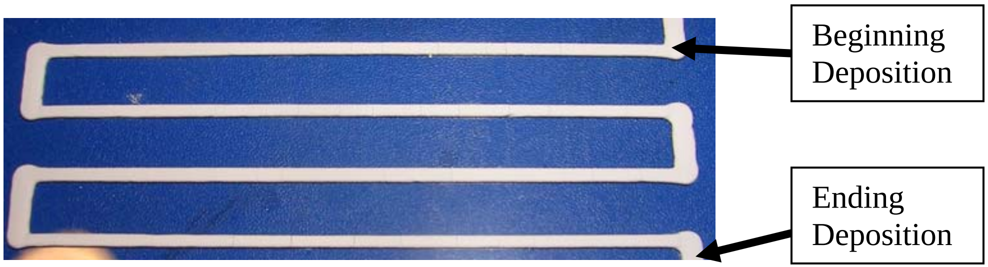

Figure 3: Deposition lines using extrusion force controller.

Examining Figure 2 it can be seen that the material does not deposit in a constant fashion. The width of the lines varies between thick and thin in different regions. 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.

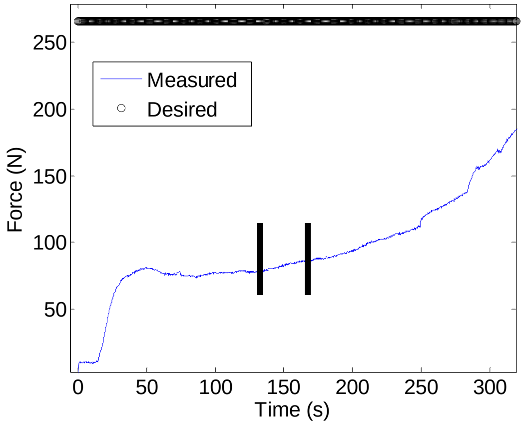

Figure 4: Extrusion force time history for lines deposited in Figure 2 ($v = 0.5$ $\mu m/s$). Vertical lines indicated beginning and ending of line deposition.

Repeating the same deposition test using the flowrate controller it can be seen from Figure 3 that the material deposition is much more constant. In order to keep the test comparison as similar as possible the same environmental conditions (temperature, humidity, etc.) were present in both experiments as well as nearly the same amount of slurry left in the material reservoir. A reference force of 260 N and a δ value of 0 were given for the on/off controller. The reference force of 260 N was chosen due to show the ability of the controller to reach a desired extrusion force rapidly when compared to application of a constant ram velocity. The δ 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 5-6 show the ram velocity and extrusion force time history corresponding to the lines deposited in Figure 3. It should be noted that the order of operation of the extrusion force controller is to command a ram velocity based on the extrusion force measured from the previous time period. Figure 6 shows this more clearly.

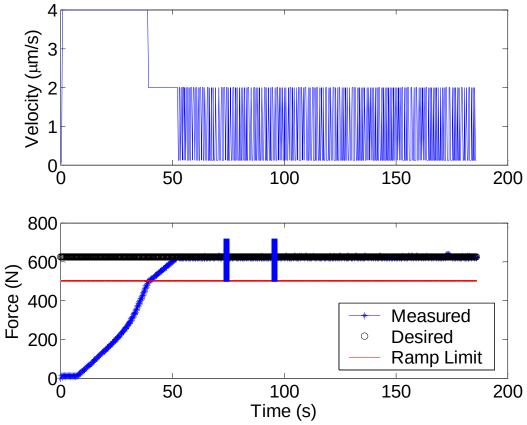

Figure 5: Ram velocity and extrusion force time history for lines deposited in Figure 3. Vertical lines indicate beginning and ending of line deposition.

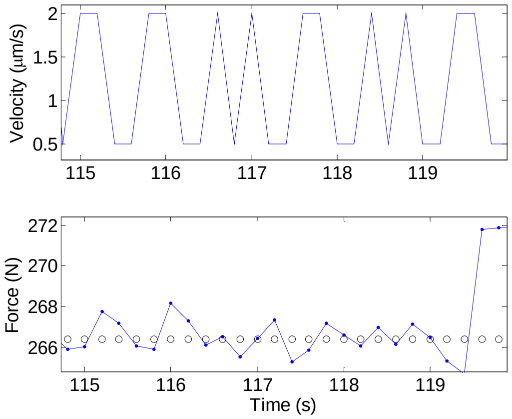

Figure 6: Zoomed in portion of Figure 5.

