ABSTRACT

CHADWELL, CODY SCOTT. High Strain Rate Mechanical Property Characterization of Additively Manufactured Polymers (Under the direction of Dr. Mark Pankow).

A challenge of using additive manufacturing (AM) is understanding how the resulting parts will behave relative to parts manufactured using traditional techniques. With one of the most widely available AM technologies being polymer extrusion, parts made using this technology are becoming more commonplace. However, we need to understand how the material behavior is influenced by the manufacturing parameters along with how it compares to traditional manufacturing methods. Many of the polymeric engineering materials have strain rate dependent properties; while low strain rate data is readily available, high strain rate behavior is not as well understood. Coupling this with a relatively new manufacturing technology, the behavior of AM parts at high strain rates is not well understood.

This work aims to study the effects of high strain rate loading for AM parts with varying raster angles made from three common engineering polymers used in high impact applications. Glass fiber reinforced acrylonitrile butadiene styrene (ABS-M30), acrylonitrile styrene acrylate (ASA), and a polycarbonate/ABS alloy (PC-ABS) are investigated in this work. A Stratasys F370 fused deposition modeling (FDM) machine capable of printing all three materials was used to manufacture the test specimens. The bond between individual strands is generally weaker than the strand itself. Therefore, the raster angle, relative to the loading direction, affects how an AM part will respond. Tensile loading is used to test the bond strength within the parts. A split Hopkinson tension bar was used to apply a unidirectional tensile load to the samples at elevated strain rates. These values will be compared to quasi-static test data to better understand the rate dependent properties, and any transitions in failure modes that occur.
High Strain Rate Mechanical Property Characterization of Additively Manufactured Polymers

by
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DEDICATION

I dedicate this to my parents and my brother for encouraging and supporting me throughout this journey, and to all my friends who have done the same despite the time I have sacrificed with them.
BIOGRAPHY

Cody Chadwell completed his Bachelor of Science degree in Mechanical Engineering at Tennessee Technological University in Cookeville, TN in May 2012. Upon graduating, he went to work for Volkswagen Group of America in Chattanooga, Tennessee through the end of summer 2016. His desire to continue expanding his engineering skills led him to North Carolina State University where, in August 2016, he began working towards his Master of Science degree in Mechanical Engineering. In January 2017, he joined the Ballistic Loading and Structural Testing (BLAST) Laboratory where he began his thesis research under the direction of Dr. Mark Pankow.
ACKNOWLEDGMENTS

I would like to thank Dr. Pankow for all of his guidance and instruction throughout my time at NC State, for pushing me to succeed when I needed it most, and for giving me a chance to work with a great group of people. Thanks to Dr. Ferguson & Dr. Horn, for their advice and everything they taught me in their respective classes, as well as for serving on my committee. Thanks to Dr. West for allowing me to use his lab’s load frame and for guidance in that testing, Dr. Patrick for use of the optical microscope, Peter and Abhi for all their help with the Hopkinson bar troubleshooting and testing, Paul for his assistance with processing DIC images. Thank you to everyone in the BLAST lab for all you have taught me, and for making such a great place to work.

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CHAPTER 1 – INTRODUCTION

1.1 – Background

First used solely for rapid prototyping, additive manufacturing (AM) is now used for a variety of applications, including producing final parts [1]. AM uses a layer-by-layer approach to build three-dimensional objects from a digital model [1]–[4]. Raw materials such as metals, resins, or thermoplastics (typically in the form of a liquid, powder, pellet, or filament) are reformed through the application of energy in a specific way.

With the increased interest and popularity of additive manufacturing technologies in recent years, the use cases of AM technologies are expanding. Automotive, aerospace, and medical industries are key fields that have great interest in the various AM technologies available [2]. However, additively manufactured parts have different structural properties than if the same item were to be made using traditional manufacturing techniques, such as injection molding [5], [6]. While this opens up possibilities from a design standpoint, the difficulty of predicting AM part behavior is greater than that of traditionally manufactured components. For an organization to use AM components in products beyond the scope of prototypes or visualization aides, understanding AM material behavior under various loading conditions is essential. Therefore, designing for additive manufacturing must also become well understood [1]. As with any manufacturing process when it was new, AM increases the potential for new engineering solutions, but the successful implementation of these solutions requires an understanding of the final part’s behavior and how that is affected by its manufacturing process.
1.1.2 – Fused Filament Fabrication/Fused Deposition Modeling

Many AM technologies are currently available, each having strengths and weaknesses for a given application based on the varying processing methods, available material selections, cost, scale, etc. Extrusion technologies are currently one of the most common AM technologies in use [1], [7]. They utilize thermoplastic feedstock material which, in addition to low-cost prototyping, makes it of interest for applications in which injection-molding is already used. Plastic extrusion technologies can use raw material in the form of pellets, however plastic filament is more common. The technology using a filament as feedstock is commonly referred to as fused filament fabrication (FFF) or fused deposition modeling (FDM), however FDM is a filament extrusion technology developed by Stratasys, USA [1]. FDM is used herein when applying specifically to the Stratasys technology.

![Figure 1 FFF Printing Process](image)

**Figure 1** FFF Printing Process [8].

Figure 1 shows a typical example of an FFF machine using stock material in the form of a thermoplastic filament. The majority of extrusion-based machines work in a comparable manner. Feedstock is heated inside a small chamber until it is in a highly viscous molten
state, at which point it can be extruded through the nozzle in a controlled manner. A drive
gear or wheel, generally of a pinch roller design, is used to force material into the heated
chamber, creating pressure that in turn forces heated material through the nozzle. Leaving the
nozzle, the material is deposited onto the printing surface, which is either the print bed or the
previous layer of printed material [1]. The deposited material bonds to adjacent filaments by
polymer chain crosslinking, as shown in Figure 2. This deposition process is likened to
squeezing toothpaste from a tube or icing a cake [1], in which the extruded filament is not
fully solid, but stays in roughly the same shape and location in which it is deposited.

Figure 2 Bond Formation Steps: (1) Surface Contact, (2) Neck Growth, (3) Molecular Diffusion At Interface
And Randomization [9].

The formation of bonds between deposited filaments is a thermally driven process, with the
print nozzle temperature being the primary heat source [9], [10]. The nozzle’s temperature
must be controlled within an operating window that balances multiple factors. The
temperature must be high enough that the filament is quickly heated to the point where it can
flow through the nozzle and bond with adjacent material, but low enough that it does not
cause adverse conditions. Higher thermal energy in the deposited material facilitates
additional crosslinking of polymer chains, resulting in a higher bond strength between
adjacent roads and layers. However, excess heat can cause polymers to burn (resulting in
contamination), to degrade (resulting in lower overall strength of the printed part), and/or cool too slowly (resulting in warping or deformation of the extruded filament) [1]. Additionally, the nozzle temperature contributes to the total time required for a print, as the rate at which a volume of raw material can be heated to acceptable extrusion temperatures and extruded must be factored in to the speed of the nozzle during printing.

As with many AM technologies, FFF can create complex geometries that would otherwise be prohibitively difficult or impossible using traditional manufacturing methods. Benefits of FFF specifically over other forms of thermoplastic manufacturing include the ability to locally control properties and internal structures, which allow for modifications of both part density and mechanical properties [1], [11]. The potential for higher strength to weight ratios, reduction of material (and potentially cost), faster prototyping processes, consolidation of assemblies, embedding objects such as electronics, and the manufacture of custom or low production run parts are among the many advantages to this technology [1], [12].

However, unlike injection molding which results in parts that are generally isotropic, FFF parts are not [13]. This anisotropic behavior is largely a result of internal fill settings and build orientation, which are key determining factors in tensile and flexural behavior [3]. The ability to locally control properties and produce more complex geometries than traditional manufacturing makes an already anisotropic part more difficult for predictive models which are currently still in development [8].
1.1.3 – FFF Polymer Characterization

The mechanical properties of an FFF part are determined by many factors including part geometry, build orientation, part density, air gap, raster pattern, raster orientation, manufacturing method, post-processing, etc. With ABS being a material that is well understood for injection molding, and one of the most common materials used in FFF processes, much of the research involving printing parameter effects on final part strength and comparisons to the nominal strength of the material has taken place using variations of ABS. Studies by Sung-Hoon Ahn et al. [13], Vairis et al. [14], and Rodríguez et al. [15] show similar results for FFF parts (tested in their strongest orientations) of approximately 80% of the tensile yield strength of the filament feedstock or an injection molded part made from the same variety of ABS tested. Comparing data available from Stratasys on their array of ABS filaments with average values of ABS material properties (Table 1), tensile yield strengths for the printed parts range from 70% - 83% of the average values for non-3D printed ABS depending on the type of filament. It is noted from the Table 1 data that flexural strength derived from 3-point bending tests have a similar reduction in strength, ranging from 76% - 82% of the raw material average value. The Stratasys values given in Table 1 are the stronger of the two print orientations provided for each loading condition.

