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Spring 2016

Developing the Stress Strain Curves for an Epoxy Undergoing High Speed Impact

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Stress Strain Curves of High Speed Impacts on Epoxy

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Department of Mechanical Engineering

Honors Research Project

Submitted to

The Honors College

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Major: Mechanical Engineering

Project Sponsor: Dr. Erol Sancaktar

Number of Project Credits: 4

Developing the Stress Strain Curves for an Epoxy Undergoing High Speed Impact

Abstract

The Hopkinson Split Bar test can be used to accurately develop the relationship between the stress and strain a material undergoes during a high speed impact (rates of 1000/s). This information has many industrial uses, for example the auto industry can use this technology to analyze how materials will behave under crash-like circumstances. In this experiment the stress-strain curves were developed for the PC-Plumbing epoxy.

One of the variables that can be adjusted in the Split Hopkinson Bar test is the ration between the height of the sample and the width of the sample (Hs/Ds). This experiment investigated how three different sample sizes (0.25, 0.33, >1) affected the results.

The stress strain curves were found, as well as the maximum strain rates, yield strengths, yield strain and modulus's of elasticity. The effect of the Hs/Ds also was that each sample size resulted within a distinct range of maximum strain rates.

Contents

I. Introduction

The purpose of this honors project is twofold. The first objective of the project is to determine the optimum experimental conditions for the use of the Hopkinson Bar test in the development of the of stress strain curves. This involved designing a set of experiments in order to find which variables produce the most reliable data, highest quality stress strain curves, and least variation within the data.

The second objective of this project is to develop a stress strain curve for PC-Plumbing epoxy at high strain rates.

II. Background

A. Hopkinson Split Bar Test

1. Overview of the Device

The Hopkinson Split Bar test is used to find the strain rate in engineering materials and the materials behavior at very high rates (order of 1000/s). This method is being used to determine the impact conditions of epoxy and to then calculate and analyze their stress-strain curves.

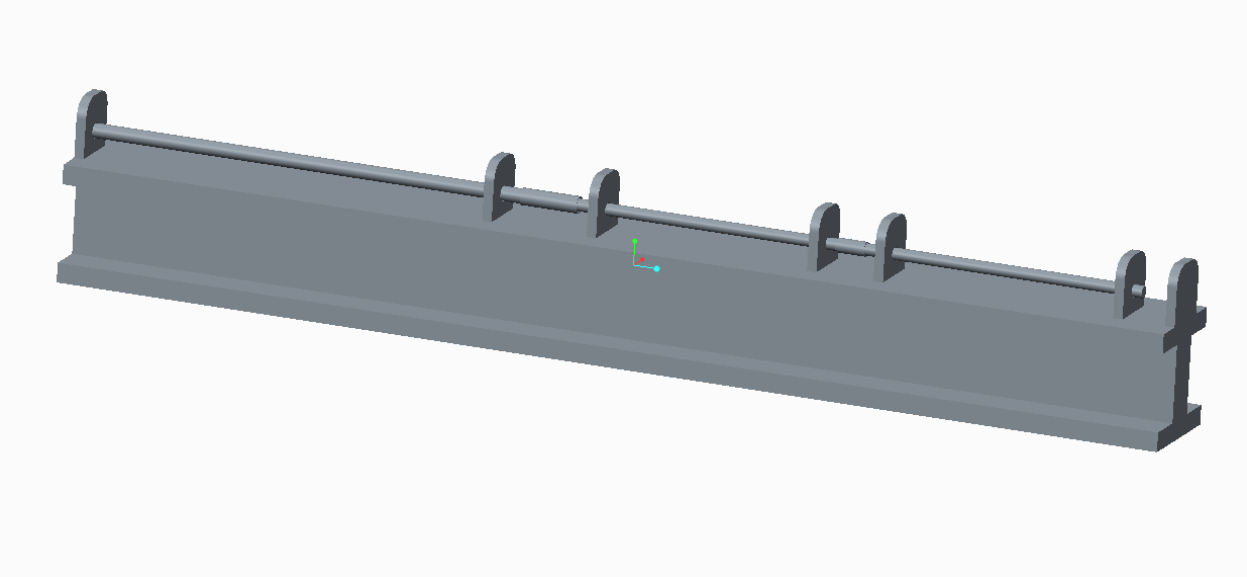

Figure 1 : 3D model of Split Hopkinson Bar Device

The Hopkinson Split Bar Test Device consists of several parts. They are a striker bar, an incident bar, a transmitter bar, a pair of strain gages, an air compression system, and a pulse shaping thin metal disc, and a housing for all of these systems. The system is then set up with a strain gauge mounted on the incident bar and a strain gage mounted on the transmitter bar.

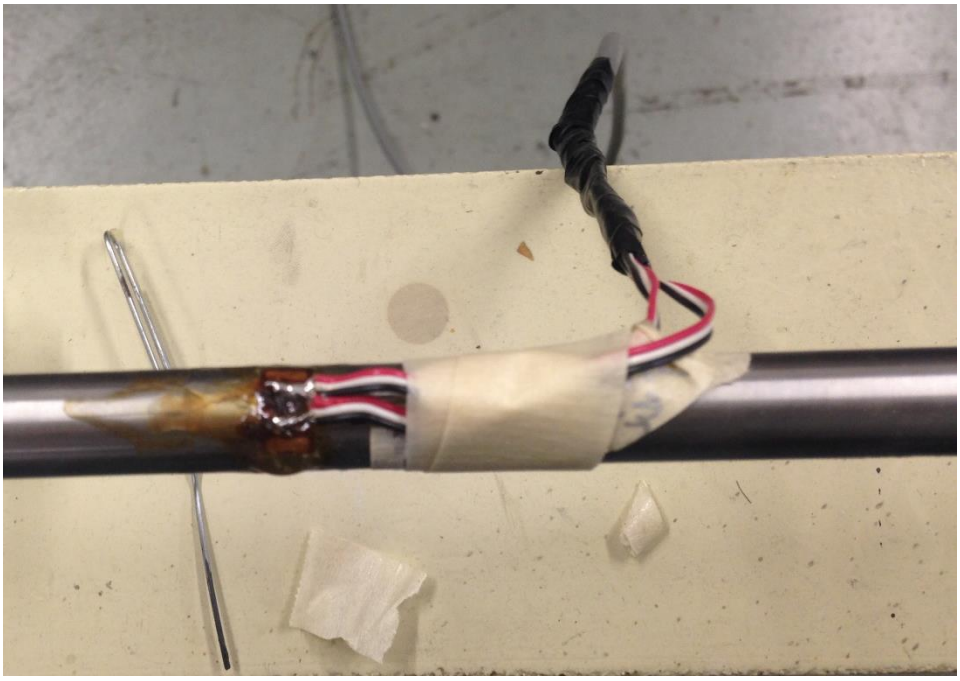

Figure 2: Strain gage on incident bar

The sample being tested is placed within a collar between the two. The pulse shaking disk is placed on the opposite side of the transmitter bar. These four components are all placed directly adjacent to each other, with no empty space between them. The striker is placed at the far end of the striker housing, which is attached to the compressed air system. When the compressed air is released, it launches the striker bar forward at high speeds. The striker hits the pulse shaper, which then allows for a smoother transfer of momentum to the incident bar. The force is then transmitted from the incident bar to the sample to the transmitter bar. The strain gauges then measure the strain in both the incident and the transmitter bars. These measurements allow us to calculate the stress that the sample experiences, as well as its strain.

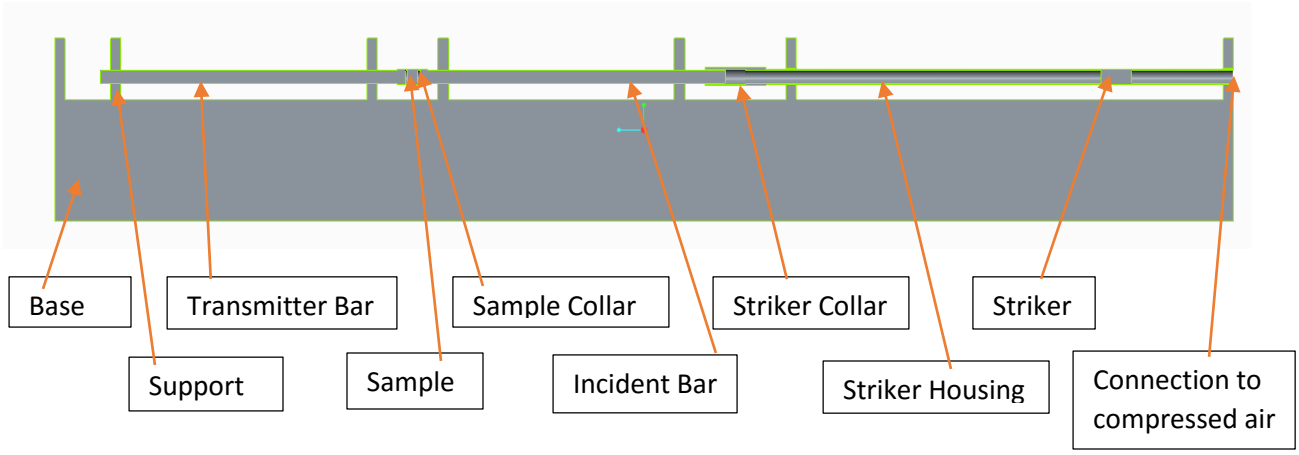

Figure 3: Cross section of Split Hopkinson Bar Device with labels

The strain gages are wired to an indicator which is the wired to an oscilloscope. The oscilloscope is connected to a computer with software that records the data.

2. Derivation of Equations

The stress and strain that the bars (and by extension the sample) experience is measured in the form of a one dimensional wave. Therefore, to calculate stress and strain we start with the one dimensional wave equation:

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} \quad (1)$$

where *x* is the axis that motion takes place on, *u* is the scalar distance along the *x* direction, *t* is time [1] and *c* is the propagation speed of the wave [7]. The differential equation can be solved using D'Alembert's method [2], giving us:

$$u = u_I + u_R = f(x - ct) + g(x + ct) \quad (2)$$

where u_I is the velocity in the incident bar, u_R is the velocity of the reflected pulse, and both *f* and *g* are arbitrary equations [2]. The equation for strain rate in the x direction is

$$\varepsilon = \frac{\partial u}{\partial x} \quad (3)$$

so differentiating Eq. (2) with respect to *x* yields [2]

$$\varepsilon = f' + g' = \varepsilon_I + \varepsilon_R \quad (4)$$

where ε_I is the strain in the incident bar and ε_R is the strain in the reflective pulse. Now, if we differentiate Eq (2) with respect to time we get the following two equations[2]

$$\dot{u_1} = c(-f' + g') = c(-\varepsilon_I + \varepsilon_{R)} \quad (5)$$

$$\dot{u_2} = -c\varepsilon_T \quad (6)$$

where ε_T is the strain in the transmitter bar.

It is also safe to assume that the stress wave propagation is negligible [2], and therefore [2]

$$\dot{\varepsilon} = \frac{\dot{u_1} - \dot{u_2}}{H_s} \quad (7)$$

where *Hs* is the instantaneous height of the sample, $\dot{u_1}$ is the particle velocity at the interface of the incident bar and the sample and $\dot{u_2}$ is the particle velocity at the interface of the sample and the transmitter bar [1]. The previous two equations ((5) and (6)) can then be substituted into Eq. (7) [2], giving us

$$\dot{\varepsilon} = \frac{c}{H_s}(-\varepsilon_I + \varepsilon_R + \varepsilon_T). \quad (8)$$

Now, if A_B is the cross-sectional area of the two bars, and E_B is their Young's Modulus, by definition we know that [2]

$$F_1 = A_B E_B(\varepsilon_I + \varepsilon_R) \quad (9)$$

$$F_2 = A_B E_B \varepsilon_T. \quad (10)$$

Now with the assumption that after a ringing up period the specimen is deforming uniformly [2] (discussed more in section II.A.4) we can then assume

$$\varepsilon_I + \varepsilon_R = \varepsilon_T \quad (11)$$

and then rework Eq. (8) [2] to be

$$\dot{\varepsilon} = \frac{2c\varepsilon_R}{H_s}. \quad (12)$$

Now assuming constancy of volume [2], we see that

$$\sigma_s(t) = \frac{A_B E_B \varepsilon_T}{A_S} \quad (13)$$

where A_s is the cross-sectional area of the sample and $\sigma_s(t)$ is, of course, the stress of the sample at a given time t. Then we also can solve for the strain of the sample [2], giving us

$$\varepsilon_s(t) = \frac{2c}{H_s}\int_0^t \varepsilon_R(t)dt \quad (14)$$

Where $\varepsilon_s(t)$ is the strain at a given time t. These two values plotted against each other gives us their stress-strain curve.

3. Split-Hopkinson Pressure Bar Test Sample Overview

The design of test samples is based on a number of factors. Firstly, the frictional and inertial effects of the system can be minimized by minimizing the difference in diameter between the samples and the incident bar. The diameter of the sample should not be less than 80% of the diameter of the incident bar.

Another aspect of the sample design is the ration of the sample height to the sample diameter. Different ratios have different design tradeoffs. For example, if H_s is the height of the sample and D_s is the diameter of the sample, then a ratio of $1.50<H_s/D_s<2.00$ then friction effects are minimized [2], but the effects of inertia are increased. Assuming D_s remains the same, having a lower H_s/D_s ratio can decrease inertial effects. An optimum ratio for minimizing inertial effects can be found by

$$H_s/D_s = \sqrt{\frac{3\nu_s}{4}} \quad (15)$$

Where ν_s is the Poisson ratio for the material. This means that $H_s/D_s=.5$ for a Poisson ratio of $\nu_s=0.33$. Since most epoxy's Poisson ratio is near 0.33 [1], this could be seen as an optimum ratio.

Additional consideration needs to be taken for soft materials though. The stress wave propagates slower through soft materials, drawing out the initial ringing up time of the test and making it difficult to for the sample to reach equilibrium. This can make thick samples hard to use. In order to minimize the ringing up time and bring the test to equilibrium sooner, thinner samples are needed [2]. The samples should not be too thin though, or the stress will no longer be uniaxial. To optimize these conditions a ratio of $0.25<H_s/D_s<0.5$ [2].

Tradeoffs and compromises between these factors must be made.

4. Assumptions

Five assumptions are made and must be true in order for the Split-Hopkinson Pressure Bar tests to be valid. The first assumption (assumption 1) is that the "stress wave propagation of the bar is [one dimensional]" [2]. This assumption is true when the test material is both isotropic and homogenous [2].

For a sample to be homogenous it must be made up of the same material throughout the entire sample. The chemical and mechanical structure should be uniform. An isotropic material is a material that its physical properties are the same about all axes [4].

The second assumption (assumption 2) made in this method is that the interface between the sample and the incident bar remain planar throughout the experiment [2]. This assumption can be fulfilled by having an acoustically soft specimen and having the sample diameter be equal or slightly smaller than the incident bar diameter [2].

The third assumption (assumption 3) made in the use of the Split-Hopkinson Pressure Bar test is that after an initial and unavoidable ringing up period is finished, the sample is at stress equilibrium [2]. This can be verified using equations (9) and (10) [2]. If

$$F_1 = F_2 \qquad (16)$$

then assumption three is valid.

The fourth assumption (assumption 4) is that the experimental sample is not compressible [2].

The final assumption (assumption 5) made in the Split-Hopkinson Pressure Bar test is that the friction effects on the system are negligible and also that inertial effects are also small enough to be neglected [2].

B. Epoxy

The epoxy being used is PC-Plumbing epoxy. Its composition (by weight) is Bisphenol A-epichlorohydrin polymer (10%-30%), 2,4,6-tri(dimethylaminomethyl)phenol (1%-5%), crystalline silica (0.1%-1%)[5]. The remainder of the ingredients were proprietary. When mixed and set, the epoxy can be assumed to be homogenous and isotropic.

The mixture results in an epoxy with a tensile strength of 650 PSI and a compressive strength of 12000 PSI[6]. There is no available data on its stress-strain curve or its impact properties.

