PROCESS MONITORING OF RESISTANCE SPOT WELDING OF AUTOMOTIVE STEEL SHEETS

A Thesis Presented

By

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ABSTRACT

Resistance spot welding is frequently used welding method in a mass production like: electric industry, production of white goods and production of body assembly in automotive industry. Quality of a spot weld can be tested by both destructive and non-destructive methods. As most of these quality testing methods have only post-weld applicability and higher costs, a monitoring system that can detect the weld quality using the process data can be beneficial for cost reduction and quality improvement. Selected welding parameters often cause excessive input, that assure better reliability of full penetrating welds even in the case of deviations of sheet thickness, surface conditions and deviations of electrode tips due to heat and mechanical damage influences. Excessive energy inputs lead to excessive heating of welded material that can cause unwanted expulsions and electrode tips damages. It shows up that in such cases we get unwanted surface appearance of welded pieces at excessive energy consumption with negative environmental influence and more expensive process. This is way users want different sensors systems to monitor and control the welding process to attain optimal conditions. This thesis has been developed keeping in mind the monitoring of a spot welding system. For data acquisition different sensors have been applied, for the purpose of data acquisition. The process of data acquisition also uses the National instrument Labview software. Data acquired is then processed using matlab. A matlab script has been developed, which allows us to acquire graphs of various process parameters.

Keywords: resistance spot welding, Monitoring, Automotive steel, sensor, Data Acquisition.

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CHAPTER 1
RESISTENCE SPOT WELDING

1.1 Introduction

Welding is the process of joining two materials together permanently. In the resistance spot welding the materials to be joined are pressed between two electrodes, then for a small passage of time a large quantity of current passes through the electrodes thus fusing together the two materials. The fusion is the result of Joule heat generated because of the resistance of materials to be welded; this heat is mostly accumulated at the surface which melts the material. In order to assure the weld quality, the heat accumulation on the surface and heat input rate should be sufficient enough, depending on the material micro structure and the desired nugget size. But at times due to progressive degradation of the electrodes, varying surface condition of material, fit-up errors or other manufacturing problems this cannot be achieved, thus emergence of the need to control and monitor the welding process. Welding is a metallurgical process and it is difficult to get the information about the nugget formation and microstructure during the welding. That is why macro parameters like Temperature, Voltage, Current, Resistance, Force, Displacement, etc can be used to monitor and control the welding process.

1.2 Physical phenomena in resistance welding

The most important part of Resistance spot welding is the physical process of heat generation at the material surface. The material to be welded undergoes through five stages: mechanical deformation, heating, melting, fusion and solidification.

1.2.1 Joule effect

The amount of heat generated when current is passing through the work piece during RSW can be described by Joule's law, Equation 1

$$Q = I^2Rt$$

Q is the heat generated, I is the current passing through the work piece, R is the total resistance and t is the time the current is allowed to flow though the circuit.

1.3 Weld inspection and requirements

The inspection and evaluation of the weld quality is of critical importance. Whenever a new material or sheet thickness combination is being welded, it is very important to ensure that the process is qualified to generate a reliable weld according to relevant industry and process standards. Once the qualification is attained this process is used for general production.

1.3.1 Evaluation attributes

The weld quality is evaluated by its physical characteristics and performance. All the attributes of weld quality discussed in this chapter are evaluated according to American National Standard AWS D8.1M:2013 (Welding, 2013). The physical characteristics can be inspected by either destructive or non-destructive methods. The most common parameters evaluated after welding are: (Welding, 2013)

- Nugget size
- Edge weld
- Penetration
- Indentation
- Cracks (surface and internal)
- Porosity/voids
- Shear and Cross tension strength

Among these attributes the nugget size is the most frequently measured and used for qualified evaluations. The nugget size represents the weld size in terms of nugget width or diameter. An acceptable weld has a nugget width greater or equal to the minimum weld size shown in Table 1.

MINIMUM ACCEPTABLE WELD SIZE (a, b)	
Governing Metal Thickness (mm)	**Weld Size (mm)**
0.60-0.79	3.5
0.80-0.99	4.0
1.00-1.29	4.5
1.30-1.59	5.0
1.60-1.89	5.5
1.90-2.29	6.0
2.30-2.69	6.5
2.70-3.09	7.0
3.10-3.59	7.5
a: This table does not cover more than three thickness welding. b: This table applies whether determined by destructive or metallographic inspection	

Table 1: Minimum acceptable weld size (Welding, 2013)

An illustration of nugget width is shown in Figure 1.

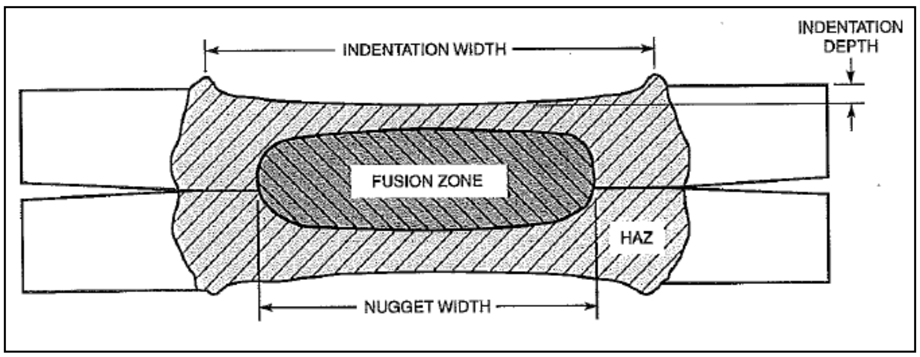


Figure 1: Example of measuring a crescent button (Welding, 2013)

In order to determine the weld size, average of the maximum and minimum dimension is taken; aforementioned dimensions may or may not be at 90 from each other. Welds with irregular shape can be measured as shown in Figure 2 and Figure 3. The aspect ratio cannot exceed 2 to 1. While measuring the nugget size, tail formed due to destructive tearing should not be included (Welding, 2013).