Bonds between extruded filaments (particularly interlayer bonds) are generally the weakest regions within an FFF part [9]. Two of the most influential factors in the strength of these bonds are raster angle and air gap, the distance between outer edges of neighboring deposited filaments [9], [13]. While these relative effects are known, the magnitude of these effects on a printed part can vary by material. This is due to different thermal conditions needed to print
each material type in conjunction with the thermally driven crosslinking process on a molecular level [16].

Table 1 Traditional vs. FDM Material Properties for ABS.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Raw Material (Average Values) [16]</th>
<th>Stratasys FDM (Strongest Print Orientation) [17]–[21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Yield Strength (psi)</td>
<td>6,500</td>
<td>4,550–5,400</td>
</tr>
<tr>
<td>Ultimate Tensile Strength (psi)</td>
<td>4,600 – 7,800</td>
<td>4,650 – 4,700*</td>
</tr>
<tr>
<td>Tensile Modulus (psi)</td>
<td>320,000 – 340,000</td>
<td>277,700 – 350,000</td>
</tr>
<tr>
<td>Flexural Strength (psi)</td>
<td>11,000</td>
<td>8,450 – 8,980</td>
</tr>
<tr>
<td>Flexural Modulus (psi)</td>
<td>310,000 – 330,000</td>
<td>278,000 – 350,000</td>
</tr>
</tbody>
</table>

*Information available only for ABS-M30 [17] and ABSplus-P430 [21].

Additionally, experimental data is lacking for many materials used for FFF, making estimating the behavior of final parts difficult. Current data that is available is predominately quasi-static, with little to no information available at high strain rates [7], [22], [23], making it more difficult to design for impact loading conditions. These materials are currently used in injection molded parts in conditions where impact loads must be taken into consideration; various automotive parts such as trim and bracket pieces being a key example. Organizations are researching printing the bulk of car bodies using FFF technology as well [24]. Faster functional prototyping of various components that would normally require expensive molds is also of great interest to industries such as automotive in which large cosmetic design changes are implemented every 3 – 5 years. Various thermoplastics are also used in aerospace for their light weight impact resistance. With possibilities for part consolidation and reduction of material, weight reduction is a driving factor for use in this industry.

Between a relatively new manufacturing method and the strain rate dependency of polymeric
materials, it is necessary for additional experimental data to be collected to develop a more comprehensive understanding of their behavior.

For FFF parts, it is of particular interest to study the bond strength at various strain rates to better understand the operational window of a part under load. Polymeric materials exhibit different material properties under tensile loading versus compression [23], and to best characterize the bond strength (the weakest region of an FFF part) tensile testing is preferred. This allows for better study of failure/fracture and is therefore desirable to use in the bond strength testing of the materials herein [22]. To better characterize materials at these higher strain rates, a split-Hopkinson tension bar (SHTB) can be used to achieve impact loading conditions with strain rates in the $10^2$-$10^4$ sec$^{-1}$ range, which is higher than many test fixtures can accurately achieve and measure [25]. However, polymeric materials’ relatively low mechanical properties, such as modulus and yield stress, result in low transmitted signals and high signal-to-noise ratios, making it difficult to capture data dynamic loading data for polymers in general [22], and FFF parts even more so.

1.2 – Research Questions

1. How does high strain rate tensile loading of Stratasys ABS-M30, ASA, and PC-ABS materials compare to quasi-static tensile loading?

2. How do infill raster angle and layer height affect the mechanical properties of the three materials for both tensile loading rates?
1.3 – Thesis Outline

Chapter 1 provided an overview of the understanding of polymeric material characterization for FFF processes. Chapter 2 provides details on the materials that were chosen for testing as well as test specimen design and manufacturing parameters. Detailed software settings for setting up the Stratasys printer are given in Appendix A. Chapter 2 also discusses quasi-static and dynamic testing equipment as well as data acquisition methods used for each testing type. The chapter concludes with data processing and analysis methods of the various data types collected, including code written to assist in this endeavor. An example of the SHTB data analysis code is given in Appendix B. Chapter 3 presents the analyzed data from both quasi-static and dynamic testing of the three polymers. Results include effects of the variables studied as well as observations and commentary on the how the test specimen manufacturing process influenced the results. Chapter 4 contains conclusions that resulted from this work and discusses possible future work to expand on the data found herein.
Additively manufactured tensile samples of three polymers were tested; raster patterns and layer heights are varied for each material. A load frame was used to conduct quasi-static tests to provide a baseline for test specimen behavior. Data was collected using a load cell and a camera. A split-Hopkinson tension bar was used to test samples at elevated strain rates. SHTB data was collected using strain gauges and a high-speed camera. Strain analysis was performed using digital image correlation for both testing types. Prior to testing, samples were speckled to facilitate the DIC analysis.

2.1 – Additive Manufacturing

A Stratasys F370 3D printer, shown in Figure 3, was used to manufacture the tensile test specimens. The parts from the F370 are printed in a heated environment, allowing for better part quality by preventing warping and decreasing the thermal gradients within the printed parts. All parts are printed with layers of support material, sometimes called a raft, between each test specimen and the build plate, providing a flat surface for the build as well as allowing the finished part to be easily removed from the build plate.
2.1.1 – Test Specimen Materials

The three thermoplastics chosen for this work, listed in Table 2 are used in both additive and traditional manufacturing processes. These materials are used in applications with static and/or dynamic loading conditions, therefore impact resistance is an important factor.

Stratasys provides material property data sheets for each material; the mechanical properties are listed in Table 3. This data was reported to have been collected using a rate of 0.2”/min for tensile testing.

Figure 3  Stratasys F370.
### Table 2 FDM Polymers Used For Testing.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Acronym</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile butadiene styrene with 30% glass fiber reinforcement</td>
<td>ABS-M30</td>
<td>Black</td>
</tr>
<tr>
<td>Acrylonitrile styrene acrylate</td>
<td>ASA</td>
<td>Red</td>
</tr>
<tr>
<td>Polycarbonate/ABS alloy</td>
<td>PC-ABS</td>
<td>Black</td>
</tr>
<tr>
<td>Dissolvable Raft Support Material (Quick Support Release)</td>
<td>QSR</td>
<td>White</td>
</tr>
</tbody>
</table>

### Table 3 Mechanical Properties of Test Specimen Materials [17], [26], [27].

<table>
<thead>
<tr>
<th></th>
<th>ABS-M30</th>
<th>ASA</th>
<th>PC-ABS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>4,550 psi</td>
<td>4,200 psi</td>
<td>5,900 psi</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>4,650 psi</td>
<td>4,750 psi</td>
<td>Not Provided</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>320,000 psi</td>
<td>290,000 psi</td>
<td>278,000 psi</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>7%</td>
<td>9%</td>
<td>7%</td>
</tr>
<tr>
<td>Glass Transition Temperature</td>
<td>226°F</td>
<td>226°F</td>
<td>257°F</td>
</tr>
</tbody>
</table>

According to the material data sheets, pigments could cause up to a 10% change in material properties. The Stratasys test data was collected using the natural colors for ABS-M30 and ASA [17], [26]. The PC-ABS material data sheet does not list which color, if any, was used [27].

#### 2.1.2 – Slicing Software and Test Specimen Design

The test specimen profile is sized to fit the tensile grips of the split-Hopkinson tension bar used in this work. The tabs have the largest area possible to reduce slipping and improve specimen alignment inside the tensile grip assembly. The two-dimensional profile (Figure 4) is extruded to 0.1 inches. This will be the through-thickness direction of the final printed part. The final SolidWorks part is converted to an STL file type for slicing and toolpath creation.
Figure 4  Tensile Specimen Dimensions (Inches).