III. Experimental Methods

A. Design of Experiment

1. Conceptual Design

As explained in Section II.A.1, we see that there are many parts to the Hopkinson Split Bar machine and most of these stages can be adjusted as variables and effect the results of the experiment. We can see many of them in the following Function Diagram:

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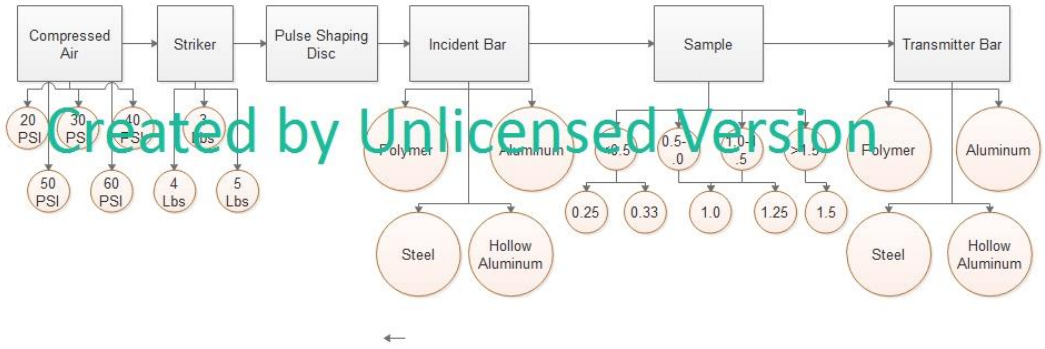

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Figure 4: Function Diagram for Hopkinson Split Bar Machine

In the diagram, the row of blue squares are the functioning parts of the machine and the pink circles are the related variables.

There are also some constraints on the design of the experiment. The first is time. The Hopkinson Split Bar machine is owned by the Akron Rubber Development Laboratory, not the University of Akron. As such machine time is limited, and scheduling is difficult. Therefore the amount of time spent at the site should be limited.

The second is the cost of materials, and by extension the amount of samples used and trials run. Thus, the minimal amount of trials should be run while maintaining the integrity and workability of the data. The remaining constraints will show up individually within each variable.

With these constraints in mind, we can analyze the variables in the Function Diagram and develop a decision matrix for them.

Compressed Air: The pressure of the compressed air can be made anywhere from 20PSI to 70PSI. The gage used to measure the air pressure is analogue though, so a lack of precision in the process is an additional constraint. For the sake of consistency and ease, the best options for the compressed air are then to be multiples of ten (20PSI, 30PSI, 40PSI, etc.).

Previous experimentation has found that the air pressure does not drastically effect the results of the experimentation. Higher pressures can result in a faster striker and less noise in the data, but it is not a great deal better, and does not affect the data beyond that. It can be good to vary the air pressure to verify the equations with different inputs. Thus the following weighted decision matrix can be made:

Weighted Decision Matrix, Compressed Air													
		20 PSI		30 PSI		40 PSI		50 PSI		60 PSI		Varied PSI	
Design Criteria	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Cost	0.17	10	1.7	10	1.7	10	1.7	10	1.7	10	1.7	10	1.7
Experiment Time	0.33	10	3.3	10	3.3	10	3.3	10	3.3	10	3.3	10	3.3
Data Quality	0.5	8	4	9	4.5	8	4	7	3.5	6	3	8	4
total	1		9		9.5		9		8.5		8		9

Figure 5: Weighted Decision Matrix for Compressed Air

The three criterion in this matrix were the cost, experiment time, and data quality. Since the cost of compressed air is low, it was given a small weight and because the cost difference between each pressure is negligible, they were all given the same score. The difference between experiment times is also negligible, so they were given the same score in that category as well. This left quality of data as the only remaining criterion. As such, the option with the highest score in that area was chosen for the experiment, being 30 PSI.

Striker: There are three available strikers. They are all the same material, but one is three pounds, one is four pounds, and one is five pounds. As the same material, they all have the same density, and therefore the difference between the three strikers is their mass. Previous experiments have shown that the striker mass has a negligible effect on the data. Due to time constraints, it is best not to vary the striker between trials. The following weighted decision matrix was generated:

Weighted Decision Matrix, Striker Mass									
		3 Lb Striker		4 Lb Striker		5 Lb Striker		Varied Striker	
Design Criteria	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Cost	0.17	10	1.7	10	1.7	10	1.7	10	1.7
Experiment Time	0.33	9	2.97	9	2.97	9	2.97	4	1.32
Data Quality	0.5	8	4	8	4	8	4	9	4.5
total	1		8.67		8.67		8.67		7.52

Figure 6: Weighted decision matrix for Striker Mass

The criterion were similarly weighted in the decision matrix for striker mass. Since we have all three strikers, the cost involved in using each of them is the same. The experiment will also take the same

amount of time to run for each of the masses, with the exception of varying the striker. Changing out the strikers takes a fair amount of machine disassembly, and as such varying between masses would add to the experimental time significantly. The final criterion is data quality, and as mentioned previously, the difference between each striker is negligible. While varying the striker mass would help the data and verification of equations a little bit, this would not be enough to make up for the increased run time of the experiment.

Incident Bar/Transmitter Bar: Hopkinson Split Bar Tests can be done with almost any type of material in the incident bar, as long as its properties are known. Common materials are steel, aluminum, hollow aluminum, or various polymers. For soft materials, incident bars with low impedance are best [2]. The use of polymers is good for this, but when using polymers additional analysis needs to be done due to their visco-elastic properties. This leads to the following weighted decision matrix:

Weighted Decision Matrix, Incident/Transmitter Bar									
		Aluminum		Hollow Aluminum		Polymer		Steel	
Design Criteria	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Cost	0.5	10	5	6	3	6	3	4	2
Experiment Time	0.17	9	1.53	7	1.19	5	0.85	7	1.19
Data Quality	0.33	7	2.31	8	2.64	9	2.97	4	1.32
total	1		8.84		6.83		6.82		4.51

Figure 7: Weighted decision matrix for the incident/transmitter bar material

In this case, cost was a much more relevant factor than the previous two. This is because only one of them is owned by the lab, so we would have to purchase them. This made the aluminum bar much more viable. The need to purchase new bars would also contribute to the time it would take to do the experiment. The polymer bar would require further calculations due to the visco-elastic effects, as mentioned earlier. This would also add to the time. With the quality of data, we see that the polymer is the best, followed by the hollow aluminum, aluminum, and steel. These gains weren't able to make up for the previous flaws though.

Sample: The effect of the samples height to width is the purpose of this experiment. There are a number of choices for this, as well as a number constraints on this. One is the cost of materials. One or more epoxies need to be chosen for their costs and availability. Another factor is the height to width ratio. The four main distinctions in this category are an $Hs/Ds<0.5$, $0.5<Hs/Ds<1.0$, $1.0<Hs/Ds<1.5$, and $Hs/Ds>0.5$. The constraints on this are the ability manufacture the sample, as well as time and cost.

The following weighted decision matrix was made for the possible materials:

Weighted Decision Matrix, Sample Material							
		PC-Plumbing		RectorSeal EP-200		JB Weld Adhesive	
Design Criteria	Weight Factor	Score	Rating	Score	Rating	Score	Rating
Cost	0.4	8	3.2	9	3.6	7	2.8
Availability	0.6	10	6	7	4.2	10	6
total	1		9.2		7.8		8.8

Figure 8: Weighted decision matrix for sample material.

The two primary factors were cost and availability. Of the three options PC-Plumbing epoxy was both the cheapest and the easiest to obtain.

The second weighted decision matrix for the samples is about the sample size:

Weighted Decision Matrix, Sample Size													
		.25 Hs/Ds		.33 Hs/Ds		.75 Hs/Ds		1.0 Hs/Ds		1.25 Hs/Ds		1.5 Hs/Ds	
Design Criteria	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Cost	0.1	10	1	10	1	9	0.9	9	0.9	9	0.9	9	0.9
Experiment Time	0.1	10	1	10	1	10	1	10	1	10	1	10	1
Manufacturability	0.5	8	4	9	4.5	4	2	7	3.5	6	3	6	3
Relevence	0.3	9	2.7	9	2.7	5	1.5	8	2.4	9	2.7	9	2.7
total	1		8.7		9.2		5.4		7.8		7.6		7.6

Figure 9: Weighted decision matrix for sample size

As we can see, the cost difference between these designs is pretty small, and doesn't affect the weighted decision matrix much. Each of the samples will take just as long to test, their Hs/Ds doesn't affect how long it takes to run the trial. The most important criteria was manufacturability, because if we can't make a good sample, the data won't be consistent or work well. Relevance to the experiment was also pretty important. If it doesn't fit with what we are trying to find, how much does it matter if we can make it. Due to the nature of the experiment a range of Hs/Ds samples will be needed, but the numbers that were made reflect the totals in the weighted decision matrix.

2. Embodiment Design

The analysis in the in section III.A.1 has lead us to a few clear choices in the design of the experiment. The first being that it is best to vary the compressed air pressure that powers the Hopkinson's Split Bar Test machine. Previous experimentation has showed that an air pressure of 30 PSI yield data with the least noise. Therefore that pressure was used

There is also a clear choice of material for incident and transmitter bar. This is, of course, aluminum. It is the least expensive option and the least time consuming option. These two facts more than make up for the slight deterioration in the data quality from the yield of a polymer or hollow aluminum bar.

The mass of the striker leaves no clear decision because of how little it effects the data. As long as they are kept consistent across the experiments they will yield good results and no one striker will work noticeably better than the rest.

As mentioned previously, the samples will have variable Hs/Ds. The analysis showed that the best options were Hs/Ds=0.25 and Hs/Ds=0.33. These will also need to be compared to higher Hs/Ds ratios. What works best is an Hs/Ds=1.0. Higher Hs/Ds ratios would also be good to analyze, on a smaller scale though. Not much time should be committed to Hs/Ds=1.25 and Hs/Ds=1.5, but they should be considered.

3. Detail Design

The elements of the previous two sections can now be boiled down to an experimental set up, detailed in the following chart

Experiment Set Up						
Trial	Material	Hs/Ds	Incident Bar	Transmitter Bar	Striker	Air Pressure
1	PC Plumbing	0.33	aluminum	aluminum	4	30
2	PC Plumbing	0.33	aluminum	aluminum	4	30
3	PC Plumbing	0.33	aluminum	aluminum	4	30
4	PC Plumbing	0.25	aluminum	aluminum	4	30
5	PC Plumbing	0.25	aluminum	aluminum	4	30
6	PC Plumbing	0.25	aluminum	aluminum	4	30
7	PC Plumbing	1	aluminum	aluminum	4	30
8	PC Plumbing	1	aluminum	aluminum	4	30
9	PC Plumbing	1.25	aluminum	aluminum	4	30
10	PC Plumbing	1.5	aluminum	aluminum	4	30

Figure 10: Experiment Set Up

This shows that for the more easily made Hs/Ds samples we will have three trials, all at 30 PSI. The Hs/Ds of 1.0 will have two trials. All experiments will also be the same material (PC Plumbing Epoxy), the same incident and transmitter bars (aluminum) and the same striker. An additional trial will be run on a sample with Hs/Ds=1.25, and a trial will be run for an Hs/Ds=1.5. This will produce a reliable data set of trials at the easily made Hs/Ds and allow a couple trials at a higher Hs/Ds ratio.

This is a relatively low number of trials being run (a total of ten), but this is due to both time constraints of running the tests and the constraints of production of the samples (time, cost, viability of created samples, etc.). This number of tests will yield enough data to make reasonable findings though.

B. Making The Samples

The sample was made out of PC-Plumbing Epoxy. This is a multipurpose epoxy putty produced by PC-Epoxy. For the samples with a height to diameter ratio under 1.00, metal molds and a compression molder were used. The materials used were the putty, molds, a razor, an 11mm punch, a roller, Teflon sheets, the compression plates and the compression molding machine. As seen in the following figures

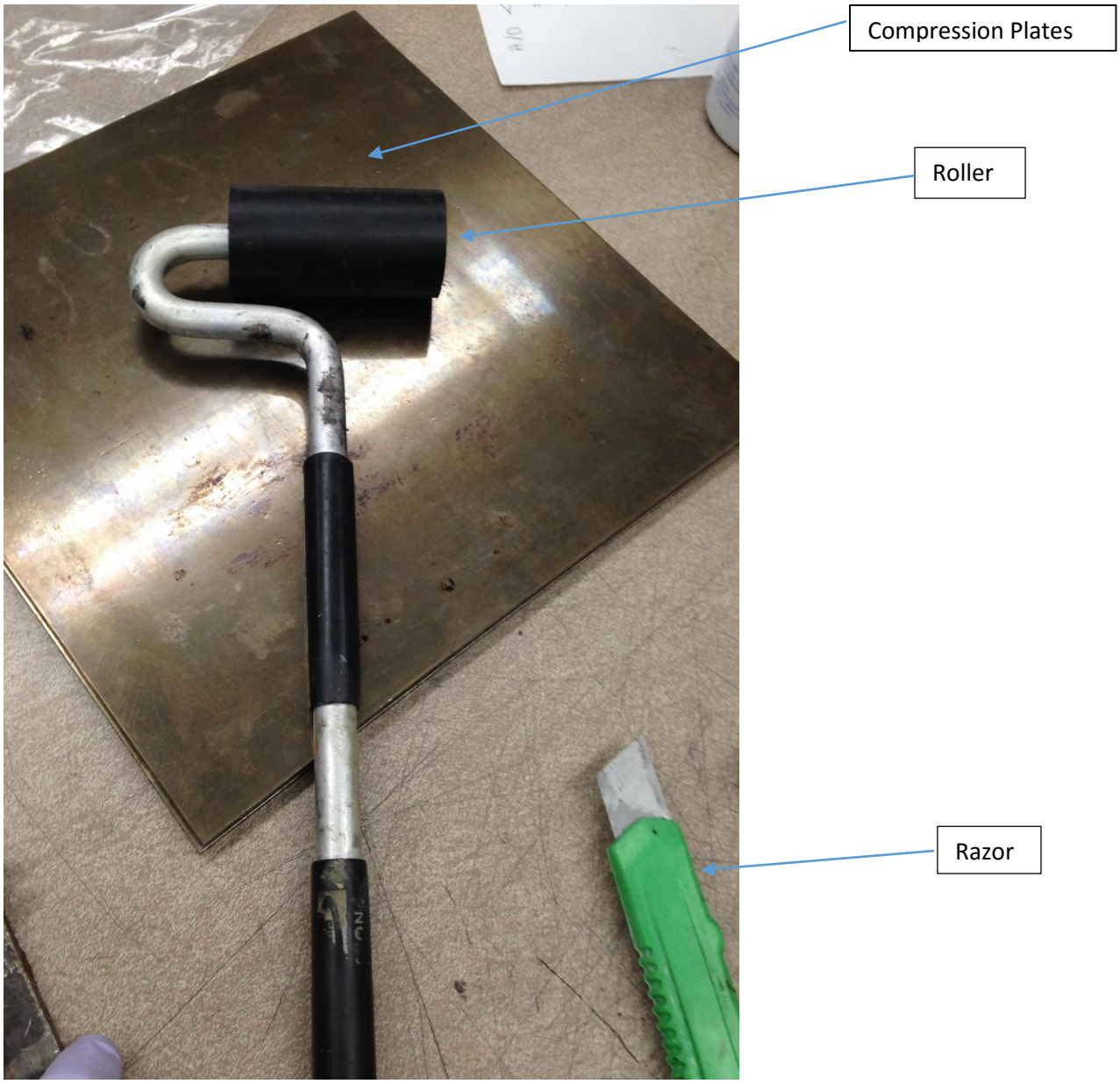

Figure 11: Production Materials

Figure 12: 11 mm Punch

Figure 13: PC-Plumbing (in Packaging) [3]

Figure 14: PC-Plumbing Epoxy (out of packaging)

Before forming the epoxy the mold would be set up. The bottom compression plate would be laid down. On top of the plate would be a plastic sheet, and on top of that would be the mold.

Figure 15: Mold set up

Then the putty could be formed. First, the desired amount of epoxy was cut off of the stick. It was then mixed for one minute. After three minutes the epoxy would begin to cure.

The following steps would be completed before curing began. The mixed epoxy would be pushed into the mold. The mold would be over-filled, with excess coming over the top side. Then another layer of

plastic would be placed on top of the epoxy filled mold. It would then be flattened with the roller. Then the top compression plate would be placed on the top of the plastic.

This resulted in a five layer set-up that would be used within the compression molding machine. Starting from the bottom was the bottom compression plate, then one layer of plastic, then the epoxy filled mold, a second layer of plastic sheet, and on top was the top compression plate. As seen in the following sketch

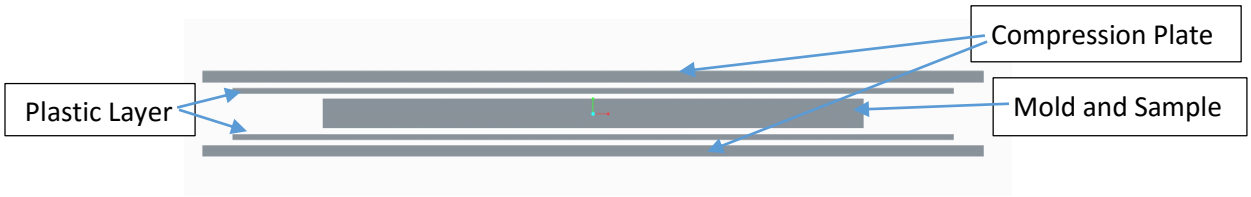

Figure 16: Sketch of the mold set up layers

The set-up was then taken to the compression molding machine. It was then compressed at 2500 PSI for one minute.

