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Dynamic Body Armor Shape Sensing Using Fiber Bragg Gratings
and Photoassisted Silicon Wire-EDM Machining

Ivann Civi Lomas-E Velasco

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Dynamic Body Armor Shape Sensing Using Fiber Bragg Gratings and Photoassisted Silicon Wire-EDM Machining

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Master of Science

In this thesis, a method to improve survivability is developed for fiber Bragg gratings under high velocity impact in dynamic body armor shape sensing applications by encasing the fiber in silicone. Utilizing the slipping of the fiber within the silicone channel, a proportionality relationship between the strain of the fiber to the acceleration of the impacting projectile is found and is used to obtain the rate of the back-face deformation. A hybrid model is developed to handle errors caused by the stick-slip of the fiber by fitting an inverse exponential to stuck sections found in a captured strain profile and double integrated to transform the stuck section to its equivalent slipping. Displacement errors below 10% was achieved using the hybrid model. A graphical user interface with a step-by-step walkthrough and a fiber Bragg grating interrogation system was designed for test engineers to utilize this technology. Test engineers from the Army Test Center in Aberdeen, MD were trained on this technology and successfully captured and processed shots using this technology.

A method for cutting Silicon through wire-EDM machining is developed by utilizing the photoconductive properties of Silicon. Cut rates for unilluminated and illuminated Silicon was compared and a 3x faster cut was achieved on the illuminated cuts.

Keywords: fiber optic sensors, body armor testing, fiber Bragg gratings, Silicone wire-EDM.
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CHAPTER 1. INTRODUCTION AND CONTRIBUTIONS

This thesis covers the implementation of body armor shape sensing using fiber Bragg gratings under high dynamics to characterize backface deformation (BFD) of the armor under ballistic impact. The field testing done at the Army test center (ATC) in Aberdeen, MD with the use of the new sensor system is also covered. In addition, another project involving a new method of cutting silicon by using wire-EDM technology and the photoconductive property of silicon is covered.

A summary of my contributions are as follows:

1. Developed a graphical user interface (GUI) implementing a hybrid model for shape sensing to make it field deployable and trained personnel at the ATC in Aberdeen, MD.
   - Foundational work on the algorithm that is implemented in the GUI is covered in [8]. My main contribution in the development of the GUI is the taking of a complicated algorithm with numerous steps and simplifying it into three steps so that test engineers, with no knowledge of the shape sensing algorithm, can easily use and obtain data with the same accuracy as someone with a deep knowledge of the algorithm.
   - Another main contribution is the fine tuning of the stick-slip compensation method used to adjust stuck sections to be consistent with slipping sections. I processed numerous shot data captured at ATC and NCSU to tune the method of
optimizing the fitting parameters in an inverse exponential that is used to fit to stuck sections then double differentiated to obtain the slipping counterpart.

2. Created a method of fiber survivability under high dynamics. This means that the optical fiber does not break during the BFD or that information of the whole shot event, from beginning to end, is obtained before the fiber breaks.
   
   - This contribution was in conjunction with North Carolina State University (NCSU). Much of the testing done in the design and development of the sensing layer for fiber survivability was done at NCSU. My main contribution was in the fabrication design process by designing and creating molds for sensing layers which were sent to NCSU to use for testing. In addition, I created essential fabrication steps, such as the method used to apply uniform coats of Vaseline onto the optical fiber, that lead to the final design and fabrication process of the sensing layer.

3. Field testing of the developed sensor system.
   
   - The final testing of the system was performed by ATC personnel. I developed the user’s manual and the GUI to enable the testing to be performed by personnel that were not directly involved in the development of the system.

4. Developed a method to cut silicon using a wire-EDM.
   
   - I was the primary contributor to this work. It was done in combination with an undergraduate student (Brad Ferguson) and with personnel that work in the Prototype Manufacturing Lab (PML)
CHAPTER 2. BODY ARMOR SHAPE SENSING BACKGROUND

Modern body armor is extremely effective at stopping projectiles from penetrating the wearer and is used extensively in the military, police forces, or any occupation that involves dangerous situations. Though effective at stopping projectiles, users can still suffer from serious internal injuries known as blunt force trauma. Blunt force trauma can come in the form of broken bones, severe organ injuries, internal bleeding, etc. and are caused by the deformation of the body armor during impact with the projectile [1][2].

This deformation is known as backface deformation (BFD). The speed of the BFD is the main contributor to how the force of the projectile is delivered to the user. As a result, there is a huge focus on redesigning body armor that mitigates injuries caused by the BFD of the armor. Therefore, much of body armor testing is done to characterize the BFD but, to do so, capturing the dynamics is essential.

Popular testing methods for armor are done using clay backing or ballistics gel with a high-speed camera. Figure 2-1 shows that the body armor is shot with clay behind it with the resulting indentation made in the clay measured. The standard clay that is used is Roma Plastilina #10 because it has a good correlation with soft human tissue in that the depth of penetration as a function of time, when impacted by a hemispherical missile, is the same between clay and human tissue [3].
There are several primary deficiencies in the BFD measurement using this method: (1) This method does not provide information on the dynamics of the BFD making it difficult to fully characterize the BFD to better design body armor (2) The response of the clay varies greatly and is dependent on factors such as strain rate, shear and thermal loading history. These variations lead to significant variations in the final BFD measurement [4]. (3) The measurement of the BFD in clay assumes that all of the deformation in the clay is plastic, therefore the post-impact BFD matches the maximum BFD. However, measuring the indentation in the clay backing can often underestimate the BFD [4].

![Figure 2-1. Example of using clay for body armor testing. Armor is shot with the clay behind it and the indentation of the clay from the deformation of the armor is measured](image)

While the use of primarily elastic backing materials, such as ballistic gel, could alleviate some of the variation found in using clay, high-speed imaging throughout the impact would be required. Implementation of this method is difficult and is expected to not be cost-effective [4]. In order to attain a dynamic measurement of the BFD without requiring a high-speed camera, this work uses an optical fiber strain sensor in a sensing layer placed between the body armor
and the backing material. Figure 2-2 shows an example of a sensing layer sandwiched between body armor and the backing material.

Figure 2-2. Sensing layer is placed in between body armor to be measured and the backing material used such as clay, or ballistic gel.

The sensing layer senses the strain during the deformation of the body armor, this measures the strain caused by the body armor as a function of time which can then determine the dynamic BFD. Previous work was done to develop a method used to extract deformation shape from a strain profile collected by the optical strain sensor, the following subsections in this chapter covers the algorithm used to determine shape from a strain profile. Beginning with the fiber Bragg grating which is the main sensor for strain, the strain is related to the friction of the fiber and the deformation of the body armor. From the strain, the shape of the deformation is attained.
2.1 Fiber Bragg Grating Background

Due to their compact and lightweight nature, fiber optic sensors are ideal for many sensing applications [10-16]. Common applications used with fiber sensors are in shape sensing. The main sensing element in most of these applications involve using Fiber Bragg gratings (FBG).

![Figure 2-3. A fiber Bragg grating is composed of Bragg reflectors found within an optical fiber line. These reflect a certain wavelength of light depending on the spacing of the reflectors.](image)

Equation (2-1) shows the relationship between the reflected wavelength $\lambda_B$ of the reflectors and the period $\Lambda$. As the period of the reflectors change, the reflected wavelength changes along with it.

$$\lambda_B = 2n_e \Lambda.$$  (2-1)
Figure 2-4. Illustration of a shift of reflected wavelength (dashed orange line) from the original wavelength (blue solid line) from the FBG from a change in the period of the Bragg reflectors.

The graph in Figure 2-4 contains two plots that illustrates the relationship between the reflected wavelength of the FBG and the period of its reflectors in Equation (2-1). The blue solid line corresponds to the Bragg wavelength or the original wavelength reflected by the reflectors. Strain on the fiber causes a change in period resulting in a shift in reflected wavelength shown by the dashed orange line. The strain to Bragg relationship for this work is given by [4]

\[
\frac{\Delta \lambda_B}{\varepsilon} = 1.2 \frac{nm}{me},
\]

where \(\Delta \lambda_B\) is the shift in wavelength and \(\varepsilon\) is the strain. This strain sensitivity allows for sensing small levels of strain on the FBG.
Common applications of using FBG’s for shape sensing include airplane wings, windmill blades, or bridges for structural monitoring [17-19]. Typically, these methods of shape sensing involves adhering the fiber sensor onto the structure and, using strain to determine the shape. Under high dynamics involved in body armor tests these methods of shape sensing fail. As a result, this work focuses on the use of having the fiber sensor slip along the surface that it is sensing on and builds off the method used in previous work [9].

2.2 Basic Body Armor Dynamics

This section describes how to model the BFD of body armor as a first order system. The results of this section are an ideal plot of the BFD and an estimate for the required interrogation speed. The estimate for the speed is based on high-speed side-imaging.

The body armor decreases the speed of projectile. So, the initial velocity of the BFD is the same as the projectile velocity immediately before impacting the body armor. The body armor then decreases the velocity of the projectile. A simple model of the projectile dynamics is to model the velocity of the BFD as a first order linear system as given by

\[ \tau \frac{dv}{dt} + v = 0, \]  

(2-3)

where \( \tau \) is the system time-constant. The value of \( \tau \) depends on the specific body armor. The solution of Equation (2-3) is given by,

\[ v(t) = v_0 \exp \left(-\frac{t}{\tau}\right). \]  

(2-4)

The BFD is calculated from the velocity by taking the integral as given by,

\[ x(t) = \int v_0 \exp \left(-\frac{t}{\tau}\right) dt. \]  

(2-5)
Taking the integral and using the initial condition of $x(0)=0$ results in,

$$x(t) = v_0 \tau \left(1 - \exp\left(-\frac{t}{\tau}\right)\right). \quad (2-6)$$

The acceleration can also be calculated from the velocity by taking the derivative of the velocity as given by

$$a(t) = -\frac{v_0}{\tau} \exp\left(-\frac{t}{\tau}\right). \quad (2-7)$$

High-speed imaging into ballistics gel is one method for capturing the full dynamics of the BFD. However, this method is expensive and difficult to implement. Ballistics gel is also elastic and; therefore, recovers its shape after impact, unlike clay which retains its shape which allows for a full analysis of the shape the BFD leaves in the backing material.

Work has been done with high-speed imaging to get an estimate of the system time constant $\tau$. Figure 2-5 shows an example of a frame taken from high-speed imaging. It is possible to gauge the BFD over time by compiling the BFD tracked from individual frames over time.

Figure 2-5. Frame taken with a high-speed camera and the corresponding pixilation used to determine the BFD.
Figure 2-6. Example of high-speed imaged BFD [7].

Figure 2-6 shows the BFD measured with high-speed imaging at different speeds [7]. The BFD with an initial velocity of 294.3 m/s is fit to the first-order approximation given in Equation (2-3) results in a time constant of $\tau=0.146$ milliseconds.