The software packages used to prepare the toolpath files are Insight and GrabCAD Print.

Insight is used to set up individual specimen configurations. The test specimen STL file is loaded into Insight, where print settings are adjusted. The model is then sliced, and toolpaths are generated. This information is exported as a CMB file. A unique file is created for each of the print setting combinations. The unique CMB files are loaded into GrabCAD Print and duplicated to reach the desired quantity for a print job. All files within a print job must have matching material types and layer heights. The individual parts are organized on the build plate and a new toolpath file for the entire print job is created. GrabCAD Print determines the order in which the parts are printed within a given layer of the build, adds the travel moves between individual parts, and creates a new toolpath for the entire build. A new CMB.GZ compressed toolpath file is exported from GrabCAD Print.
Figure 5 Sliced Model With Toolpaths (Specimen Shown With Raft).

Test specimens were printed flat, such that the print direction is in the direction of the smallest external dimension, as shown in Figure 5. Each specimen was printed on a 10-layer raft of QSR support material. Table 4 lists the printing parameter variables used in this work are listed in

Table 4 Variables For Print Parameters.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Raster Angles</th>
<th>Layer Heights</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS-M30</td>
<td>0°</td>
<td>0.01”</td>
</tr>
<tr>
<td>ASA</td>
<td>45°</td>
<td>0.005”</td>
</tr>
<tr>
<td>PC-ABS</td>
<td>90°</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6 shows the raster angles used, where 0° is in line with the test direction. Typical raster patterns alternate, with each layer being orthogonal to the last, to increase overall strength for the in-plane directions of a print. However, these unidirectional raster patterns are preferred to study bond strength [9].
The overall thickness for each test specimen is 0.1”. Layer thicknesses of 0.010” and 0.005” were used, as shown in Figure 7, resulting in a total of 10 layers and 20 layers, respectively.

In addition to the variables being studied, certain settings were changed from their default states in the Insight software to ensure parts were printed such that the raster pattern could be studied more effectively. The major changes are the interior of the parts were printed solid, the enhanced visible surface feature was turned off to have the top surface print in the same manner as the previous layers, a single contour was used to minimize contour effects during testing [6], the parallel offset part raster option was used to keep the same raster orientation
on each layer, and the road width settings were changed to best fit the test specimen
geometry. One parameter of note that is not varied in this work is the air gap. This was kept
at the default setting of 0 inches in order to compare cross-linking strength of the different
materials at this bonded region. Appendix A – Insight Settings/Setup contains further
details regarding Insight settings.

Due to the way the raster pattern is generated within in a given geometry, it is possible to
create gaps in the model if the widths of the raster cannot fit within the model’s exterior
dimensions evenly. This effect was greatest in the 45° samples as seen in Figure 8. These
gaps were found to be visible with the Insight software prior to printing. Test prints
confirmed their presence, with each gap extending one, sometimes two, layers into the
sample from both the top and bottom surfaces, thus compromising the cross section and
biasing the failure location.

![Figure 8](image.png)

**Figure 8** Raster Width Test Prints – 0.012” to 0.016”. 
The road width has been found to not have a significant effect on part strength [6], [13] so the smallest raster width size is desired for this testing to maximize the number of bonds within the area of interest. For each variable combination the smallest combination of contour width and raster width that eliminated these gaps was determined. The smallest available width for both settings is 0.012”. Table 5 details the settings used in this work.

Table 5  Road Width Settings.

<table>
<thead>
<tr>
<th>Material</th>
<th>Raster Orientation</th>
<th>Raster Width (in.)</th>
<th>Contour Width (in.)</th>
</tr>
</thead>
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<td>0.012</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>ASA</td>
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<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.012</td>
<td>0.012</td>
</tr>
<tr>
<td>PC-ABS</td>
<td>0°</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>0.013</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>0.012</td>
<td>0.012</td>
</tr>
</tbody>
</table>

2.2 – Quasi-Static Testing

An Applied Test Systems (ATS) load frame, shown in Figure 9, was used for quasi static tensile testing. Displacement control was used, samples were pulled at 0.02 in/min and the resulting force on the sample was measured with a load cell.
A 5-megapixel Point Grey Grasshopper2 camera equipped with a 50mm lens was used to capture images during testing. Images were captured at 5 fps for initial tests and changed to 3 fps later due to the large number of tests required. Additionally, force-displacement curves for each sample were recorded by the load frame’s controller computer.

2.3 – Dynamic Testing

The split-Hopkinson tension bar setup, as shown in Figure 10, has the test specimen mounted between the incident and transmission bars which are supported in brass bushings. The incident bar passes through the center of the gas gun cylinder and barrel, terminating with a flange used to transfer the projectile’s energy. The projectile, or striker tube, is a hollow maraging steel cylinder that fits around the incident bar. Two plastic bushings are
mounted to the projectile which serve to keep the barrel, projectile and bar concentric. The gas gun is pressurized with air and triggered with a release valve. Upon firing, the projectile travels from the cylinder, through the barrel, and strikes the transfer flange. The impact of the projectile on the transfer flange creates the stress wave that travels the length of the incident bar and strains the specimen to failure. The transfer flange strikes a short momentum transfer (Figure 11) bar after the projectile impact event. This transfer bar assists with motion damping after the initial impact event. Energy is transferred to this bar which then impacts a stationary 6061 aluminum cylinder. The aluminum cylinder deforms slightly due to impact, thus damping gross motion of the momentum transfer bar and, successively, the incident bar.

![Figure 10 Split Hopkinson Tension Bar Layout [25].](image-url)
Both the incident bar and momentum transfer bar are made from 0.75” diameter maraging steel. Generally, the incident and transmission bars would be the same material, however, due to the relatively small stress that reaches the transmission bar, increased sensitivity is required to measure the strain gauge response at this location. To accomplish this, the transmission bar is aluminum and has a 0.375” diameter region at the center of the bar. Both changes amplify the strain experienced by the bar at the location of measurement, resulting in a signal more easily registered by the strain gauge on the transmission bar [22], [25].

The tensile test specimen is mounted with grips on each end of the specimen. Each grip consists of two hardened steel pieces that have a textured surface, increasing the friction between themselves and the test specimen.
The hardened steel pieces are roughly trapezoidal in shape. The test specimen, with hardened steel pieces on each side of the grip tab, is placed inside a threaded cylinder with a specially shaped hole, shown in Figure 12, matching the hardened steel pieces. The hole changes size from one side of the threaded cylinder to the other. A hand operated Enerpac hydraulic cylinder is used to press the specimen and hardened steel pieces through the threaded cylinder.

Figure 12  Threaded Cylinder - Top (Left) and Bottom (Right).

Figure 13  Test Specimen In Threaded Cylinder With Hardened Steel Clamps.
With the threaded cylinder constrained, the pieces are pressed through the narrowing hole in the cylinder. As the pieces are moved further into the cylinder, the clamping pressure on the test specimen increases. Once both ends of the test specimen have the grips in place (Figure 13), they are threaded into couplings that attach the test specimen to the threaded incident and transmission bars. A jig is used to ensure that the sample is never torqued or loaded during this mounting process.

2.3.1 – SHTB Data Acquisition

The data acquisition used for the high-speed tests is made up of two distinct systems: strain gauge data recorded by an oscilloscope, and a high-speed camera. Figure 14 shows the equipment included in these two systems and their connections. The strain gauges attached to the bars, a multi-channel signal conditioner/amplifier, multi-channel oscilloscope with trigger output capabilities, high speed camera, and a PC for camera settings and control.

Strain gauges mounted to the incident and transmission bars are used to collect data from the testing event. The gauges are connected to a signal conditioner/amplifier that supplies an excitation voltage for the gauges and amplifies their signal. The output of the signal conditioner/amplifier is connected to an oscilloscope capable of recording at 100 MHz. The oscilloscope has a digital trigger capability that governs data recording of the testing event.
Figure 14 Layout of SHTB Data Acquisition Systems.

