

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE Technical Report		3. DATES COVERED (From - To) -	
4. TITLE AND SUBTITLE Dynamic Evolution of Acrylonitrile Butadiene Styrene (ABS) Subjected to High Strain Rate Compressive Loads			5a. CONTRACT NUMBER W911NF-12-1-0061		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 206022		
6. AUTHORS Alex Peterson, Ed Habtour, Jarek Riddick, Michael Coatney, Denzell Bolling, Gbadebo Owolabi			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Howard University 2400 6th Street, NW Washington, DC 20059 -0002			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 60436-EG-REP.7		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT The goal of the present investigation is to better understand the potential energy absorption benefits of components fabricated using fused deposition modeling additive manufacturing. Tensile test specimens were fabricated, according to the ASTM D638 standard, to characterize the general mechanical behavior of the of 3D-printed Acrylonitrile Butadiene Styrene material to assess potential strain rate dependency. The mechanical evaluation was also necessary to determine properties necessary to characterize the dynamic evolution of ABS in compression at					
15. SUBJECT TERMS Acrylonitrile Butadiene Styrene; high strain rates, tensile testing, energy absorption					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		Gbadebo Owolabi
				19b. TELEPHONE NUMBER 202-806-6594	

Report Title

Dynamic Evolution of Acrylonitrile Butadiene Styrene (ABS) Subjected to High Strain Rate Compressive Loads

ABSTRACT

The goal of the present investigation is to better understand the potential energy absorption benefits of components fabricated using fused deposition modeling additive manufacturing. Tensile test specimens were fabricated, according to the ASTM D638 standard, to characterize the general mechanical behavior of the of 3D-printed Acrylonitrile Butadiene Styrene material to assess potential strain rate dependency. The mechanical evaluation was also necessary to determine properties necessary to characterize the dynamic evolution of ABS in compression at various strain rates. The ABS specimens were subjected to high strain rate deformation through the use of the split-Hopkinson Pressure Bar. During compression a new phenomenon described as a multistage collapse in which the sample undergoes multiple stages of compression and expansion was observed. As the velocity increases the capability for energy absorption decreases to where there is only one stage of compression equivalent to the initial stage.

Dynamic Evolution of Acrylonitrile Butadiene Styrene (ABS) Subjected to High Strain Rate Compressive Loads

Alex Peterson^{1*}, Ed Habtour², Jaret Riddick², Michael Coatney², Denzell Bolling¹,
Gbadebo Owolabi¹

¹Department of Mechanical Engineering, Howard University, Washington, DC

²US Army Research Lab, Vehicle Technology Directorate, Aberdeen Proving Ground, MD

*Email: rapeterson@bison.howard.edu

ABSTRACT

The goal of the present investigation is to better understand the potential energy absorption benefits of components fabricated using fused deposition modeling additive manufacturing. Tensile test specimens were fabricated, according to the ASTM D638 standard, to characterize the general mechanical behavior of the of 3D-printed Acrylonitrile Butadiene Styrene material to assess potential strain rate dependency. The mechanical evaluation was also necessary to determine properties necessary to characterize the dynamic evolution of ABS in compression at various strain rates. The ABS specimens were subjected to high strain rate deformation through the use of the split-Hopkinson Pressure Bar. During compression a new phenomenon described as a multistage collapse in which the sample undergoes multiple stages of compression and expansion was observed. As the velocity increases the capability for energy absorption decreases to where there is only one stage of compression equivalent to the initial stage.

INTRODUCTION

Through the use of Direct Digital Manufacturing (DDM), more commonly known as additive manufacturing (AM), various thermoplastics can be used as the basis for creating models and to be printed for a vast amount of applications that could be potentially beneficial with respect to mechanical and structural designs. Using this approach Acrylonitrile Butadiene Styrene (ABS) can be printed at various orientations, and further understanding the effect that this process has could lead to potential benefits that were previously unexplored. DDM uses a combination of computer aided design (CAD) and computer aided manufacturing (CAM) as well as computer codes designed to interface with advanced 3-D additive manufacturing prototyping machines to produce a design [1]. Riddick et al. [2] observed that building in the horizontal direction with a 0° rotation achieved the highest tensile strength (32.60 MPa). Table 1 describes the mechanical results from different build directions and orientations within those build directions.