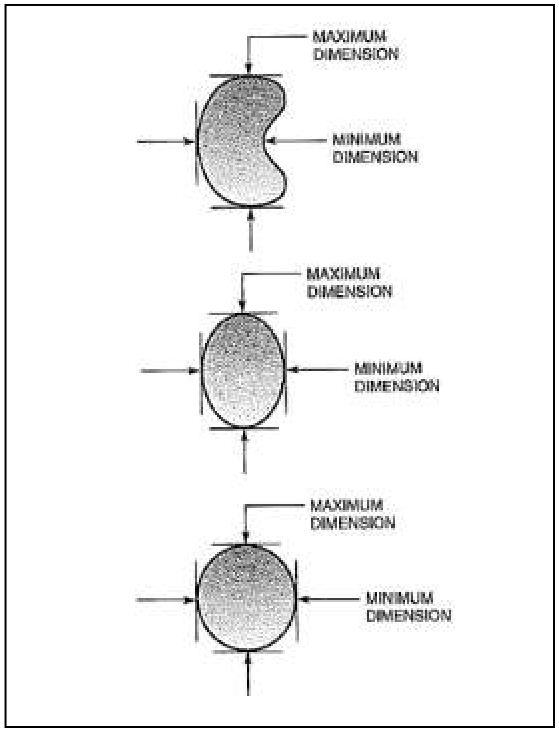


Figure 2: Measurement Method (Welding, 2013)

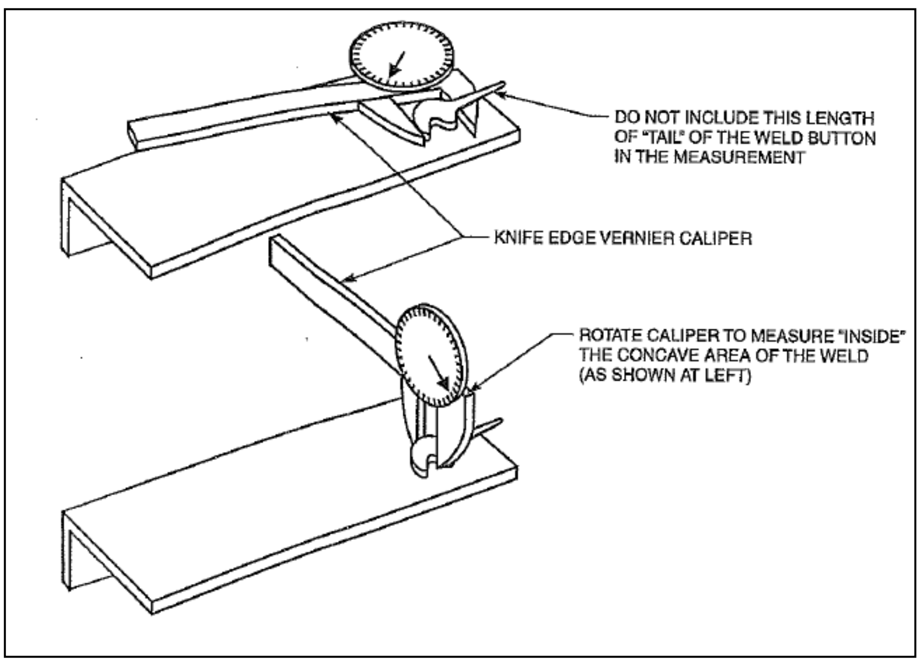


Figure 3: Attributes of a Spot Weld Measured from a Cross Section (Welding, 2013)

Penetration must be more than 20% thickness of both base sheets; full penetration is not desired and could result in some other discrepancies (Welding, 2013). An illustration of fusion zone and penetration is shown in Figure 4.

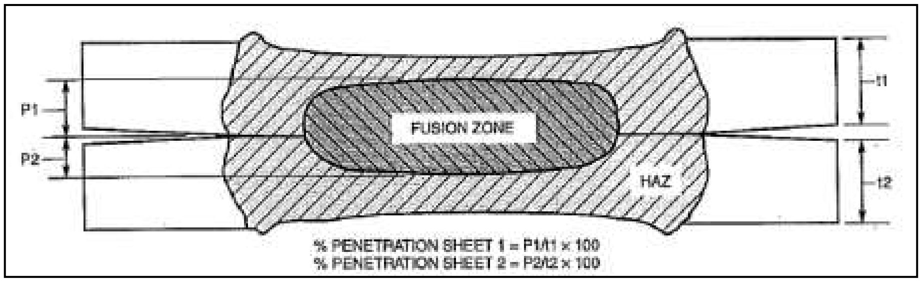


Figure 4: Penetration measurement (Welding, 2013)

Indentation due to electrode force should be less than 30% of the thickness of the sheets to be joined. Measurement method is illustrated in Figure 5.

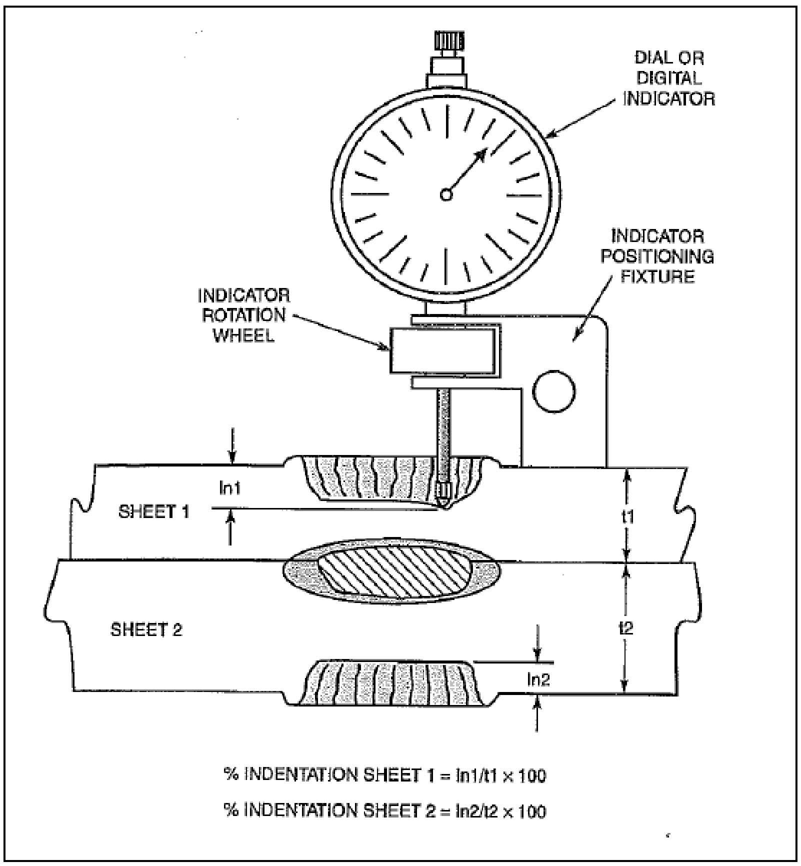


Figure 5: Indentation Measurement (Welding, 2013)

The acceptability of welding cracks when looked with naked eye depends on the position of crack and steels being welded. Acceptance criteria are shown in Figure 6.