Figure 2-7. a) Simulated deceleration. b) Simulated velocity. c) Simulated displacement over time with an initial velocity of $V_0=294.3$ m/s and time constant of 0.146 ms.
2.3 Strain

It is essential for the sensing fiber to slide along the surface it is shape sensing due to high strains involved in the deformation of the armor. Strain is a unitless ratio between an original length and the change in length given by

\[ \varepsilon = \frac{\Delta L}{L}, \]  

where \( L \) is the original length of the structure and \( \Delta L \) is the change in length. Figure 2-8 shows the depth and spread of a measured BFD. This BFD measurement was taken using clear ballistic gelatin and a high-speed camera image taken from the side. A sensing element that is adhered along the face of this deformation experiences a strain roughly over 120%.

Figure 2-8. Depth and spread of a deformation.

In addition to the fiber being strained during the deformation, the adhesive that holds the fiber down also gets strained. Figure 2-9 shows the result of a strain test done with fiber glued down. The blue line represents the wavelength shift of the FBG as it was being strained. At about
3.57% strain on the fiber, the adhesive used to hold the fiber down broke. The strain amount experienced before breaking is significantly less than the strain exhibited on a deformation similar to that of Figure 2-8. The high strain requirement from the deformations in this work necessitates that the fiber slips along the deformation.

![Figure 2-9. Fiber and adhesive strain testing.](image)

2.4 Shape Sensing Algorithm

The shape sensing algorithm from [8] used in this work utilizes the relationship between friction and force to obtain a proportionality relationship between strain and acceleration.

2.4.1 Force and friction relationship

Figure 2-10 shows the relationship between static friction force and kinetic friction force. The force required to move a stationary object is larger than the force required to keep that object moving [20]. The fiber containing the sensing FBG is required to slide along the surface that it is shape sensing. As a result, during initial impact with the projectile, because the fiber starts off
stationary, the fiber experiences a large amount of strain as lateral forces on the fiber increase from the effects of the impact. The fiber eventually slips along the surface but the force for it to slip is less than what is required to initially move the fiber. Once the optical fiber is slipping, the friction force stays constant since the kinetic friction force is independent of the relative speed difference between the optical fiber and the surface.

Figure 2-10. The measured force on an object as the object transitions from static to kinetic friction. Image from [21].

Figure 2-11a Shows how the deformation affects the fiber. Figure 2-11b Shows the free body diagram of the forces acting on the fiber during this deformation [8]. $F_{proj}$ is the force from the projectile, $N$ is the normal force exerted by the backing material, $F_{fiber}$ is the force from the spring constant of the stretching of the optical fiber as given by [8]

$$F_{fiber} = k\epsilon,$$  \hspace{1cm} (2-9)
where \( k \) is the spring constant of the optical fiber and \( \varepsilon \) is the strain of the optical fiber. \( F_{\text{friction}} \) is the static friction force between the optical fiber and backing material. The friction force is proportional to the normal force of the projectile as given by [8]

\[
F_{\text{fiber}} = \mu_s F_{\text{proj}},
\]

(2-10)

where \( \mu_s \) is the coefficient of static friction. As long as the friction force is greater than the spring force, the fiber remains stuck to the backing material and continue to stretch. This stretching results in a shift in the reflected wavelength of the FBG.

Figure 2-12 illustrates the force vs time on the fiber during impact. The friction force is decreasing as a function of time because the projectile is decelerating and the spring force of the optical fiber is increasing. When the spring force exceeds the friction force, the optical fiber starts to slip and the friction force transitions to kinetic friction force.

![Figure 2-11. a) Deformation of backing material and resulting stretching on fiber caused by deformation. b) Free body diagram of the optical fiber from [8]](image-url)
Figure 2-12. Force vs time illustration. The spring force of the optical fiber increases as the optical fiber is stretched and the friction force is decreasing as the projectile decelerates. When the spring force of the optical fiber exceeds the friction force, the optical fiber starts to slip [8].

Figure 2-13. a) Before impact, the fiber (blue line) starts off stationary and the period of the FBG is unchanged. b) At the moment of impact, the deformation will induce a lateral friction force on the fiber causing strain to be experienced by the FBG. c) Once the spring force on the fiber exceeds the static friction force the fiber will then start to slip and the strain is relieved.

Figure 2-11 illustrates the process of the fiber going from static to kinetic regime during impact. As shown, before impact, the fiber starts off stationary and the period of the reflectors in the FBG remain unchanged. When a projectile impacts the shot pack, the shot pack deforms. As the shot pack deforms, the fiber behind it deforms as well. This deformation causes a lateral
force to be applied to the fiber through the friction force which, in turn, applies strain across the FBG. The resulting strain across the FBG then causes the spacing between its reflectors to change and increase the spring force of the fiber. Once the spring force exceeds the static friction force keeping the fiber stationary, the fiber starts to slip. As the fiber slips, the strain across the FBG is relieved and the spacing on the reflectors approach their original spacing causing the reflected wavelength to approach the original reflected wavelength.

Figure 2-14. Wavelength to time plot of the FBG. When the projectile impacts the sensing layer, strain will be applied across the FBG. The strain across the FBG will cause the reflected wavelength of the FBG to increase until the fiber starts to slip. When the fiber is slipping the strain of the fiber will decrease resulting in a decrease in the reflected wavelength.
Figure 2-14 is an example capture of the wavelength of a shot from an FBG. The increasing wavelength indicates that the FBG is experiencing strain, which correlates to the initial impact of the shot. As the shot impact causes deformation on the sensing layer and the FBG, the spring forces of the fiber that the FBG eventually exceeds the friction force on the fiber causing the fiber to slip. The slipping will relieve strain from the FBG resulting to a downward shift in wavelength.

Strain is obtained from a wavelength vs time plot by comparing the reflected wavelengths after impact to the wavelength reflected before impact. The reflected wavelength before impact is constant and is the Bragg wavelength of the FBG, or the wavelength reflected when no strain is applied to the FBG. The Bragg wavelength is the reference point from which any wavelength shift is determined. Equation (2-2) is used to take the wavelength shifts throughout the shot and transform it into strain over time. Figure 2-15 shows an example of a strain profile, which displays strain over time, and is obtained using the wavelength shifts captured and the strain sensitivity relationship in Equation (2-2). It can be seen the points in which the fiber is impacted (strain jumps up), to where it starts to slip (strain starts to go down) and where all strain is relieved from the FBG (strain hits zero).

### 2.4.2 Strain to acceleration

Figure 2-16 shows that the acceleration of the surface is proportional to the strain. The lateral force on an object can be equated to the normal force acting on it and its friction coefficient as given by Coulomb’s law. The normal force acting on the object can be equated to mass and acceleration as given by Newton’s 2nd law. For this work, the normal force is the force that the projectile is exerting on the fiber as the shot pack deforms. The lateral force is the force
pulling on the fiber during deformation. The lateral force acting on the fiber can then be converted into strain using Hooke’s law. From here a proportionality relationship between strain and acceleration is made.

Figure 2-15. Conversion from wavelength to strain.

Figure 2-16. The flow chart from friction to a proportionality relationship between strain and acceleration. Coulomb’s friction law relates lateral force to friction. Newton’s 2nd law is then used to relate normal force to the force of the projectile. Hooke’s law is finally used to relate the lateral force to strain which gives proportionality relationship between strain and acceleration.
2.4.3 Strain to Shape

Since strain is proportional to acceleration, the resulting strain profile can be double integrated to obtain position over time. If the velocity of the projectile is known, the velocity of the deformation can be calculated as

\[ v(t) = v_0 + \int_0^t C \varepsilon(\tau) d\tau, \]  

(2-11)

where \( v_0 \) is the impact velocity of the projectile and \( t=0 \) is the start of the fiber slipping. Since the final velocity of the system is zero, the constant \( C \) can be solved for by

\[ C = \frac{v_0}{-\int_0^\infty \varepsilon(\tau) d\tau}. \]  

(2-12)

In practice, the integration of the strain would only go up to the time that the deformation reaches its maximum as determined by the FBG. This is when the reflected wavelength from the FBG returns to its original reflected wavelength. The deformation over time is then determined by integrating the velocity resulting in

\[ x(t) = \int_0^t \left[ v_0 + C \int_0^\alpha \varepsilon(\tau) d\tau \right] d\alpha. \]  

(2-13)

2.5 High Speed Interrogation and Ballistic Setup

This section covers the interrogation method used to probe the FBG and the ballistic setup used to verify the output of the shape sensing algorithm used in this work.
2.5.1 Fiber Bragg Grating Interrogation Method

Extracting data from the FBG sensor is performed using a high speed swept laser. Figure 2-17 shows an image of the swept laser source from Insight Photonics Solutions that is used in this work.

Figure 2-17. Swept laser source from Insight Photonics Solutions capable of sweeping over a range of user defined wavelengths

This laser source is a solid state swept laser source capable of sweeping at a range of 90 kHz with an 80nm sweep band centered on 1560 nm. The use of this swept laser to interrogate the FBG in this work is similar to the methods found in [6]-[8]. The complete optical setup is shown in Figure 2-18. The output of the swept laser source is fed into the sensing FBG, any reflected light from the FBG travels back through an optical circulator and into a photodiode. The photodiode transforms the detected light into current which is then transformed into voltage by a transimpedance amplifier. Finally, an oscilloscope captures the output voltage over time. Since the sweep range and sweep time of the swept laser source is known, the captured voltage can be mapped back into the output spectrum at that time. This mapping can then be used to produce a wavelength over time plot.
Figure 2-18. Optical setup with high speed swept laser source used to capture reflected wavelengths from FBG consisting of a swept laser source, a fiber optic circulator, photodiode (PD), transimpedance amplifier (TIA), and an oscilloscope (OSCOPE).

Figure 2-19. Illustration of output from optical setup. a) The rising and falling edges of the internal clock of the swept laser source indicating new sweeps. b) Linear wavelength sweep for each clock cycle. c) Voltage signal picked up by oscilloscope d) a mapping of output wavelength from the laser source to the voltage from the oscilloscope. e) Finalized plot correlating wavelength to time.
The output from the optical setup is shown in Figure 2-19. An internal clock from the swept laser source is provided that indicates the start and end of a linear wavelength sweep.

Figure 2-20 shows an example of a few captured clock sweeps along with the reflected spectrum from the FBG. The spikes in the blue plot represent the reflected spectrum from the FBG and captured in the form of a voltage on the oscilloscope.

**Figure 2-20.** Example capture from the oscilloscope. Orange plot is the captured clock sweep, blue plot is the reflected spectrum from the FBG and picked up as a voltage.

**Figure 2-21.** Example sensing layer composed of FBG(s) encased within a silicone mat.
2.5.2 Ballistic Setup

Figure 2-23 shows the gas gun and imaging setup used for testing. A compressed gas cylinder is used for firing projectiles down the barrel. Projectiles used in this work are a 12.7mm diameter 8.24-gram metal ball, or a 124 grain 9 mm round nose full metal jacket (FMJ) round. The speed of the projectile is measured by two photogates in the containment chamber before the projectile impacts the shot pack in the containment chamber. A high-speed camera is also placed on the side outside of the containment chamber to image the actual BFD over time. For the verification of the output from the shape sensing algorithm in this work, a NATO standard (20%) synthetic clear ballistics gel is used along with a 30-layer Kevlar shoot pack. Figure 2.21 shows an example of the sensing layer that is placed between the shot pack and the ballistic gel backing. The FBG is positioned in the sensing layer such that the projectile has a direct impact with the FBG. Figure 2-22 illustrates the order of the complete shot pack with the ballistic gel backing.