Table 1 Build orientation response [8]

Table 1. ASTM 638 test results for ABS specimens using FDM				
Build	Raster	Poisson's	Tensile Strength	Tensile Modulus
Horizontal	0°	0.374	32.60	2.69
	90°	0.360	15.26	2.45
	0°/90°	0.371	25.69	2.59
Side	0°	0.386	34.17	2.79
	90°	0.372	24.24	2.53
	0°/90°	0.373	29.11	2.65
Vertical	0°	0.329	4.57	2.45
	90°	0.349	15.30	2.40
	0°/90°	0.321	8.56	2.31

Advanced 3-D additive manufacturing prototyping (3-D Printing) has been used in a variety of applications, which include medical designs, oil filter assemblies, prototypes, replacement parts and dental crowns [3]. The present research is aimed at understanding the effect of the 3-D printing process, through use of the fused deposition modeling (FDM) and the printing orientation as a means to quantify the potential benefits to allow for a more cost effective, time efficient, in-house fabrication of designs, while optimizing the mechanical and structural integrity. In FDM, CAD software is used to convert a file containing a 3-D model into 3-D stereolithography (STL) format. The STL file is imported into a CAM software, which produces a physical replica of the 3-D model sliced into thin layers comprised of tool paths used by the 3-D printing machine to place continuous feedstock filament comprised of ABS and onto a surface building it up the 3-D component layer-by-layer [2].

In the design of mechanical and structural components it is essential to understand the mechanical behavior at different loading rates based on the required design. The present investigation is aimed at understanding the effect of high strain rate loading ($> 10^2 \text{ s}^{-1}$) on various forms of Acrylonitrile Butadiene Styrene (ABS) for potential benefits in energy absorption, as well as mechanical and structural applications. In the area of high strain rate deformation, there has been extensive work on understanding the effects of high strain rate on metals such as aluminum alloys, steels and other metals [4-7]. Limited exploratory research has been done in the area of plastics, more specifically ABS. Many experiments have been conducted through the usage of the split-Hopkinson Pressure Bar for strain rates greater than 10^2 [8]. The range of interest for the present study ($10^2 - 10^3$) falls squarely within the capability of the split-Hopkinson bar test making this setup suitable for completing the test required to investigate the dynamic evolution of ABS.

Figure 1 shows the formation of two different types of ASB within a steel specimen. Distorted grain regions that are associated with large amounts of shear characterize deformed bands. The white etching (transformed) bands are given their name because of their appearance in the microscopy after the sample has been prepared. They are also known to be harder and more brittle and observed in hardened steels [9].

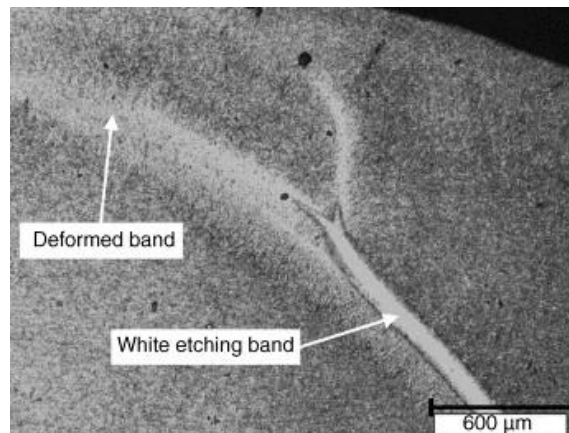


Figure 1 Deformed and transformed bands with steel specimen [1]

When observing metals at high strain rates, one of the main relationships that are being analyzed is the relationship between the stresses the material undergoes as the strain is increased. Yazdani et al. [10], Qiang et al. [11], Lee et al. [12] conducted studies observing the dynamic deformation of copper and titanium alloys and observed that the maximum stress at these high

strain rates does not change drastically relative to surrounding strain rates. Siviour et al [13] showed that the final strain achieved on polymers is a directly related to the strain rate applied along with its relationship to the stress experienced in a material at high strain rate deformation.

For polymers, such as ABS, the mechanical properties vary considerably from those observed in metals. Gaining a better understanding of the strain rate dependency of ABS will help in effectively knowing what stress limits due to the required design application as a function of the strain rate. Mulliken and Boyce [14] studied the strain rate dependency of glassy polymers from (10^{-4} to 10^4 s^{-1}) and were able to show that an increase in strain rate sensitivity was observed at elevated loading rates compared to those observed at quasi-static loading. Wally and Field [15] conducted multiple tests on the strain rate sensitivity of polymers subjected to loads ranging from quasi-static to high strain rates, using a solid block of ABS to conduct mechanical property evaluation at various strain rates (figure 2). The novelty of the present research is that rather than testing a solid block of ABS, machined down to the appropriate size, here, an advanced 3-D additive manufacturing approach is used to create highly optimized logical structures for energy absorption.