Figure 15 Wave Propagation In Split Hopkinson Bar - Duration Of Strain Gauge Signals Shown For Incident (Lower Left), Reflected (Upper Left), & Transmitted (Right) Waves [25].
The trigger is set such that a voltage spike coming from the incident bar will begin the data recording process, but noise inherent in the signal will not. Once triggered, the oscilloscope captures data within a 200 µs time window, recording the incident, reflected, and transmitted strain wave signals (shown in Figure 15) as they propagate through the bars and test specimen.

A Photron FASTCAM SA-X2 is used for high-speed imaging. The camera is set up orthogonally to the surface of the test sample, as shown in Figure 16. The camera captures images at 100,000 frames per second (fps) at a resolution of 384 x 264 pixels. To provide the necessary lighting at this framerate, LED lights are used to the sample, as ambient lighting was not sufficient at that frame rate.

![Figure 16 Photron FASTCAM SA-X2 High-Speed Camera & Lighting.](image)

The camera is triggered via a direct connection to the oscilloscope, which has a TTL (transistor-transistor logic) output signal capability, allowing both devices to be triggered simultaneously. The camera is operated using the Photron FASTCAM Viewer (PFV)
software. Controls are set up such that it is in an endless recording state prior to the testing event, effectively keeping its internal memory buffer full. Once triggered, the software sets the trigger time to zero, with an equal number of frames ranging both positive and negative away from zero until the memory is full. This center trigger setup is used to prevent loss of data prior to the camera receiving the trigger.

2.4 – Data Processing and Analysis

Data processing took place in multiple steps for both the quasi-static and dynamic testing to obtain the stress-strain curves for each test specimen. Stress data was calculated using the raw data collected from each of the test fixtures, while the strain data was calculated via DIC analysis.

Stress data was calculated for the quasi-static tests using the ATS load data and dividing by the cross-sectional area of the test specimens. The dynamic testing, however, required more advanced calculations to process the strain gauge output voltage data. MATLAB was used to analyze the strain gauge data collected by the SHTB’s oscilloscope. For relating one dimensional stress wave theory to SHTB testing, the following assumptions (as outlined by Chen et al. [25]) are made: the test specimens are in stress equilibrium, stress waves propagate in the bars without dispersion, and deformation in the specimen is nearly uniform. By these assumptions, equation (1) is used to calculate uniform stress [25], which is a function of the signal received by the transmission bar.

\[
\sigma = \frac{A_B}{A_S} E_B \varepsilon_T
\]  

(1)
\( A_B \) is the cross-sectional area of the bar, \( A_S \) is the cross-sectional area of the test specimen, \( E_B \) is Young’s modulus of the bar, and \( \varepsilon_T \) is the transmission bar strain.

Uniform strain and uniform strain rate strain rate are also calculated using this analysis, with the strain data used for comparison to the DIC analysis later. Uniform strain [25] was calculated using

\[
\varepsilon = -2 \frac{C_B}{L_S} \int_0^t \varepsilon_R dt \tag{2}
\]

and uniform strain rate [25] was calculated using

\[
\dot{\varepsilon} = -2 \frac{C_B}{L_S} \varepsilon_R \tag{3}
\]

where \( C_B \) is the elastic bar wave speed, \( L_S \) is the length of the test specimen, and \( \varepsilon_R \) is the bar strain based on the reflected wave [25]. Bar strain is a function of the gauge factor of the attached strain gauge as well as the input and output voltages of those gauges. A quarter bridge configuration is used for each strain gauge’s Wheatstone bridge. Therefore, bar strain data [25] is calculated using

\[
\varepsilon = \frac{4U_0}{G_F U_i} \tag{4}
\]

where \( U_0 \) is the output voltage of the strain gauge, \( U_i \) is the excitation voltage of the strain gauge, and \( G_F \) is the gauge factor. Additionally, this equation was multiplied by the gain values used for a given test. Appendix B – SHTB Data Analysis Code contains additional information regarding the MATLAB files.
Images taken during testing for all samples (example shown in Figure 17) were processed using the Correlated Solutions Vic-2D 2009 software, to acquire strain-time histories for each specimen. In the DIC analysis, a subset of 15 and step size of 3 were used for the quasi-static tests. For dynamic tests, a subset of 15 and step size of 1 were used. A digital extensometer was used for the analyzed DIC images to extract strain-time curves for each specimen.

![Figure 17](image.jpg)

**Figure 17** Speckled ASA Specimen (Top) And DIC Analysis Image (Bottom) – Image Taken With Photron FASTCAM SA-X2 High Speed Camera.

Using MATLAB, each sample’s strain-time curve from the DIC analysis was graphically overlaid with its stress-time curves from the ATS load frame to confirm the maximum stress maximum stress coincided with the strain at failure. The stress and strain vectors for each sample were then plotted together to develop the final stress-strain curve.
For dynamic testing, the strain-time curves calculated using equation (1) were overlaid with the DIC strain-time data in MATLAB. Similar to the quasi-static comparison, the alignment of the maximum stress value with the strain at failure value for each test was confirmed. The strain-time curves calculated using equation (2) were also compared to the DIC strain-time data in order to further validate the strain response of each tests specimen. These were graphically overlaid and compared to confirm the strain response for each specimen was similar for both data acquisition tools. The final stress-strain curves for dynamic testing were developed using the stress data calculated in equation (1) and the strain data resulting from the DIC analysis.
CHAPTER 3 – RESULTS AND OBSERVATIONS

Representative curves for each combination of material, raster orientation, and layer height are presented. The stress-strain curves for all tests are evaluated up to the point of primary failure in which a large portion of the cross section broke; resulting in a drop off of the load experienced by the test specimen.

3.1 – Quasi-Static Tensile Testing

The load-displacement curves recorded by the ATS load cell contained a plateau region that is caused by the lower grip (Figure 18) used in this testing.

Figure 18  ATS Load Cell Lower Grip With Pinned Connection To Threaded Anchor.
The difference between the pin diameter and hole diameter caused travel of the lower grip once the load experienced by the test specimen matched the weight of the grip (approx. 26 lbs). During analysis, data in this plateau region was omitted in order to properly calulate stress-strain curves. A typical load-displacement curve for this testing is shown in Figure 19.

![ATS Load-Displacement Curve](image)

**Figure 19** ATS Load-Displacement For ABS-M30 Sample (0° Raster Angle, 0.01” Layer Height).

Individual filament separations and breakages after the primary failure of the test specimens resulted in extreme reductions in load on the specimen. While load data was able to be recorded, filament separations after the primary failure caused unknown reduced cross sections (and generally caused intact filaments to begin bending), making a one-dimensional stress analysis impossible. Additionally, DIC correlation is lost after the primary failure due to the formation of cracks in the test specimen. This in turn prevents accurate measurement of strain data. Results for the three materials are therefore presented as stress-strain data until the point of this primary failure.
Results for the quasi-static ABS-M30, ASA, and PC-ABS tests are shown in Figure 20, Figure 21, and Figure 22, respectively.

**Figure 20** Quasi-Static ABS-M30 Results.

**Figure 21** Quasi-Static ASA Results.
All materials showed the $0^\circ$ raster angle to be the strongest in tension and the $45^\circ$ raster pattern to be the weakest, with a notable decrease in strength for the $45^\circ$ and $90^\circ$ raster angle tests of the PC-ABS 0.005” layer height.

**Figure 22** Quasi-Static PC-ABS Results.

**Figure 23** ASA Specimens With $90^\circ$ Raster Angle Tested In Load Cell – Layer Heights Shown: 0.01” (Top) & 0.005” (Bottom).
ABS-M30 and PC-ABS tests had consistent failures near the fillet for specimens with a 90° raster orientation. ASA samples, however, exhibited a tendency to fail outside the gauge section for both layer heights due to the stress concentrations caused by the fillets. As shown in Figure 23, this phenomenon was observed in all 0.005” layer height tests and was found in one of the four 0.01” layer height specimens tested. This is an indication of the effect of layer height on bond strength in this material.

**Figure 24** 90° Raster Angle, 0.01” Layer Height ASA Specimen With Voids In Fracture Surface.

Upon visual examination of the fracture surfaces, ASA and PC-ABS samples were found to have voids inside the deposited filaments. These are most easily seen in the 45° and 90° raster angle samples. An example of this for a 90° raster test specimen is shown in Figure 24. With the 45° and 90° raster angles showing worse bond strength than that of the ABS-M30 samples, this is likely a significant factor to the reduction in strength for these raster orientations.
Comparing the materials by raster angle, the 0° raster tests (Figure 25) reveal the relative tensile strengths of the three materials, with results similar to those provided by Stratasys in Table 3. ASA tests are noted as having a somewhat higher yield strength than expected.