Figure 2-22. Sensing layer is placed between shoot pack and ballistic gel backing.
Figure 2-23. Gas gun setup. a) Compressed air is stored in the gas tank and is capable of firing projectiles up to 400 m/s. b) A containment area is mounted at the end of the projectile path allowing the ability to observe the impact of the projectile. c) A high-speed camera is used to observe the projectile in the containment area.
Figure 2-24 shows an example of the ballistic setup used for testing at the Army Test Center in Aberdeen, MD. Figure 2-24a shows a chamber loaded with a 9mm FMJ round. The chamber is fired via remote trigger. Figure 2-24b shows where the projectile passes through two photogates to measure the speed. Figure 2-24c shows where the projectile impacts a block holding a shot pack with a sensor in it on a clay backing. Speeds from this set up can go up to 450m/s. The clay used is Roma Plastilina No. 1, which is the standard clay used for ballistic testing and is one of the standard for the National Institute of Justice (NIJ) body armor testing standards [10].

Figure 2-24. a) A round is loaded into a chamber. b) Once fired, the projectile passes through two photogates which are used to calculate the speed at which the projectile is moving. c) A shot pack with clay backing is mounted down range where the projectile will impact.
CHAPTER 3. FBG SURVIVABILITY

At speeds of up to 450m/s, a direct impact on the FBG with just the shot pack consisting of multiple Kevlar layers breaks the FBG. In order for the FBG to survive a direct impact at higher speeds, the FBG is encased in silicone. The purpose of encasing the fiber in silicone is to spread the force experienced by the fiber while minimizing the effect the silicone layer has on the deformation. Two silicone products were tested: 1) Smooth-Sil 950 and 2) Sorta-Clear 40. Table 3-1 shows the two silicone products tested and their modulus, tensile strength and percent strain at failure. The percent strain at failure needs to be high enough to handle the high strains during deformation.

Table 3-1. Three silicone samples tested and their Modulus, Tensile Strength, and percent strain at failure.

<table>
<thead>
<tr>
<th>Silicone</th>
<th>Modulus (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Strain at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth-Sil 950</td>
<td>1.88</td>
<td>5.00</td>
<td>320</td>
</tr>
<tr>
<td>SORTA-Clear 40</td>
<td>0.621</td>
<td>5.52</td>
<td>400</td>
</tr>
</tbody>
</table>

To ensure that the added silicone layer has little to no interference with the overall deformation, five shots were performed without a silicone layer and their deformations characteristics measured to be used as a control for the shots with a silicone layer. Table 3-2 shows the captured control shots and their deformation characteristics. Roma Plastilina #1 at
approximately 90 degrees Fahrenheit was used as the backing, a 9mm FMJ round shot at 1100-1200 fps was used as the projectile.

Table 3-3 shows the five shots done to each silicone sample and their corresponding deformation. The silicone layer for these shots were done with 2mm thickness. Table 3-4 shows shots done with 1mm silicone layers. The 1mm sample layers had less of an impact on the overall deformation volume so it was chosen as the thickness for the silicone layers of this work. The Sorta-Clear samples had the closest average deformation characteristics to the deformation of the control shots. Figure 3-1 shows that one great advantage to using the Sorta-Clear silicone layer is that it allows a more accurate positioning of the FBG along the fiber axis because of its transparent nature. Figure 3-2 shows an example of positioning the fiber within a Sorta-Clear silicon mat.

<table>
<thead>
<tr>
<th>Table 3-2. Control shots and the deformation characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Width (mm)</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Test 1 (no sensing 1)</td>
</tr>
<tr>
<td>Test 2 (no sensing 2)</td>
</tr>
<tr>
<td>Test 3 (no sensing 3)</td>
</tr>
<tr>
<td>Test 4 (no sensing 4)</td>
</tr>
<tr>
<td>Test 5 (no sensing 5)</td>
</tr>
<tr>
<td><strong>Average</strong></td>
</tr>
</tbody>
</table>
Table 3-3. 2mm thick silicone layer and the deformation characteristics

<table>
<thead>
<tr>
<th>Test (Sorta-Clear)</th>
<th>Width (mm)</th>
<th>Depth (mm)</th>
<th>Velocity (ft/s)</th>
<th>deformation volume (cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.88</td>
<td>35.76</td>
<td>No Trigger</td>
<td>44.29</td>
</tr>
<tr>
<td>2</td>
<td>51.41</td>
<td>29.20</td>
<td>1187.08</td>
<td>36.71</td>
</tr>
<tr>
<td>3</td>
<td>52.10</td>
<td>33.34</td>
<td>1204.24</td>
<td>41.73</td>
</tr>
<tr>
<td>4</td>
<td>54.55</td>
<td>29.19</td>
<td>1193.89</td>
<td>39.15</td>
</tr>
<tr>
<td>5</td>
<td>52.17</td>
<td>36.09</td>
<td>1200.77</td>
<td>45.47</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>52.42</strong></td>
<td><strong>32.72</strong></td>
<td></td>
<td><strong>41.47</strong></td>
</tr>
<tr>
<td>1 (Smooth Sil)</td>
<td>53.50</td>
<td>33.57</td>
<td>1180.36</td>
<td>44.17</td>
</tr>
<tr>
<td>2</td>
<td>56.54</td>
<td>33.85</td>
<td>1197.32</td>
<td>No scan</td>
</tr>
<tr>
<td>3</td>
<td>56.68</td>
<td>31.74</td>
<td>1243.78</td>
<td>41.00</td>
</tr>
<tr>
<td>4</td>
<td>54.94</td>
<td>34.82</td>
<td>1187.08</td>
<td>43.14</td>
</tr>
<tr>
<td>5</td>
<td>54.22</td>
<td>33.10</td>
<td>1207.73</td>
<td>37.40</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>55.18</strong></td>
<td><strong>33.42</strong></td>
<td></td>
<td><strong>41.43</strong></td>
</tr>
</tbody>
</table>

Table 3-4. 1mm thick silicone layer and the deformation characteristics

<table>
<thead>
<tr>
<th>Test (1 mm Smooth Sil)</th>
<th>Width (mm)</th>
<th>Depth (mm)</th>
<th>Velocity (ft/s)</th>
<th>deformation volume (cm^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>54.76</td>
<td>37.90</td>
<td>1207.73</td>
<td>48.67</td>
</tr>
<tr>
<td>2</td>
<td>54.73</td>
<td>35.65</td>
<td>1221.90</td>
<td>45.23</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>54.75</strong></td>
<td><strong>36.78</strong></td>
<td><strong>1214.81</strong></td>
<td><strong>46.95</strong></td>
</tr>
<tr>
<td>1 (1 mm Sorta-Clear)</td>
<td>50.87</td>
<td>34.37</td>
<td>1190.48</td>
<td>42.39</td>
</tr>
<tr>
<td>2</td>
<td>56.45</td>
<td>33.86</td>
<td>1200.77</td>
<td>51.72</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>53.66</strong></td>
<td><strong>34.12</strong></td>
<td><strong>1195.62</strong></td>
<td><strong>47.05</strong></td>
</tr>
</tbody>
</table>
Figure 3-1. a) Sorta clear sample layer. b) Smooth-Sil sample layer

Figure 3-2. Sorta-Clear silicone layer with FBG positioned in center.

Encasing the fiber in silicone requires a larger lateral force for the fiber to slip along the fiber axis during deformation. This introduces higher strain on the fiber that would potentially break the fiber during impact. To reduce the force required for the fiber to slip, the fiber was coated with different lubricants to reduce the friction between the silicone and the fiber. Table 3-5 shows the different lubricants used for reducing friction between the fiber and silicone in a sensing layer. Figure 3-3 shows that an optical fiber is wrapped around a pull-handle which is then pulled and measured by a force meter to measure the pull-out force of the fiber with different lubricants.
Figure 3-3. Force meter used to measure pull-out force of fiber from silicone layer.

Table 3-5. Different lubricants and the pullout force required to loosen the fiber within the silicone and the force required to pull the fiber out after it has been loosened

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Loosening Force (N)</th>
<th>Extraction Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Coating</td>
<td>2.26</td>
<td>1.14</td>
</tr>
<tr>
<td>Vaseline</td>
<td>0.77</td>
<td>0.71</td>
</tr>
<tr>
<td>Super Lube</td>
<td>1.64</td>
<td>1.05</td>
</tr>
<tr>
<td>Tribo Gel</td>
<td>1.32</td>
<td>1.39</td>
</tr>
<tr>
<td>Polishing Wax</td>
<td>0.54</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 3-6. Comparison of sensing layers with and without Vaseline

<table>
<thead>
<tr>
<th>Test</th>
<th>Vaseline (Y/N)</th>
<th>Projectile Velocity (m/s)</th>
<th>Deformation Depth (mm)</th>
<th>Deformation Width (mm)</th>
<th>Measured Offset (mm)</th>
<th>Max Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N</td>
<td>408</td>
<td>38.9</td>
<td>52.0</td>
<td>4.28</td>
<td>5.92</td>
</tr>
<tr>
<td>2</td>
<td>N</td>
<td>396.9</td>
<td>37.5</td>
<td>55.3</td>
<td>6.32</td>
<td>5.25</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>399.4</td>
<td>30.6</td>
<td>58.7</td>
<td>0.00</td>
<td>5.13</td>
</tr>
</tbody>
</table>

Polishing wax performed the best, however it needed to be heated to a certain temperature to be effective. Vaseline did not need to be heated, is easy to be applied and inexpensive so it was chosen as the lubricant to be used in the silicone layer.
Table 3-6 shows a comparison of the resulting impacts between layers with and without Vaseline. An offset from the point of impact was necessary for the layers without Vaseline because the samples would not survive the shot. With Vaseline, no offset was needed and it would still survive the impact. From these results, the effectiveness of friction reduction between fiber and silicone as a result of Vaseline is seen.

### 3.1 Fabrication Process

The fabrication process for creating the silicone mats involves multiple steps. Optical fiber with an FBG is first coated with Vaseline by hand then run through a thick needle to ensure uniform coating. The coated fiber is then placed in molds filled with uncured silicone. Figure 3-4 shows molds that are used to hold uncured silicone during the curing process. Uncured silicone mixture is poured into the mold. Once the silicone mixture is poured into the mold, the optical fiber is placed. Each mold has grooves on a set of opposing sides where an optical fiber is placed. These grooves suspend the fibers in the middle of the curing silicone. Each mold also comes with a top plate that is placed on top of the mold and uncured silicone at the end of the fabrication process.