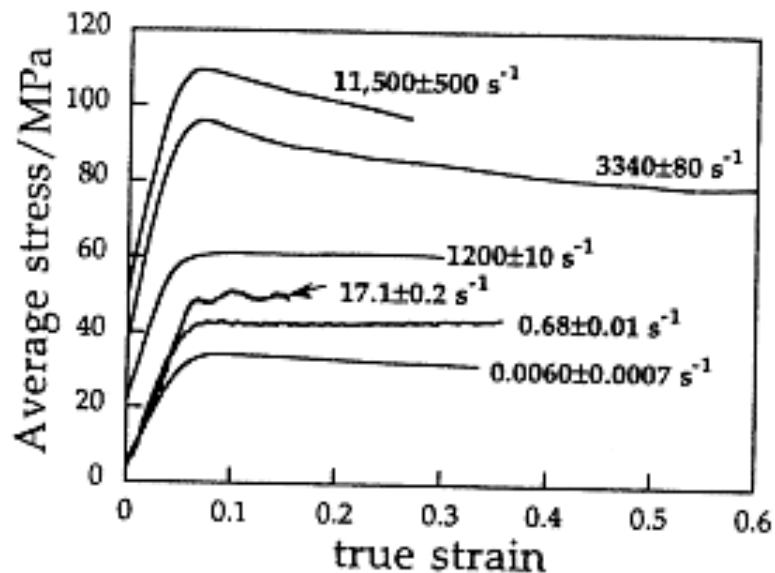


Figure 2 Solid ABS stress strain curve [14]

Through the analysis of this solid ABS a linear relationship between the strain rate applied and the maximum stress observed in the quasi-static region was observed [15]. As the transitional phase from quasi-static to dynamic loading is entered, there is a drastic change in the increase in the gradient of the slope. Unlike observations of adiabatic conditions occurring with metals there is no drastic change in temperature. Using this analysis as comparison to those obtained here, it is desirable to understand whether the potential benefits of 3-D printed polymer can be harnessed for use in mechanical and structural applications.

EXPERIMENTAL APPROACH

Before experiments at high strain rates can be conducted, it is essential to understand how the material will behave at quasi-static loading conditions. This interest arises from the fact that

majority of polymers are strain rate sensitive, i.e., the maximum stress observed in an object before deformation, or failure, is directly related to the rate of strain being applied to the material. In Figure 2 it is noticed that over a wide range of strain rates there are different levels of maximum stress observed in the ABS throughout testing. In order to understand the tensile properties of the 3-D printed ABS, preliminary tensile tests were conducted using the ASTM D638-03 Standard Test method for Tensile Properties of Plastics. The standard recommends Type I specimen for rigid and semi rigid plastics [16]. Tensile [testing](#) is prescribed at a rate of 5mm/min. Type I specimen dimensions used in the tensile testing are shown in Figure 2.

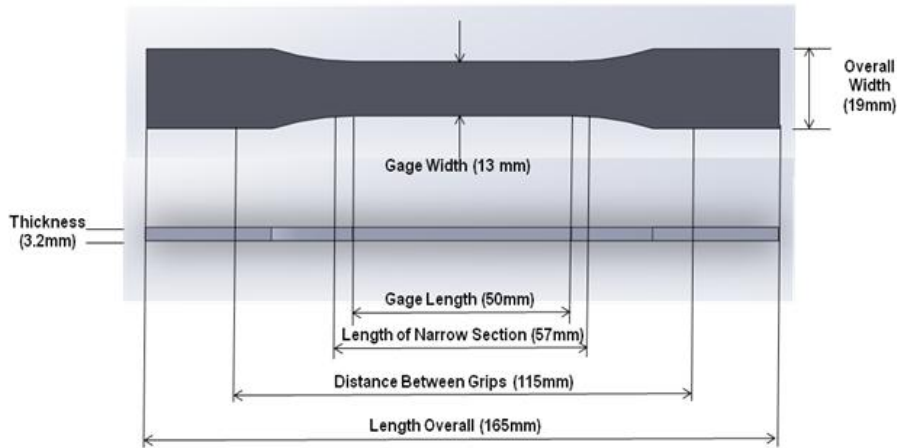


Figure 3 ASTM D638-03 Dog Bone [9]

When designing the specimen for tensile testing, it is important that the tensile specimen is built such that the orientation of the tensile test loads corresponds to the subsequent dynamic tests. The tensile specimen was built with each successive layer composed of 0° and 90° orientations built from the ground up, as shown in Figure 4. According to the ASTM D638-03 standard [16], the test specimen is to be tested at minimum of 0.50 cm/min to extract material properties such as yield point, elastic modulus and ultimate tensile strength. Using this as a starting point and in order to understand if the material was strain rate dependent, tests were performed at displacement rates of 0.5, 5, 25, 35, and 50 cm/min. Figures 5 and 6 show the specimen before and after testing was conducted.