Figure 17: Compression of the Sample

After the compression curing would begin. The epoxy was placed under weights and left to cure at room temperature for one hour.

The top compression plate and top layer of plastic were removed, leaving the epoxy filled mold, and a smooth layer of plastic outside of the mold where the epoxy overflowed, as seen in the following figure.

Figure 18: Cured epoxy in molds

Using the razor, the molds were cleaned up, with the overflow being trimmed off, resulting in the following figure:

Figure 19: Cleaned up mold

The epoxy could be easily extracted then. The 11mm punch was then used to make appropriately sized samples, resulting in the following:

Figure 20: Top view of punched samples

Figure 21: 45° view

Three sets of samples were made, with three different H_s/D_s ratios, 0.25, 0.33, and 1.0, as seen in the following figures

Figure 22: Three categories, overhead view

Figure 23: three categories, 45° view

The following chart shows all of the samples that were made:

Sample #	Dia 1	Dia 2	Dia 3	Dia avg	dia std	Thick 1	Thick 2	Thick 3	Thick avg	Thick std	h/d
1	11.25	11.26	11.23	11.25	0.01	3.66	3.70	3.72	3.69	0.02	0.33
2	11.32	11.19	11.18	11.23	0.06	3.72	3.75	3.74	3.74	0.01	0.33
3	11.31	11.36	11.18	11.28	0.08	3.55	3.58	3.58	3.57	0.01	0.32
4	11.31	11.27	11.15	11.24	0.07	3.53	3.55	3.53	3.54	0.01	0.31
5	11.21	11.19	11.19	11.20	0.01	3.60	3.61	3.62	3.61	0.01	0.32
6	11.19	11.18	11.26	11.21	0.04	3.56	3.60	3.55	3.57	0.02	0.32
7	11.18	11.25	11.18	11.20	0.03	3.52	3.51	3.50	3.51	0.01	0.31
8	11.20	11.29	11.25	11.25	0.04	3.62	3.58	2.57	3.26	0.49	0.29
9	11.15	11.16	11.18	11.16	0.01	3.61	3.61	3.59	3.60	0.01	0.32
10	11.26	11.35	11.34	11.32	0.04	2.48	2.51	2.53	2.51	0.02	0.22
11	11.17	11.18	11.14	11.16	0.02	2.61	2.69	2.65	2.65	0.03	0.24
12	11.23	11.27	11.18	11.23	0.04	2.45	2.42	2.45	2.44	0.01	0.22
13	11.26	11.24	11.18	11.23	0.03	2.82	2.91	2.91	2.88	0.04	0.26
14	11.23	11.26	11.34	11.28	0.05	2.80	2.84	2.79	2.81	0.02	0.25
15	11.28	11.25	11.26	11.26	0.01	2.80	2.79	2.73	2.77	0.03	0.25
16	11.24	11.27	11.22	11.24	0.02	2.66	2.64	2.65	2.65	0.01	0.24
17	11.20	11.19	11.13	11.17	0.03	2.79	2.81	2.78	2.79	0.01	0.25
18	12.00	11.84	11.77	11.87	0.10	12.11	12.15	12.21	12.16	0.04	1.02
19	12.71	12.45	12.67	12.61	0.11	12.69	12.76	12.80	12.75	0.05	1.01
20	12.59	12.54	12.34	12.49	0.11	12.95	13.02	12.98	12.98	0.03	1.04
21	12.17	12.74	12.85	12.59	0.30	13.16	13.13	13.10	13.13	0.02	1.04
22	12.72	12.78	12.62	12.71	0.07	13.60	13.52	13.08	13.40	0.23	1.05
23	12.59	12.24	12.36	12.40	0.15	15.50	15.79	15.63	15.64	0.12	1.26
24	12.47	12.36	12.12	12.32	0.15	19.33	19.28	19.14	19.25	0.08	1.56

Figure 24: Chart of all samples made

C. Hopkinson Split Bar Test

The Hopkinson split bar test was run out of Labview software. The software would be loaded on the computer attached to the screen and the sample diameter, height, and the length of the projectile would be inputted into the software.

After the software was set up the sample would be lubricated with WD-40 and placed between the incident bar and the transmitter bar.

Figure 25: Sample placed between transmitter bar and incident bar

The collar would then be set in place over the sample, as seen in the following figure:

Figure 26: Sample with collar in place

Then we would ensure that the striker was in position, pushed all the way to the back of the barrel.

Then a signal shaper would be placed on the end of the incident bar with metal assembly paste and a collar would cover it up as well:

Figure 27: Signal Shaper

Figure 28: Metal assembly paste

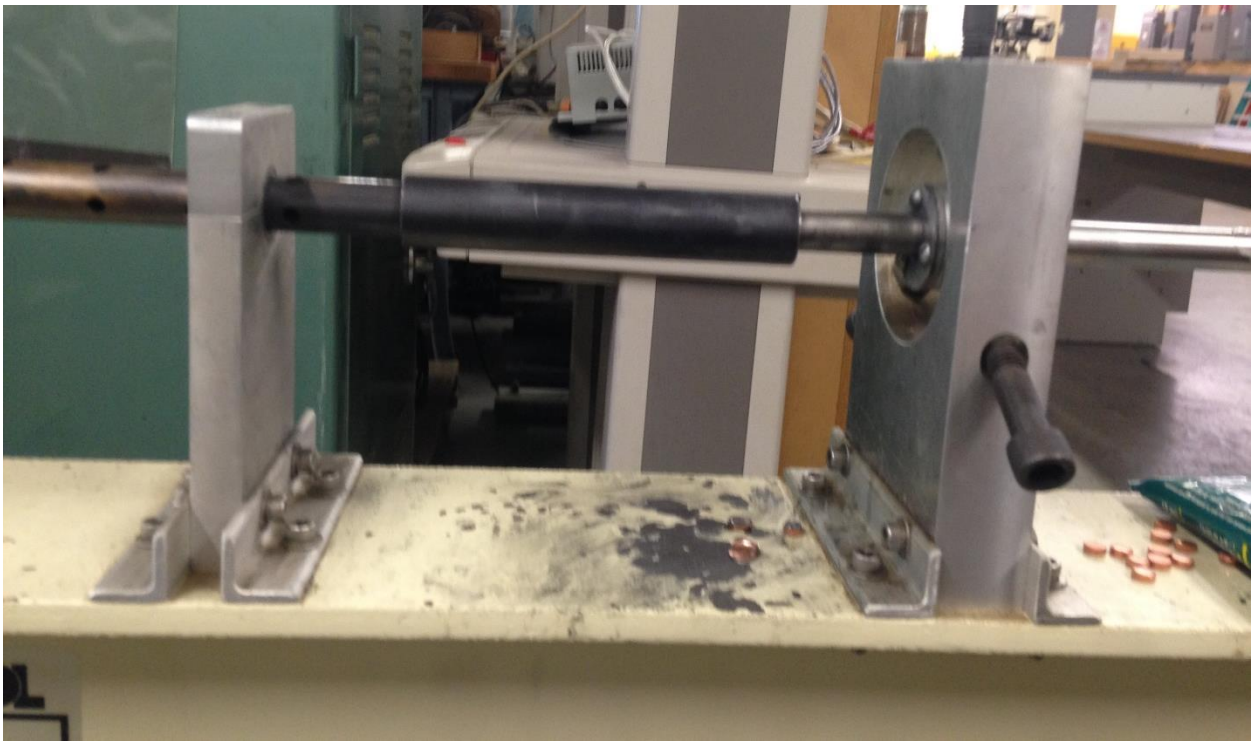

Figure 29: Signal Shaper in collar

The pressure would be set at 30 PSI using two switches.

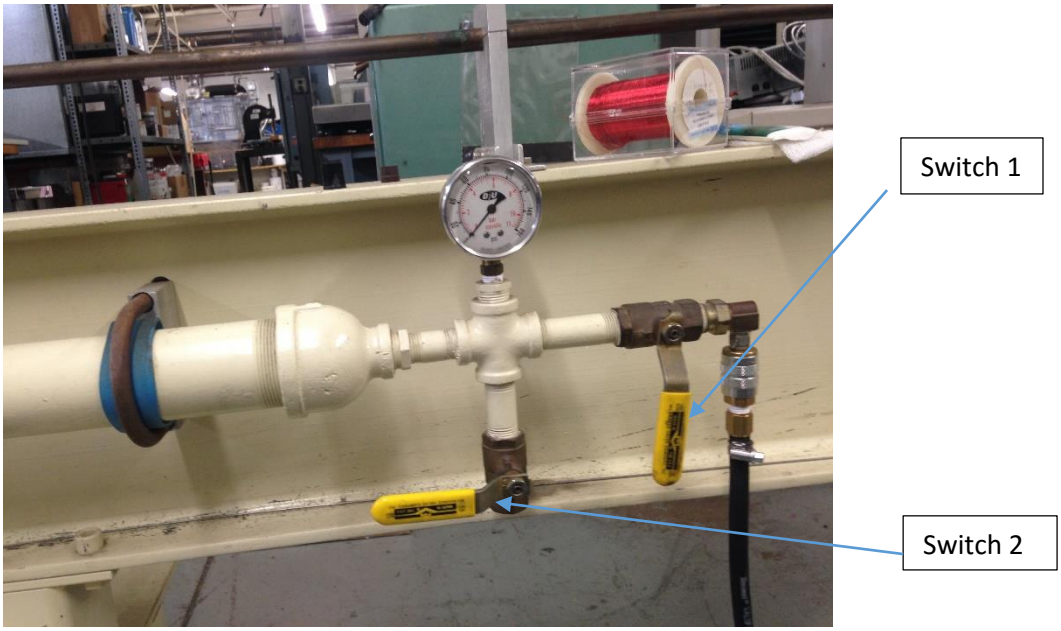

Figure 30: compressed air system

All three switches would initially be set to the close position. Then switch 1 would be opened to allow around 40 PSI into the system. Switch two would be used to ease air out until the system was at the desired pressure.

The signal for the strain gages would then be balanced and the mode of the oscilloscope would be set to single.

A third switch would be set open to let out the pressurized air and send the striker into the incident bar through the signal shaper, which would then transfer its momentum into the sample, and then into the transmitter bar.

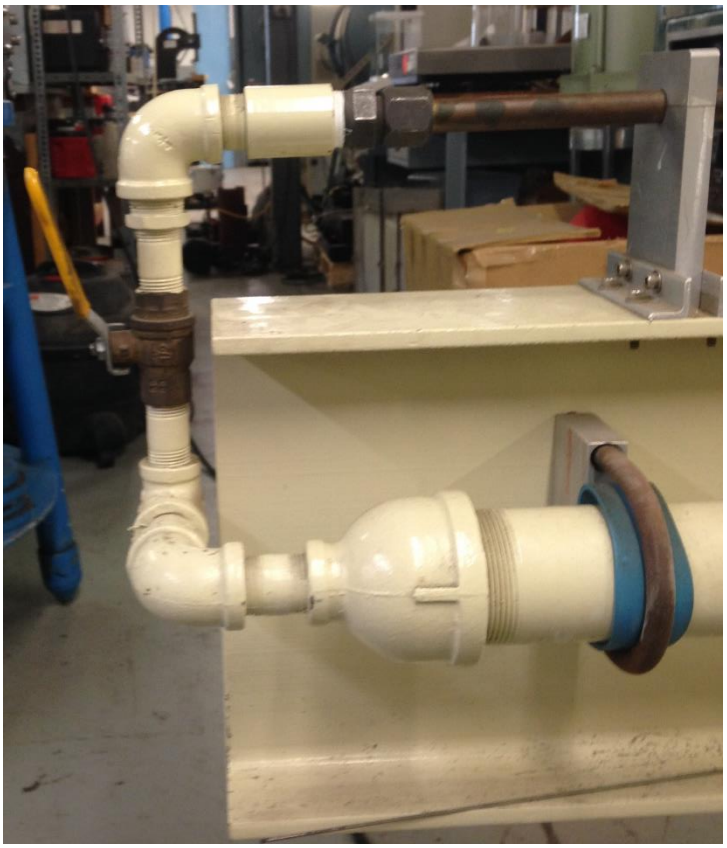

Figure 31: Compressed air release switch

That signal data would then be recorded on the software, as seen below:

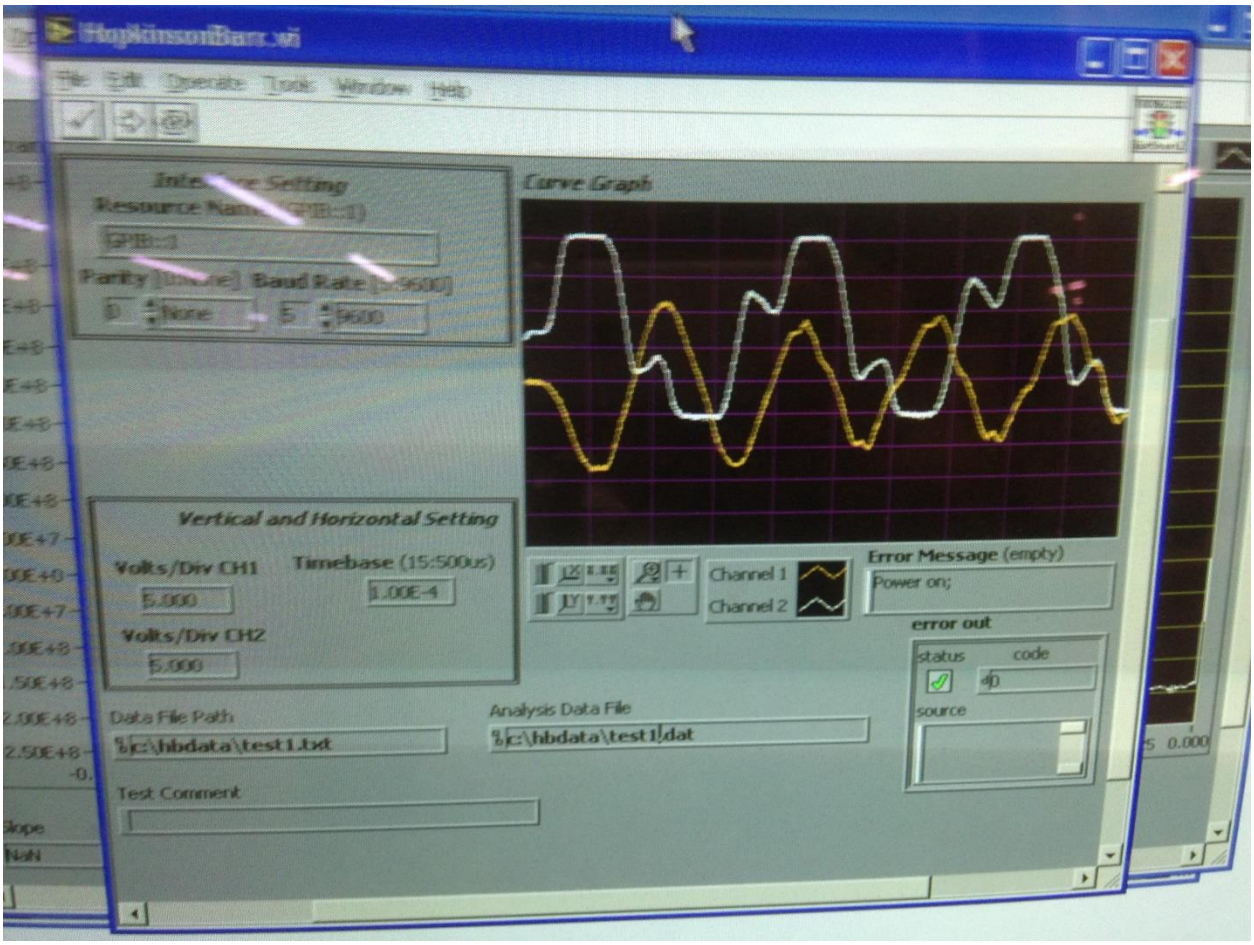

Figure 32: Software with data

The data was also exported into a text file, which could then be used in analysis.

The experiment would then be reset and the steps repeated for each sample.