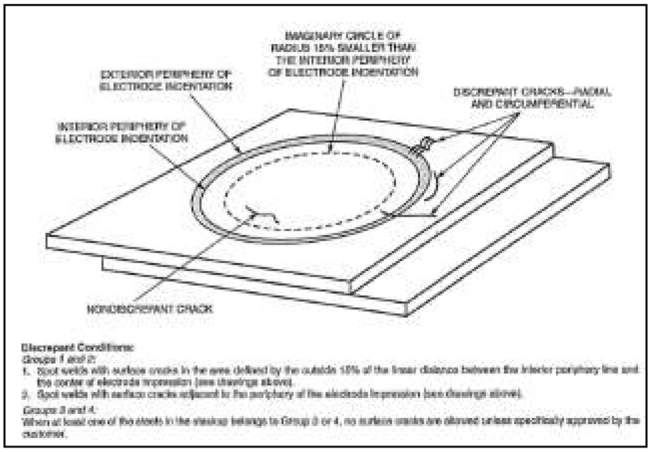


Figure 6: Surface Cracks (Welding, 2013)

When visualized with a magnification of 10X, the acceptance criteria is described in Figure 7.

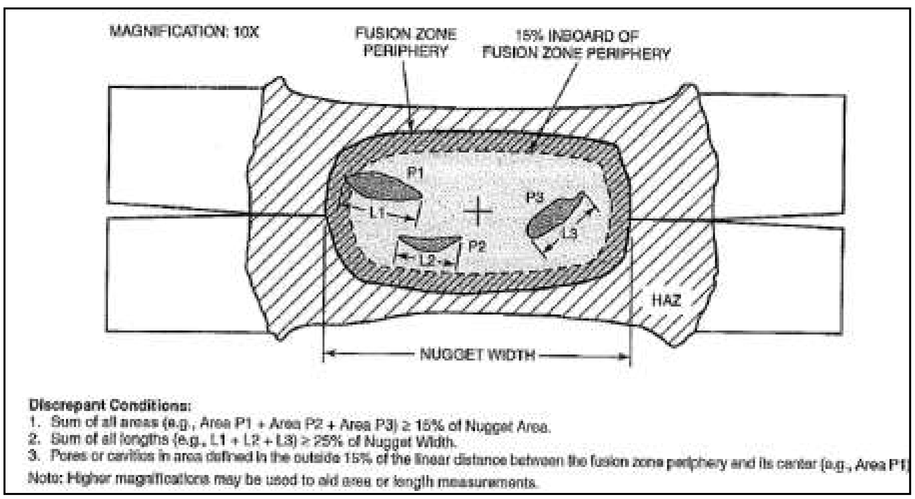


Figure 7: Examples of Discrepant Pores and Cavities (Welding, 2013)

Internal Cracks acceptance criteria, when visualized with 10 X magnification are explained in Figure 8.

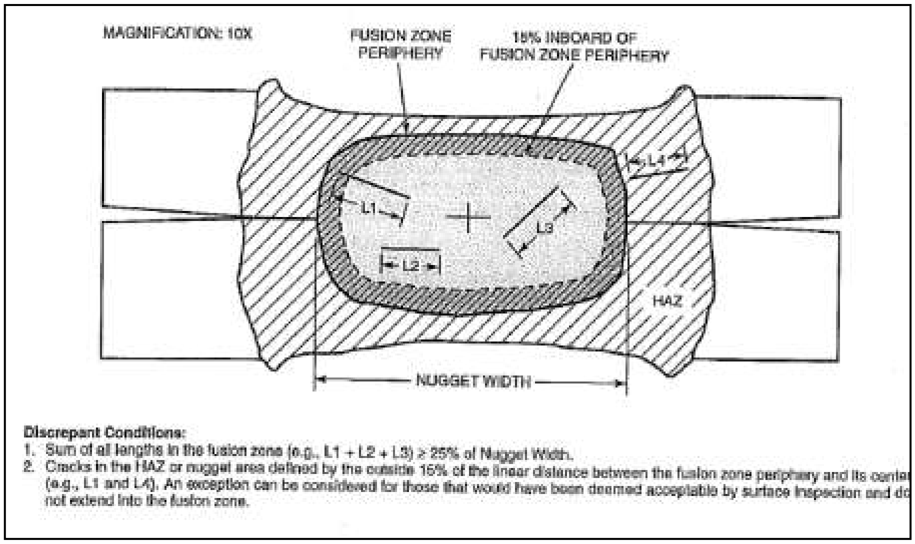


Figure 8: Example of Discrepant Internal Cracks (Welding, 2013)

A weld is discarded when visualizing the weld with naked eye, an opening contained inside the impression of electrodes found extending through the whole material thickness

In order to evaluate the quality of the weld, the mechanical properties to be considered are weld strength and weld energy. The strength of the weld is evaluated by the peak load achieved during shear or cross tension testing. Both of which are the measures of weld mechanical strength, minimum expected values of these, are calculated using Equation 2 and Equation 3 respectively (Welding, 2013):

<u>Equation 2:</u>

$$ST = \frac{(-6.36 \times 10^{-7} \times S^2 + 6.58 \times 10^{-4} \times S + 1.674) \times S \times 4 \times t^{1.5}}{1000}$$

Where

$ST = Shear\ Tension\ Strength\ (kN)$
$S\ \ = Base\ Metal\ Tensile\ Strength\ (MPa)$
$t\ \ = Material\ Thickness\ (mm)$

Equation 3:

$$CT = 1.25 \times t^{2.2}$$

Where

$CT = Cross\ Tension\ Strength\ (kN)$
$t\ = Material\ Thickness\ (mm)$

A shear tension test is performed on a tensile testing machine, by pulling the lap-joined specimen. The test is performed according to (AWS D8.9M, 2010), also the tests performed during this thesis were performed according to the standard mentioned above. The results of which are mentioned in chapter 3 and in appendix 1. From these results the values of peak load, displacement up-to the peak load, energy defined by the area under the load-displacement curve up to the peak load can be extracted and the value of shear strength can be evaluated according to equation 2.
The cross tension test is performed on a tensile testing machine by applying a quasi-static force by pulling two coupons that have been spot welded together perpendicular to each other. The procedure is documented in (AWS D8.9M, 2010). From the tests performed the peak value of load, displacement up to the peak load, energy defined by the area under the load-displacement curve up to the peak load and fracture mode can be evaluated.

CHAPTER 2

RSW PARAMETERS AND THEIR MONITORING

2.1 INTRODUCTION

The process of resistance spot welding is controlled by different parameters. These parameters along with the physical phenomenon and the material to be welded, determine the quality of welds performed.
The vital problems in resistance spot welding (RSW) quality evaluation are related to the complexity of the basic welding processes and their complicated interactions. Apart from them, variations in material composition and surface coating, process conditions such as electrode wear, machine compliance, water cooling rate, and work-piece fit-up, also influence the RSW monitoring. Electric current, voltage, force, displacement, and dynamic resistance signals are the most used in a monitoring and control system. However, some difficulties are encountered in obtaining these signals because of the strong magnetic interference of the process, especially when alternating current is used in welding. The monitoring and control of a resistance welding process are very closely related to the quality definition of welds.