The next step is to place the silicone mat in a vacuum chamber for degassing as shown in Figure 3-5. The silicone is degassed by depressurizing the vacuum chamber to below atmospheric pressure. This is to minimize air pockets that are formed in the mixing of the silicone. Figure 3-6 shows an example of a silicone mat that has not been degassed and a silicone layer that has been degassed. As shown, there are many large air pockets in the silicone layer that
has not been degassed and a very minimal amount on the degassed silicone. Multiple air pockets in a silicone layer that has not been degassed creates a discontinuity in the interface between the slipping optical fiber and the material it is slipping on. The shape sensing algorithm assumes that the fiber is maintaining contact with the material as it is slipping and any discontinuities in the slipping channel may produce undesired results.

![Figure 3-4. Molds for silicone layers.](image)

![Figure 3-5. Vacuum chamber used for degassing silicone layers.](image)
Once the fiber is placed and the silicone layer is degassed, the mold and uncured layer is then capped with a plate and clamped together for the duration of the curing process. Figure 3-7 shows an example of the mold clamped with a top plate for curing. When the silicone is completely cured, an angle polished connector (APC) is then used to terminate the optical fiber using the Optical fiber termination and repair kit from Thorlabs. Figure 3-8 and Figure 3-9 show an image of the optical fiber termination and repair kit and a fiber terminated with an APC respectively.
Figure 3-8. Thorlabs optical fiber termination and repair kit.

Figure 3-9. Fiber with APC termination.
CHAPTER 4. STICK SLIP ALGORITHM

Figure 4-1 shows the comparison of the normalized strain profile from an FBG and the normalized acceleration profile from high-speed imaging with the optical fiber embedded in silicone. Impact from the projectile can be seen by the large initial increase in strain. Once the lateral forces from the deformation caused by the impact exceed the static forces keeping the fiber stationary, the fiber starts to slip resulting in the strain being relieved as shown by the drop in strain. However, with the optical fiber embedded in silicone to enable survivability, the fiber gets stuck resulting in an increase in strain. The fiber then starts to slip again when the lateral forces exceed the static friction force.

Figure 4-1. Strain profile as captured by the FBG (orange) vs actual acceleration profile as captured by high-speed imaging (solid blue)
The shape sensing algorithm presented in Chapter 2 is based on the deceleration being proportional to strain. This proportionality condition is only valid when the optical fiber is slipping. Therefore, the algorithm is only valid if the stuck portions are negligible. Figure 4-1 shows that the acceleration profile and the strain are only proportional for the beginning time of the impact.

Figure 4-2 shows the resulting displacement profile when the captured strain profile from the FBG is processed using the shape sensing algorithm from Chapter 2 vs the displacement profile captured by high-speed imaging. There is a large difference in overall displacement. Embedding the FBG in silicone introduces additional sticking sections resulting in the stuck sections no longer being negligible.

Figure 4-2. Resulting displacement profile using shape sensing algorithm on the captured strain profile from the FBG (orange) vs the displacement profile as captured by high-speed imaging (blue)
4.1 Hybrid Model

The essence of the hybrid model is to convert the stuck sections of the strain into slipping equivalent strain and then running the modified strain profile through the algorithm presented in Chapter 2. The silicone layer is modeled as a membrane. Deflections on a membrane with fixed boundary conditions are related to the stress on the membrane [22]. In this configuration there are no fixed boundaries on the silicone mat under the test conditions presented in this work. However, the slip of the actual sensing layer against the backing material is considered negligible for the short period of time that the FBG is sticking, resulting in the strain profile under static friction being directly related to the depth of the BFD. In other words, if it is assumed that all boundary conditions are held constant for the short period of time that the optical fiber is in the static friction regime and being stretched, then the amount of stretching induced on the optical fiber is proportional to the position or BFD. The resulting relationships for the strain when the optical fiber is stuck and slipping are given by

\[ \varepsilon_{\text{stuck}} = C_1 x, \]  

(4-1)

and

\[ \varepsilon_{\text{slipping}} = C_2 a = C_2 \frac{d^2 x}{dt^2}, \]  

(4-2)

where \( C_1 \) and \( C_2 \) are proportionality constants. Therefore, the stuck portions are converted into slipping equivalent by double differentiating and scaling to obtain acceleration so that it can be placed back into the kinetic regime as given by

\[ \varepsilon_{\text{slipping}} = \beta \frac{d^2}{dt^2} (\varepsilon_{\text{stuck}}), \]  

(4-3)
where $\beta = C_2/C_1$ is the scaling factor that scales the double differentia ted set of points so that they are continuous with the points before them.

As the fiber sticks, the reflected wavelength as captured by the oscilloscope often experiences peak spreading which introduces noise into the captured wavelength. Figure 4-3a shows the measured strain for a ballistic impact. The portion in the black box is a stuck section. Stuck sections are determined by the fact that the strain starts to increase.

![Figure 4-3. a) Measured strain profile for a ballistic impact. b) Stuck section of an impact with an exponential fit.](image)

Figure 4-3b shows that the stuck portion is too noisy to perform a numerical differentiation. Before differentiation, to reduce noise, the stuck sections are fit to an inverse exponential of the form

$$
\varepsilon_{\text{stuck}} = A \left( 1 - e^{-\frac{t}{B}} \right),
$$

(4-4)

where $A$ and $B$ are the fitting parameters. This exponential equation is chosen because over this small time frame, the BFD is assumed to follow a first-order system as presented in Chapter 2.2.
The fitting parameters $A$ and $B$ are constrained to be positive. The resulting fit is then double differentiatiated and scaled resulting in

$$\varepsilon_{\text{stip}} = \beta * e^{-\frac{r}{B}}.$$  

(4-5)

Figure 4-4 shows how this is implemented on a captured strain profile. Figure 4-4b and Figure 4-4c identifies the stuck section and double differentiates it. It then is scaled so that the new section is continuous to the previous section. Figure 4-4d and Figure 4-4e then takes the points after the stuck section and shifts it down so that the last point is at zero then scales it so that the data is continuous with the datapoints preceding it. The data points at the end are shifted down to zero because it is assumed that there is no hysteresis in the system.

**Figure 4-4. Illustration of handling stuck sections.** a) obtain strain profile, b) identify stuck section, double differentiate then scale to previous datapoints. d)-e) shift data points after stuck section down so that the last datapoint is at zero then scale so it is monotonous with previous points.
Often, there are multiple stuck sections in the captured strain profile. The process of fitting and differentiating is done to each stuck section starting with the last one. Prior stuck sections are then fit in the same manner however, the constant for $B$ in Equation (4-4) for these fits use the same constants from the first fit. This is because the constant $A$ takes into account the changing boundary conditions and the amount of strain on the grating as a result of changing boundary conditions but, in general, the timing of the deformation, represented by $A$ and $B$ should remain the same between stuck sections. Figure 4-5 shows a summary of the process for multiple stuck sections.

![Flowchart](image)

**Figure 4-5. Summary of sticking compensation.**
4.2 Results

Figure 4-6 shows a captured strain profile with multiple stuck sections. Figure 4-7 shows that the original shape sensing method without any compensation for the stuck portions produces a displacement profile with over 100% error when compared to the displacement profile as captured by high-speed imaging.

![Figure 4-6. Strain profile with multiple stuck sections](image)

![Figure 4-7. Displacement profile output using original shape sensing algorithm (blue) plotted against the actual displacement profile as captured by high-speed imaging (orange). The resulting error for the maximum displacement is over 100%](image)
Figure 4-8 shows the strain profile produced using the Hybrid model method to handle the stuck sections. The strain points corresponding to the stuck sections from Figure 4-6 have been moved from the static regime to the kinetic regime. Figure 4-9 shows the displacement profile produced when processing the strain profile with stuck sections being compensated using the hybrid model. When compared against the actual displacement profile as captured by high-speed imaging, the displacement over time follows closely and the maximum displacement is below 10% error.

Figure 4-8. Strain profile after using Hybrid model to accommodate stuck sections. The stuck sections have been moved from the static regime to kinetic regime.
Figure 4-9. Displacement profile after processing the new strain profile. The resulting error of the maximum displacement is under 1% and the shape of the displacement over time is close to the actual displacement over time as captured by high-speed imaging.
CHAPTER 5.  GRAPHICAL USER INTERFACE

The end goal for the shape sensing algorithm using the hybrid model in this work is for a test engineer without a deep understanding of the algorithm to apply it in body armor tests and generate shape over time from captured data in 15 minutes or less. Application of the algorithm requires multiple intricate steps to take captured waveforms from the oscilloscope and convert them to strain and then extract the shape from the strain. The conversion from waveform to strain involves taking both the captured waveform from the oscilloscope channel monitoring the TIA, which transforms reflected wavelengths from the FBG into voltage, and the captured waveform on the oscilloscope channel that monitors the clock cycle output by the high speed swept laser source and use both waveforms to correlate signals from the TIA waveform to corresponding wavelengths of light emitted by the laser source. The wavelength that corresponds to a captured TIA waveform is determined by the sweep range of the laser source and the corresponding time the TIA waveform aligns within each clock cycle. Once the wavelength per clock sweep is determined, the strain is calculated by determining the shift in reflected wavelength from the Bragg wavelength of the FBG per clock cycle. This process of correlating the TIA waveform to wavelength using the clock cycle and the wavelength sweep is illustrated in Figure 2-19. Following this process then generates the strain over the duration, or time, of the shot.

Once the strain and time data are generated, the strain to shape process is started by removing any stuck portions found in the strain data and replacing them with their equivalent
kinetic versions. This involves taking the strain data and finding the appropriate time ranges where stuck portions occur. Parsing through the strain data numerically to find stuck portions can be very time consuming and it can be difficult to determine when the end of a shot is. Each datapoint within the strain data would need to be compared to its neighbors to determine if the datapoint is in a stuck section or slipping section. A stuck set of points are points that are incrementally increasing in strain over time, indicating sticking. A slipping set of points are points that would be incrementally decreasing strain over time. This method can be time consuming with high chances for error of misclassification of stuck portions from noise. A visual representation of the strain profile similar to that in Figure 4-6 allows an analyst to easily see stuck portions and when the shot ends. If there are any stuck portions, the user would then need to fit an exponential of the form found in Equation (4-4). Once the stuck portions are removed and replaced, the process discussed in 2.4.3 of double integrating to obtain velocity and displacement over time would need to be followed. The double integration can be tedious with many errors that could occur if done by hand or manually input into a computing system.

5.1 Graphical User Interface Development

The process of taking captured data from the oscilloscope to shape over time has many steps with possibilities of errors being made in between each step. In addition, the time it would take to process captured data and parse through the strain data for stuck sections manually would take too long and render this method impractical especially with large amounts of captured data needing to be processed.

A Graphical User Interface (GUI) was created to guide a test engineer through the algorithm process from taking captured oscilloscope data to strain to deformation shape while
minimizing the amount of work or data the test engineer would need to keep track of. The process is divided into three steps that a test engineer would walk through.

Figure 5-1 shows the main page of the GUI. The user is able to choose between .mat or .bin data file types to process depending on the type of data files that are saved by the oscilloscope used to capture data.