The following test was run on the following samples:

Experiment Set Up						
Sample	Material	Hs/Ds	Incident Bar	Transmitter Bar	Striker	Air Pressure
3	PC Plumbing	0.32	aluminum	aluminum	4	30
5	PC Plumbing	0.32	aluminum	aluminum	4	30
6	PC Plumbing	0.32	aluminum	aluminum	4	30
10	PC Plumbing	0.22	aluminum	aluminum	4	30
12	PC Plumbing	0.22	aluminum	aluminum	4	30
13	PC Plumbing	0.26	aluminum	aluminum	4	30
18	PC Plumbing	1.02	aluminum	aluminum	4	30
20	PC Plumbing	1.04	aluminum	aluminum	4	30
23	PC Plumbing	1.26	aluminum	aluminum	4	30
24	PC Plumbing	1.56	aluminum	aluminum	4	30

Figure 33: Samples Tested

IV. Results

A. Physical Deformation

The test caused some physical damage to the samples. Not surprisingly the thinner samples were more damaged than their thicker counterparts.

Samples 18, 20, 23, and 24 did not go through noticeable deformation, as we can see

Figure 34: Samples 18, 20, 23, and 24 after testing, top view

Figure 35: Samples 18, 20, 23, and 24 after testing, 45° angle

Samples 3, 5, and 6 went through a small amount of deformation, with faint fracture lines on samples 3 and 5. Sample 6 had a sizable portion crack off of it though.

Figure 36: samples 3, 5, and 6 after testing, top view

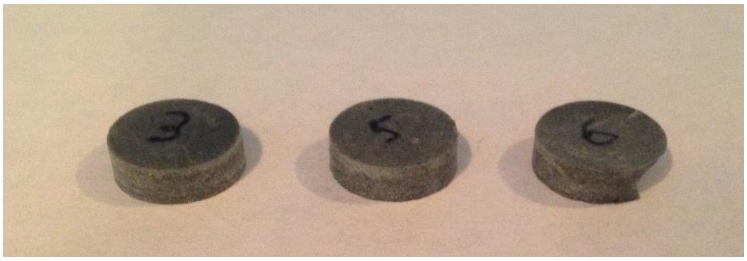

Figure 37: Samples 3, 5, and 6 after testing, 45° angle

Figure 38: Sample 6 rear view

Samples 10, 12, and 13 deformed significantly during the Split Hopkinson Bar test. Sample 10 sustained the most damage, but all three had many fracture lines across them and parts chip off of the back of them, as seen in the following figures:

Figure 39: Samples 10, 12, and 13 after testing top view

Figure 40: Samples 10, 12, and 13 after testing, 45° angle

Figure 41: Samples 10, 12, and 13 after testing, rear view

B. Stress-Strain Data

The stress-strain could was exported into a text file, which was then imported into excel, which could then be processed plotted as Time vs. The signal from the strain gages.

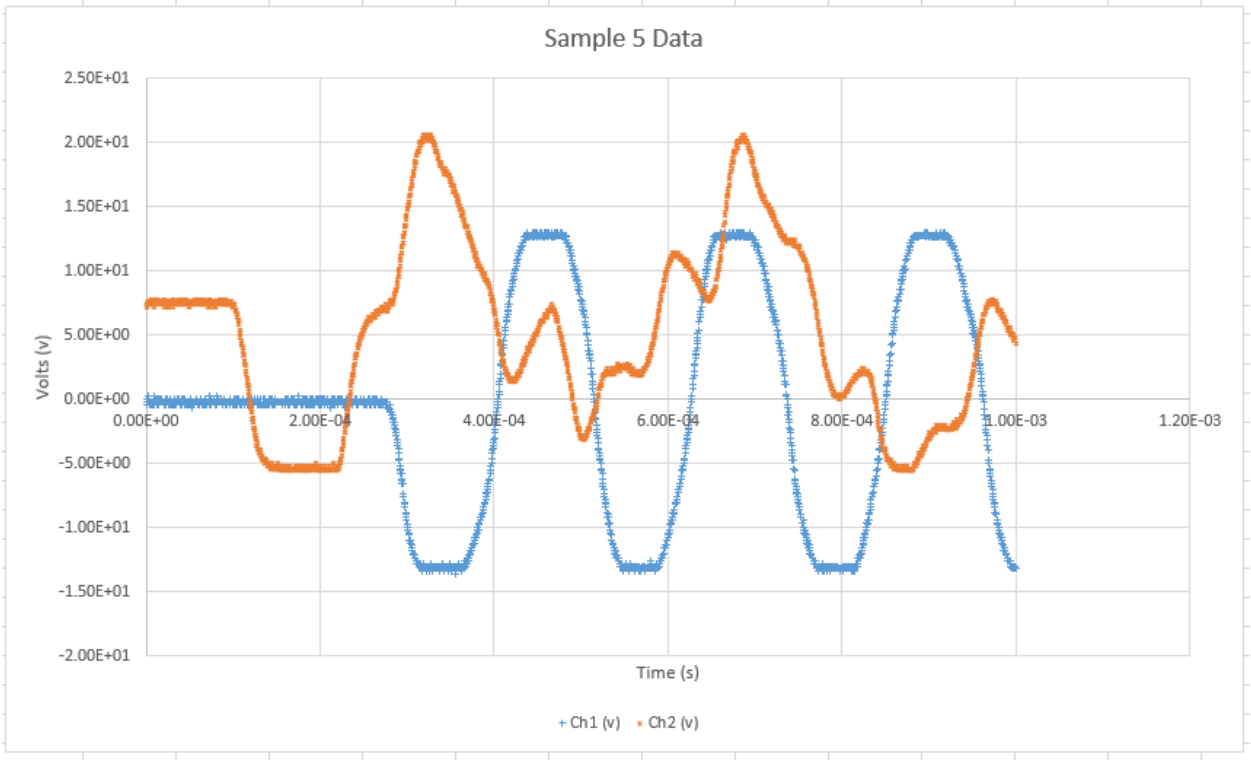

Figure 42: Example Data plat (Sample 5 Data plot)

See Appendix A. Strain Gage Signal Data for all plots.

The software also output the stress data, strain data, and strain rate data at each time.

V. Analysis

The stress data, strain data, and strain rate data were used to analyze the epoxy. First the strain data and stress data were plotted against each other for each sample, sample 10 can be used as an example:

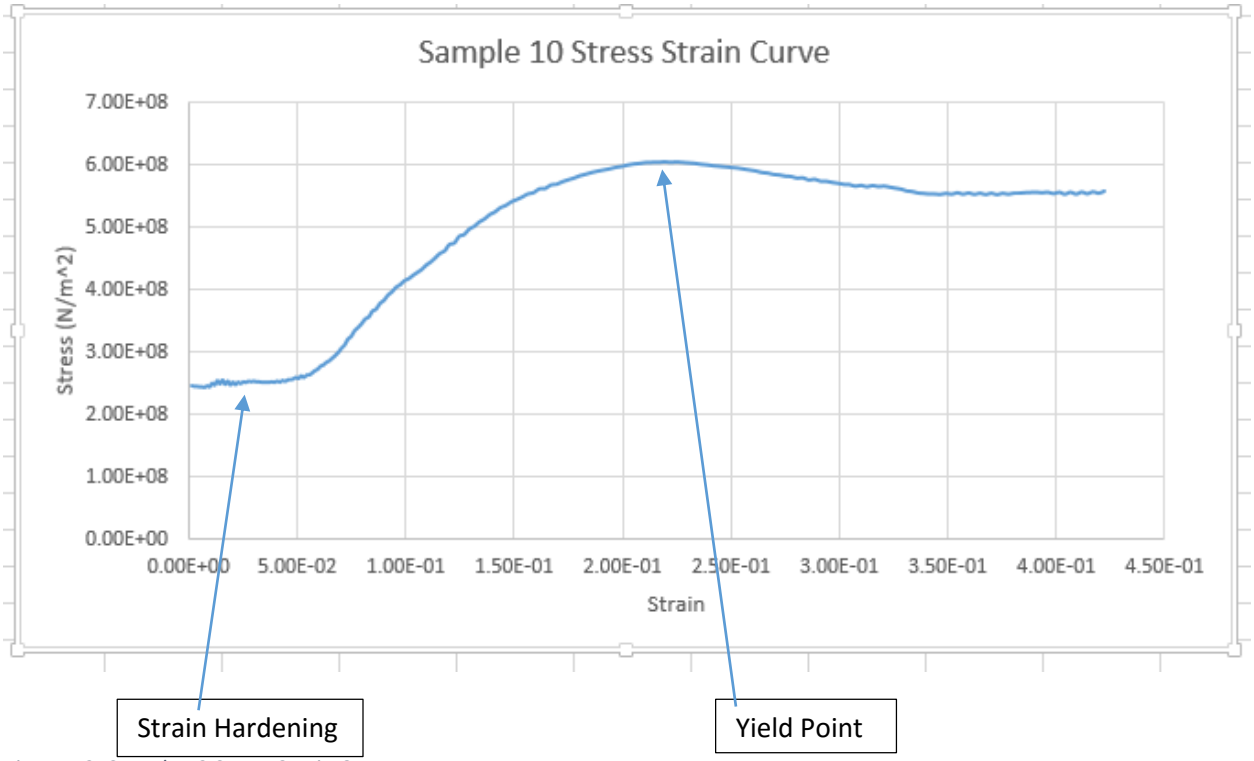

Figure 43: Sample 10 Stress Strain Curve

The curve shows us a number of things about what happened when the sample underwent a high speed impact. First, the flat slope at the beginning of the curve shows that the sample underwent strain hardening. We can also see the peak of the curve is where the yield stress and yield strain were met.

Matching Hs/Ds could be plotted together as well, to see the variance within a sample size:

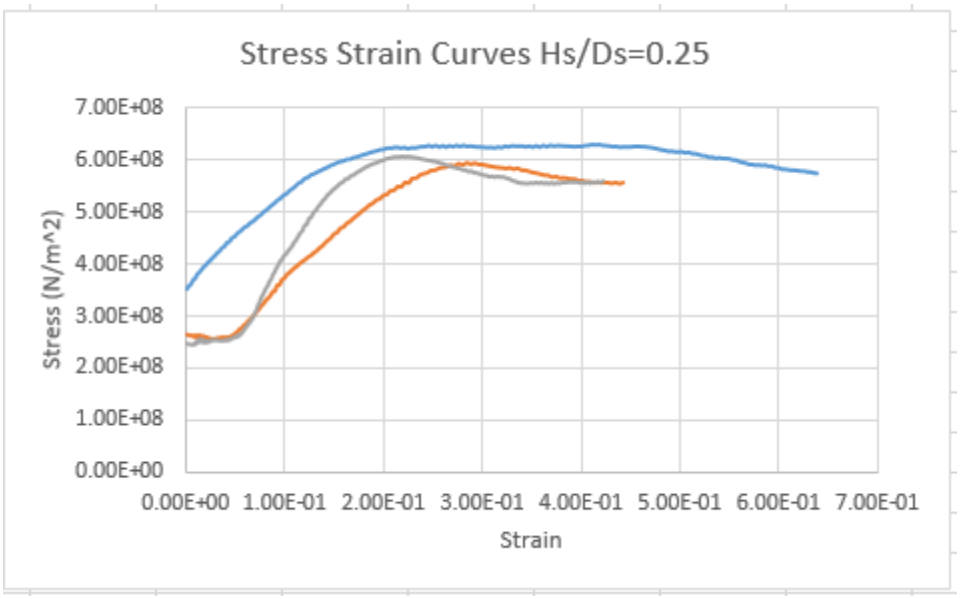

Figure 44: Stress Strain Curves Hs/Ds=.25

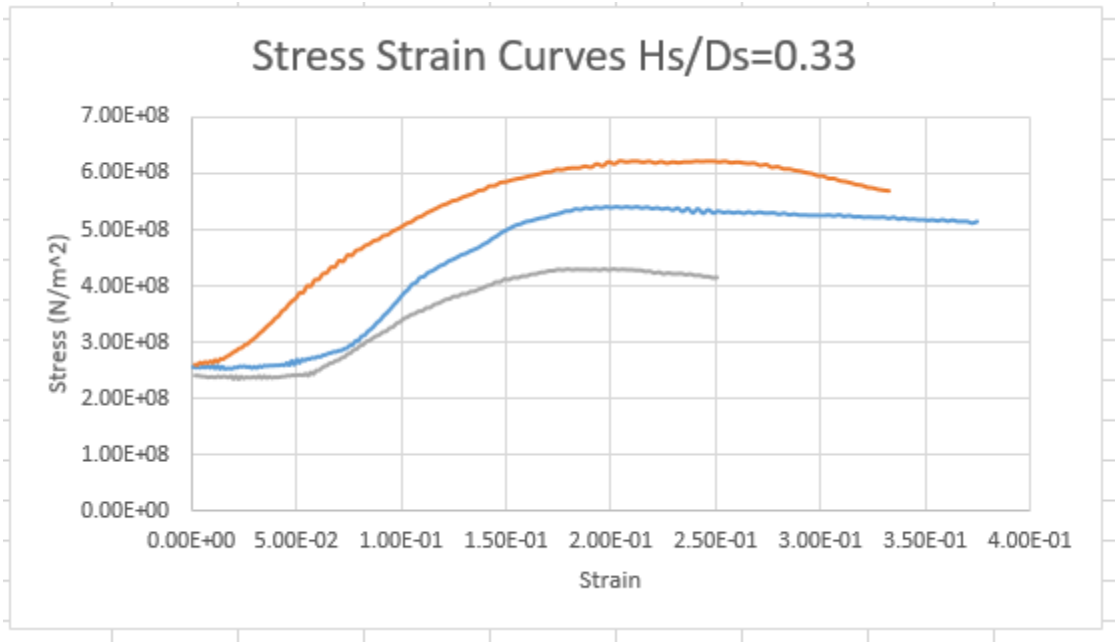

Figure 45: Stress Strain Curves for Hs/Ds=.33

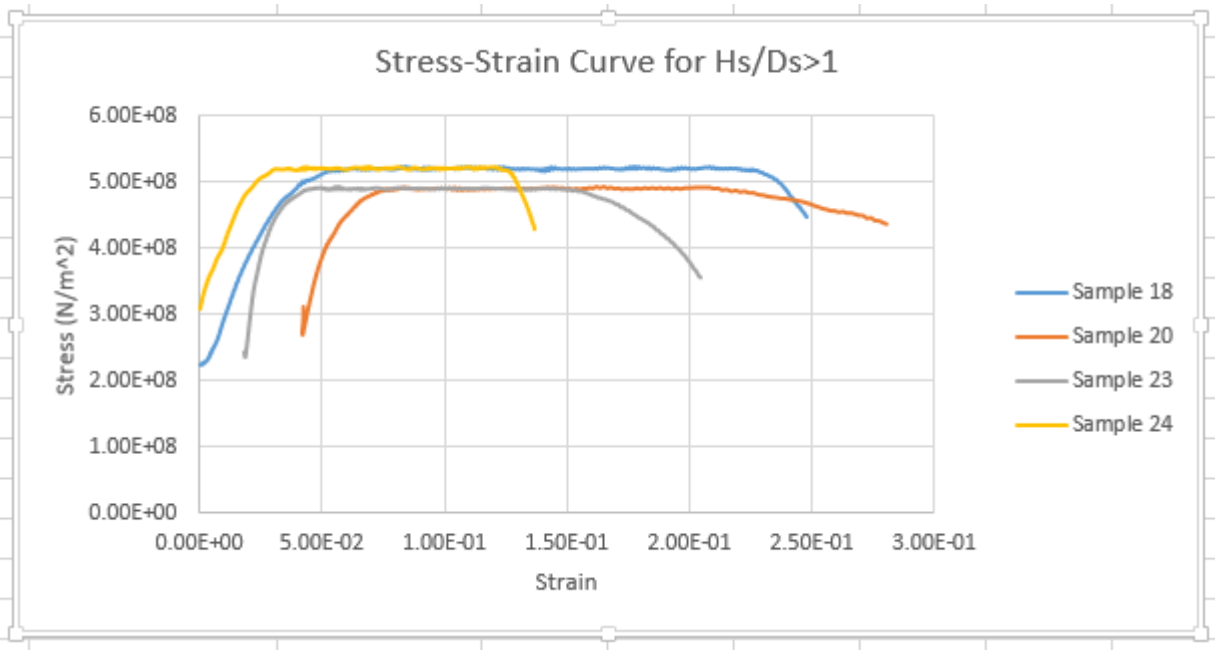

Figure 46: Stress Strain Curve for Hs/Ds>1

These show that within a sample size the shape of the curve is fairly consistent. All of the sample sizes also have strain hardening.

Using excel, the maximum stress was found, which is the yield stress. As previously stated, the corresponding strain was the yield strain. Using these data points the modulus of elasticity could be calculated.