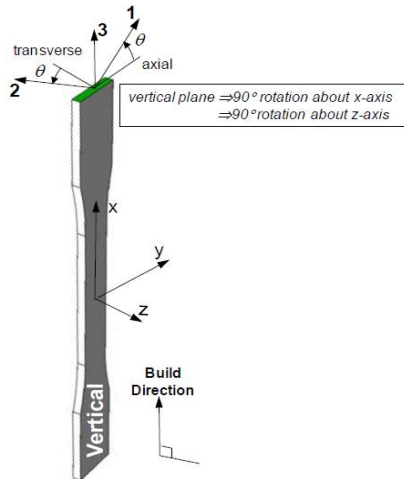


Figure 4 Material Build Direction 0/90 Orientation [5]



Figure 5 Experimental Setup Prior to Testing

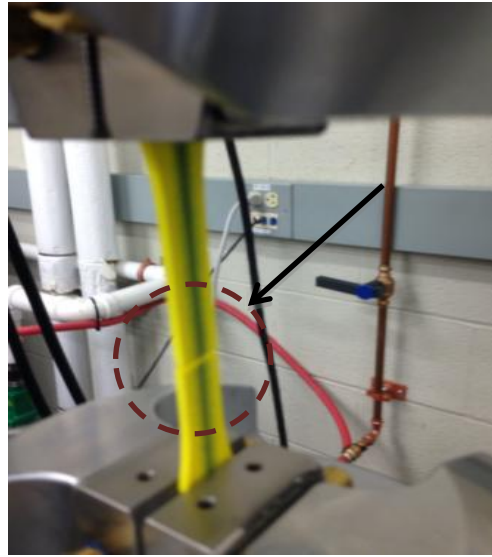


Figure 6 Experimental Setup After Testing

Once tensile testing was completed, the next phase in material design and testing was the uni-axial compression loading. The specimens for compression were 8mm in diameter by 8 mm in length. The compressive loading was conducted using the conventional split-Hopkinson pressure bar shown in Figure 7. The setup was comprised of a gas gun connected to a striker bar that induced a velocity into the system. The velocity was then transferred to an incident bar which had a strain gage attached to it to capture the dynamic response as a result of the applied compression on the specimen. The reflected waves from the specimen were captured through the same strain gage that recorded the incident waves. On the other side of the specimen was the transmitted bar which captured the waves that were transmitted through the specimen as a result of compressive loading. The measurements were then relayed from the strain gage to the oscilloscope, which provided a profile of the outputs, these results were converted into stress, strain, velocity over time, displacement, force and strain rate [17]. Finally, these properties are observed to consider the effects of dynamic loading on the ABS cylindrical specimen.