![Stress-Strain Curve](image)

**Figure 25** Quasi-Static 0° Raster Orientations.
Figure 26 Quasi-Static $45^\circ$ Raster Orientations.

Figure 27 Quasi-Static $90^\circ$ Raster Orientations.
Figure 26 compares the 45° raster tests. It was found that the 45° samples tended to have a peeling type of failure resulting from localization of the applied load after a crack began to propagate through the bonded sections between filaments. This is similar to the failure mode found in 3D printed lap joints, where the lap joint is made of a single material, including the bonded section [28]. As a result, the 45° raster orientation generally has the lowest yield stress of the three raster angles. The ABS-M30 and ASA samples with a 90° raster angle were found to have similar strain-to-failure responses to the 45° samples of the same material.

The 90° raster angle tests are shown in Figure 27. Differences in the stress-strain curves due to layer heights are most notable for PC-ABS. This data shows significantly lower yield strengths of the three raster angles at the 0.005” layer height when compared to the 0.01” layer tests of the raster angle. In most cases, a smaller strain-at-failure for the 0.005” layer height is found for the 45° and 90° raster angles as well. This suggests the PC-ABS has more difficulty cross-linking to adjacent material during filament deposition. Samples of each orientation are shown in Figure 28, noting that the majority of the PC-ABS samples similarly remained as a single piece after failure for quasi-static testing.
3.2 – Dynamic Tensile Testing And Comparison To Quasi-Static

Five samples were tested for each combination of variables (material, raster orientation, layer height) for the dynamically loaded test specimens, resulting in a total of 90 tests.

Representative curves for each variable combination are used to compare trends. Similarly, representative curves for the quasi-static tests were selected and plotted against the dynamic representative curves. Plotted results are organized by material type, with comparisons by raster orientation and layer height.
Images of specimens tested with the SHTB are shown in Figure 29. Typical fracture patterns are shown here. It is of note that many test specimens with 0° and 90° raster orientations had two fractures that occurred simultaneously at each end of the gauge length. This is a demonstration of the test specimen being in stress equilibrium during loading [23], which is one of assumptions necessary for analysis of the SHTB strain gauge voltage data. Similarly, the DIC analysis shows full field strain in equilibrium immediately before failure in 0° and 90° raster angle specimens. Localization can also be seen at boundary regions between deposited filaments in the 45° raster angle specimens. Examples of these images are shown in Figure 30.
3.2.1 – Combined Results: Strain Rate Comparison

To compare strain rate at failure for both testing types, the strain rate at maximum stress is plotted for each material in Figure 31. Quasi-static tests had near-zero strain-rate values, as the controlled displacement rate of the load cell was 0.02”/min. Strain rates for dynamic tests ranged from $2 \times 10^2$ – $7 \times 10^2$ sec$^{-1}$ for most tests. The exception being PC-ABS $0^\circ$ raster angle tests, which ranged from $2.1 \times 10^3$ – $2.7 \times 10^3$ sec$^{-1}$. This relatively high strain rate is expected from polycarbonate; Siviour et al. [29] reported strain rates of approximately $3.5 \times 10^3$ for non-3D printed polycarbonate, suggesting the PC-ABS blend used here behaves more similarly to polycarbonate than ABS.
3.2.2 –Combined Results: Raster Angle Comparison

Results for the ABS-M30 samples are shown in Figure 32 and sorted by raster orientation. The dynamic tests resulted in somewhat higher maximum stresses for the 0° raster orientation when compared to the quasi-static tests, and lower values for the other two raster angles.
Figure 32  ABS-M30 Stress-Strain Curves By Raster Angle: 0° (Top Left - Black), 45° (Top Right - Red), 90° (Bottom Center - Blue).
Figure 33 Cross Section Image Of Fracture Surface For ABS-M30 0° 0.01” Layer Test Specimens – Quasi-Static Loading (Top), Dynamic Loading (Bottom).

The 0° angle tests show the brittle behavior of this material at high strain rates; the point of failure is located more closely to the elastic deformation region than in the quasi-static tests. This can also be seen by imaging the fracture surfaces, as shown in Figure 33. The specimen
that underwent quasi-static loading has a relatively smooth fracture surface, while the dynamically loaded test specimen displays jagged features consistent with a brittle fracture.

**Figure 34** ASA Stress-Strain Curves By Raster Orientation: 0° (Top Left - Black), 45° (Top Right - Red), 90° (Bottom Center - Blue).

**Figure 34** compares the raster orientations of the ASA tests. The dynamically loaded samples again show a more brittle failure mode than the quasi-static tests for each raster angle. The 0° raster angle tests had similar maximum stress values between the two loading scenarios. Both the ABS-M30 and ASA dynamic tests continue the trend of the 0° orientation specimens having the highest yield stress and 45° specimens having the lowest yield stress, given all other variables are the same. Again, study of the fracture surfaces reveal the more brittle nature of dynamically loaded ASA test specimens, as seen in **Figure 35**.
Figure 35 Cross Section Image Of Fracture Surface For ASA 0° 0.01” Layer Test Specimens – Quasi-Static Loading (Top), Dynamic Loading (Bottom).
Results for PC-ABS samples, shown in Figure 36, display the trend of dynamic tests having lower maximum stress values than their quasi-static counterparts for each raster angle and layer height. One exception to note is the 45° raster angle with a 0.005” layer height, which tended to failed at a slightly lower stress value during the quasi-static tests. This is contributed to the peeling effect that occurs once a crack begins to propagate through the specimen. Coupled with the increased difficulty cross-linking after deposition, a crack should be able to propagate more easily in PC-ABS prints with smaller layer heights, as they contain more filament bond regions than larger layers.
3.2.3 – Combined Results: Layer Height Comparison

Figure 37 Combined ABS-M30 Stress-Strain Curves – 0.01” Layer Height (Left) & 0.005” Layer Height (Right).

Comparing the layer height behavior showed that the ABS-M30 (Figure 37) and ASA (Figure 38) tests resulted in lower stress values, and in most cases lower strain values, for the 45° and 90° raster angles. Meanwhile, 0° tests remained largely unaffected with changes in layer height for both materials.

Figure 38 Combined ASA Stress-Strain Curves – 0.01” Layer Height (Left) & 0.005” Layer Height (Right).
Differences in the PC-ABS layer heights for both loading conditions are shown in Figure 39. The effects of layer height are more apparent in PC-ABS than the other materials tested. Specimens of the smaller layer height with 45° and 90° raster angles showed extreme decreases in stress at failure. Specimens with a 0° raster orientation were less affected, similar to the other materials. Even so, the differences in the crosslinked bond region of both layer heights is apparent in the 0° raster angle specimens by examining the fracture surfaces.
Figure 40 and Figure 41 show the fracture surfaces of dynamically loaded PC-ABS test specimens of both layer heights.

**Figure 40** PC-ABS Samples Tested With SHTB – 0° Raster Orientation Imaged Orthogonally To Fracture Surface: 0.01” Layer Height (Left), 0.005” Layer Height (Right).

**Figure 41** PC-ABS Samples Tested With SHTB – 0° Raster Orientation Imaged Obliquely: 0.01” Layer Height (Left), 0.005” Layer Height (Right).
It can be seen here that the 0.005” layer height filaments had significantly smaller bond regions than the 0.01” layer height tests. Additionally, it can be seen in Figure 41 that fracture surfaces are nearly non-existent on the sides of the filaments, further reinforcing the lower bond strength of the PC-ABS material. It is of note that the PC-ABS tests with a 0° raster angle experienced a strain softening effect. Polycarbonate, as a glassy amorphous polymer, undergoes strain softening followed by strain hardening at high enough strain rates [30]. These results show the PC-ABS blend had a similar strain softening response when loaded dynamically at these strain rates; however, the ABS present in the polymer blend does differ its behavior from that of a pure polycarbonate.
CHAPTER 4 – CONCLUSIONS AND FUTURE WORK

Experimental testing of FDM specimens was conducted using quasi-static and high strain rate tensile loading conditions. Specimens were manufactured with three raster angles and two layer heights for each material and loading scenario, and speckled to facilitate strain analysis through the use of digital image correlation. Load-displacement data and DIC images were collected during quasi-static testing using a load cell and a framerate controlled camera, respectively. A modified split Hopkinson tension bar was used to test samples dynamically. Output voltage data from the SHTB’s strain gauges was collected via an oscilloscope. A high-speed camera was used to collect DIC images for the SHTB testing. The collected data from both testing setups was analyzed using the processes outlined in Chapter 2 to calculate stress-strain curves for all tests. The processed data from quasi-static tests provided a baseline for material behavior of each variable combination, and served as baseline data for dynamic testing. Comparing data from both loading conditions reinforces the validity of the SHTB data and provides trend data for how each material’s behavior changes with strain rate.