![Figure 5-1. Home screen for GUI. User has the option of choosing between .mat files or .bin files.](image)

Figure 5-2 shows the data input page once a user chooses the type of data to work with in Figure 5-1. This page is where most of the relevant information is input to start the shape sensing algorithm. The green box is where data associated with the shot is input, this includes the sweep rate of the swept laser source, the start and end wavelength of the sweep range of the swept laser source, the recorded projectile velocity, the measured BFD and the associated oscilloscope.
waveform captures which includes: the actual waveform from the reflection of the FBG, the waveform for the clock of the laser source and the data valid file provided by the swept laser source. Once the required data has been input into their respective locations, the user can then follow the step-by-step process as outlined by the red box.

Figure 5-2. Data input page. User inputs the data associated with the shot in the green box such as files captured by the oscilloscope. After inputting the data, the user can then follow through the steps outlined by the red box.

5.1.1 Step 1

Step 1 of the data input page takes the Waveform, Clock and Data Valid files along with the Sweep rate and the wavelength sweep range to generate a strain profile from the shifts in
wavelength. Figure 5-3 shows an example of a generated strain profile from the shifts in wavelength. The generated strain profile is displayed as strain vs datapoints so that the user is able to identify and indicate stuck sections that is needed for Step 2 of the process. The visual representation of the strain profile allows the user to easily locate where the stuck portions are in a strain profile and avoids the user from having to go through each datapoint manually and compare it to neighboring points in order to identify stuck sections.

![Strain Profile](image)

**Figure 5-3. Generated strain profile from Step 1. The x-axis is in data points so that the user can identify and indicate where the stuck sections are for Step 2.**

In addition to the strain profile, the user has the option to click on the Waveform plot button to view the contour plot that the strain profile is generated from. Figure 5-4 shows the associated contour plot with the strain profile from Figure 5-3. This plot shows the wavelength that the FBG is reflecting over certain points in the shot and the user can see the shift in wavelength that the strain profile is generated from.
5.1.2 Endpoint and Autofind

Before the Step 2 button, the user is asked to input the end data point of the shot and the number of stuck sections seen in the “Enter End Data Point” and “How many static portions to input?” text boxes respectively. With the original shape sensing algorithm, the end data point is chosen near where the strain reaches zero or where the reflected wavelength of the FBG returns to its original Bragg wavelength indicating the end of the shot and all strain has been relieved. However, with silicone mats, it has been observed that the endpoint that works is usually in the
area around the last stuck portion. Any endpoint chosen at the end of the shot, where the strain drops back down to zero, usually ends in an overshoot of the displacement. One of the likely reasons for why this occurs is because as the shot nears the end, the lateral forces pulling the fiber starts to decrease. Once the lateral forces fall below the force required to keep the fiber in the kinetic regime the fiber starts to stick. The drop of the strain to zero after the final stuck section could be a result of the silicone’s elastic properties acting on the fiber in that the silicone pulls itself back slightly, taking the fiber with it and relieving strain on the fiber. Since the endpoint is very tricky to choose, the user has the option of checking the “Autofind” check box under the Step 3 button in Figure 5-2. Pressing the Step 3 button with this box checked runs the algorithm and process the data at different end points near the last stuck section until the final displacement is within a user defined percentage error as defined by the “Enter Percent Limit (%)” text box in Figure 5-2.

5.1.3 Step 2

Figure 5-5 shows the popup window that appears when the user clicks the Step 2 button on the data input page. This window allows the user to input the offset point or the point where the algorithm starts processing and the stick points found in the strain profile from Step 1. The input of the strain points begins from the last stuck section to the first stuck section or the first stuck section from the right to the last stuck section to the left (excluding the initial stuck section). This is to ensure that the algorithm is be able to fit stuck sections correctly before the shifting and scaling of points as discussed in Chapter 4.
Figure 5-5. Popup window after clicking the Step 2 button. This allows the user to indicate what data point range the stuck sections are in the strain profile. It also asks the user for the offset point which is the point where the fiber starts slipping or where the strain starts to decrease after the initial stuck section in the strain profile.

5.1.4 Step 3

Clicking on the Step 3 button initiates algorithm processing of data. The strain profile from Step 1 and the information provided by the user in Step 2 is taken by the algorithm and processed. Figure 5-6 shows the results window that displays the results from the algorithm. The information enclosed in the red box displays the resulting displacement profile, acceleration
profile, speed profile and the end strain profile after stuck sections are accommodated for. The green box displays the maximum calculated BFD and is then compared against the measured BFD input by the user and shows the percentage difference from measured BFD. The user also has the option of saving the resulting data as a .mat file or a .csv file and access it for reference by using the Load Previous Shot Results button.

Figure 5-6. Results window after clicking Step 3. It takes the strain profile from Step 1 and the user provided information up to step 2 and runs the algorithm on the information to produce the resulting acceleration profile, displacement profile, strain profile, velocity profile.
CHAPTER 6. TESTING

The objective of this work is to make the technology transferable for test engineers to use in body armor testing. Test engineers at the Army Test Center (ATC) in Aberdeen were trained to utilize this technology from fabrication of silicone mats as discussed in Chapter 3 to shot processing using the GUI as discussed in Chapter 5. The optical setup from the “High Speed Interrogation and Ballistic Setup” section of Chapter 2 was also simplified and labeled. Figure 6-1 shows the interface box used to simplify the optical interrogation setup. Figure 6-2 shows the interior of the interface box. It holds the optical circulator, photodiode, and transimpedance amplifier and simplifies the process by keeping the connections between those components connected within the box and only allows the user access to the necessary outputs and inputs of the system. This is to prevent a user from making wrong connections by reducing the amount of connecting a test engineer is required to do to setup the system and ensures correct connections between test shots.

Thirty shots were tested with their deformations recorded. Six of the shots broke during impact where data for the whole shot event was not captured due to the sensing fiber breaking during impact. Table 6-1 shows the set of data containing all thirty shots captured and processed by test engineers using this technology. Shots resulting with a broken fiber during impact were excluded in these tables. These tests were performed with a clay backing and the output of the GUI was compared against the maximum depth as measured on the clay. From the tables, the use
of the GUI in implementing the algorithm generated profiles with errors less than 10% of the measured displacements in 14 of the shots, 2 of the shots were between 10 and 20% error and another 8 were above 20%. Appendix A contains the original strain profiles and the resulting fitted strain profile from using the algorithm, along with the acceleration and displacement profile for each shot.

Figure 6-1. Interface box containing optical circulator, photodiode, and amplifier. (Top) Front face of the box containing the ports for the oscilloscope, FBG and laser input. (Bottom) Back face of the box containing the power switch to turn the module on or off.

Figure 6-2. Interior of interface box.
Table 6-1: First data set of processed shots done by test engineers at ATC

<table>
<thead>
<tr>
<th>Shot</th>
<th>Striking Velocity (m/s)</th>
<th>Scanned BFD (mm)</th>
<th>Algorithm BFD (mm)</th>
<th>Error (%)</th>
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<tr>
<td>5</td>
<td>432.816</td>
<td>33.302</td>
<td>23.142</td>
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<td>34.716</td>
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One of the main causes of error is determined by how well a fit is made on a stuck section. Figure 6-3 shows the strain profile for shot 29 with multiple stuck sections, that a user uses to identify which datapoints to be fitted, and the resulting strain profile generated using the algorithm from the hybrid model. Incorrect or inaccurate fits can result in undesired slipping behavior in the resulting strain profile and is shown in fit number 2 of Figure 6-3, where the slip looks more like a straight horizontal line instead of an exponential-like descent. Figure 6-4 shows the stuck sections from Figure 6-3 being fit to an exponential with the form of Equation (4-4). The resulting fit for the first stuck section fits very well, however the fits for the following
stuck sections (sections 2, 3 and 4) do not have very good fits and are far from the actual set of datapoints the fits are fitting against. The incorrect fits occur because of the constraint that subsequent fits from the first fit need to have the same time and offset constant (constants $B$ and $C$) from Equation (4-4). This is why the fit for section 1 fits very well, while sections 2, 3, and 4 are very far off. The incorrect fits cause additional higher strain to be introduced resulting in additional displacement being calculated into the final displacement. For the shot example used in Figure 6-3, the resulting error was an overshoot with a 43% error which is likely caused by the incorrect fits.

![Figure 6-3. Original strain profile with stuck sections (left). Final strain profile with stuck sections fitted using hybrid model.](image)

Another cause of error is how well the fiber slips within the channel in the silicone mat. The original strain profile in Figure 6-3 shows that the strain moves sideways instead of downwards. This implies that the fiber is stuck in transitioning between kinetic and static regimes. The fiber being stuck in this way suggests that the friction coefficient between the fiber and the silicone is high. This could be a result of not enough Vaseline being coated on the fiber to encourage slipping. The sideways movement of the strain profile also makes it very difficult to determine where the endpoint of the shot should be.
Figure 6-4. Resulting fits (orange) to the datapoints of the stuck sections being fit against (blue) obtained from Figure 6-3.

Figure 6-5 shows a comparison of the slipping characteristics of two captured shots. Both shots have relatively similar maximum strain values. The strain profile on the left shows that it takes approximately 11 datapoints for the strain to get to half of its maximum strain value, while the strain on the right only takes 5 datapoints. Each datapoint is an equal slice of time and is the same slice for both shots. This suggests that the shot on the left is slipping slower than the shot
on the right despite having similar shot speeds, backing material and silicone thickness. This undesired type of slipping causes large deformation errors as this does not fully reflect the acceleration of the shot and contributes additional displacement to the final displacement. The BFD produced using the hybrid model algorithm when processing the shot on the left, resulted in an overshoot with a 92.49% error from the scanned BFD. The shot on the right resulted in an undershoot with a 9% error. This undesired slipping is likely caused by inadequate or uneven coating of Vaseline along the fiber. One possibility is that, before the shot, the fiber in the silicone channel is adequately coated with Vaseline. However, during impact, as the fiber gets pulled in during the deformation, fiber outside the silicone mat not coated with Vaseline gets pulled in and interacts with the silicone. The difference in friction coefficients between coated fiber and uncoated fiber and their interaction to the silicone contributes to the undesired slipping in the strain profile. Figure 6-6 shows the acceleration and speed profile generated from the strain profiles in Figure 6-5 with the appropriate stuck sections fitted. As shown, the shot with the bad slip generates an acceleration with a lower amplitude and a slower decay while the shot with the good slip generates an acceleration profile with a higher amplitude. A lower amplitude in acceleration causes the speed to be relatively high throughout the duration of the shot so that when the speed over time is integrated to obtain distance over time, the resulting distance of the speed profile with relatively high speed results in a deeper deformation. Figure 6-7 shows the difference in depth from integrating the speed profiles, the difference in depth is very significant despite both shots having similar initial speeds, shot environments (clay backing, shot location, etc.), and silicone thickness.
Figure 6-5. Comparison of slipping characteristics between a bad slip (left) and a good slip (right).