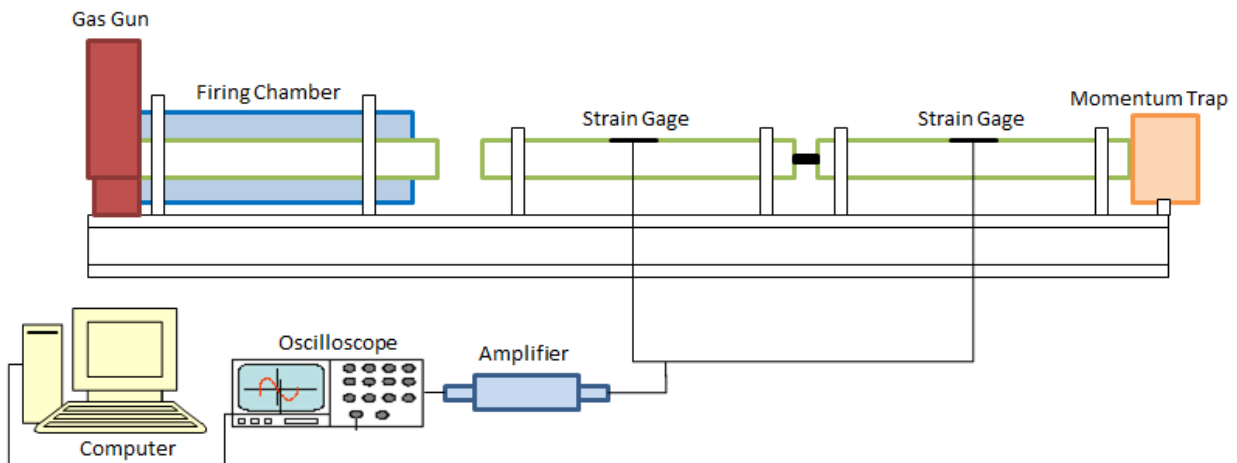


Figure 7 Split-Hopkinson Pressure Bar

In conjunction with the data captured through the use of strain gages and oscilloscopes, the material deformation was captured through the use of a digital image correlation (DIC) system, which captured the compression at 124,000 frames per second (fps). The DIC program that is being used is ARAMIS, which captures the movement of certain points along the load axis as a result of deformation by tracking dots that are applied through spray painting patterns of black and white along the length of the specimen. Figure 8 shows what a typical 8-mm specimen after being spray-painted, in comparison to a plain specimen.

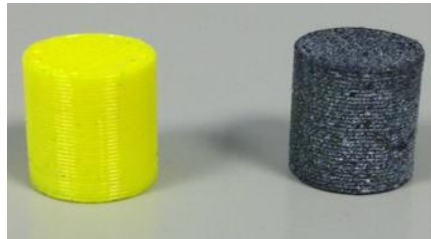


Figure 8 (a) Unpainted Specimen (b) Painted specimen

RESULTS AND DISCUSSION

Testing for this material was done in two different stages. First being tensile testing to capture further understand the possibility of strain rate dependency for the ABS tested as well as the maximum stress observed to allow for calculating values of the strain rate. The compression ABS samples were tested at strain rates from 500 s^{-1} to 2000 s^{-1} and the data collected and capture was an average of three tests at these strain rates.

Material Characterization

The material is brittle so there is no real evident plastic deformation observed in tensile testing, which is directly related to the manner in which the material is built. Figure 9 shows the stress strain graph as a result of the tensile testing at various displacement rates. Table 2 shows the specimen testing rates for strain rate dependency. The minimum is that prescribed by the ASTM D638-03 standards and the maximum capability of the MTS 22kip, along with the resulting modulus of elasticity.