2.2 PROCESS MONITORING METHODS

2.2.1 Process Monitoring Using Infrared Thermography

In this method of monitoring resistance spot welding process infrared radiometer is used for process monitoring. As the isotherm radiated at the electrode/base material surface contains important information that can be used in the detection of the weld nugget and its quality. Weld nugget measurement and tensile shear tests results show good correlation between isotherm geometry, weld joint strength, and weld nugget size (Brown, 1986).

2.2.2 Process Monitoring Using Multi-Sensor Technology

As mostly systems of process monitoring use current, voltage and electrode force to give an indication of weld quality; however these systems fail to provide any warning regarding the changes in the weld environment. These changes could include material variability or electrode condition, which could result in low quality weld. To solve this problem a system that utilizes an array of sensors, including current, voltage, infrared and ultrasonic is applied (J.D. Cullen, 2011).

2.2.3 Acoustic Emission Measurement

When there is a deformation or cracking by force on a metal, deformation energy in the form of elastic wave is generated. If this energy is big enough it emits an audible sound. Also in resistance welding during the nugget formation and metallurgic transformation a sound wave is generated. For different welding quality, the sound wave is different, which is the principle of monitoring welding process by using structure-borne acoustic emission signals (S. I. Rocklin and L. Adler, 1985) (Z. Luo, 2004) (Y. luo, 2013) (H.-T. Lee, 2003).

2.2.4 By Monitoring Dynamic Resistance Signatures

Since the flow of current is at the heart of a spot welding process, many researchers believe that dynamic weld resistance can serve as a valuable indicator of the quality and consistency of the underlying welding process. In view of this, a number of researchers have attempted to develop reliable techniques for estimation of the dynamic resistance profiles. (D.Watney, 1983) (S.A.Gedeon, 1987), (K.Asokkumar, 1997), (C.K.Datta, 1996) (Frank Garza, 2001)

2.2.5 Process Monitoring by Symbolic Regression

A method is used for modeling the observable process dynamics. This can be modeled by parametric functions which can either be determined solely by expert knowledge and Nonlinear Curve Fitting using an additional correction term that is found via Symbolic Regression. The obtained model parameters characterize the process dynamics and can be used to detect abnormal process behavior in order to adapt the process parameters by a control unit (Ingo Schwab, 2012).

2.3 OBJECTIVES OF PROCESS MONITORING

1. ***Weld size estimation:*** The nugget width or button diameter is the most commonly used quality index, as it is directly related to the strength of a joint

when there is no expulsion. Because of dependence of the RSW process on various parameters, a weld's nugget size is determined by many factors, and much of this dependence is not fully understood. An ideal monitoring system should be able to provide an accurate on-line estimation of a nugget size based on the signals obtained from process monitoring.

2. ***Detection of expulsion and evaluation of its severity:*** As it adversely influences weld quality, thus inducing many unfavorable features to it. Therefore, a robust monitoring system should be able to detect when expulsion occurs and its severity, so that when deemed necessary, required corrective actions can be implemented.
3. ***Process fault diagnosis:*** Discrepant welds (undersized welds, stick welds, and welds with discontinuities or expulsions) are often resulted because of sub-standard process conditions. The study of process faults is of critical importance, as it is the first step to link laboratory-developed monitoring and control algorithms to real-life production.
4. ***Process control:*** Effective control algorithms can be developed based on the data obtained from process monitoring.

2.4 PARAMETERS MONITORED DURING RSW

As welding voltage and current are directly related to Joule Heating, so intuitively they should be monitored as these directly influence the formation of weld nugget. As the phenomenon of expansion or shrinkage of sheet metal stack-up reflects the thermal process during resistance spot welding, it is beneficial to monitor them; these changes can be measured and controlled by monitoring the changes in electrode displacement and electrode force. The voltage, current, electrode force, and displacement are each discussed in detail in this section.

2.4.1 WELD CURRENT

As evident from equation 1, current I, is the principal parameter, which influences the heat generated during the welding process, as it is squared. It plays the vital role in weld quality, if it is too low, it will not generate the required heat, thus forming the weld nugget which is smaller than required. On the other hand, too high current can create problems like expulsion and electrode damage both of which negatively affect weld quality, and can also be hazardous for surrounding environment and personnel involved.

2.4.1.1 MONITORING OF WELD CURRENT

In the secondary circuit the magnitude of electric current is very high, because of this reason current is measured indirectly, it is normally measured either by using a sensor based on the Hall effect or a toroidal helical sensor. Both are based on the voltage induced by a welding current. A high alternating or high frequency current induces a strong time-varying magnetic field. Any wire loops present in this field will get the induced voltage, the magnitude of which is given by Faraday's law:

$$V = \frac{d\,I}{dt} A cos\theta$$

Where

V = Induced Voltage

I = Induced Current

$\frac{d\,I}{dt}$ = Rate of change of current

A = $Area\ of\ the\ loop$

θ = $Angle\ of\ loop\ to\ the\ magnetic\ field$

A toroidal helical sensor measures the current on the basis of Faraday's law. Other than this current can be measured either by using a Hall affect sensor or a resistive shunt. The voltage induced by the magnetic fields, is measured across a semiconductor placed inside the field. These sensors are small in size and are sensitive to temperature change, and to the variations in orientation and position. The induced voltage is measured across a known resistance in the resistive shunt method; it is the standard mode of measuring low magnitude current and direct current. For the application resistive shunt method in resistance spot welding, modifications in electrodes shape is required.

2.4.1.2 Rogowski Coil

Rogowski coil was proposed in 1912 (Yi Li, 2012), by a German physician Walter Rogowski (M. H. Samimi, 2015). It can measure, both high-speed impulse current and alternating current, on the basis of Ampere's and Faraday's law (M. H. Samimi, 2015). Thanks to microprocessor based technology and modern signal processing techniques, Rogowski coil sensors have become suitable for various applications (C. C. Yii, 2017). Due to its non-magnetic core there is no saturation, and it can measure large currents ranging from a few milliamperes to 1 mega ampere. It is compact and light weight.

The Rogowski coil is consisted of a wire wounded around a non-magnetic core. In order to measure the current the coil is placed inside the magnetic field generated by the current flowing through the conductor (Hofer-Noser, 2000). This field is converted into a signal according to Faraday's induction law; this signal is proportional to the current or rate of change current flowing through the conductor (Hofer-Noser, 2000). Rogowski coil consists of helical coil of wires, which has both terminals of wire at the same end of coil. The Rogowski coil is connected with integrator circuit. A basic illustration of Rogowski coil can be seen in Figure 9.