Figure 6-6. Comparison of acceleration (top) and speed (bottom) profiles of shots from Figure 6-5.
Figure 6-7. Displacement profile comparisons obtained from integrating the speed profiles from Figure 6-6.
CHAPTER 7. BODY ARMOR SHAPE SENSING CONCLUSION

This work has shown a new method of dynamic shape sensing on body armor. The methods used to extract strain from [8] do not perform well under higher dynamics involved in body armor deformation from a high velocity projectile. This failure is primarily due to the FBG in the sensing layer not surviving. This work has shown that encasing the FBG in a 1mm silicone layer and coating the FBG with Vaseline improves the survivability of the FBG during impact. However, the FBG encased in silicone introduced a higher friction coefficient and the shape sensing algorithm used in [8] results in an overshoot in calculated displacement when compared against the actual displacement of a deformation (often above 100% error). This error comes as a result of the FBG sticking during impact. The original shape sensing algorithm requires the FBG to be slipping for the duration of the impact so any stuck sections that appear where the algorithm is expecting the FBG to be slipping results in a higher error. In order to compensate for the stick sections, this work has introduced a hybrid model that treats each stuck section as displacement and takes the double derivative of those sections to obtain acceleration. This acceleration profile is then scaled to obtain the equivalent strain over time for those sections. Application of this hybrid model resulted in errors below 10% when comparing the calculated displacement from the model vs the actual displacement of a shot. Certain conditions in a shot can cause the error to exceed the error threshold of 10%. These conditions come in the form of incorrect slipping or inaccurate fits to stuck sections. The end goal of this work is to make the
technology transferrable to test engineers at the Army Test Center in Aberdeen for body armor tests. This work has shown a GUI created to guide test engineers through the process of the algorithm without needing a deep knowledge of the algorithm to obtain desired results. Test engineers were also trained on the fabrication process involved in encasing the FBG in silicone and performed actual tests using the technology.

7.1 Future Work

Future work for this project would be to improve the errors from the generated displacement profiles. This can be done by improving the survivability method used such that the fiber should not stick more than once after the initial stuck section on impact. Ideally, the fiber should not re-stick after the initial sticking section. A better lubricant or method of evenly spreading the lubricant along the sensing fiber could be used to improve the slipping characteristics of the fiber within the silicone channel. Ensuring that the fiber does not stick more than once after the initial stuck section reduces the risk of wrong fits and noise from the fiber transitioning between kinetic and static friction regimes can be avoided.
CHAPTER 8.  SILICON WIRE-EDM INTRODUCTION

Silicon is used widely in electronics especially in the Photovoltaic (PV) industry. The quality of the silicon is determined by the number of imperfections found on the wafer. Having the least number of imperfections is essential in the overall quality of the product as degradation of the silicon, caused by imperfections, affects the ability of the silicon to operate within the limits of an acceptable criteria [23]. One of the causes of degradation in silicon is the presence of cracks. Cracks often occur in the manufacturing process, particularly in the slicing portion done to create disks or wafers of silicon before being diced and packaged [23]. Throughout the years, the thickness of silicon wafers sliced from a boule of silicon has been decreased significantly to reduce the material costs involved. This reduction in thickness causes the silicon to be more brittle and therefore more susceptible to cracking in the manufacturing process. In addition to cracking, the slicing process can also introduce groove pits or chipping along the surface of the silicon, which further degrades the silicon [23] [25].

Currently, the two main methods of cutting silicon wafers are loose abrasive wire sawing (AWS) and fixed abrasive diamond wire sawing (DWS) with DWS becoming the more preferred method due to its numerous advantages over AWS. Some of the advantages of DWS over AWS is lower kerf loss or material loss, higher productivity rate, shallow depth of grooves and pits caused in slicing resulting in a smoother surface finish and is more environmentally friendly [24-30]. Despite these advantages, the presence of microcracks still exist. The focus of this work is in
reducing surface imperfections on silicon wafers from slicing and increasing throughput using Wire Electrical Discharge Machining (EDM) or wire-EDM technology.

8.1 Wire-EDM Introduction

From [31], EDM is a thermal erosion process in which material is removed using electrical discharges between a cutting tool acting as an electrode and a conductive workpiece in dielectric fluid. The type of EDM used in this work is wire EDM. One major benefit of using EDM is that it is a non-contact process and produces no cutting forces. The lack of cutting forces implies that thinner more fragile materials can be produced. From [32] another benefit using EDM is the resulting surface finish on cuts. With traditional cutting processes using hard materials to grind away material from a workpiece, directionality can be found in the resulting cut. This directionality in the cut causes surface finishes that are often unwanted. However, with EDM, the directionality in the cut does not exist and it is possible to achieve a mirror-like finish. In addition to ideal surface finishes, wire-EDM can cut at high rates of 22mm/min [32]. Comparing the cut rate of a DWS of 1.1 mm/min [24], achieving a wire-EDM cut rate would result in a 2000% increase in cut rate.

The surface finish and the rate at which a wire-EDM cuts is highly dependent on the electrical resistivity of the material. Figure 8-1 shows the material removal rate (MRR) is increased, translating to faster cuts, as the electrical resistivity of a material decreases. The surface finish, or surface roughness (SR), is also improved with decreased electrical resistivity. Figure 8-2 shows that the SR of a cut trends lower as the electrical resistivity decreases.
Cutting silicon using wire EDM can utilize the benefits of making thinner cuts and having cleaner surface finishes. Previous work has shown the possibility of cutting silicon using wire EDM [35]-[38]. Wafer thicknesses ranging between 140 µm to 200 µm were achieved in this process. Surface roughness ranged from 1 to 2.3 µm, which is much less than the surface roughness using traditional abrasive methods of 3 to 5 µm [37]. Comparing these results to wafer
properties using DWS, the wafer thickness that is achieved in mass production settings are around 170 µm [30]. Work has also been done to achieve a wafer thickness up to 100 µm using DWS methods, however, without inspecting the surface quality post cut, 30% of the wafers that were cut broke during the sawing process [33].

Silicon cut in the previous works [35]-[38] had resistivities ranging from .02 to 3 Ω-cm. Metal that is usually cut in wire-EDM machines such as aluminum, steel, etc. are several orders of magnitude lower in resistivity. Intrinsic silicon, which is silicon that is not doped with dopants like Boron or Phosphorous that make it more conductive, can have resistivities of over 1E4 Ω-cm [46]. For wire-EDM to be practical in slicing silicon, it needs to be able to slice through any range of conductivity in silicon. However, silicon with too low of a conductivity will not cut on the wire-EDM machine. To achieve improved cut rates, surface finish and kerf loss, similar to that obtained when cutting metal on a wire-EDM machine, it is necessary to increase the conductivity of silicon. This work focuses on increasing the conductivity of silicon by using its photoconductive properties and utilizing the increased conductivity in wire-EDM cutting.

8.2 Silicon Photoconductivity Introduction

Photoconductivity in silicon is the generation of carriers (holes and electrons) when it is illuminated with photons of sufficient energy [41]. Figure 8-3 shows that the resistivity of silicon lowers as the concentration of carriers increases. Eventually, as the concentration of the carriers increases, the silicon starts acting more like a metal than a semiconductor.
8.2.1 Carrier and Illumination calculations

For carriers produced through photogeneration, two main factors are considered for use in wire-EDM machining in this work: 1) wavelength and 2) irradiance. Due to high recombination velocity, which translates to low lifetime, carriers that are formed near the surface of the silicon recombine faster than carriers formed farther, or the bulk [42]. In the scope of a wire-EDM cut, carriers with a high lifetime will allow for the silicon to be conductive enough for cuts before recombining. Therefore, it is essential to generate carriers at the bulk for wire-EDM cuts. Figure 8-4 shows the absorption depth in silicon at different wavelengths of light. In other words, Figure 8-4 shows how deep certain wavelengths of light travels through the silicon before being absorbed. The deeper the light travels before being absorbed, the farther the generated holes and electrons are from the surface. Ideally, many excited electrons and corresponding holes are created near the wire-EDM cutting location. For this work, where cuts are made near the end of
an ingot, the ideal wavelength maximizes the absorption of light in the range of 50 µm to 300 µm.

Figure 8-4. Absorption depth vs wavelength from [43]

To calculate the optimal wavelength, the Beer-Lambert law for optical absorption was used, where the fraction of the power that is transmitted to the depth of $z$ and is given by

$$P(z) = e^{-\alpha z},$$  \hspace{1cm} (8-1)

where $\alpha$ is the absorption coefficient. The absorbed light is separated into three regions, P1 is the total light absorbed within 50 µm, or near the surface; P2 is the desired absorption region between 50 µm and 300 µm; and P3 is the power past 300 µm. Figure 8-5 shows an example of the optical power vs depth for a 1030nm wavelength going through silicon. Figure 8-6 shows the absorbed power for each region of P1, P2, and P3. The wavelengths with normalized powers that are the highest in the P2 region are between 950 and 1050 nm. In this work a wavelength of 960 nm was chosen for the illuminating wavelength.
The second factor considered for illumination is the irradiance of the light source. The irradiance determines the carrier density and using the right irradiance is essential to obtain the necessary carrier density. For this work, a target concentration of about $10^{18}$/cm$^3$ is used. To calculate the needed irradiance, it was assumed that the silicon was in steady state under illumination. In this state, the generation rate and recombination rate are equal [39]. A carrier lifetime of $\tau = .3$ms is used in these calculations. It was also assumed that, within the carrier lifetime, half of the generated carriers have recombined. Therefore, to maintain the desired
carrier density, the required irradiance is calculated to produce the necessary generation rate.

Using dimensional analysis, the required irradiance is derived by first taking the desired carrier density in \( \frac{\text{carriers}}{\text{cm}^3} \) and dividing by the lifetime \( \tau \) in seconds to produce the generation rate in \( \frac{\text{carriers}}{\text{cm}^3 \text{s}} \). Since each carrier is generated by a photon, the units can then be changed to \( \frac{\text{photons}}{\text{cm}^3 \text{s}} \).

The energy per photon in Joules, or \( \frac{\text{Joules}}{\text{photon}} \), is found by [40]

\[
E_{ph} = h\omega, \tag{8-2}
\]

where \( E_{ph} \) is the energy in Joules per photon, \( h \) is Planck’s constant, and \( \omega \) is the frequency of the wavelength. The generation rate is multiplied by the energy which results in \( \frac{\text{Joules}}{\text{cm}^3 \text{s}} \), or \( \frac{\text{Watts}}{\text{cm}^3} \) since a watt is a Joule per second. The result is then multiplied by the length of the silicon in cm where the carriers are generated, in this work the length required is the length of P2 (50e-4 cm to 350e-4 cm) or 250e-4 cm. The resulting units after multiplying the length is then in \( \frac{\text{Watts}}{\text{cm}^2} \).