The maximum strain rate was also extracted from the data set. These values for each sample can be seen below:

Sample	max strain rate	max stress	strain at max stress	Elastic Modulus
3	5530.5	4.30E+08	0.19651	2.19E+09
5	6995	6.20E+08	0.20407	3.04E+09
6	6138.6	5.42E+08	0.20298	2.67E+09
10	7093	6.06E+08	0.21918	2.76E+09
12	10077	5.96E+08	0.28506	2.09E+09
13	8857.2	6.28E+08	0.41104	1.53E+09
18	2098.7	5.23E+08	0.084215	6.21E+09
20	4637.7	4.91E+08	0.16523	2.97E+09
23	2624.1	4.93E+08	0.055769	8.83E+09
24	1330	5.24E+08	0.06911	7.58E+09

Figure 47: Data from Hopkinson Split Bar

The maximum strain rate was plotted against the other three values

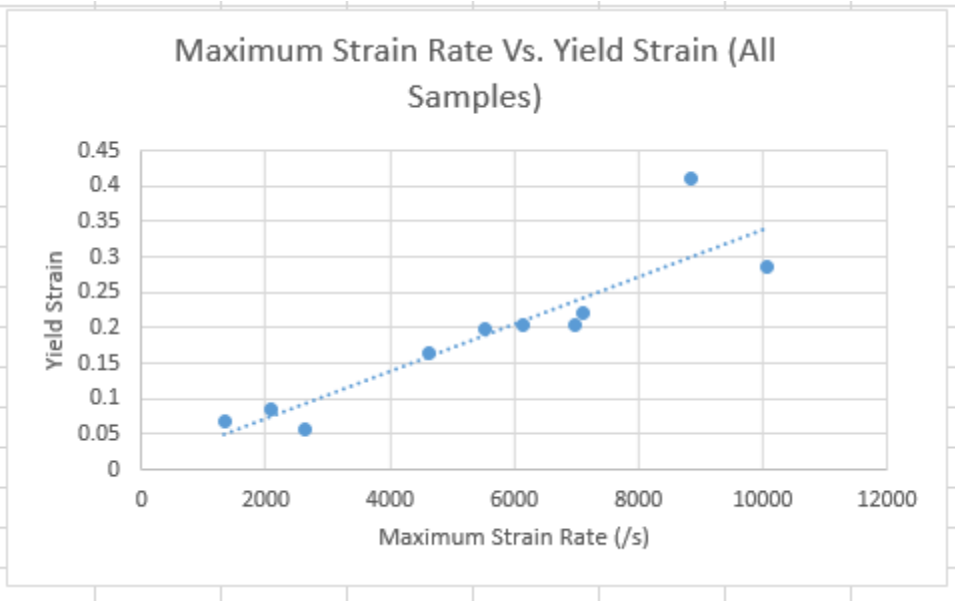

Figure 48: Maximum Strain Rate Vs. Yield Strain for all samples

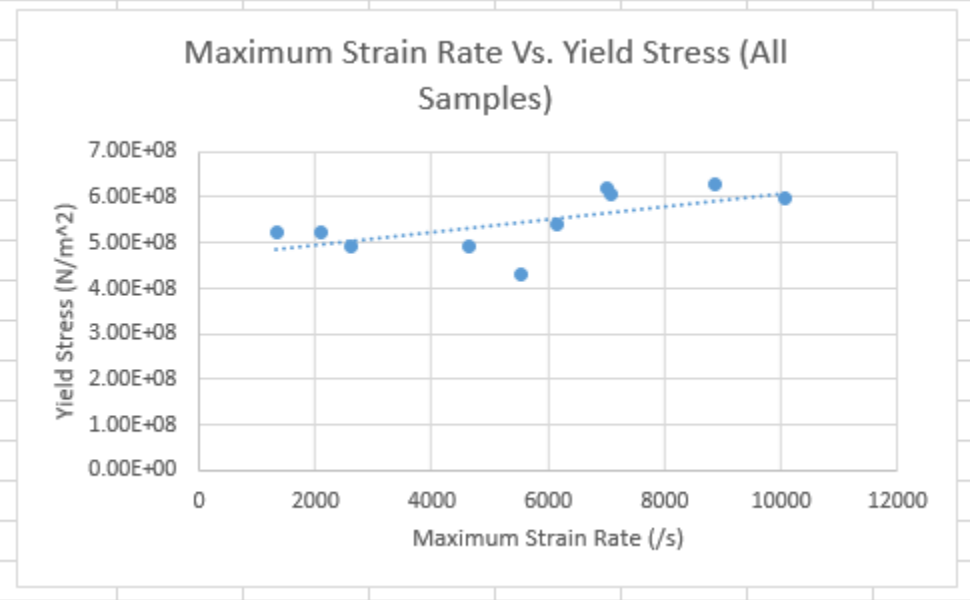

Figure 49: Maximum Strain Rate vs. Yield Stress for all samples

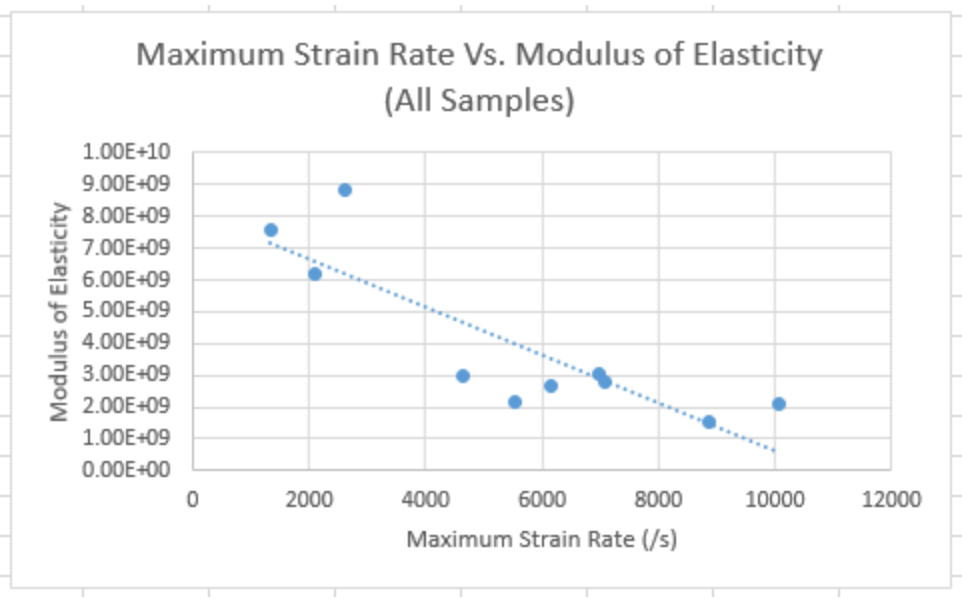

Figure 50: Maximum Strain Rate vs. Modulus of Elasticity for all samples

The data was then divided between Hs/Ds ratios. The data clusters that can be seen in the previous plots can now be seen as each of the Hs/Ds ratios (.25, .33, and >1).

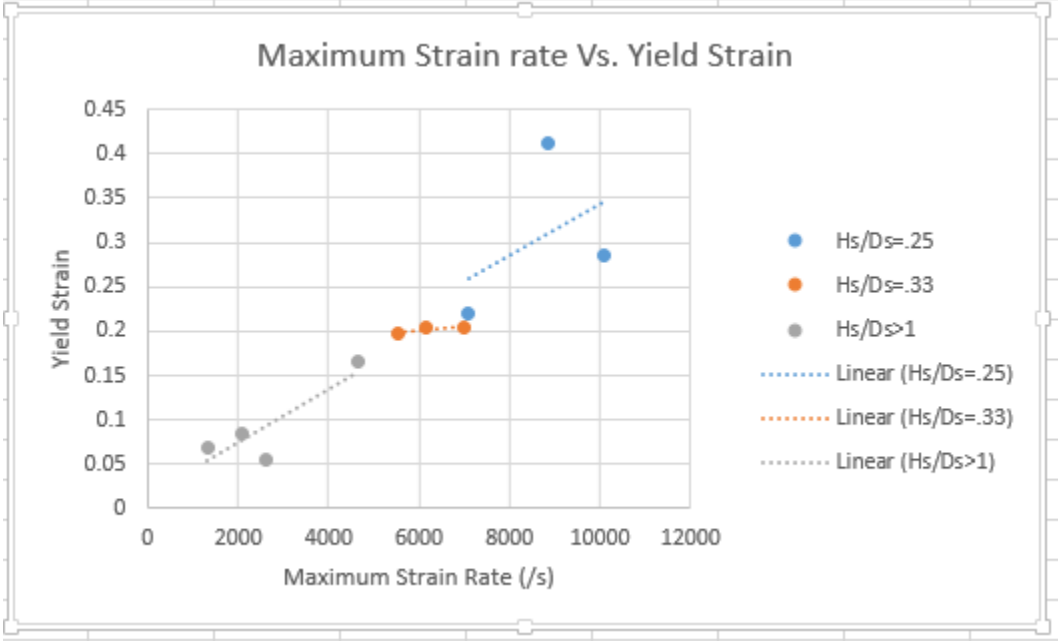

Figure 51: Maximum Strain Rate vs. Yield Strain separated for Hs/Ds

In this plot we see that the right most cluster is the Hs/Ds>1 sample size. It has a steeper slope than the Hs/Ds=.33 (middle group). The Hs/Ds group is too inconsistent for its trend line to mean anything.

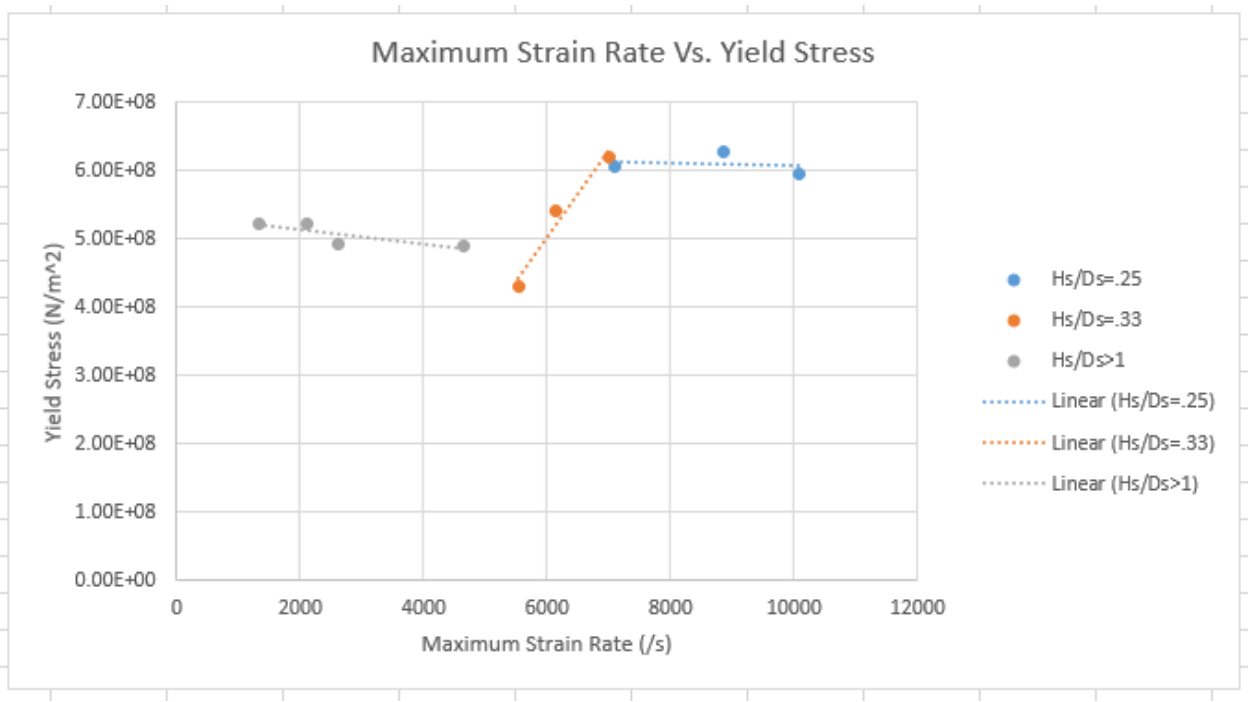

Figure 52: Maximum Strain Rate vs. Yield Stress separated for Hs/Ds

Each data set has a good, steady trend line in this plot, and Hs/Ds>1 has a similar slope as Hs/Ds=.25, but Hs/Ds=.33 has a steeper slope and in the opposite direction.

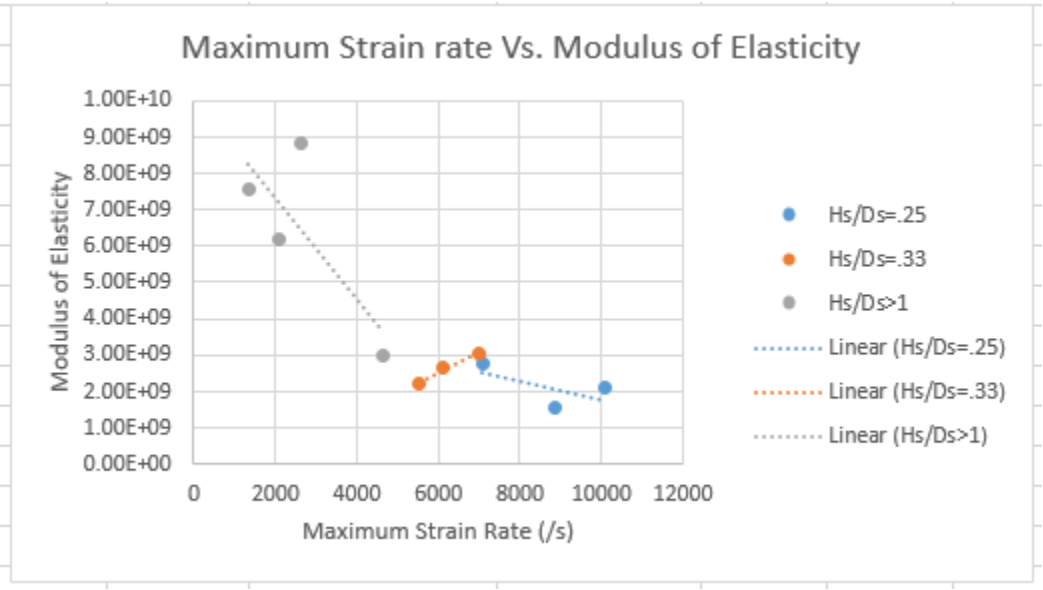

Figure 53: Maximum Strain Rate vs. Modulus of Elasticity separated for Hs/Ds

There are very few similarities between the trend lines of the different sample sizes in their Modulus's of Elasticity

Each of these data sets can be averaged and variance between them can be calculated in order to see which sample size is the most consistent.

Hs/Ds	avg max strain rate	var	avg max stress	var	avg yield strain	var	avg Elastic Modulus	var
0.25	8675.733333	0.17	610066666.7	0.03	0.305093333	0.32	2127928227	0.29
0.33	6221.366667	0.12	5.31E+08	0.18	0.201186667	0.02	2.63E+09	0.16
>1	2672.625	0.53	5.08E+08	0.04	0.093581	0.525	6.40E+09	0.39

Figure 54: Averaged Results for Sample Sizes

The variance was calculated by dividing the standard deviation by the average value that it is related to, giving a ratio between the standard deviation and the related value. The consistency is pretty consistent across the sample sizes, with Hs/Ds being the most consistent, Hs/Ds=.25 being the second best and Hs/Ds>1 being the most varied. This is probably due to the fact that the range of Hs/Ds within Hs/Ds>1 is much greater than the other two.

In the preceding plots the data clusters don't often overlap, showing that Hs/Ds=0.25 is mostly within maximum strain rates of 7,000-10,000 /s, Hs/Ds=0.33 is usually within a range of maximum strain rates from 5,000-7,000 /s and Hs/Ds>1 for a range of maximum strain rates of 1,000-5,000 /s.

VI. Conclusion

As seen in the previous section, stress-strain curves were developed for each sample, and the data that was used also found the maximum strain rate, yield stress, and yield strain for each sample. Using these the modulus of elasticity was calculated. These numbers were then used to find an average for each sample size.

For Hs/Ds=0.25 the average maximum strain rate was 8675.7/s, the average yield stress was 6.1×10^8 N/m^2, the average yield strain was .305, and the average modulus of elasticity was 2.13×10^9 N/m^2.

For Hs/Ds=0.33 the average maximum strain rate was 6221.4/s, the average yield stress was 5.311×10^8 N/m^2, the average yield strain was 0.201, and the average modulus of elasticity was 2.63×10^9 N/m^2.