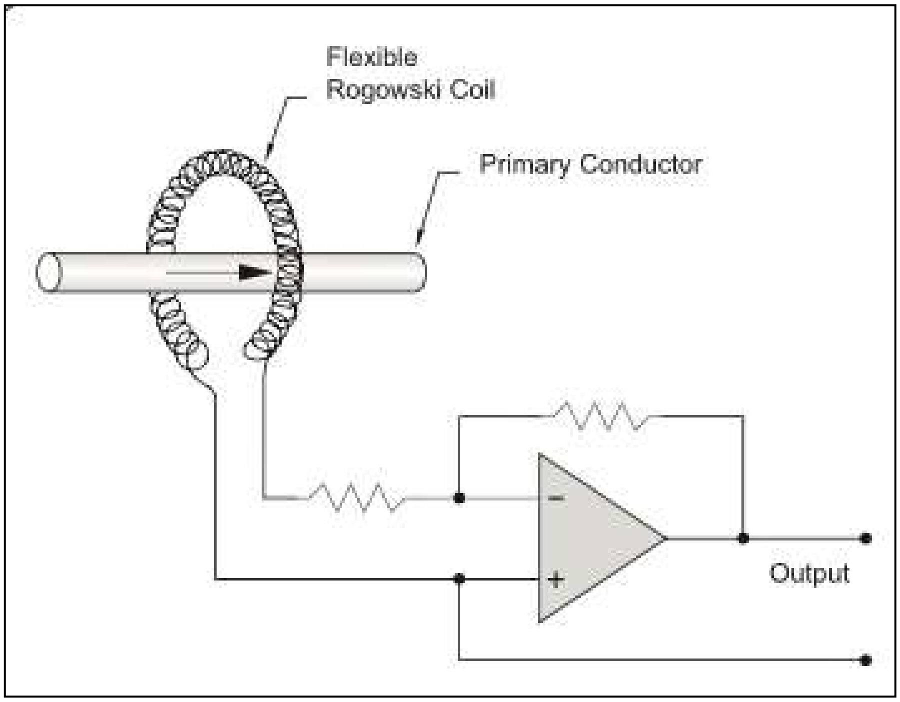


Figure 9: A Simple illustration of Rogowski Coil

2.4.2 Electric Voltage

As the voltage is kept at a fairly low level at the electrode tips, its value can be measured directly, by using standard equipment. This voltage is influenced by the noise induced by current; to reduce this noise, twist pairs can be used to reduce the area of wire loop, the two wire leads follow the arms and cover the entire throat of welding machine and also a compensating loop can be added to suppress the noise.

2.4.3 WELD TIME

Weld time, t, is the duration for which the current I passes through the electrodes. As evident from equation 1, weld time t is also one of the parameters that directly influence the heat generated thus the quality of the weld. Current is measured in both milliseconds and cycles, depending on the current regulator being used. For alternate current AC cycles are used and for direct current DC milliseconds is used, the later has been brought to use fairly recently with the arrival of medium frequency direct current MFDC technology.

In automotive industry to reduce the weld cost, there is an incentive to keep the weld time as low as possible, so it is common to regulate the weld current instead of weld time to obtain the required results.

2.4.4 Electrode Displacement

The relative motion of electrode tips is called electrode displacement and it reflects the thermal process occurring during welding. The displacement sensors are mounted as close as possible to the electrodes, in order to avoid the influence of other components of welder. To measure electrode displacement normally linear variable differential transducer (LVDT) sensors and fiber-optic sensors are used.

2.4.5 ELECTRODE FORCE

Electrode force presses the sheets together and provides the required connection during the welding process and it directly influences the weld quality. A high magnitude of electrode force during the welding process will lower the contact resistance between the sheets, thus decreasing the heat generated during the process thus affecting the weld quality and weld nugget size. Too high electrode force may also deform the material to be welded. On the other hand if electrode force is too small it increases the risk of excessive heat formation and expulsion.

2.4.5.1 MONITORING ELECTRODE FORCE

Strain gauge-based sensors and piezoelectric sensors are commonly used to measure electrode force. As the force measurement is influenced by the noise generated by induced voltage, as the sensor set up has wire loops in magnetic field that cannot be avoided, to nullify this noise twist pairs can be used as it may help in reducing the wire loop area.

2.4.6 ELECTRODE GEOMETRY

The shape and size of electrode affects the contact area, which in turn changes the contact pressure and the current density in the sheets. A general guideline is that the diameter of the electrode tip should be approximately $5\sqrt{t}$, where t is the thickness of the thickest sheet. Specific geometries of various electrodes are described in detail in the international ISO standard (ISO 5821:2009, 2009).

It is beneficial for the weld quality if different electrodes are used on each side depending on the stack-up of the sheets. A smaller electrode can increase the current density, thus providing higher heat generation while a larger electrode can increase the contact resistance over the interface by distributing the force over a larger area and thus obtaining lower pressure. Different types of electrodes can be seen in Figure 10.

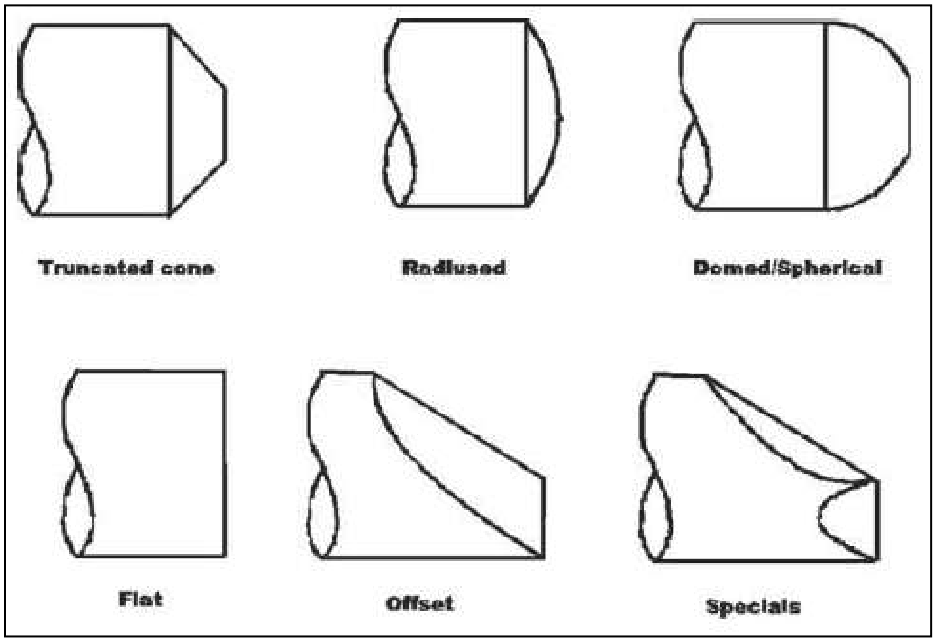


Figure 10: Different electrode geometries (Senkara, 2012)

2.4.7 ELECTRODE MATERIAL

Electrodes are one of the most important components in a spot weld machine, and provide two important functions of holding the sheets together and to conduct the electric current. Most important properties are thermal and electrical conductivity, compressive strength and hardness. It is important to find the balance between afore mentioned material characteristics while selecting the electrodes. As copper and copper based alloys provide high electric and thermal conductivity, for this reason most electrodes are made from them. The electrode materials are described in the international standard (ISO 5821:2009, 2009).