It is assumed that the irradiance is constant along the face of the silicon that is illuminated by the lasers. The optical power is attenuated depending on the target depth as determined by Equation (8-1). In the region of interest as defined by P2 in Figure 8-6, the optical power is attenuated by approximately 50% for the 960nm wavelength used in this work. This attenuation is accounted for by dividing irradiance by the fraction of optical power in that section to produce the modified irradiance needed. In addition to optical attenuation, not all photons released by the illuminating source produces a photon. The ratio of how many carriers is produced to released photons is called the quantum efficiency. If \( E_{ph} > E_g \), where \( E_g \) is the bandgap energy, the quantum efficiency is close to unity [40]. For this work, a quantum efficiency of .79 was used. Dividing the resulting modified irradiance by the quantum efficiency produces the finalized irradiance.
needed for illumination that accounts for the attenuation and the efficiency of the system. The process for calculating irradiance can be summarized by

$$I = \frac{\Delta n \cdot \Delta l \cdot E_{ph}}{2 \cdot \tau \cdot Q \cdot P},$$

(8-3)

where $\Delta n$ is the desired carrier density in $\frac{\text{carriers}}{\text{cm}^3}$, $\Delta l$ is the desired length where the carriers are produced in cm, $E_{ph}$ is the energy per photon in Joules, $Q$ is the quantum efficiency, $P$ is the fraction of the optical power in the area of interest, and $\tau$ is the carrier lifetime in seconds. The division by 2 is to reflect the assumption that half of the carriers generated have recombined and therefore, to maintain the desired carrier density, the irradiance needs to generate the same amount that was recombined. For this work, using this process produced a required irradiance of approximately 22 $\frac{\text{Watts}}{\text{cm}^2}$.

### 8.2.2 Silicon Photoconductivity Test

To test the effects of photoconductivity, a laser array was built to illuminate a silicon rod. Figure 8-7 shows the interior and exterior of the laser array. Figure 8-8 shows that each laser has a wavelength emission centered at 960nm and are placed in series. The lasers are commercially available and are used in the telecom industry as pump lasers for erbium doped optical fiber amplifiers. These lasers are readily available in high power and are coupled to optical fiber, which is advantageous for guiding light to illuminate desired locations on a sample. The optical output of the laser array is controlled by a voltage regulator that tunes the amount of current being supplied to the lasers through the voltage drop across the lasers. The optical fibers extending from the laser are terminated onto a fiber mount that hold the fibers in position. There
are approximately 14 lasers used to illuminate the face of the silicon rod, each laser produces approximately $2 \frac{Watts}{cm^2}$ individually which results in a combined $28 \frac{Watts}{cm^2}$ of irradiance.

Figure 8-7. Laser array interior (left) and exterior (right).

Figure 8-8. Laser array output wavelength.
Figure 8-9 shows the fiber mount used to hold the fibers extending from the lasers. These fiber mounts direct the output light onto the silicon rod and illuminate specific locations for cutting on the wire-EDM machine and for measuring resistivity using a four-point probe for photoconductivity tests.

![Figure 8-9. Fiber mount (pink) that holds optical fibers and is mounted with a silicon rod on wire-EDM machine.](image)

Four-point probes are used to measure the sheet resistivity of metals. Figure 8-10 illustrates the circuit diagram and functionality of a four-point probe. A steady current is sent between probes 1 through 4. The area between each of the four probes should have equal resistance and is determined by measuring the voltage reading between probes 2 and 3. Taking the voltage reading and dividing by the known current results in a resistance measurement of ohms. Since the distance between probes are equal and known, the resistance measurement can then be translated to ohms-distance or, more commonly, ohms-cm.
Figure 8-10. Four-point probe from [47].

Figure 8-11 shows the resulting resistivity measurements on the silicon done using a four-point probe. The green lines represent when the silicon was illuminated with the lasers with 1 amp of current running through the array while the red lines represent when the lasers are turned off. When the lasers are turned on, the measured resistivity trends downwards and when it is turned off, the resistivity trends upwards. This trend is expected because illumination produces more carriers which in turn increases the conductivity of the silicon. With less carriers, the conductivity of the silicon decreases which is the case for when the laser is turned off. These four-point probe measurements were done by hand which is the likely reason why the resulting graph is noisy, however, the expected trend is still manifested.
8.3 Experimental Setup

Figure 8-12 shows how the fiber for the output of the laser array and the silicon is mounted in the wire-EDM machine. The silicon rod is wrapped with aluminum, except at the area where a cut occurs, and is held down by two copper braces onto an aluminum mount which is then bolted into place on the wire-EDM platform. Aluminum is used to wrap the silicon to help create an ohmic contact for the silicon and the wire-EDM machine. The blue optical fiber mount in Figure 8-12, was the initial design for holding the optical fibers in place. To ensure sufficient illumination on the silicon rod and additional robustness in the handling of fibers, a new version was designed utilizing additional lasers to illuminate at different angles with a protective casing around the fibers as previously introduced in Figure 8-9 in section 8.2.2.
8.3.1 Initial Cut Attempts and Experiments

To measure any improvements or differences made by illumination, cuts were done on silicon with no illumination to find the setting on the wire-EDM machine that would allow for the fastest cut without the wire breaking. Wire breakage occurs when the wire approaches the material being cut too quickly with no time to arc resulting in the wire getting pushed against the material. This results in the wire touching the material and no arcing occurs. Eventually, as the machine further pushes the wire into the material, the wire breaks due to lateral forces being applied on it. Previous work has shown what energy threshold is required to initiate a cut on silicon using a wire-EDM machine [35]. Figure 8-13 shows the different material removal rates (MRR) versus energy. As shown, increasing the voltage across the gap between the cut piece and
the wire, increases the MRR of the cut. Too low of a voltage results in lower energy, and, if the energy is too low, no cuts are initiated resulting in an MRR of zero. On the contrary, too high of a voltage results in wire or wafer breakage.

Figure 8-13. Energy vs MRR from [35]

Initial cutting attempts resulted in no sparks across the gap and no indication of cutting occurring at the supposed spark point between the wire and the silicon. Each attempt would result in the wire physically rubbing against the silicon with no visible indication of cutting via arcing. Work done in [35] used silicon with a resistivity of 0.5 Ω-cm while the resistivity of the silicon used in this work is between 10-100 Ω-cm. The open voltage or open gap voltage, which is the voltage required to start a spark, is much higher than the working voltage which is the voltage that is read across the gap after the arcing has started.

Due to a significant difference in resistivity, it was assumed that a much higher overall voltage, which translates to a higher energy requirement, is needed to initiate and continue cuts. Measurements were taken to characterize the voltage on the wire-EDM machine by using an oscilloscope. Figure 8-14 shows that the voltage between the wire and the ground plane of the
EDM machine swings between +70 V and -70 V so it was assumed that a voltage swing of up to 100V is needed.

Table 8-2 shows the parameters displayed on the control panel of the wire-EDM machine. These parameters control the cutting characteristics of the wire-EDM machine cut. ON and OFF reflect the on and off time of a cut respectively. Figure 8-15 shows an example of how the on and off time affect the cutting characteristics and also shows the open gap voltage, which is the voltage required to initiate a spark. V is a code for the Voltage, it affects the output Open Gap voltage, however it is not the only parameter that affects the Open Gap Voltage. HRP is also a parameter that controls the High Voltage Circuit, and according to [45], is supposed to increase the voltage by a factor of 2 or more. Tuning of this parameter produced an increase of about 10 to 20% but did not achieve the desired voltage. WS controls the speed the wire spools through.
This reduces the tendency of wire breakage while cutting at faster speeds as it allows for damaged wire from an arc to be quickly replaced before the next arc. SF is a parameter that controls the speed of the material feed to the wire. A slower speed creates smoother surface finishes. SV refers to, “Servo Voltage,” which is a parameter that is set to a voltage level that the wire-EDM tool monitors during an electrical arc and either speeds up or slows down the cutting speed of the wire to maintain the set voltage. WP refers to “Water Pressure,” and is the parameter that controls the flushing power of the water around the area of the cut.

![Figure 8-15. Wire-EDM waveform of a cut.](image)

Tuning of these parameters did not produce the higher voltage desired and each cut resulted in no arcs produced. Figure 8-16 shows a closeup of a test structure that was built to simulate the wire-EDM arcs without cutting into the material. The setup involved a piece of silicon with half of the piece sandwiched between two aluminum plates and the other half exposed. Leads from a high voltage supply were attached to the wire and the aluminum with the positive lead on the wire and the negative lead on the aluminum. The aluminum plate is mounted
onto an optical stage that can shift in the XYZ plane at approximately 500 um increments using turn knobs. The experimental process for this setup involved setting the silicon and wire a distance apart. The voltage difference between the two is then set via the high voltage supply and the silicon is incrementally advanced closer to the wire until a spark occurs. It was observed that sparking would occur at the wire-EDM’s voltage swing of 70V under the condition that the approach speed was slow. Too fast of an approach speed would result in no sparking.

Table 8-1. Parameters used to control the cutting characteristics of wire-EDM cut

<table>
<thead>
<tr>
<th>ON</th>
<th>OFF</th>
<th>IP</th>
<th>HRP</th>
<th>MAO</th>
<th>SV</th>
<th>V</th>
<th>SF</th>
<th>C</th>
<th>WT</th>
<th>WS</th>
<th>WP</th>
<th>WC</th>
</tr>
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<tr>
<td>007</td>
<td>011</td>
<td>2215</td>
<td>000</td>
<td>252</td>
<td>018</td>
<td>8</td>
<td>0020</td>
<td>00</td>
<td>160</td>
<td>120</td>
<td>000</td>
<td>000</td>
</tr>
</tbody>
</table>

Figure 8-16. Test structure built to simulate wire-EDM arcing.

Following cut attempts on the wire-EDM machine used a slower approach with successful cuts. Figure 8-17 shows the captured waveform of a successful cut. The drop in voltage indicates arcs have occurred between the wire and the silicon. The shape of the waveform during a cut is similar to the waveform in Figure 8-15. The frequency of the cuts is determined by the speed. The slower the speed, the less frequent the cuts or drop in voltage will occur. The cut parameters
tuned in this work for slower speeds are SV and SF. SV controls the speed of the wire by adjusting the distance the wire is from the material being cut through the voltage potential between the wire and the cutting piece [35][44]. In other words, a lower SV requires the wire to get closer to the cut piece, decreasing the gap between cut piece and wire, while a larger SV does the opposite. A higher SV decreases the cut speed by introducing more discharge delays, these delays effectively reduce the slicing rate which directly affect the cut speed of the material. SF is the servo feed, this affects the speed at which the wire travels along an axis and the type of servo used [45]. Tuning both SV and SF is needed to control the speed of a cut [45]. For this work, an SV of 070 and an SF of 0007 was found to be the combination that produces the fastest cut rate of 0.3 mm/min on unilluminated silicon with no wire breakage.

![Silicon cut](image)

Figure 8-17. Captured waveform of a successful cut with a slower speed. The drop in voltages indicate sparking and cutting.

### 8.4 Results

Tests were done at the headquarters of Sodick, Inc. in Chicago, Illinois to compare the cutting characteristics between unilluminated and illuminated silicon. Table 8-2 shows the cut characteristics and the associated SV and SF settings used to achieve the cut. Each cut was done on the same silicon rod. The total cut time varied because of the machinist having to adjust SF
and SV as the wire approached the middle of the rod where exposure between the wire and the silicon were greater. This necessitated a decrease in cut speed in order to avoid wire breakage. The unilluminated cuts stayed relatively the same in terms of cut rate and total cut time while the illuminated cuts were able to achieve cut rates and cut times of up to 3x what the unilluminated cuts were able to achieve. It was observed that the silicon rod would get hot to the touch with illuminated cuts which most likely is a result of over saturation of light.