To see the effect of the inconsistent deposition highlighted between Figures 2 and 3, two bars were fabricated, one with constant ram velocity and one with extrusion 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 was 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 (standoff distance, table velocity, horizontal and vertical shifts) except the extrusion force controller was implemented instead of a constant ram velocity. Comparing the test bars in Figures 7 and 8 it can be seen that the fabrication process is dramatically improved when the extrusion controller is implemented. This is due to the fact that the extrusion force is maintained at a constant value. Figures 11 - 13 show the ram velocity and extrusion force time history for the bar fabricated with the extrusion force controller. A reference force of 260 N was chosen due to successful results in previously fabricated parts. The δ was once again chosen as 0 for a quick reaction to changes in the extrusion force. 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.

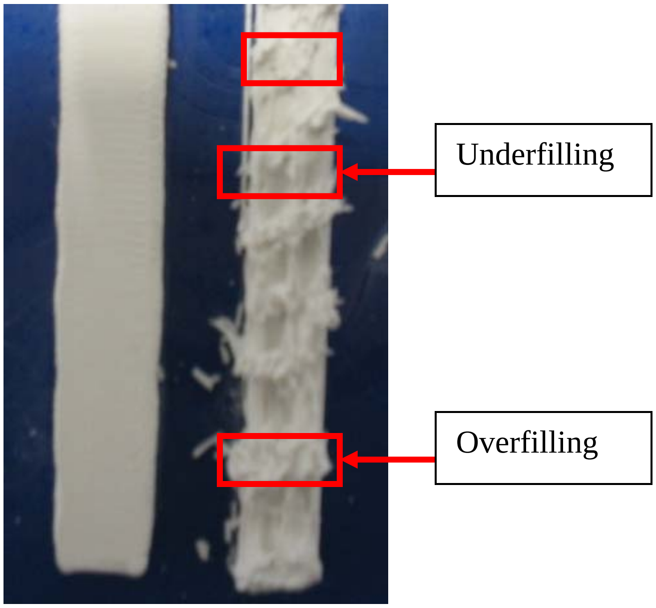

Figure 7: Top view of bars fabricated using extrusion force controller (left) and constant ram velocity (right, $v = 2\ \mu m/sec$).

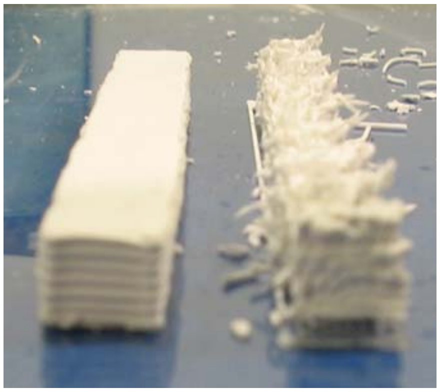

Figure 8: Side view of bars fabricated using extrusion force controller (left) and constant ram velocity (right, $v = 2\ \mu m/sec$).

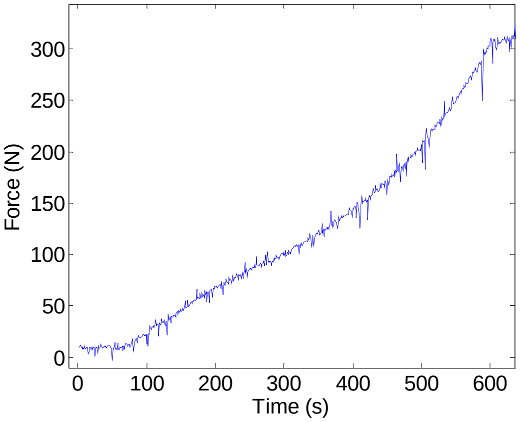

Figure 9: Extrusion force time history for test bar made with constant ram velocity ($2\ \mu m/sec$).

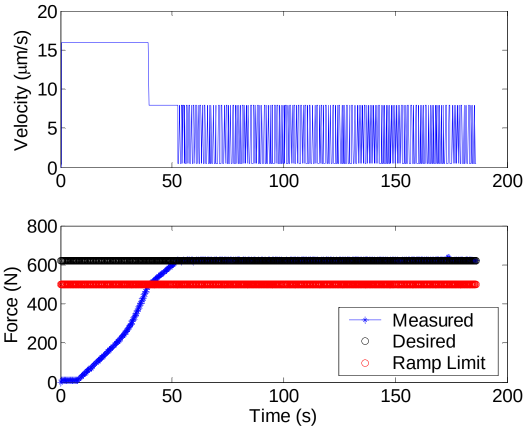

Figure 10: Ram velocity and extrusion force time history for bar fabricated with extrusion force controller.