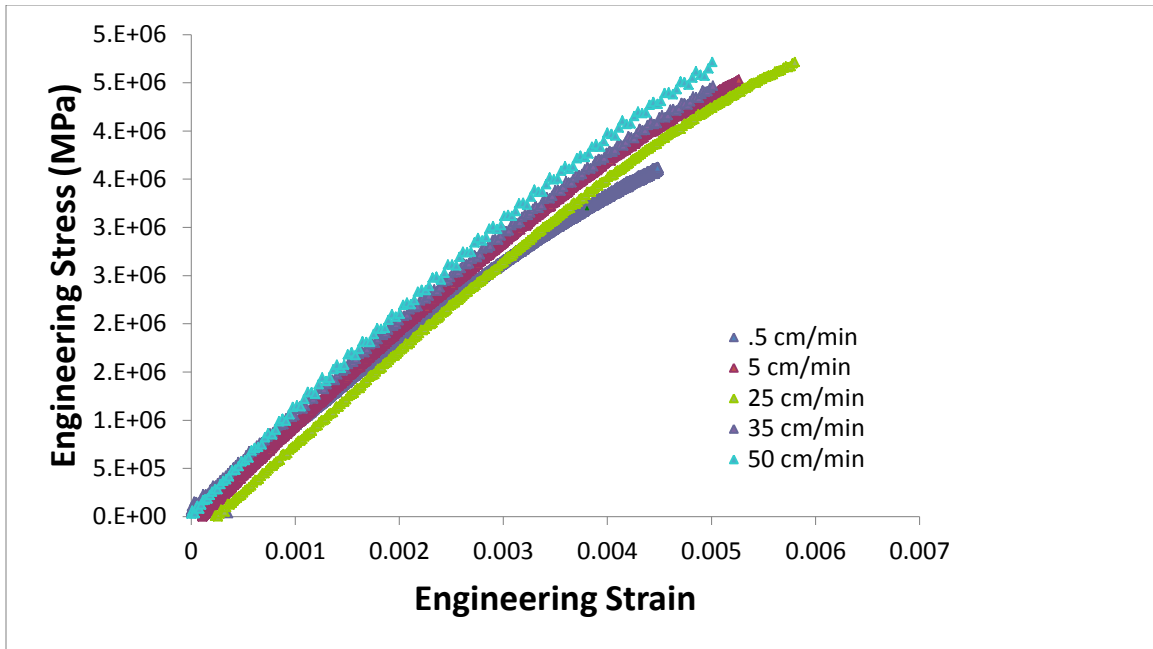


Figure 9 Stress, Strain Tensile Results

At the initial strain rate the stress observed in the system is 3.4 MPa, which is the lowest out of the four stresses observed. However, the modulus of elasticity appears to be consistent among the specimens. As load rate is increased from 0.5 cm/min to 50 cm/min the stress felt by the specimen is around the same levels as well as the maximum strain experienced before failure occurs.

Table 2 Tensile Testing Results

<u>Displacement Rate</u>	<u>Value</u>
0.5 cm/min	1.0
5 cm/min	0.9
25 cm/min	1.0
50 cm/min	1.0
Average	0.975

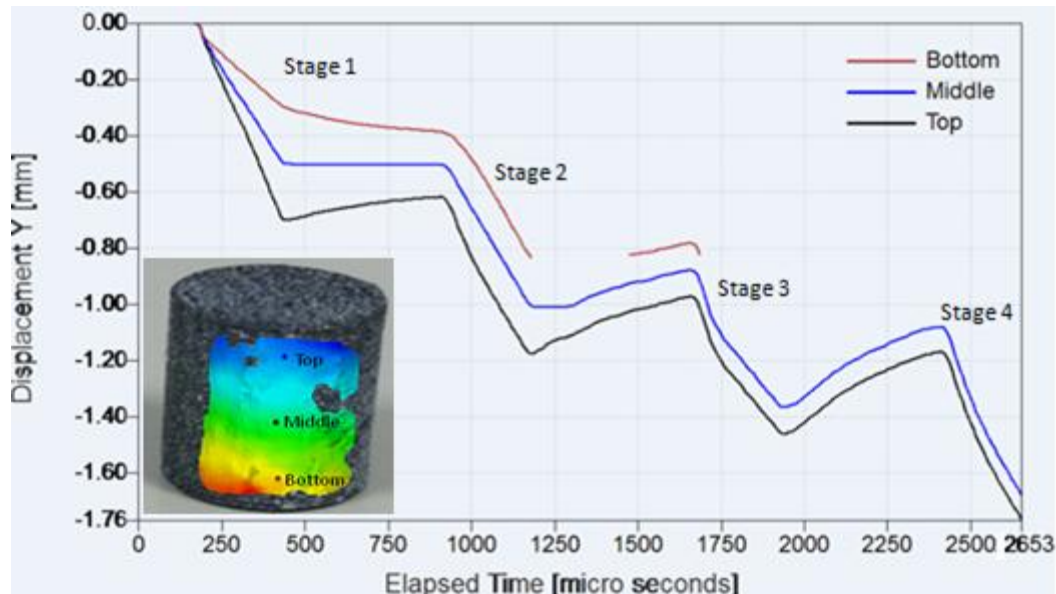
Using these results, the maximum stress is applied to calculations relating for the bar properties and applied pressure to capture various strain rates based on the specimen size. From these calculations a relationship between material properties, strain rate, velocity and tank pressure are established (as seen in Table 3).

Table 3 Strain rate, pressure, and velocity relationship

ABS 8 x 8 mm ² Cylindrical Specimen			ABS 10 x 10 mm ² Cylindrical Specimen		
Strain Rate (s ⁻¹)	Velocity (m/s)	Pressure (kPa)	Strain Rate (s ⁻¹)	Velocity (m/s)	Pressure (kPa)
500	4.096	20.68	500	5.154	26.82
750	6.097	32.96	750	7.656	44.61
1000	8.097	48.33	1000	10.158	68.19
1500	12.097	91.08	1500	15.162	114.80
2000	16.098	150.86	2000	20.165	224.84

Compression Analysis

Throughout testing it was evident that at lower strain rates there were different stages of deformation observed while the specimen underwent one initial impact. Figure 9 shows the deformation observed due to compression with respect to time, where Y is the longitudinal displacement.