Table 8-2. Cut characteristics with associated SV and SF settings on wire-EDM machine for illuminated and non-illuminated cuts.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Illumination</th>
<th>Cut Rate (mm/min)</th>
<th>Total cut time (min)</th>
<th>SV</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>.3</td>
<td>38</td>
<td>055</td>
<td>0003</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>.83</td>
<td>12</td>
<td>060</td>
<td>0012</td>
</tr>
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<td>3</td>
<td>No</td>
<td>.3</td>
<td>33</td>
<td>070</td>
<td>0007</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
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<td>5</td>
<td>Yes</td>
<td>.57</td>
<td>14</td>
<td>065</td>
<td>0012</td>
</tr>
</tbody>
</table>

8.5 Conclusion

Using the photoconductive properties of silicon, a speed of 3x faster cut was achieved with illumination on the silicon rod than on an unilluminated cut. The maximum cut speed achieved did not reach the cut speed of a DWS cut, however, there is potential in further increasing the speed of the cut through optimizing of the wire-EDM cut parameters and better control of the voltage for arcing. The surface finish and kerf-loss of wire-EDM cut silicon was not analyzed in this work but can be optimized for future work.
REFERENCES


46. Brigham Young University, “Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon,” Electrical and Computer Engineering, https://cleanroom.byu.edu/resistivitycal

APPENDIX A. HISS CHARACTERIZATION RESULTS

This appendix includes the results of the HISS characterization that was performed by ATC personnel on October 30, 2019 and October 31, 2019.

The HISS-Phase4-ATC-2 Shot 1 sensor mat broke before the shot was taken so no data was collected.

Figure C1 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 2. This measurement is too inconsistent to perform a reconstruction.
Figure C1. Strain profile for HISS-Phase4-ATC-2 Shot 2.

The HISS-Phase4-ATC-2 Shot 3 sensor mat broke on before the shot was taken so no data was collected.

Figure C2 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 4. This measurement is too inconsistent to perform a reconstruction.
Figure C2. Strain profile for HISS-Phase4-ATC-2 Shot 4.

Figure C3 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 5. This measurement has three stuck sections (Start Stick 1: 724, End Stick 1: 734, Start Stick 2: 696, End Stick 2: 703, and Start Stick 3: 682, End Stick 3: 686) that were removed. Figure C4 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 5.
Figure C3. Strain profile for HISS-Phase4-ATC-2 Shot5.
Figure C4. Reconstructed profile for HISS-Phase4-ATC-2 Shot 5.

Figure C5 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 6. This measurement has three stuck sections (Start Stick1: 623, End Stick1: 627, Start Stick2: 594, End Stick2: 597, and Start Stick3: 587, End Stick3: 589) that was removed. Figure C6 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 6.
Figure C5. Strain profile for HISS-Phase4-ATC-2 Shot 6.
Figure C6. Reconstructed profile for HISS-Phase4-ATC-2 Shot 6.

Figure C7 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 7. This measurement has three stuck sections (Start Stick1: 623, End Stick1: 627, Start Stick2: 594, End Stick2: 597, and Start Stick3: 587, End Stick3: 589) that was removed. Figure C8 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 7.
Figure C7. Strain profile for HISS-Phase4-ATC-2 Shot 7.
Figure C8. Reconstructed profile for HISS-Phase4-ATC-2 Shot 7.

Figure C9 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 8. This measurement has one stuck sections (Start Stick1: 588, End Stick1: 609) that was removed. Figure C10 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 8.
Figure C9. Strain profile for HISS-Phase4-ATC-2 Shot 8.
Figure C10. Reconstructed profile for HISS-Phase4-ATC-2 Shot 8
Figure C11 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 9. This measurement has one stuck section (Start Stick1: 598, End Stick1: 616) that was removed. Figure C12 shows the reconstructed profile for HISS-Phase4-ATC-2D Shot 9.

Figure C11. Strain Profile for HISS-Phase4-ATC-2 Shot 9.
Figure C12. Reconstructed profile for HISS-Phase4-ATC-2 Shot 9
Figure C13 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 10. This measurement has one stuck section (Start Stick1: 606, End Stick1: 625) that was removed. Figure C14 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 10.
Figure C14. Reconstructed profile for HISS-Phase4-ATC-2 Shot 10.
Figure C15 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 11. This measurement has three stuck sections removed. Figure C8 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 11.

**Figure C15. Strain profile for HISS-Phas4-ATC-2 Shot 11.**
Figure C16. Reconstructed profile for HISS-Phase4-ATC-2 Shot 11.
Figure C17 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 12. This measurement has two stuck sections (Start Stick1: 625, End Stick1: 635, and Start Stick2: 598, End Stick2: 606) that was removed. Figure C18 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 12.

Figure C17. Strain profile for HISS-Phas4-ATC-2 Shot 12.
Figure C18. Reconstructed profile for HISS-Phase4-ATC-2 Shot 12.
Figure C19 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 13. This measurement has three stuck sections (Start Stick1: 616, End Stick1: 633, and Start Stick2: 593, End Stick2: 604) that was removed. Figure C20 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 13.

Figure C19. Strain profile for HISS-Phase4-ATC-2 Shot 13.
Figure C20. Reconstructed profile for HISS-Phase4-ATC-2 Shot 13.
Figure C21 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 14. This measurement has one stuck section (Start Stick1: 590, End Stick1: 605) that was removed.

Figure C22 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 14.

Figure C21. Strain profile for HISS-Phase4-ATC-2 Shot 14.
Figure C22. Reconstructed profile for HISS-Phase4-ATC-2 Shot 14.
Figure C23 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 15. This measurement has three stuck sections (Start Stick1: 623, End Stick1: 627, Start Stick2: 594, End Stick2: 597, and Start Stick3: 587, End Stick3: 589) that was removed. Figure C24 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 15.

![Strain profile: Use to determine points of interest](image)

Figure C23. Strain profile for HISS-Phas4-ATC-2 Shot 15.
Figure C24. Reconstructed profile for HISS-Phase4-ATC-2 Shot 15.
Figure C25 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 16. This measurement has one stuck section (Start Stick1: 1139, End Stick1: 1148) that was removed. Figure C26 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 16.
Figure C25. Strain profile for HISS-Phas4-ATC-2 Shot 16
Figure C26. Reconstructed profile for HISS-Phase4-ATC-2 Shot 16.
Figure C27 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 17. This measurement has one stuck section (Start Stick1: 1139, End Stick1: 1148) that was removed. Figure C28 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 17.

Figure C27. Strain profile for HISS-Phase4-ATC-2 Shot 17.
Figure C28. Reconstructed profile for HISS-Phase4-ATC-2 Shot 17.
Figure C29 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 18. This measurement has no stuck section that was removed. Figure C30 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 18.

![Strain profile: Use to determine points of interest](image)

**Figure C29. Strain profile for HISS-Phase4-ATC-2 Shot 18.**
Figure C30. Reconstructed profile for HISS-Phase4-ATC-2 Shot 18.
Figure C31 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 19. This measurement has one stuck section (Start Stick1: 1147, End Stick1: 1152) that was removed. Figure C32 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 19.

Figure C31. Strain profile for HISS-Phase4-ATC-2 Shot 19.
Figure C32. Reconstructed profile for HISS-Phase4-ATC-2 Shot 19.
Figure C33 shows the strain profile for HISS-Phas4-ATC-2 Shot 20. The strain profile was inconsistent so it was unable to be processed.

Figure C33. Strain profile for HISS-Phas4-ATC-2 Shot 20.
Figure C34 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 21. This measurement has one stuck sections (Start Stick1: 1149, End Stick1: 1171) that was removed. Figure C35 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 21.
Figure C34. Strain profile for HISS-Phas4-ATC-2 Shot 21.
Figure C35. Reconstructed profile for HISS-Phase4-ATC-2 Shot 21.
The fiber for HISS-Phase4-ATC-2 Shot 22 broke so no data was obtained.

Figure C36 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 23. This measurement has two stuck sections (Start Stick1: 1152, End Stick1: 1154, and Start Stick2: 1139, End Stick2: 1141) that was removed. Figure C37 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 23.
Figure C36. Strain profile for HISS-Phas4-ATC-2 Shot 23.
Figure C37. Reconstructed profile for HISS-Phase4-ATC-2 Shot 23.
Figure C38 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 24. This measurement has no stuck sections that was removed. Figure C39 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 24.

**Figure C38. Strain profile for HISS-Phase4-ATC-2 Shot 24.**
Figure C39. Reconstructed profile for HISS-Phase4-ATC-2 Shot 24.
Figure C40 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 25. This measurement has two stuck sections (Start Stick1: 1165, End Stick1: 1174, and Start Stick2: 1149, End Stick2: 1154) that was removed. Figure C41 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 25.

Figure C40. Strain profile for HISS-Phase4-ATC-2 Shot 25.
Figure C41. Reconstructed profile for HISS-Phase4-ATC-2 Shot 25.
Figure C42 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 26. This measurement has one stuck section (Start Stick1: 1148, End Stick1: 1183) that was removed. Figure C43 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 26.

Figure C42. Strain profile for HISS-Phase4-ATC-2 Shot 26.
Figure C43. Reconstructed profile for HISS-Phase4-ATC-2 Shot 26.
Figure C44 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 27. This measurement had no stuck section removed. Figure C45 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 27.

![Strain profile: Use to determine points of interest](image)

Figure C44. Strain profile for HISS-Phas4-ATC-2 Shot 27.
Figure C45. Reconstructed profile for HISS-Phase4-ATC-2 Shot 27.
Figure C46 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 28. This measurement has one stuck section (Start Stick1: 1152, End Stick1: 1158) that was removed. Figure C47 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 28.

Figure C46. Strain profile for HISS-Phase4-ATC-2 Shot 28.
Figure C47. Reconstructed profile for HISS-Phase4-ATC-2 Shot 28.
Figure C48 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 29. This measurement has four stuck sections (Start Stick1: 1199, End Stick1: 1206, Start Stick2: 1163, End Stick3: 1175, Start Stick3: 1154, End Stick3: 1157, and Start Stick4: 1135, End Stick4: 1137) that was removed. Figure C49 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 29.

Figure C48. Strain profile for HISS-Phase4-ATC-2 Shot 29.
Figure C49. Reconstructed profile for HISS-Phase4-ATC-2 Shot 29.
Figure C50 shows the measured strain profile for HISS-Phase4-ATC-2 Shot 28. This measurement has one stuck section (Start Stick1: 1151, End Stick1: 1200) that was removed. Figure C51 shows the reconstructed profile for HISS-Phase4-ATC-2 Shot 28.

Figure C50. Strain profile for HISS-Phas4-ATC-2 Shot 30.
Figure C51. Reconstructed profile for HISS-Phase4-ATC-2 Shot 30.
Figure C51. Reconstructed profile for HISS-Phase4-ATC-2 Shot 30.
Figure C51. Reconstructed profile for HISS-Phase4-ATC-2 Shot 30.