For Hs/Ds>1 the average maximum strain rate was 2672.6/s, the average yield stress was 5.081×10^8 N/m^2, the average yield strain was .093, and the average modulus of elasticity was 6.40×10^9 N/m^2.

We also found that each sample size had a range of maximum strain rates that they data fell into. This leads to the conclusion that the preferred sample size depends on the range of strain rates that is being investigated. If someone wanted to investigate for maximum strain rates of 7,000-10,000/s then they would use a sample of Hs/Ds=0.25. If they want to investigate a range of 5,000-7,000/s they should use an Hs/Ds of 0.33. An Hs/Ds that is greater than one should be used to investigate a range of maximum strain rates of 1,000-5,000/s.

We also saw that PC-plumbing epoxy undergoes strain hardening.

VII. Appendix

A. Strain Gage Signal Data

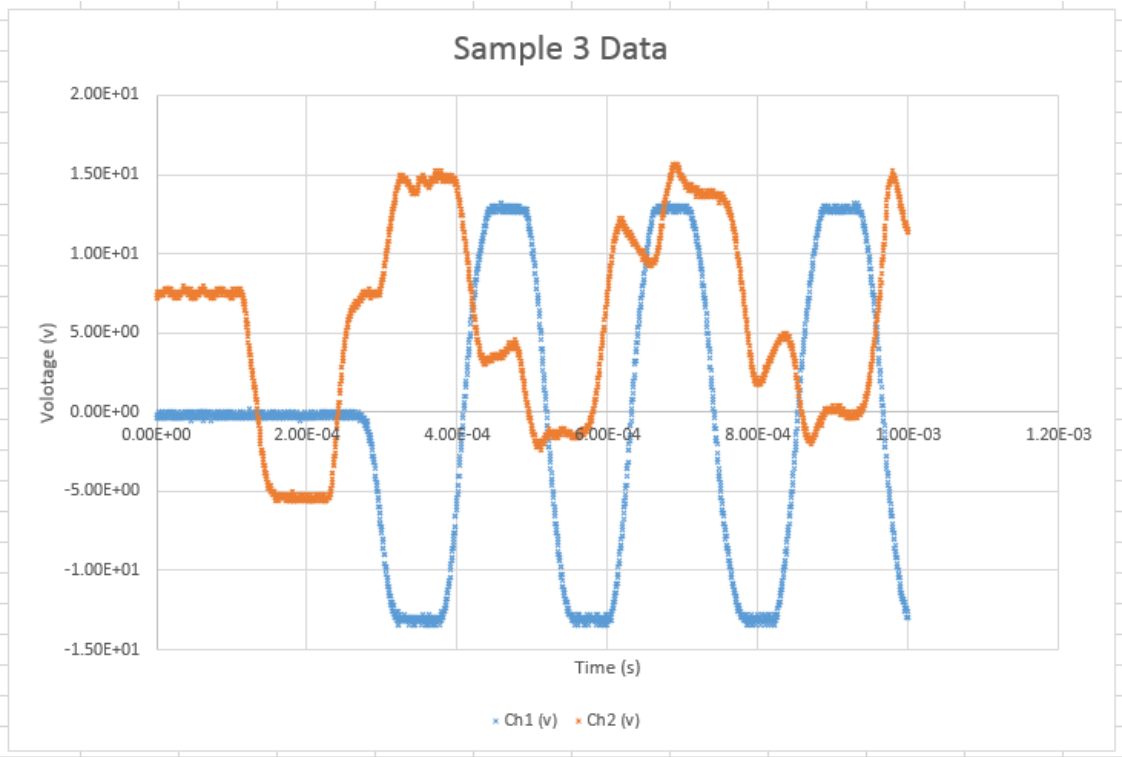

Figure 55: Sample 3 Data Plot

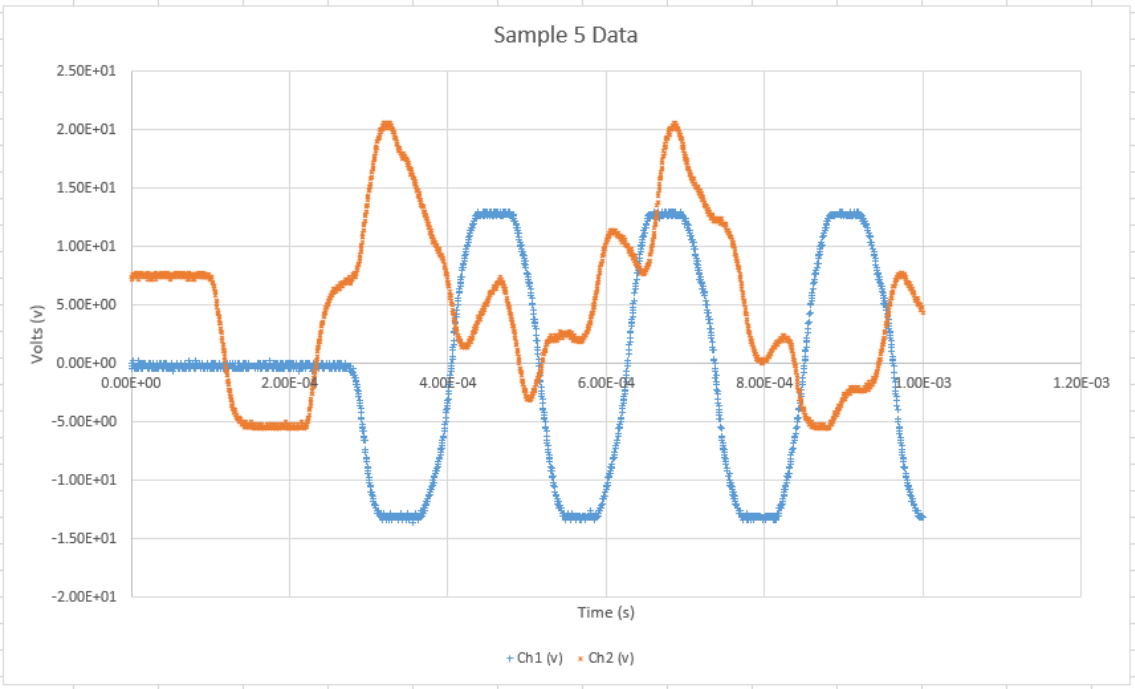

Figure 56: Sample 5 Data Plot

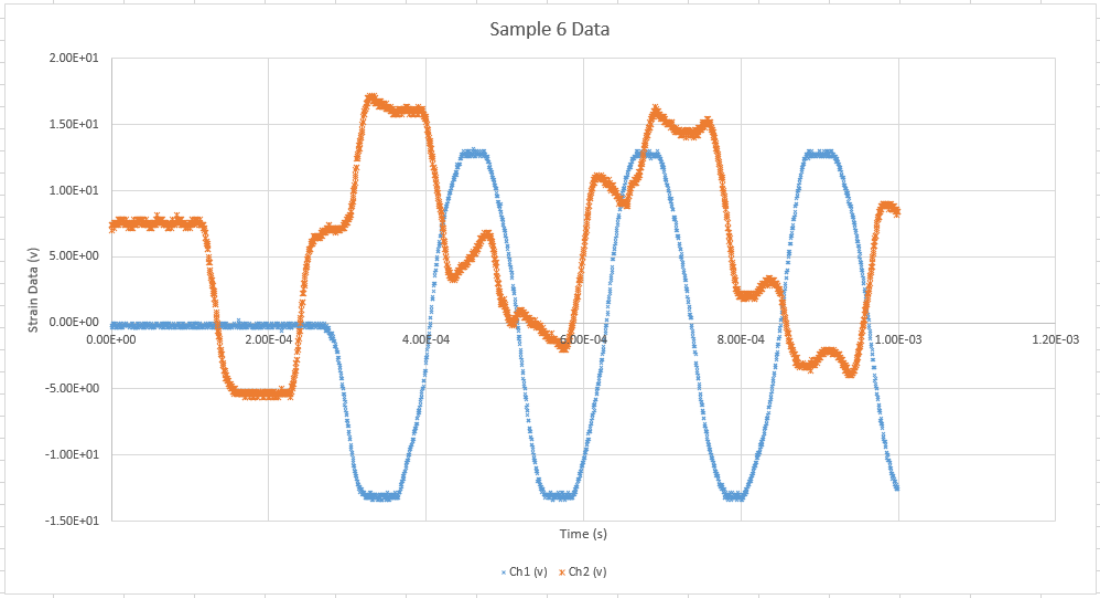

Figure 57: Sample 6 Data Plot

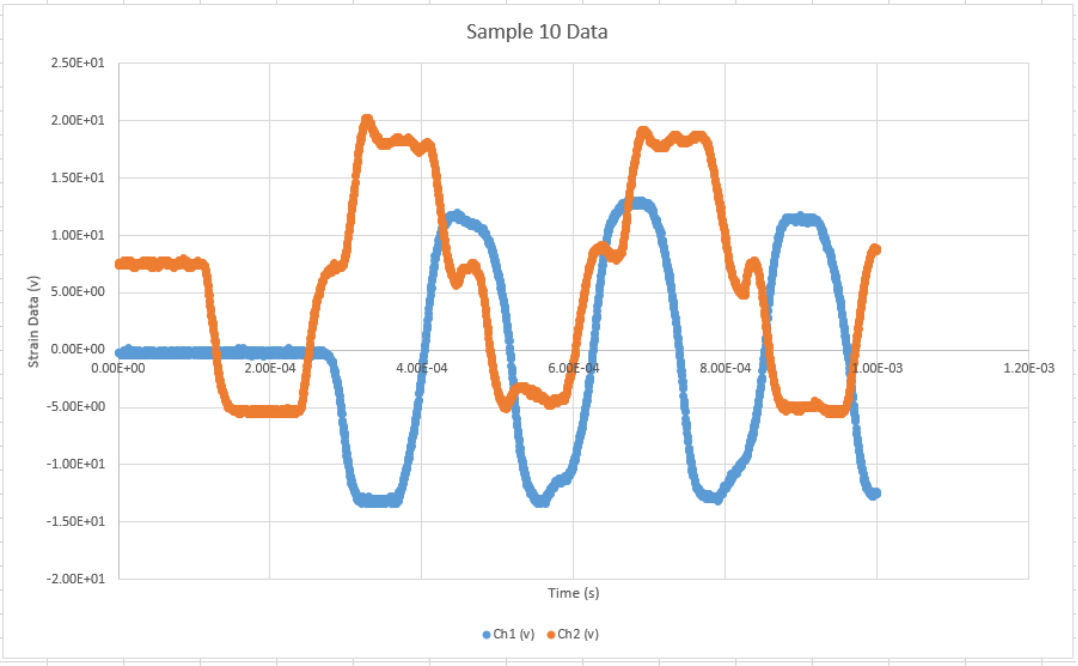

Figure 58: Sample 10 Data Plot

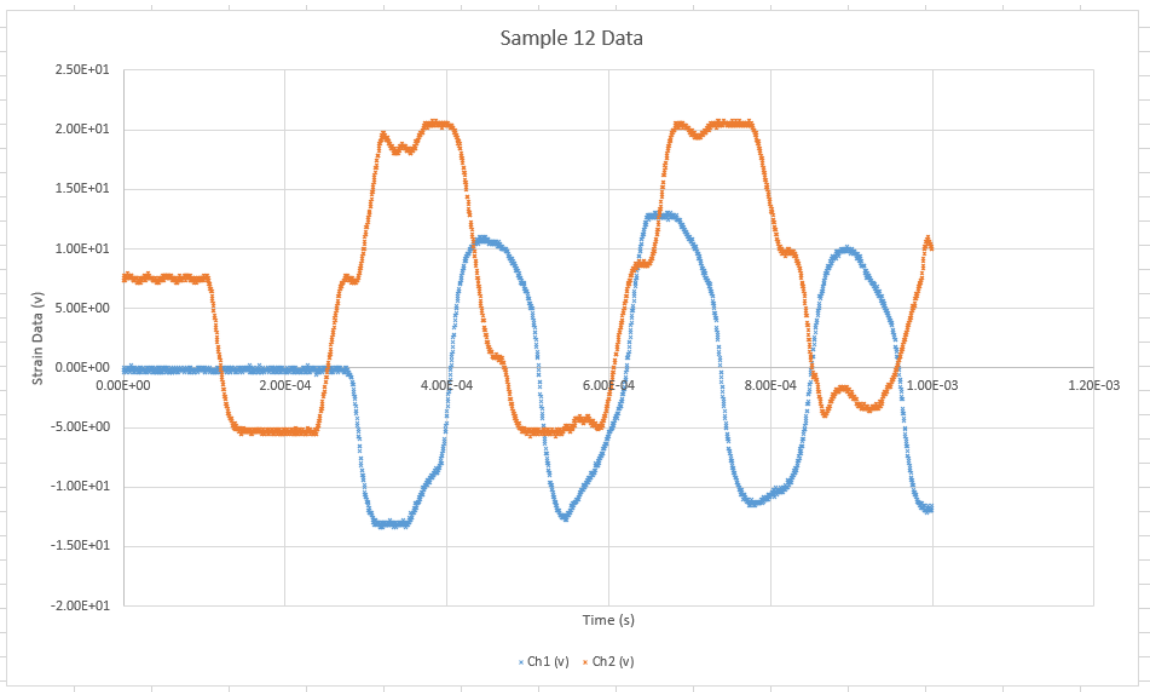