**Figure 10 Longitudinal Stage Displacement 500 strains/s**

Using the DIC, three different points throughout the material were captured and analyzed as the specimen went under compression (as seen in Figures 9), which gives a reference to the points labeled top, middle and bottom in conjunction with the results displayed in the graph. These points were selected to give a better representation of the specimen. At a strain rate of 500 s⁻¹, the compression is not evident until about 200 microseconds and initially it is minimal. Beyond this stage however, the compression begins and the specimen contracts. Towards the end of this stage the material expands slightly noting that the overall displacement increases until the next stage of contractions occur. This continues over the final 4 stages until the overall deformation of the material is completed and as the induced strain rate increases the stages of deformation decrease until eventually there is only one stage at 2000 s⁻¹. This displacement observed by the system is also evident in the compression video captured by the camera.

Table 2 shows the initial height of the specimen before deformation in comparison to the final height. Interestingly, at these lowest strain rate displayed the specimen show signs of actually expanding after the compression process was completed. Once a strain rate of 750 s^{-1} was reached the average final height began gradually decrease until failure occurred. At a strain rate of 2000 s^{-1} the specimen undergoes about a 60% reduction in size, which is the strain rate at which failure occurs.

Table 3 Specimen Height

<u>Strain Rate</u>	<u>Initial Height (mm)</u>	<u>Average Final Height (mm)</u>
500	8	8.11
750	8	7.95
1000	8	7.18
1500	8	5.85
2000	8	4.07

The damage evolution of the specimen starts to become drastic once the applied strain rate goes beyond 1000 (as seen in Figure 10); these images are a sample of the specimen tested to capture the average final height.



Figure 10 Specimen Deformation

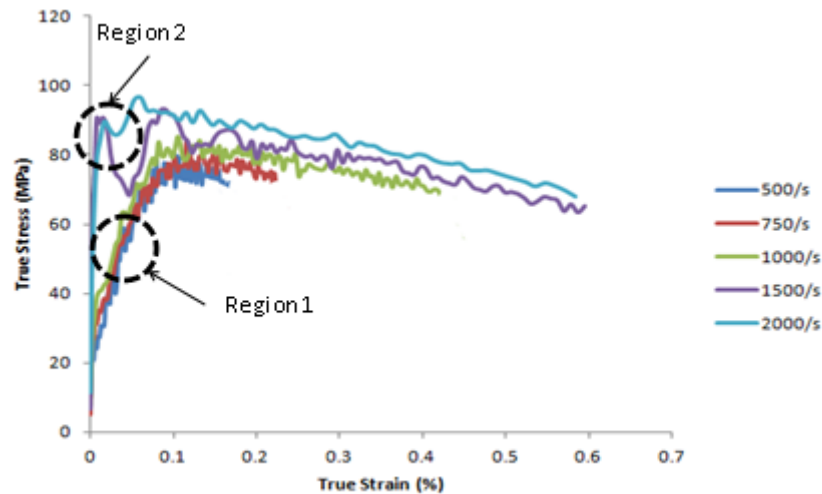


Figure 11 Stress Strain Curve

The specimen failure as a function of the strain rate can be divided into two different regions, the first consisting of $500 - 1000 \text{ s}^{-1}$ and the second consisting of the final two strain rates, 1500 s^{-1} and 2000 s^{-1} (as seen in Figure 11). Each of these specimens undergoes a multiple stages of stress increase and stress decrease but as the strain rate increase the differences become less

drastic in region one. As the transition from region one to region two occurs, the corresponding yield point changes along with the maximum stress. For a strain rate of 1500 s^{-1} the yield point is 91.64 and the maximum stress is 93.06 MPa. For the strain rate of 2000 yielding occurs at 89.67 MPa and the maximum stress is 96.67 MPa. In this region there is one significant drop in stress an increase in stress and the then a drastic decrease as a result of stress collapse.

CONCLUSION

Throughout this research exploratory studies have been conducted in understanding the effect of the 3-D printing on the response of ABS polymer. At strain rates above 1000 s^{-1} failure begins to occur in the printed ABS by buckling, where as below this there is minimal height reduction and failure observed. At the lower strain rates from images captured through the use of the DIC system there is some contraction and expansion of the material evident. This is believed to be a result of the ring that is built around the specimen holding the perpendicular layers in place absorbing the energy acting as a multi-stage spring, which results in the compression and expansion of the specimen in the longitudinal.

The specimen expresses a linear relationship between stress and strain up until it its reaches its yield point. More plastic deformation is observed at higher strain rates along with higher levels of stress. However, as the strain rate is increased there is a more evident showing of stress collapse ultimately leading to the failure of the specimen. While ABS does not display stress limits in the dynamic response similar to those seen in metals, the multi-stage collapse indicates a potential for novel energy absorption mechanism to be exploited at lower strain rates. Future work in the area should include more studies about printing orientation, as well as, investigating the impact of the presence of the outer cylindrical ring on the overall dynamic response.