Test specimens loaded in the axial direction of the deposited filaments (0° raster angle) show the strongest material response for tensile loading, both quasi-static and dynamic. The maximum stress values were fairly consistent with the maximum data values provided by reference material; however, these values are still approximately 70 – 80% of the average strengths of an injection molded part made from the same material. As expected, SHTB testing revealed a more brittle response due to the elevated strain rate as shown by both the analyzed data from the SHTB testing and microscope imaging. However, the PC-ABS 0°
tests displayed strain-softening due to the nature of a glassy amorphous polymer (i.e. polycarbonate) present in the polymer blend.

The 45° raster angle experienced a peel failure similar to that of a bonded lap joint. Due to the ease at which a crack can propagate with this failure mode, the 45° specimens had, on average, the lowest stress values at failure for each of the materials tested. The 90° raster angle tests revealed the bond strength when loaded in tension, and comparisons to 0° tests show the differences in strength between these weaker areas of the printed part to the strongest possible condition in which filaments are loaded axially; giving insight into the importance of printing parameters that facilitate crosslinking. Layer height also played an important role in how large the bonded regions could develop shortly after deposition. These effects were seen most prominently in PC-ABS test specimens, where bonds did not develop as much as in the other materials. Additionally, voids inside the filament were found in the ASA and PC-ABS samples, further influencing the strength of the printed material. How the bonds form between filaments must be taken into consideration when designing 3D printed components and selecting print parameters, as these regions can have a significant effect on the anisotropic behavior of the internal structure.

4.1 – Recommendations For Future Work

- The air gap was kept constant for this testing. More exhaustive testing is recommended for varying the air gap try to study how the effects of air gaps changes with strain rate.
Due to time constraints, a limited number of each variable combination was tested. More exhaustive testing is recommended to improve the statistical significance of the results found herein.

- High strain rate testing of additional FFF materials such as polylactic acid (PLA), nylon, and polymers with fiber filler materials.

- Use a more sensitive strain gauge on the transmission bar, such as a piezoelectric quartz crystal, to improve the signal to noise ratio of FDM samples [31].
REFERENCES


/media/files/material-spec-sheets/mss_fdm_absi_1117a.pdf.


/media/files/material-spec-sheets/mss_fdm_asa_0418a.pdf.

/media/files/material-spec-sheets/mss_fdm_pcabs_1217a.pdf.


APPENDICES
Appendix A – Insight Settings/Setup

1. Set:
   - Solid Part Interior
   - Turn Off Enhanced Surface Style

2. Open: “Configure Modeler”

3. Select:
   - Printer Type
   - Model Material/Color
   - Layer Height.

4. Slice Model

5. Open Toolpath Setup Menu
6. Select Single Contour & Confirm Surface Style/Interior Style Settings Match Step 1
7. Select Contour Width
8. Select Raster Width & Angle
9. Use Parallel Offset Part Raster Option

10. Generate Toolpath

11. Save As Toolpath For Upload To GrabCAD Print Software
Appendix B – SHTB Data Analysis Code

% Split Hopkinson Pressure Bar Data Analysis Program
% Updated 8-12-2016 by Mark Pankow
% Updated 5-16-2018 by Cody Chadwell

%% Read Me:
% INPUTS: Oscilloscope data, in .csv format.
% Column 1: Time (s)
% Column 2: Channel 1 - Incident Bar (V)
% Column 3: Channel 2 - Transmitted Bar (V)
% OUTPUTS: A .csv file containing the following
% Column 1: Time (us)
% Column 2: Strain (-)
% Column 3: Stress (MPa)
% Column 4: Strain rate (-/sec)
% Column 5: Uniform Strain (-)
% Column 6: Uniform Stress (MPa)
% Column 7: Uniform Strain rate (-/sec)
% Column 8: Stress w/ Voltage Shift Correction (MPa)

% 1. Copy this file into a folder along with the channel data files.
% 2. Match the names of the channel files with those in this program.
% 3. Enter specimen length, diameter, mass, estimated modulus information into the program code
% 4. Run the program.
% 5. Select beginning and end points of incident wave.
% 6. Iterate (Rerun program) - Shifting by changing error values to establish equilibrium if possible.
% 7. Output is the polynomial fit data

%% Plots:
% 1. Incident and Transmitted Bar strain gage signals (Raw Data & with Voltage Shift Correction)
% 2. Incident Gage - Requires user inputs to window the incident pulse
% 3. Pulse Orientation - Gauge of pulses in relation to entire signal
% 4. Incident, Transmitted and Reflected Pulses - After shift is applied
% 5. Force Balance - Equilibrium Check
% 6. Stress-Strain Curves (Polynomial fit and original)
% 7. Strainrate-Strain Curves (Polynomial fit and original)
% 8. Strain-Time History

close all;
clear all;
clc;

%% 1 Data Read In
% Read in Strain Gage Signals - file 'name-of-file.csv'
inbar = csvread('scope_11.csv',23,0);

%% 2 Specimen, Pressure Bar, Amplifier Specifications

% Specimen Information (l, w, & t for Gauge Length)
l_spec = 1.2*.0254; % Test direction - Output Meters (Inches * 0.254)
w_spec = 0.24*.0254; % Width - Output Meters
T_spec = 0.1*.0254; % Thickness - Output Meters
m_spec = 1.33*.001; % Mass - Output Kilograms (Grams * 0.001)
E_spec_guess = 2.3e09; % Output Pa
A_spec = w_spec*T_spec; % Cross sectional area (m^2)

rho_spec = m_spec / (l_spec*A_spec); %Density for rectangular prism specimen (Kg/m^3)
c_spec = sqrt(E_spec_guess / rho_spec); % Speed of sound through specimen (m/s)
tau = l_spec / c_spec; % sec

% Amplifier Information
num_gage_inc = 1; % Quarter Bridge = 1
num_gage_tra = 1; % Quarter Bridge = 1
gain_inc = 350; % Incident Bar Gain
gain_tra = 5000; % Transmitted Bar Gain
v_exc_inc = 3.5; % Excitation Voltage (Incident)
v_exc_tra = 3.5; % Excitation Voltage (Transmitted)

% Strain Gauge Information
k_factor_inc = 2.11; % K factor for incident strain gauge
k_factor_tra = 2.11; % K factor for transmitted strain gauge

% Bar Information
l_inc = 96*.0254; % Length of Incident Bar (Output meters: inches*0.0254)
l_tra = 74*.0254; % Length of Transmitter Bar (Output meters: inches*0.0254)
E_inc = 200e9; % Modulus of Incident bar in Pascals
E_tra = 69e9; % Modulus of Transmitted bar in Pascals
d_inc = 0.75*0.0254; % Bar Diameter in Meters
d_tra = 0.375*0.0254; % Bar Diameter in Meters
A_inc = pi*(d_inc/2)^2; % Cross sectional area of bars (m^2)
A_tra = pi*(d_tra/2)^2; % Cross sectional area of bars (m^2)
c_inc = 5416.67; % Velocity of sound in bars (m/s)
c_tra = 5055; % Velocity of sound in bars (m/s)
 rho_bar_inc = 7500; % Bar density (kg/m^3) Appears to be mid-range density mmaraging steel
rho_bar_tra = 2700; % Appears to be 1000 series aluminum