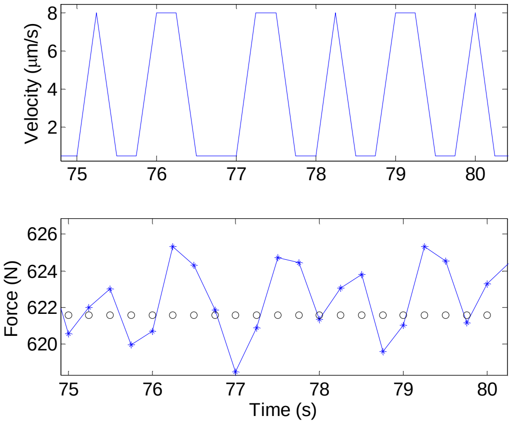

Figure 11: Zoomed in portion of Figure 10.

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 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 overhanging 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 (i.e., single line) wall 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 7 *in* without the part collapsing. The material has the ability to build taller geometries, but due to limitations of the Z-axis motion 7 *in* is the maximum build height currently. Figure 14 shows ogive hollow cones after freeze drying, the cone on the left was an initial investigation into the use of lubrication on the tip of the nozzle. The lubrication reduces material buildup on the nozzle thereby improving material deposition. The ogive cone on the right was fabricated without the use of lubrication. Different types of nozzle lubrications will be examined in the future. Figure 15 shows the same ogive cones after surface finishing. 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.

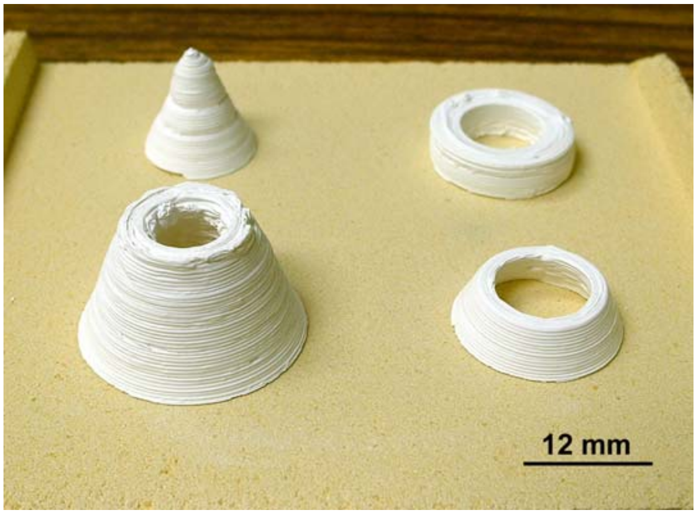

Figure 12: Hollow cones and cylinder (after sintering) fabricated with extrusion force controller.

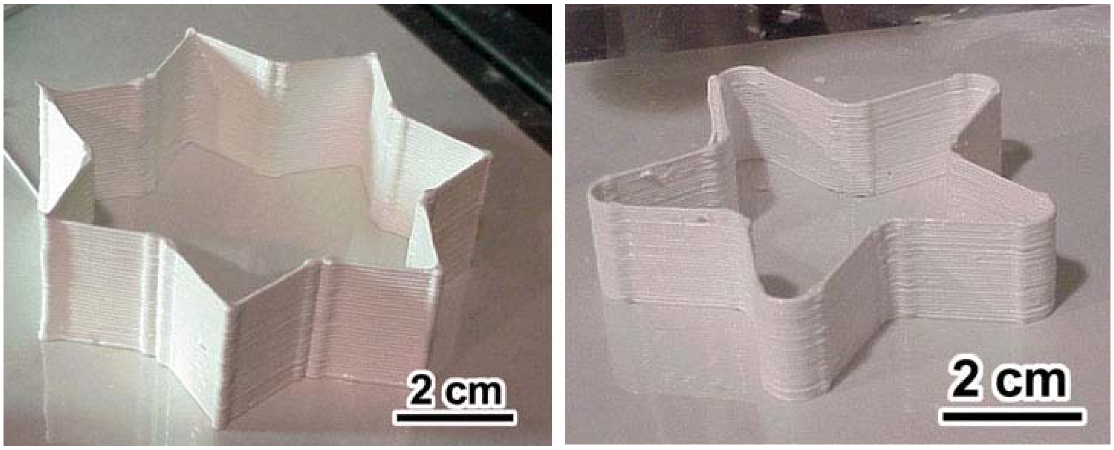

Figure 13: Thin wall polygonal parts (before binder burnout and sintering) fabricated with extrusion force controller.