2.4.8 ELECTRODE DEGRADATION

The contact between the electrode and sheet effects several factors such as current density, contact resistance and electrode pressure. So the condition of the electrode tip affects significantly the weld result. Following are the mechanisms that contribute the most in degradation of electrode tip (M. Kondo, 2010).

- Softening of the electrode contact area

- Pitting and deformation of the contact area
- Alloy formation
- Re-crystallization

Continuous and repeated temperature changes can lead to softening of electrode tip and increase the electrode deformation. As a result it can lead to an enlarged contact area and lower current density. Pitting of the electrode area refers to a phenomenon where irregularities and cavities form on the tip of the electrode. This reduces the contact area and creates localized spots with high heat generation, which can further lead to premature expulsion. When welding coated steels such as galvanized- and aluminized steels the coating can interact with the electrode tip and accumulate oxide layers on it. This accumulation of oxides will increase the resistance between the tip and sheet, thus increasing the temperature, which results in further degradation of the electrodes and increased risk for expulsion. Re-crystallization is the formation of new grains formed by increased temperature as the material has been deformed. This results in lowered hardness of the electrode tip. Electrode dressing is a specialized technique used to clean the electrodes between welding. A standardized tool is used which cuts away the upmost layer of material from the electrode tip as well as any oxides or alloy formation. The frequency of electrode dressing in production can be modified depending on the type of material being welded and on the welding parameters. Coated steels have the tendency to form oxide layers on top of the electrodes, thus typically requiring more frequent electrode dressing as oxides accumulation degrades the electrodes faster, and also require relatively higher currents and longer weld times to ensure optimum weld quality.

CHAPTER 3

DATA ACQUISITION AND ANALYSIS

3.1 INTRODUCTION

The first step in monitoring of Resistance spot welding process is collection of process information. The data acquired is related to the electrode tip voltage, electrode force, welding current and electrode displacement as evident from Figure 11. In order to capture the signals directly related to welding process, transducers are usually mounted on a weld gun. The voltage is measured between the electrode tips. A toroidal helical sensor can be used to measure the induced voltage, while the magnitude of weld current is measured by integrating the toroid voltage. A strain gauge based force sensor is installed near an electrode. In order to scale the signals to the desired scale level for the analog-to-digital converter board in the computer, the signal conditioning box is used to provide excitation to some sensors. Then the data is acquired by using National instrument's Labview software. All the data is then extracted from the software in form of a text file. Then with the help of matlab all the important signals have been analyzed.

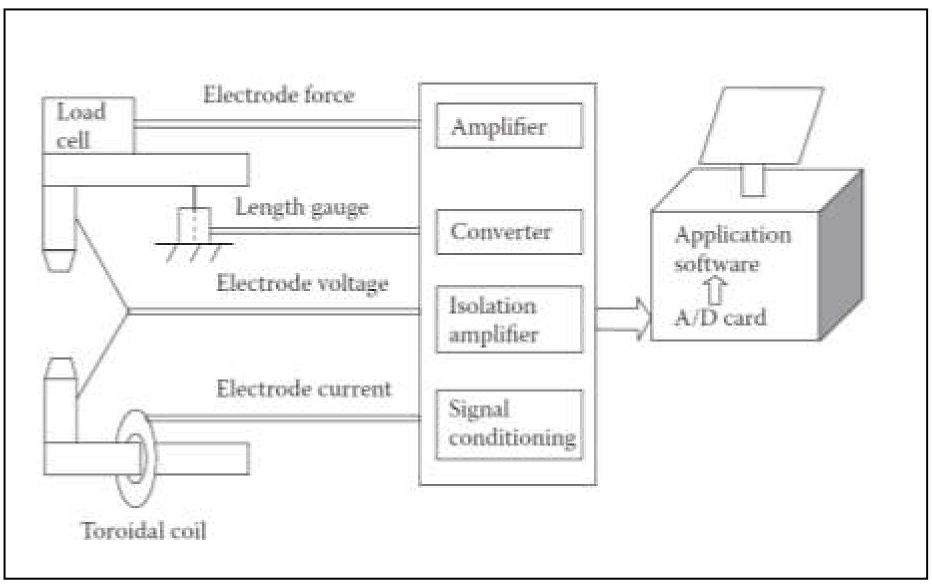


Figure 11: A Simple Data Acquisition System for RSW (Senkara, 2012)

3.2 DATA ANALYSIS

Data acquired from labview software is stored in a text file. In Figure 12 a snap of the text file can be seen. As evident, columns 2 to 7 provide the data related to primary current and primary voltage. Whereas in columns 8 to 15 the data related to force, air pressure, secondary voltage, secondary current, displacement, temperature, energy and resistance can be seen.

Force	Air Pressure	Secondary Voltage	Secondary Current	Displacement	Temperature	Energy	Resistance
5,621758	-0,003166	-0,011696	3,387039	0,000000	200,000763	0,000000	0,000000
5,243492	-0,001251	-0,011696	0,711769	0,000000	200,000763	0,000000	0,000000
5,101784	-0,000614	-0,011696	3,387039	0,000000	200,000763	0,000000	0,000000
4,865509	2,670288E-5	-0,013356	7,510391	0,000000	200,000763	0,000000	0,000000
4,392677	-0,001251	-0,011696	0,711769	0,000000	200,000763	0,000000	0,000000
4,581810	2,670288E-5	-0,015025	7,510391	95999,988556	200,000763	0,000000	0,000000
4,676376	-0,001892	-0,011696	3,387039	95999,988556	200,000763	0,000000	0,000000
4,014412	-0,003166	-0,015025	0,711769	95999,988556	200,000763	0,000000	0,000000
4,628952	-0,000614	-0,011696	3,387039	95999,988556	200,000763	0,000000	0,000000
4,439819	-0,002529	-0,011696	0,711769	95999,988556	200,000763	0,000000	0,000000
3,919846	-0,002529	-0,013356	3,387039	95999,988556	200,000763	0,000000	0,000000
4,298111	2,670288E-5	-0,011696	3,387039	95999,988556	200,000763	0,000000	0,000000
4,298111	-0,003166	-0,015025	7,510391	95999,988556	200,000763	0,000000	0,000000
4,014412	-0,003166	-0,013356	0,711769	95999,988556	200,000763	0,000000	0,000000
4,014412	-0,004444	-0,013356	3,387039	95999,988556	200,000763	0,000000	0,000000
3,399872	-0,003166	-0,011696	7,510391	95999,988556	200,000763	0,000000	0,000000