% 3 Data Breakout
% Separating the single input file into multiple arrays

zero_point = find(inbar(:,1)==0)+23; %Finds zero value in time vector (from oscope)
csv_step = 0.000000032; %Step size of time vector from oscpe
for i=1:length(inbar(:,1))
    time_vector(i,1) = (i - zero_point)*csv_step;
end
% Split loaded data into time and voltage vectors for each wave
\[ t_{\text{inc}} = \text{time\_vector}; \]
\[ t_{\text{ref}} = t_{\text{inc}}; \]
\[ t_{\text{tra}} = t_{\text{inc}}; \]
\[ v_{\text{inc}} = \text{inbar}(;2); \]
\[ v_{\text{tra}} = \text{inbar}(;3); \]
\[ v_{\text{ref}} = v_{\text{inc}}; \]

% Voltage correction for incident signal
% Averages first 1/3 of noise, offsets entire signal by this amount
\[
v_{\text{inc\_avg}} = \text{mean}(v_{\text{inc}}(1:(\text{length}(v_{\text{inc}})/3)));
\]
\[
\text{if } v_{\text{inc\_avg}} < 0 \\
\quad \text{for } i = 1:\text{length}(v_{\text{inc}}) \\
\quad \quad v_{\text{inc\_shift}}(i) = v_{\text{inc}}(i) + \text{abs}(v_{\text{inc\_avg}}); \\
\quad \text{end} \\
\text{else} \\
\quad \text{for } i = 1:\text{length}(v_{\text{inc}}) \\
\quad \quad v_{\text{inc\_shift}}(i) = v_{\text{inc}}(i) - \text{abs}(v_{\text{inc\_avg}}); \\
\quad \text{end} \\
\text{end} \\

% Voltage correction for transmitted signal
% Averages first 1/2 of noise, offsets entire signal by this amount
\[
v_{\text{tra\_avg}} = \text{mean}(v_{\text{tra}}(1:(\text{length}(v_{\text{tra}})/2)));
\]
\[
\text{if } v_{\text{tra\_avg}} < 0 \\
\quad \text{for } i = 1:\text{length}(v_{\text{tra}}) \\
\quad \quad v_{\text{tra\_shift}}(i) = v_{\text{tra}}(i) + \text{abs}(v_{\text{tra\_avg}}); \\
\quad \text{end} \\
\text{else} \\
\quad \text{for } i = 1:\text{length}(v_{\text{tra}}) \\
\quad \quad v_{\text{tra\_shift}}(i) = v_{\text{tra}}(i) - \text{abs}(v_{\text{tra\_avg}}); \\
\quad \text{end} \\
\text{end} \\

% Plotting raw and shifted voltage signals from oscilloscope
\text{figure(1)}
\text{plot}(t_{\text{inc}},v_{\text{inc}},t_{\text{inc}},v_{\text{inc\_shift}},t_{\text{inc}},v_{\text{tra}},t_{\text{inc}},v_{\text{tra\_shift}})
\text{xlabel('Time (s)','FontSize',18); ylabel('Voltage (V)','FontSize',18)
\text{title('Strain Gage Raw Signals','FontSize',18)
\text{legend('Incident Bar Gage','Incident Bar Gage Shifted','Transmitter Bar Gage','Transmitted Bar Shifted')}

% 4 Noise Correction - Simple average of closest 7 data points
\[
\text{for } k=4:(\text{length}(v_{\text{inc\_shift}})-4) \\
\quad v_{\text{inc\_shift}}(k) = (v_{\text{inc\_shift}}(k-3)+v_{\text{inc\_shift}}(k-2)+v_{\text{inc\_shift}}(k-1)+v_{\text{inc\_shift}}(k)+v_{\text{inc\_shift}}(k+1)+v_{\text{inc\_shift}}(k+2)+v_{\text{inc\_shift}}(k+3))/7; \\
\text{end} \\
\text{for } k=4:(\text{length}(v_{\text{ref}})-4) \\
\quad v_{\text{ref}}(k) = (v_{\text{ref}}(k-3)+v_{\text{ref}}(k-2)+v_{\text{ref}}(k-1)+v_{\text{ref}}(k)+v_{\text{ref}}(k+1)+v_{\text{ref}}(k+2)+v_{\text{ref}}(k+3))/7; \\
\text{end} \\
\text{for } k=4:(\text{length}(v_{\text{tra\_shift}})-4) \\
\quad v_{\text{tra\_shift}}(k) = (v_{\text{tra\_shift}}(k-3)+v_{\text{tra\_shift}}(k-2)+v_{\text{tra\_shift}}(k-1)+v_{\text{tra\_shift}}(k)+v_{\text{tra\_shift}}(k+1)+v_{\text{tra\_shift}}(k+2)+v_{\text{tra\_shift}}(k+3))/7;
%% 5 Establish Incident Wave Beginning and End - Manual Inputs Needed
% Beginning - Typically when wave begins to ramp up is - approx 250mv
% End - After wave has finished level portion and begins to decrease to 0

% Incident Wave
scrsz = get(groot,'ScreenSize'); %Stores Screen size
figure('Position',[scrsz(1) scrsz(2) scrsz(3) scrsz(4)]); %Maximizes fig 2
to fit screen
grid on;
plot (t_inc,v_inc_shift);
xlabel('Time (s)', 'FontSize', 18);
ylabel('Voltage (V)', 'FontSize', 18)
title('Incident Pulse Windowing', 'FontSize', 18)
grid on;
uiwait(msgbox('Select the BEGINNING and END of INCIDENT wave')); %User
input
[t_beg, v_beg] = ginput(1);
inc_beg = find(t_inc < t_beg);
inc_beg = max(inc_beg);
[t_end, v_end] = ginput(1);
inc_end = find(t_inc < t_end);
inc_end = max(inc_end);

%% 6 Reflected and Transmitted Wave Determination
% Time Shift Method for Determining Start Points of Waves
% Manually update error_ref & error_tra to align takeoff points of the 3
pulses

% Reflected Wave Determination
error_ref = -54e-6; % Positive
increases time gap
t_shift_ref = l_inc / v_sound_inc + error_ref; % Time shift
ref_beg = find(t_inc < (t_inc(inc_beg) + t_shift_ref)); % Start Point -
Start of Incident plus Shift Time
ref_beg = max(ref_beg);
ref_end = ref_beg + (inc_end - inc_beg); % End Point -
Same Length as Incident Pulse

% Transmitted Wave Determination
error_tra = 1.5e-6; % Positive
increases time gap
t_shift_tra = ((l_inc/2/c_inc) + (l_tra/2/c_tra)+l_spec / c_spec) +
error_tra;
tra_beg = find(t_tra < (t_inc(inc_beg) + t_shift_tra)); % Start Point -
Start of Incident plus Shift Time
tra_beg = max(tra_beg);
tra_end = tra_beg + (inc_end - inc_beg); % End Point -
Same Length as Incident Pulse

%% 7 Pulses in Relation to Total Signal - Plot for Visualization

figure(3)
hold on;
plot(t_inc,v_inc_shift, t_inc, v_tra_shift)
plot(t_inc(inc_beg:inc_end),v_inc_shift(inc_beg:inc_end),'m',... 
   t_inc(ref_beg:ref_end),v_inc_shift(ref_beg:ref_end),'m--',... 
   t_inc(tra_beg:tra_end),v_tra_shift(tra_beg:tra_end),'m:',...'LineWidth',3)
grid on;
legend('Incident Bar Gage Signal','Transmitted Bar Gage 
   Signal','Transmitted Pulse','Reflected Pulse')
xlabel('Time (s)','FontSize',18); ylabel('Voltage (V)','FontSize',18)
title('Pulse Orientation', 'FontSize',18)

%% 8 Normalizing Waves

% Convert time arrays into microseconds (s -> us)
t_inc = (time_vector(:,1) - time_vector(1,1))*1e06;
t_ref = (time_vector(:,1) - time_vector(1,1))*1e06;
t_tra = (time_vector(:,1) - time_vector(1,1))*1e06;