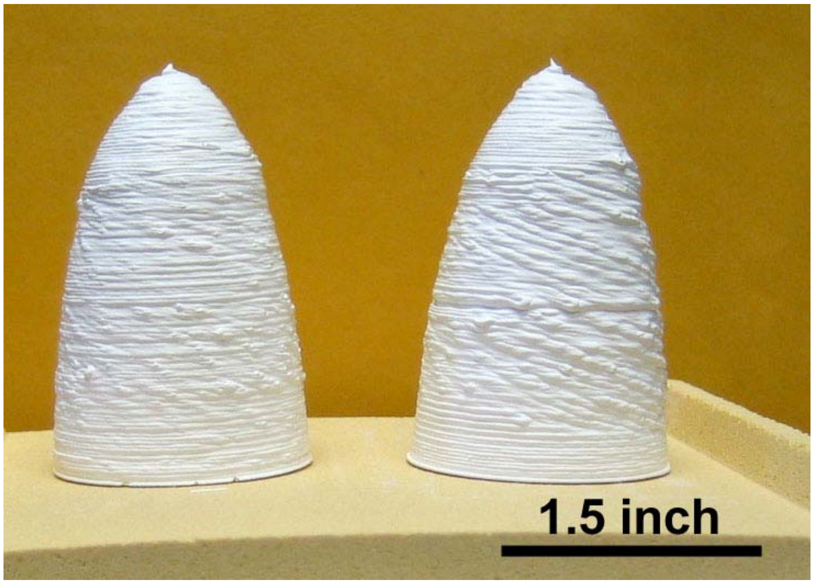

Figure 14: Hollow ogive cones (after binder burnout and before sintering) fabricated with extrusion force controller.

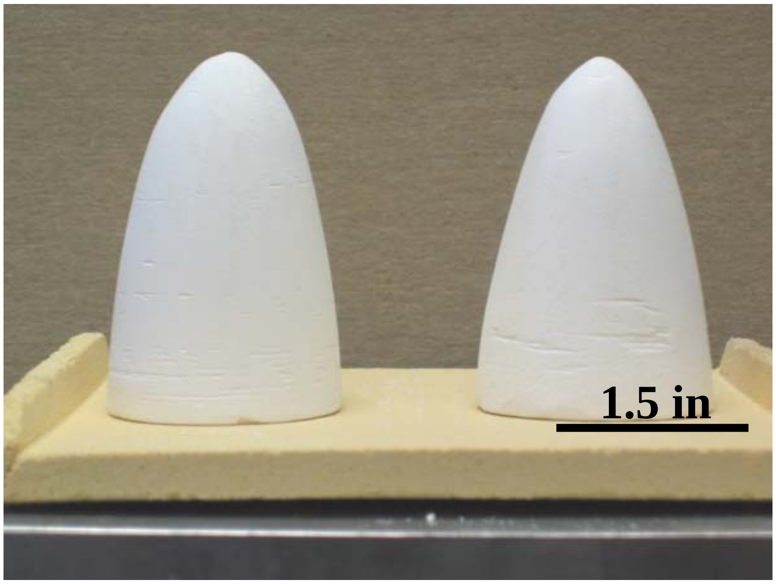

Figure 15: Hollow ogive cones from Figure 14 (after surface finishing) fabricated with extrusion force controller.

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. Mechanical test bar parts were made with and without the extrusion force controller and the surface finish 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 bad material deposition leads to future deposition problems due to a lack of consistent material deposition. Application of a constant ram velocity for material deposition leads to a continuous increase in extrusion force.

ACKNOWLEDGEMENTS

This work was supported by the Air Force Research Laboratory under Contract FA8650-04-C-5704. The authors would also like to thank Mike Hayes of Boeing for his technical support.

REFERENCES

1. M. Munson, D. Young, and T. Okiishi, *Fundamentals of Fluid Mechanics*, Third Edition, New York, John Wiley and Sons Inc., 462-468 (1998).
2. B. Russell, J. Lasenby, S. Blackburn, and D. Wilson, "Signal Processing for On-line Control of Paste Extrusion," *AICHE Annual Meeting Conference Proceedings*, San Francisco, California, November 16-21 paper 47d (2003).
3. Y. Li and J. Bridgwater, "Prediction of Extrusion Pressure Using an Artificial Neural Network," Powder Technology, Vol. 108, 65-73, (2000).
4. B. Russell, "Signal Processing for On-Line Control of Paste Extrusion," PhD Dissertation, Jesus College, Cambridge, England (2003).