Figure 12: Snap showing the data acquired

In order to analyze the data obtained, the file is then opened in matlab software, where all the data related to various parameters mentioned above is stored in vector arrays.
For the purpose of this thesis initially only four parameters are further analyzed. These parameters are secondary voltage, secondary current, energy and resistance. In the next step data related to only these four parameters is plotted against time. Time interval throughout the data acquisition was 0.000025 seconds. The graphs obtained are shown in following figures.

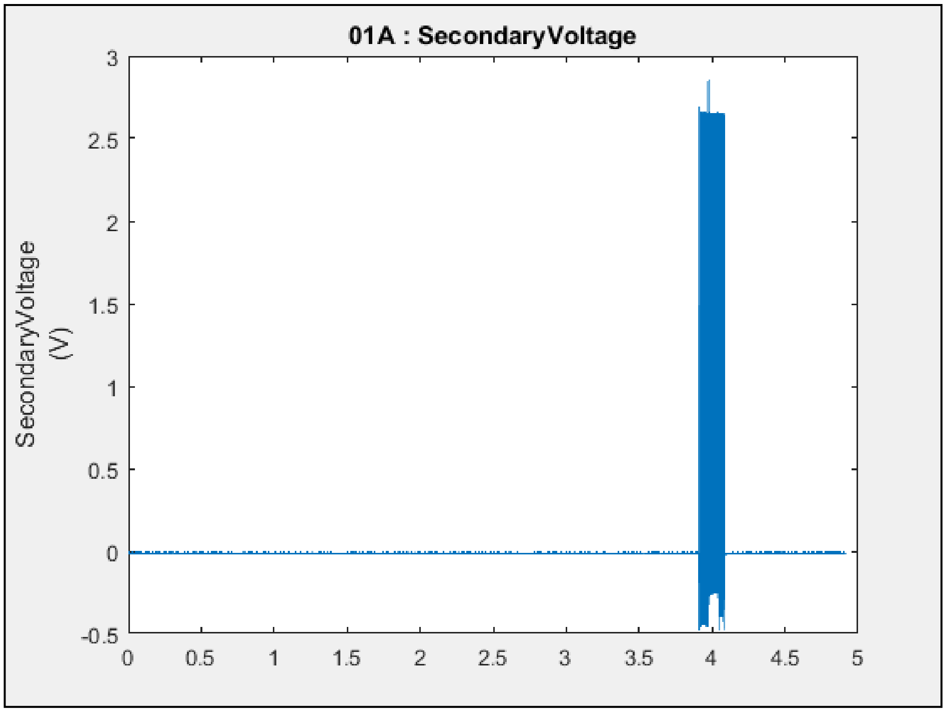


Figure 13: Secondary Voltage