Figure 59: Sample 12 Data Plot

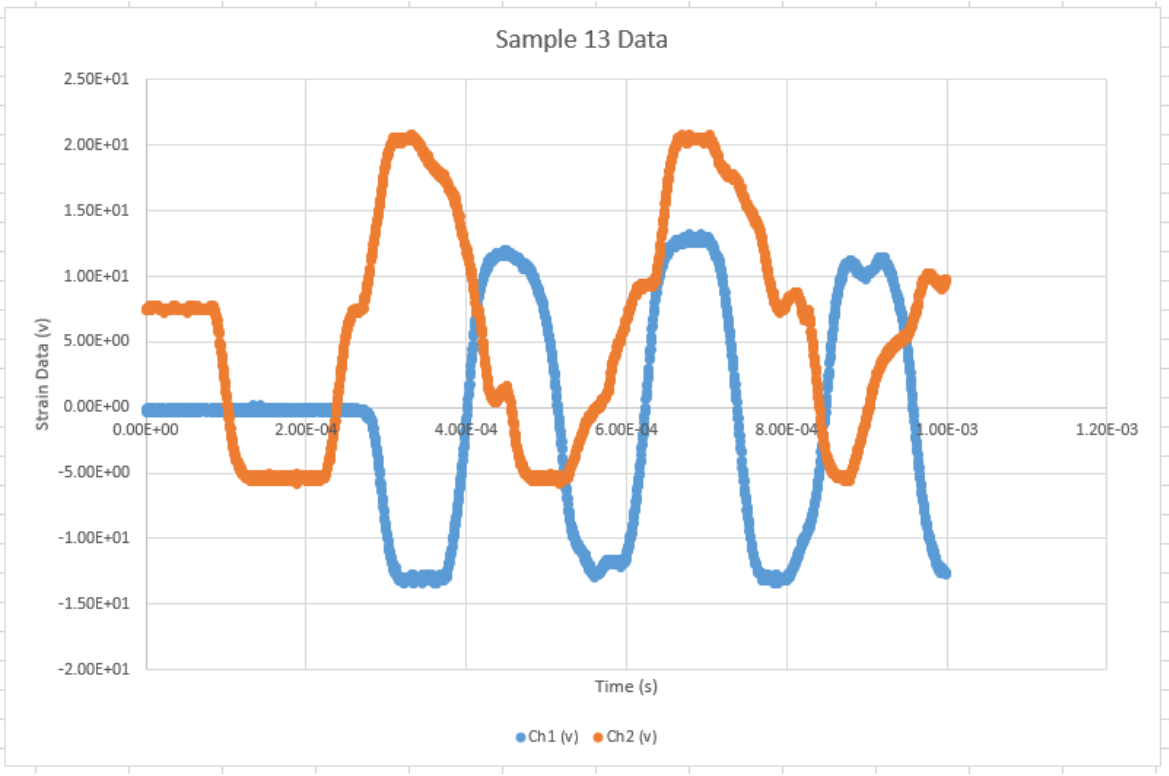

Figure 60: Sample 13 Data Plot

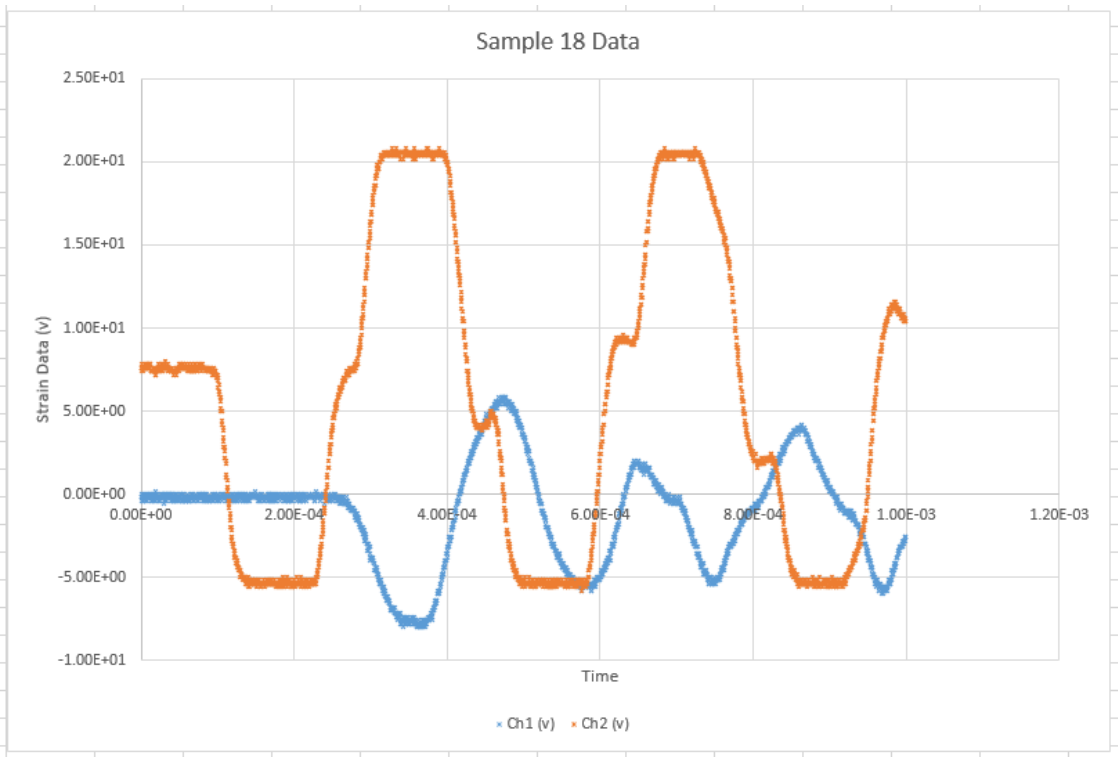

Figure 61: Sample 18 Data Plot

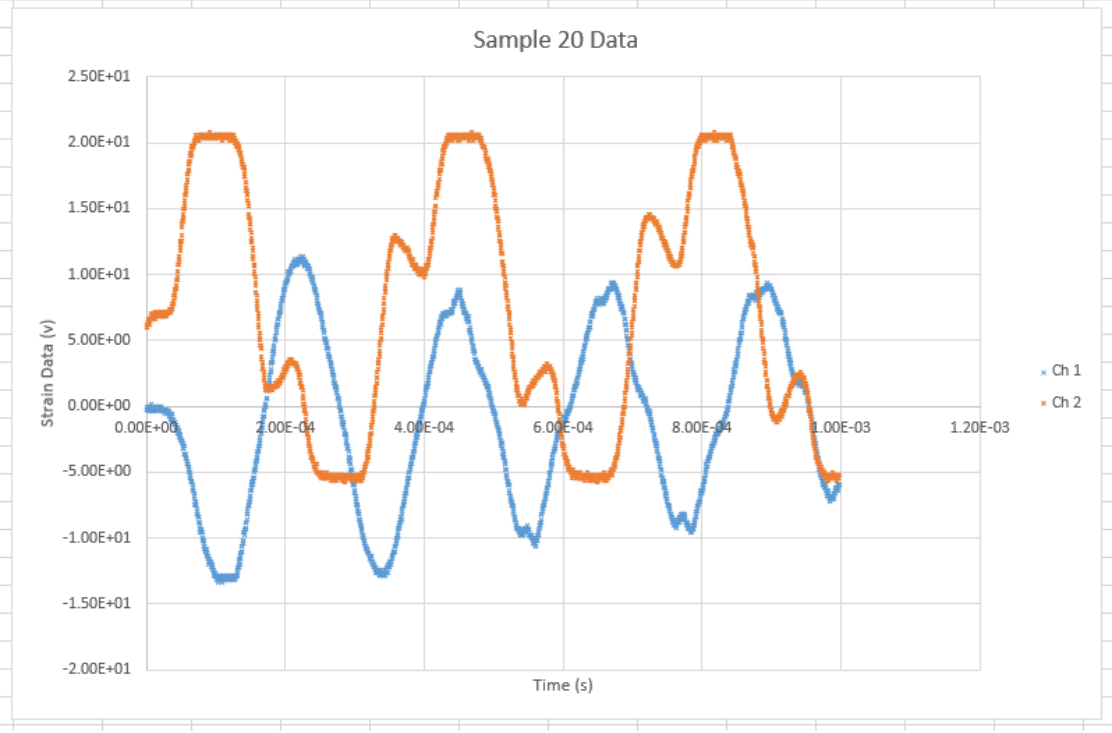

Figure 62: Sample 20 Data Plot

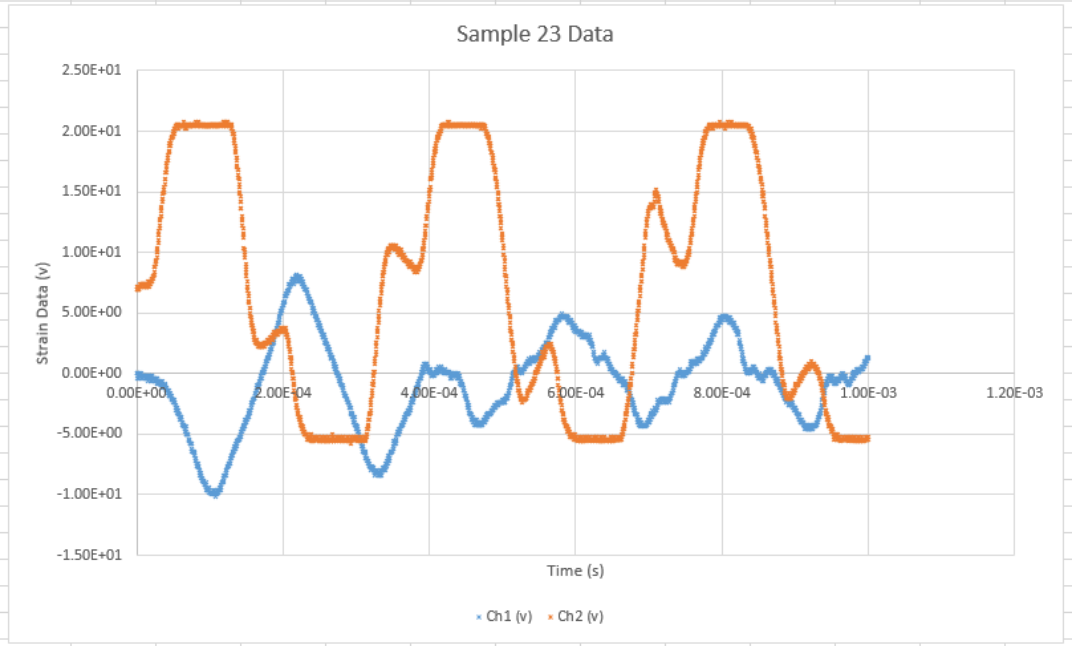

Figure 63: Sample 23 Data Plot

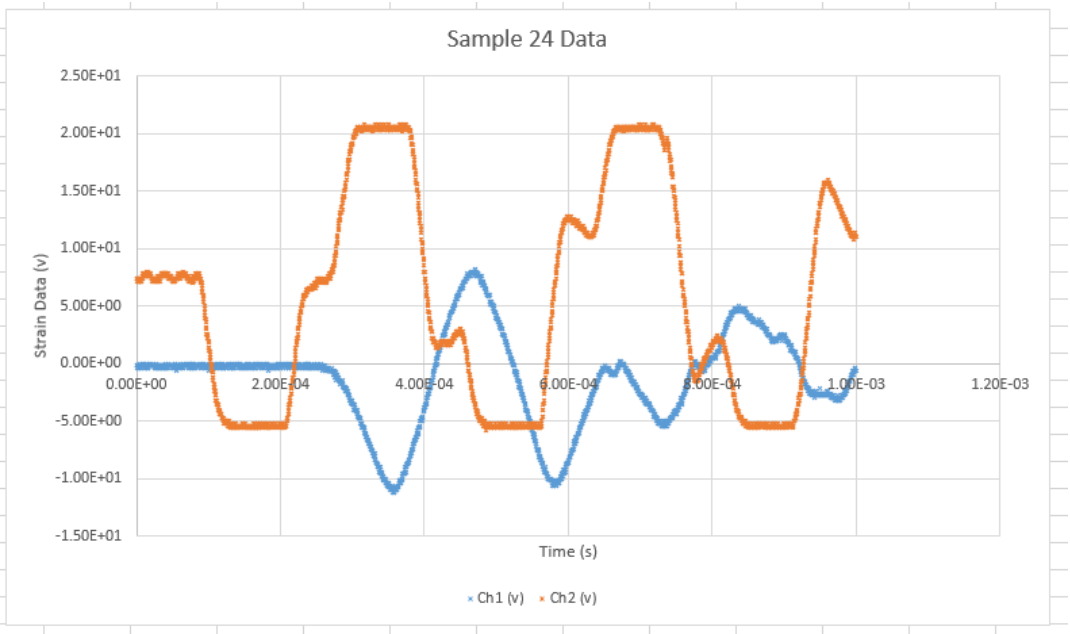

Figure 64: Sample 24 Data Plot

B. Stress Strain Curves

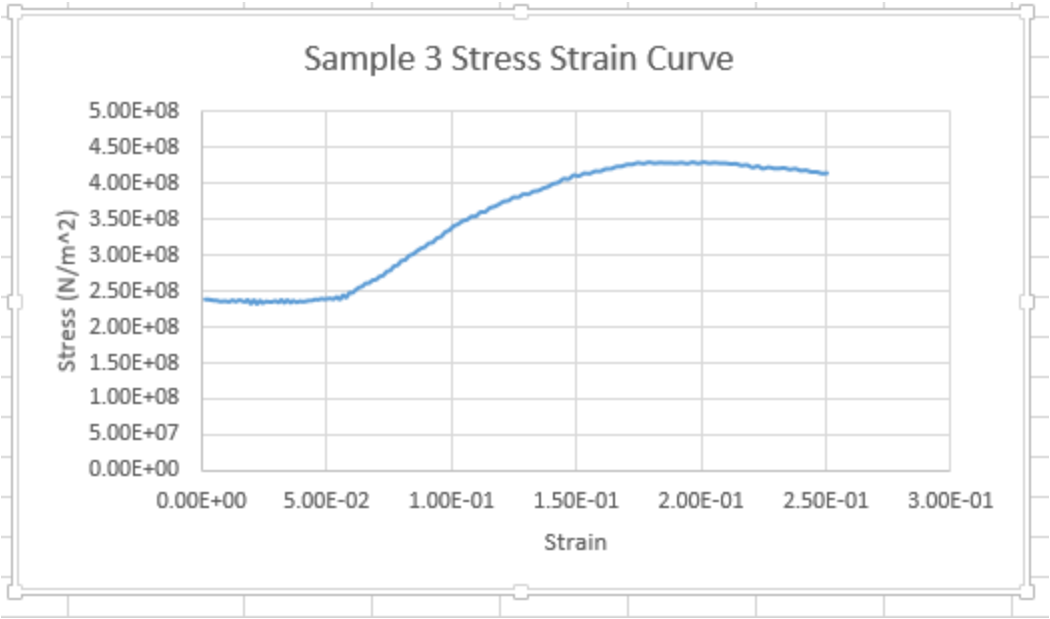

Figure 65: Sample 3 Stress Strain Curve

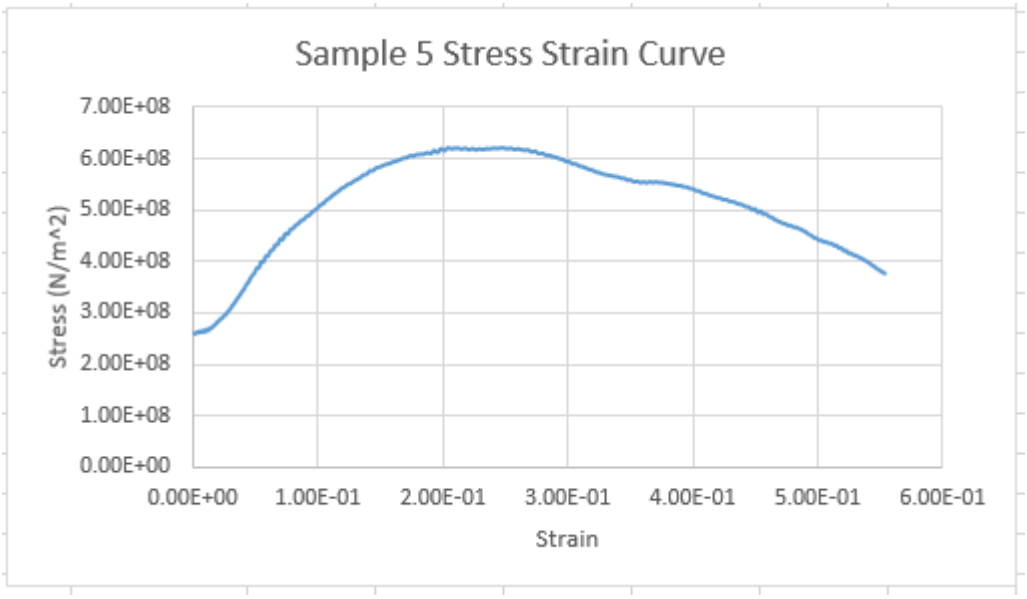

Figure 66: Sample 5 Stress Strain Curve

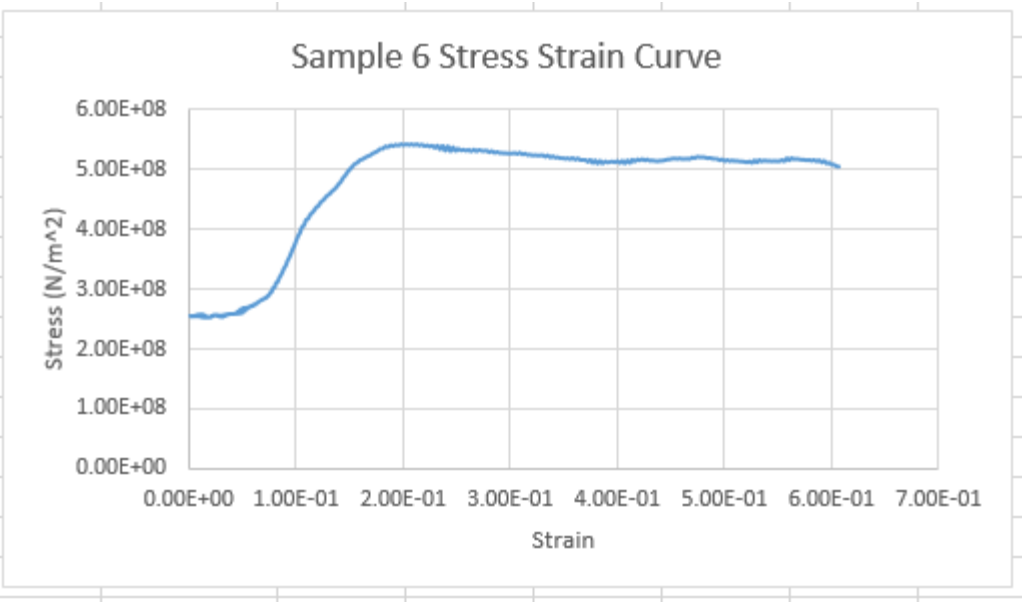

Figure 67: Sample 6 Stress Strain Curve

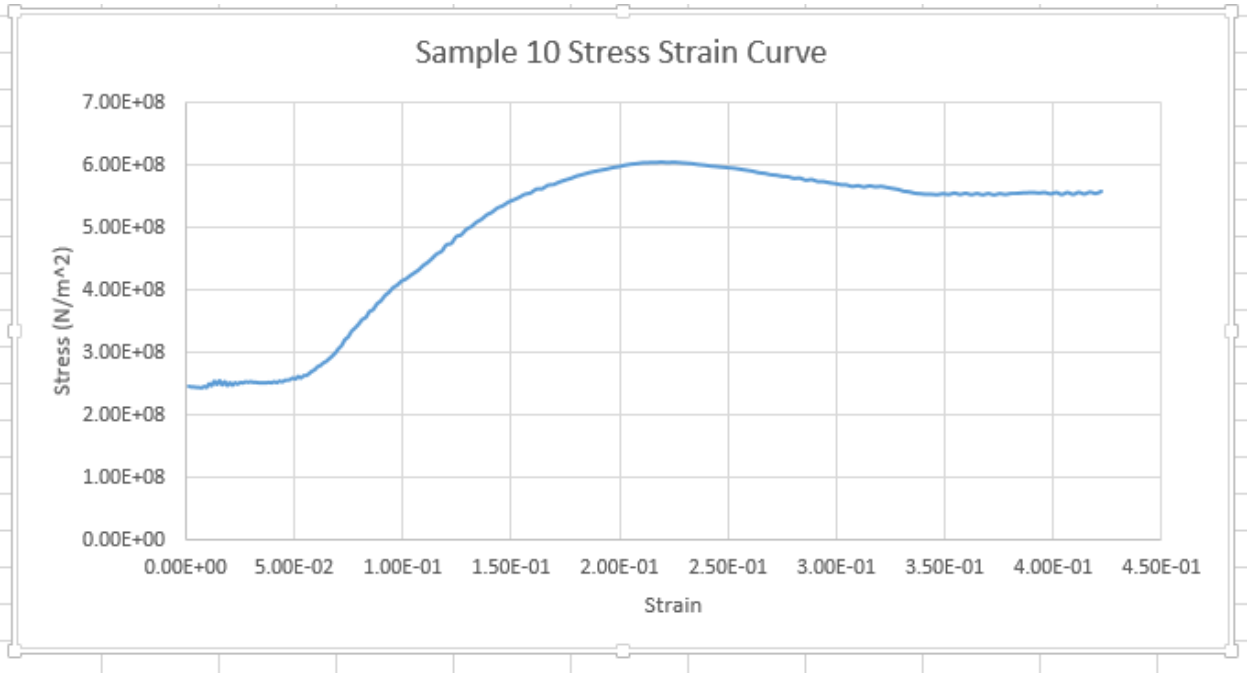

Figure 68: Sample 10 Stress Strain Curve

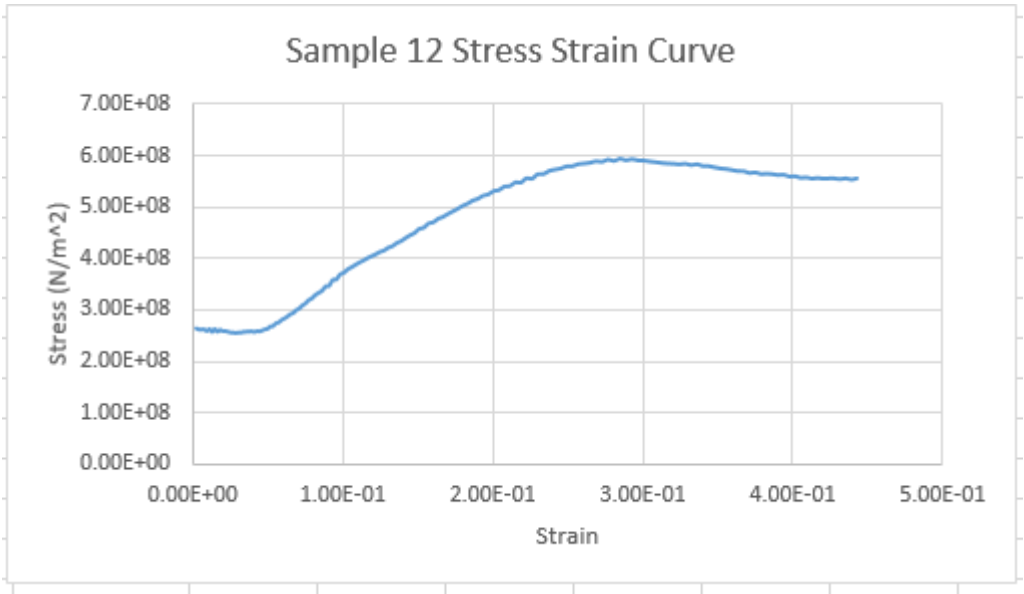

Figure 69: Sample 12 Stress Strain Curve

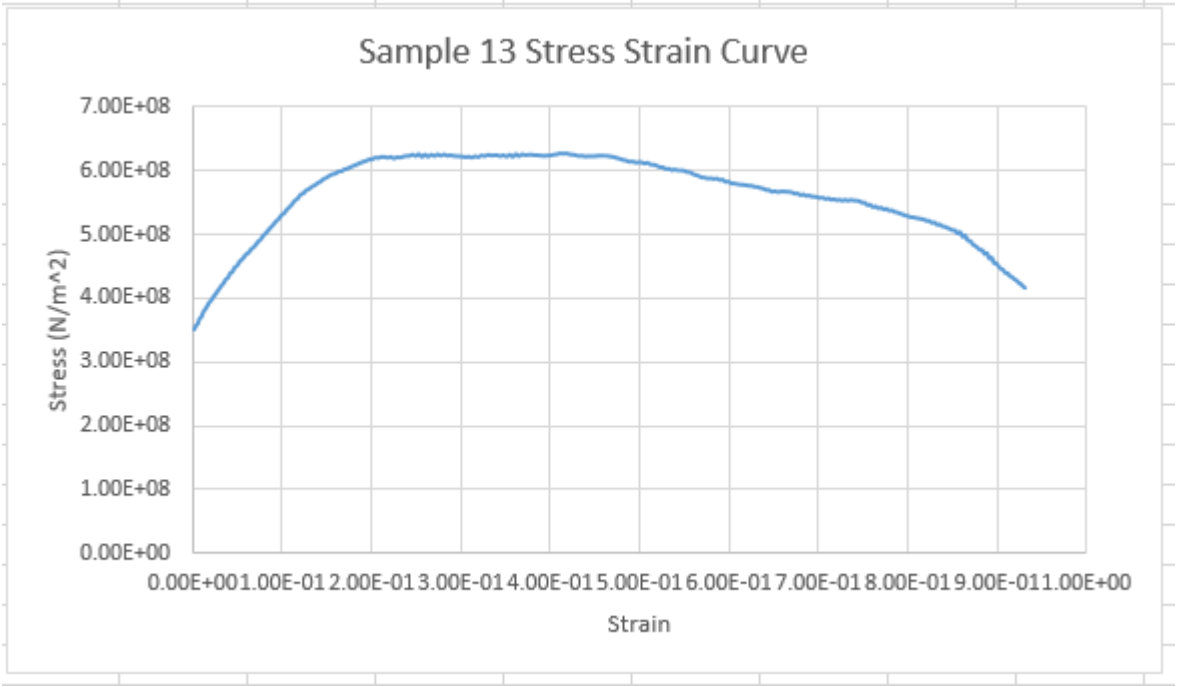

Figure 70: Sample 13 Stress Strain Curve

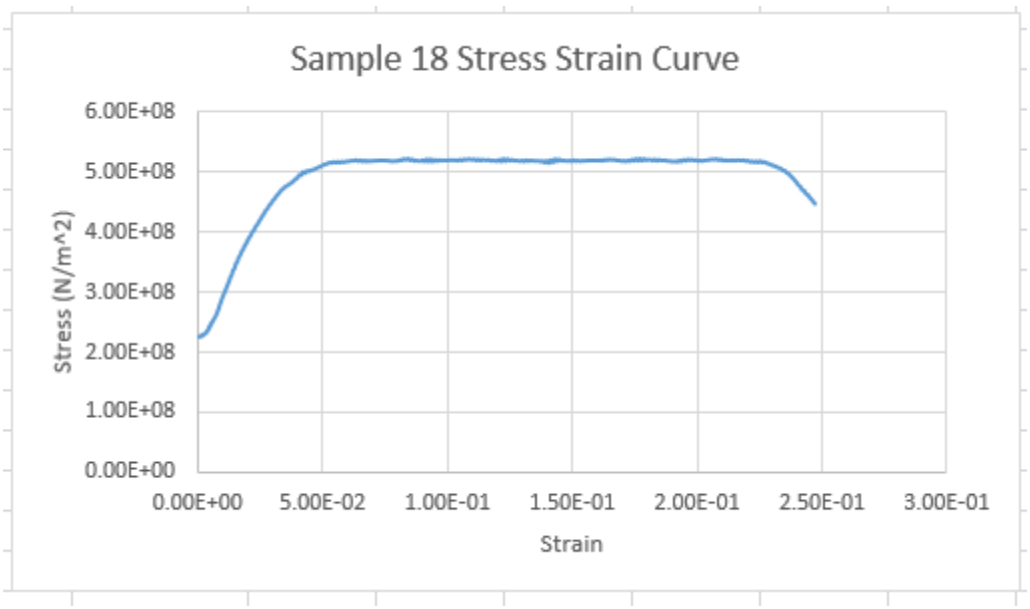

Figure 71: Sample 18 Stress Strain Curve

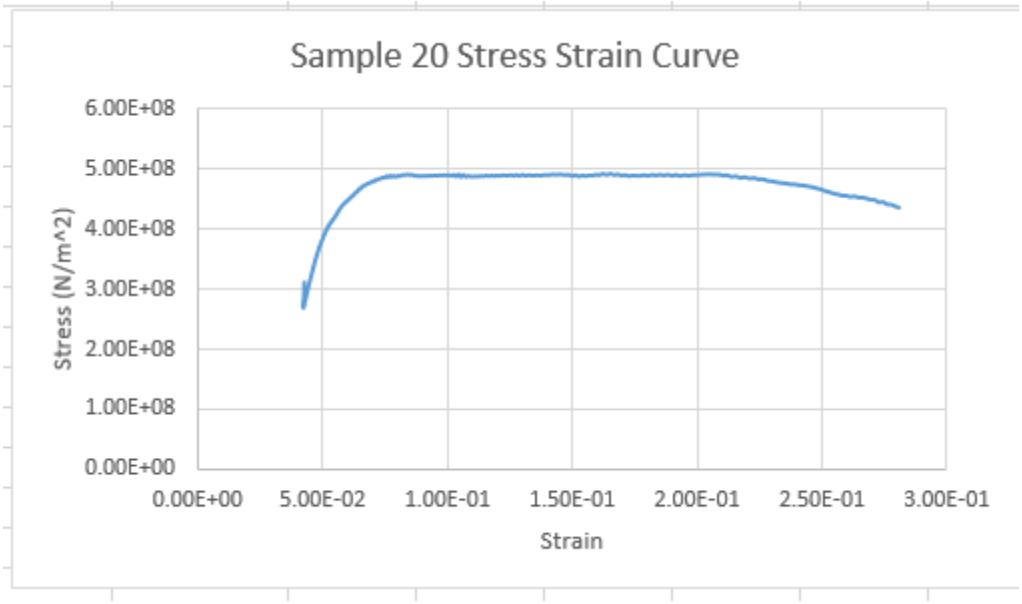

Figure 72: Sample 20 Stress Strain Curve

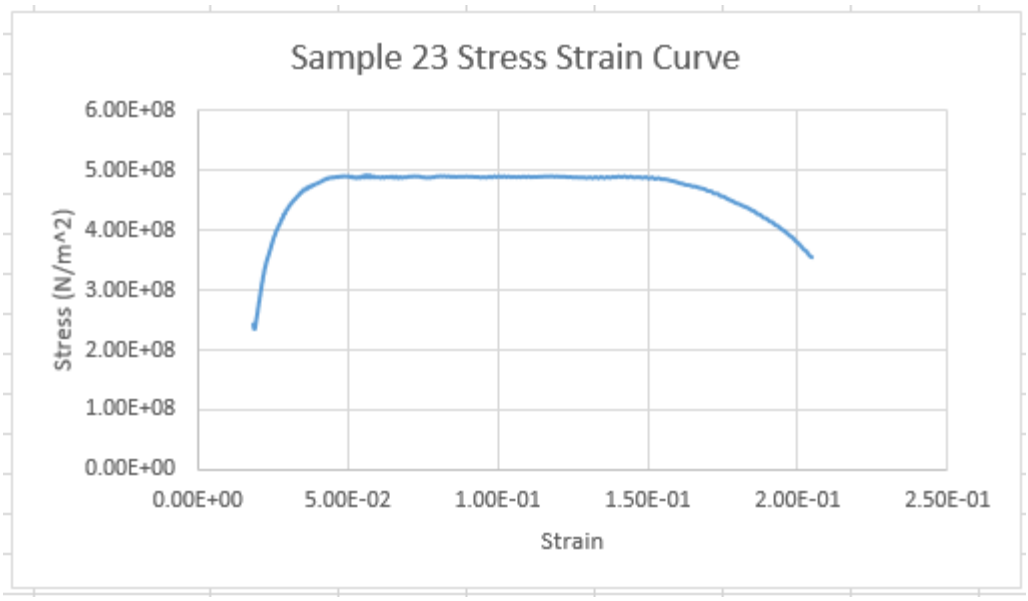

Figure 73: Sample 23 Stress Strain Curve