% Create Arrays for only Pulse Segment
l=0;
for k = inc_beg:inc_end-1 % Incident Wave
    l = l+1;
    t_wave_inc(l) = t_inc(k);
    v_wave_inc(l) = v_inc_shift(k);
end

l=0;
for k = ref_beg:ref_end-1 % Reflected Wave
    l = l+1;
    t_wave_ref(l) = t_ref(k);
    v_wave_ref(l) = v_ref(k);
end

l=0;
for k = tra_beg:tra_end-1 % Transmitted Wave
    l = l+1;
    t_wave_tra(l) = t_tra(k);
    v_wave_tra(l) = v_tra_shift(k);
end

% Saving length of time array of each wave for later use
inc_size = size(t_wave_inc);
ref_size = size(t_wave_ref);
tra_size = size(t_wave_tra);

% Normalize Wave Start Times to Zero Time - Aligning Beginnings
   t_wave_inc = t_wave_inc - t_wave_inc(1);
   t_wave_ref = t_wave_ref - t_wave_ref(1);
   t_wave_tra = t_wave_tra - t_wave_tra(1);

% Plot of aligned pulses
   figure(4)
   plot(t_wave_inc,v_wave_inc,'g',t_wave_ref,-
      v_wave_ref,'b',t_wave_tra,v_wave_tra,'r','LineWidth',2)
   legend('Incident','Reflected','Transmitted')
   xlabel('Time (us)','FontSize',18); ylabel('Voltage (V)','FontSize',18)
title('Pulses Overlay','FontSize',18)

% Times are now a percent of the total time of the incident wave
% Determining the shortest wave, in order to set limit of integration
if ref_size(2) <= inc_size(2)
    if ref_size(2) >= tra_size(2)
        time_per = t_nor_tra;
    else
        time_per= t_nor_ref;
    end
else if inc_size(2) < ref_size(2)
    if inc_size(2) < tra_size(2)
        time_per = t_nor_inc;
    else
        time_per = t_nor_tra;
    end
end

% Time array ends with the shortest wave
% Calculating Specimen Stress, Strainrate and Strain
% Calculating the strain values from each gage, over the entire wave
% Equilibrium Check Plot
% Trans/Spec is linearly related to the Transmitted pulse.
% Calculating Stress - Non-uniform and Uniform Deformation
for k = 1:t_end(2)
    stress(k) = (1/2)*(((A_inc/A_spec)*E_inc*(strain_inc(k) + strain_ref(k)))+((A_tra/A_spec)*E_tra*strain_tra(k)));  
    stress_uni(k) = E_tra *(A_tra/A_spec) *strain_tra(k);
end

% Calculating Strainrate - Non-uniform and Uniform Deformation
for k = 1:t_end(2)
    strainrate(k) = (v_sound_inc/l_spec)*(strain_inc(k) - strain_ref(k)) - (c_tra/l_spec)*(strain_tra(k));  
    strainrate_uni(k) = -2 * v_sound_inc / l_spec * (strain_ref(k));
end

% Calculating Strain in the Specimen - Non-uniform and Uniform Deformation
multiplier_inc = (-v_sound_inc*4)/(l_spec*v_exc_inc*k_factor_inc*gain_inc);
multiplier_ref = multiplier_inc;
multiplier_tra = (-c_tra*4)/(l_spec*v_exc_tra*k_factor_tra*gain_tra);
str_inc = cumtrapz(time,v_wave_inc(1:t_end(2)));
str_ref = cumtrapz(time,v_wave_ref(1:t_end(2)));
str_tra = cumtrapz(time,v_wave_tra(1:t_end(2)));
str_uni = cumtrapz(time,v_wave_ref(1:t_end(2)));

for k = 1:t_end(2)
    strain(k) = -(multiplier_inc*str_inc(k)) + (multiplier_ref*str_ref(k)) + (multiplier_tra*str_tra(k));
    strain_uni(k) = -2 * v_sound_inc / l_spec * (str_uni(k)/v_exc_inc) * (4/k_factor_inc) * 1/gain_inc;
end

%% 10 Polynomial Fitting of Stress and Strainrate Data
% This will also include shifting of data to go through origin for stress-strain curve

% Setting up arrays for polynomial fitting
A=size(strain);
for i=1:A(1,2)
    strain_poly(i,1)=strain(1,i)*1e-06 - strain(1,1)*1e-06;
    strain_poly_uni(i,1)=strain_uni(1,i)*1e-06 - strain_uni(1,1)*1e-06;
    stress_poly(i,1)=stress(1,i)*1e-06 - stress(1,1)*1e-06;
    stress_poly_uni(i,1)=stress_uni(1,i)*1e-06 - stress_uni(1,1)*1e-06;
    strainrate_poly(i,1)=strainrate(1,i)*1 - strainrate(1,1)*1;
    strainrate_poly_uni(i,1)=strainrate_uni(1,i)*1 - strainrate_uni(1,1)*1;
end

% Polyfit Stress and Strainrate
A=polyfit(strain_poly,stress_poly,10);
stress_poly_new=polyval(A,strain_poly);
B=polyfit(strain_poly,strainrate_poly,10);
strainrate_poly_new=polyval(B,strain_poly);
C=polyfit(strain_poly_uni,stress_poly_uni,10);
stress_poly_uni_new=polyval(C,strain_poly_uni);
D=polyfit(strain_poly_uni,strainrate_poly_uni,10);
strainrate_poly_uni_new=polyval(D,strain_poly_uni);

% Shifting polyfit stress values for stress-strain curve
stress_offset = abs(stress_poly_new(1)); % Storing 1st value of stress poly array
% Changes stress offset sign depending on needed shift direction
if stress_poly_new(1) >= 0
    stress_offset = -stress_offset;
end
% Applying shift stress poly array
for index = 1:size(stress_poly_new)
    stress_poly_new_shift(index,1) = stress_poly_new(index)+stress_offset;
end

%% 11 Plotting Stress-Strain and Strainrate-Strain Curves

% Finding max values for axes limits
stress_limit = max(stress_poly_new)+50;
strain_limit = max(strain_poly)+.01;
strainrate_limit = max(strainrate_poly_new)+100;

% Plotting original and poly/shifted stress-strain curves
figure(6)
hold on;
plot(strain*1e-06, stress*1e-06,'b')
plot(strain_poly,stress_poly_new,'r','Linewidth',2)
plot(strain_poly,stress_poly_new_shift,'g') % Plots new stress shift
plot(strain_uni*1e-06, stress_uni*1e-06,'k','Linewidth',2)
axis([0 strain_limit 0 stress_limit])
xlabel('Strain(-)'),'FontSize',18); ylabel('Stress(MPa)','FontSize',18);
title('Stress-Strain Polynomial Fit and Shift','FontSize',18)
legend('Original','Polynomial Fit + Shifted','Polynomial + New Shift')

% Plotting original and poly/shifted strainrate-strain curves
figure(7)
hold on;
plot(strain*1e-06, strainrate*1e-06,'b')
plot(strain_poly,strainrate_poly_new,'r','Linewidth',2)
plot(strain_uni*1e-06, strainrate_uni*1e-06,'k')
axis([0 strain_limit 0 strainrate_limit])
xlabel('Strain(-)','FontSize',18); ylabel('Strainrate(-/s)','FontSize',18);
title('Strainrate-Strain Polynomial Fit and Shift','FontSize',18)
legend('Original','Polynomial Fit + Shifted')

figure(8)
hold on;
plot(time,strain*1e-06,'b')
axis([0 200 0 strain_limit])
xlabel('Time(us)', 'FontSize', 18); ylabel('Strain(-)', 'FontSize', 18);
title('Strain-Time History', 'FontSize', 18)
%% 12 Data Read Out - Non-uniform
for k = 1:t_end(2)
    data_saved(k,1) = time(k); % micro seconds
    data_saved(k,2) = strain_poly(k,1); % (-) (for % strain, *100)
    data_saved(k,3) = stress_poly_new(k,1); % MPa
    data_saved(k,4) = strainrate_poly_new(k,1); % (-/s)
    data_saved(k,5) = strain_poly_uni(k,1); % (-) (for % strain, *100)
    data_saved(k,6) = stress_poly_uni_new(k,1); % MPa
    data_saved(k,7) = strainrate_poly_uni_new(k,1); % (-/s)
    data_saved(k,8) = stress_poly_new_shift(k,1); % MPa
end

% Writes k array to csv file output
csvwrite('ABS_0_0.01 Sample 1 Signal Shift.csv',data_saved,0,0);