REFERENCES

- [1] A.G. Odeshi, M.N. Bassim, S. Al-Ameeri, Q. Li, Dynamic shear band propagation and failure in AISI 4340 steel, *Journal of Materials Processing Technology*, Volume 169, Issue 2, 10 November 2005, Pages 150-155
- [2] J. C. Riddick, A. J. Hall, M. A. Haile, R. Von Wahlde, D. P. Cole, S. J. Biggs
Experimental Investigation of Anisotropy in Mechanical Response of Acrylonitrile-Butadiene-Styrene Fabrication Fused Deposition Model, American Institute of Aeronautics and Astronautics
- [3] Barry Berman, 3-D printing: The new industrial revolution, *Business Horizons*, Volume 55, Issue 2, March–April 2012, Pages 155-162
- [4] R. Smerd, S. Winkler, C. Salisbury, M. Worswick, D. Lloyd, M. Finn, High strain rate tensile testing of automotive aluminum alloy sheet, *International Journal of Impact Engineering*, Volume 32, Issues 1–4, December 2005, Pages 541-560
- [5] L. Djapic Oosterkamp, A. Ivankovic, G. Venizelos, High strain rate properties of selected aluminum alloys, *Materials Science and Engineering: A*, Volume 278, Issues 1–2, 15 February 2000, Pages 225-235
- [6] A.G. Odeshi, S. Al-ameeri, S. Mirfakhraei, F. Yazdani, M.N. Bassim, Deformation and failure mechanism in AISI 4340 steel under ballistic impact, *Theoretical and Applied Fracture Mechanics*, Volume 45, Issue 1, February 2006, Pages 18-24
- [7] Woei-Shyan Lee, Chi-Feng Lin, Plastic deformation and fracture behaviour of Ti–6Al–4V alloy loaded with high strain rate under various temperatures, *Materials Science and Engineering: A*, Volume 241, Issues 1–2, January 1998, Pages 48-59
- [8] Kuhn, Howard, and Dana Medlin. *ASM Handbook: Mechanical Testing and Evaluation*. 8. Materials Park, OH: The Materials Information Society, 2000. 462-476. Print.
- [9] Ghomi, Homa M. "Adiabatic Shear Localization in AISI 1340 and 4340 Steels: The Influence of Microstructure and Geometry." Thesis. University of Saskatchewan, 2011. Print.
- [10] F. Yazdani, M.N. Bassim, A.G. Odeshi, The formation of adiabatic shear bands in copper during torsion at high strain rates, *Procedia Engineering*, Volume 1, Issue 1, July 2009, Pages 225-228
- [11] Li Qiang, Xu Yongbo, M.N Bassim, Dynamic mechanical properties in relation to adiabatic shear band formation in titanium alloy-Ti17, *Materials Science and Engineering: A*, Volume 358, Issues 1–2, 15 October 2003, Pages 128-133
- [12] Dong-Geun Lee, Yang Gon Kim, Duk-Hyun Nam, Sun-Moo Hur, Sunghak Lee, Dynamic deformation behavior and ballistic performance of Ti–6Al–4V alloy containing fine α_2 (Ti₃Al) precipitates, *Materials Science and Engineering: A*, Volume 391, Issues 1–2, 25 January 2005, Pages 221-234
- [13] Siviour, C. R., S. M. Walley, W. G. Proud, and J. E. Field. "Mechanical Behaviour of Polymers at High Rates of Strain." *Journal De Physique IV (Proceedings)* 134 (2006): 949-55. Print.
- [14] A.D. Mulliken, M.C. Boyce, Mechanics of the rate-dependent elastic–plastic deformation of glassy polymers from low to high strain rates, *International Journal of Solids and Structures*, Volume 43, Issue 5, March 2006, Pages 1331-1356
- [15] Walley, S. M., and J. E. Field. "Strain Rate Sensitivity of Polymers in Compression from Low to High Rates." *Dymat Journal* 1 (1994): 211-27. Print.'

- [16] ASTM International, "Standard Test Method for Tensile Properties of Plastics," Standard D 638-03, (2004) 1-15.
- [17] Zukas, Jonas. *High Velocity Impact Dynamics*. Canada: John Wiley & Sons, Inc. , Print.