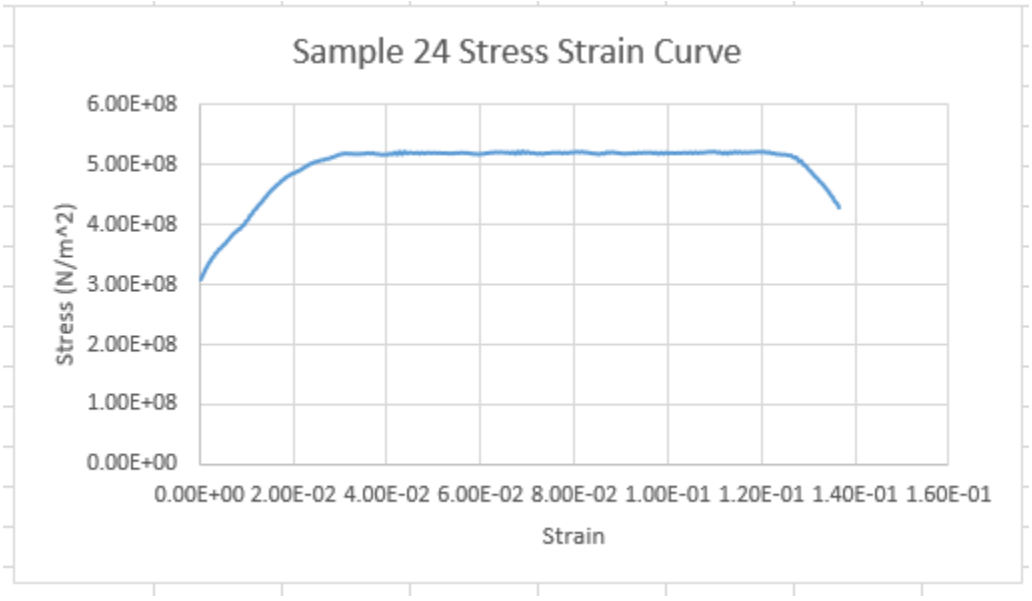

Figure 74: Sample 24 Stress Strain Curve

VIII. References

[1] EPO-TEK® Specialty Adhesives; Understanding Mechanical Properties of Epoxies For Modeling, Finite Element Analysis (FEA). (n.d.). Retrieved April 19, 2016, from http://www.epotek.com/site/files/Techtips/pdfs/tip19.pdf

[2] Gama, B. A., Lopatnikov, S. L., & Gillespie, J. W. (2004). Hopkinson bar experimental technique: A critical review. *Applied Mechanics Reviews Appl. Mech. Rev., 57*(4), 223-249. doi:10.1115/1.1704626

[3] Home Depot; PC Plumbing Epoxy. (n.d.). Retrieved April 19, 2016, from http://www.homedepot.com/s/100165318

[4] Isotropic. (n.d.). Retrieved April 19, 2016, from http://www.dictionary.com/browse/isotropic

[5] PC Epoxy by Protective Coating Company; PC-Plumbing. (n.d.). Retrieved April 19, 2016, from http://www.pcepoxy.com/our-products/putty-epoxies/pc-plumbing.php

[6] PC Epoxy by Protective Coating Company; PC-Plumbing MSDS. (n.d.). Retrieved April 19, 2016, from http://www.pcepoxy.com/documents/new-msds/SDSPCPLUMBING.pdf

[7] Weisstein, Eric W. "Wave Equation." From *MathWorld*--A Wolfram Web Resource. http://mathworld.wolfram.com/WaveEquation.html