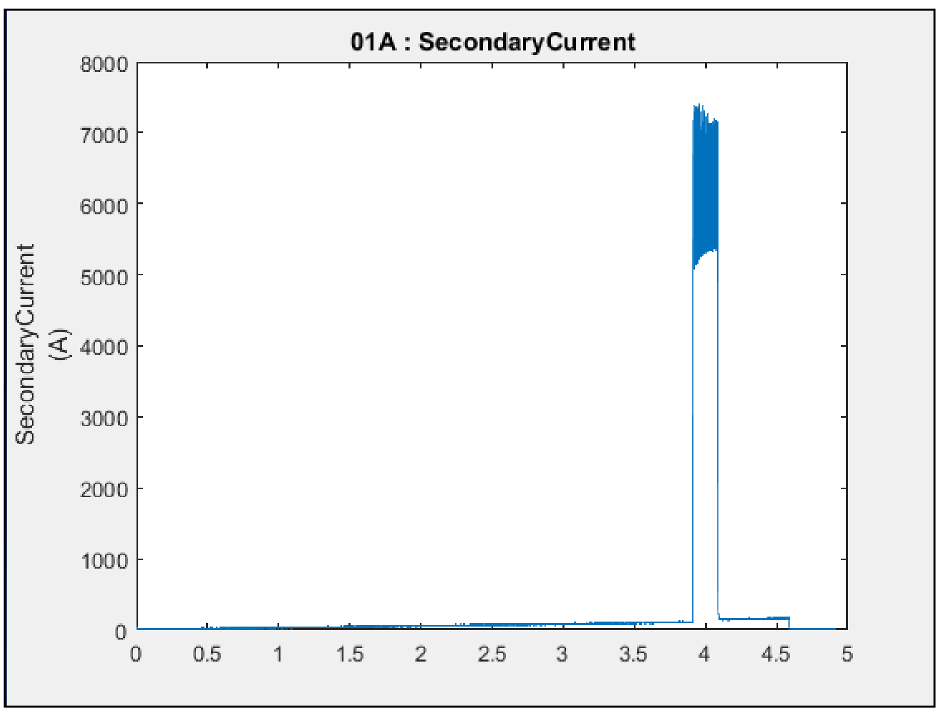


Figure 14: Secondary Current

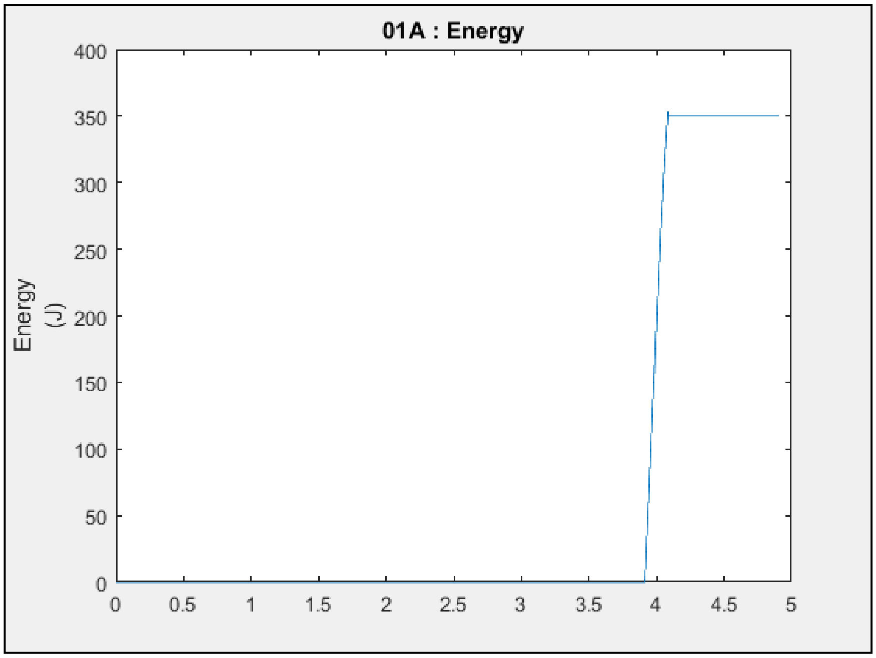


Figure 15: Energy absorbed

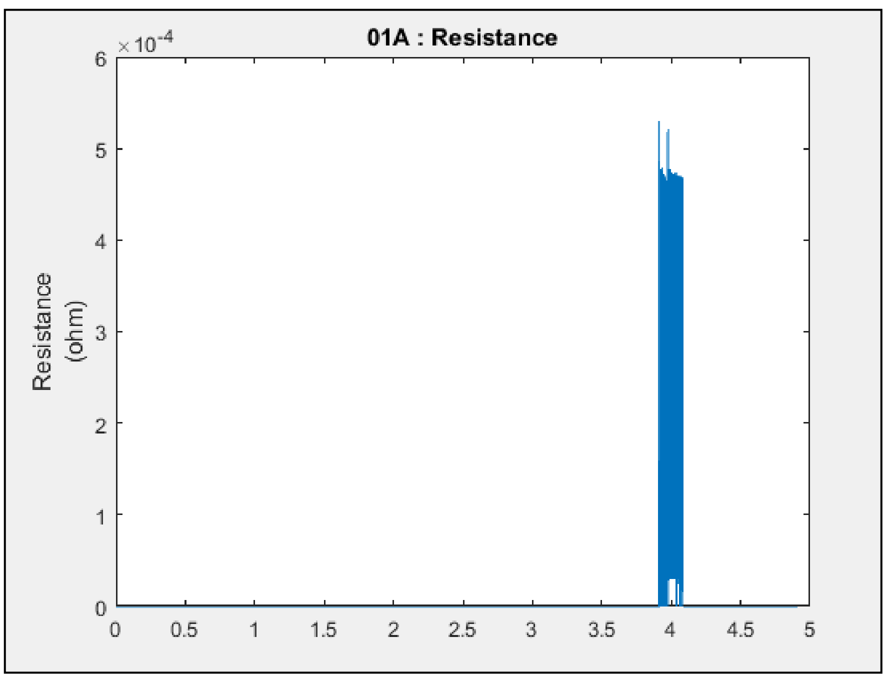


Figure 16: Resistance

As evident from the figures, during the whole weld cycle, only the section where current is passing is useful to us. Keeping in mind this objective a cut off limit was applied to all the parameters and following graphs have been obtained.

Figure 17 shows the graph of secondary voltage after the application of cut off value.

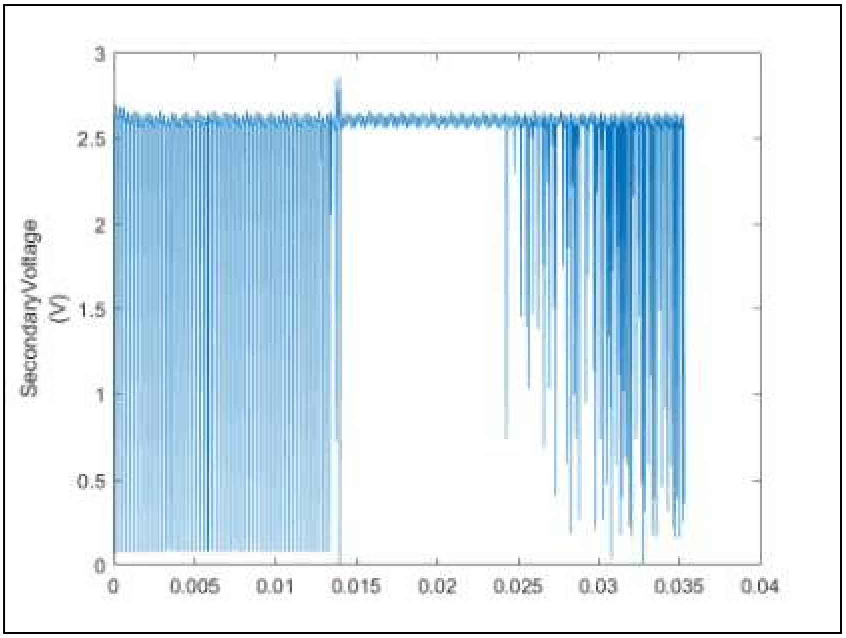


Figure 17: Secondary Voltage cut

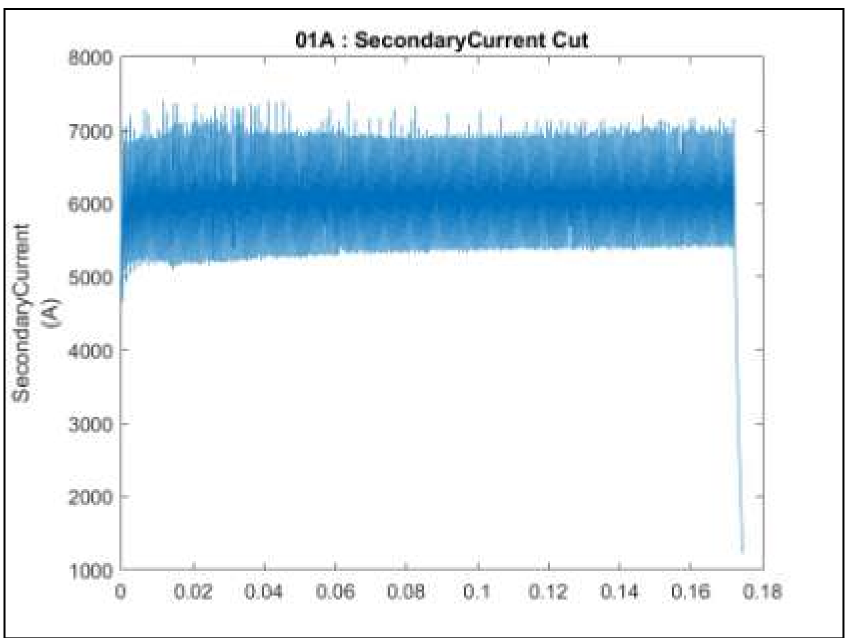


Figure 18: Secondary Current Cut

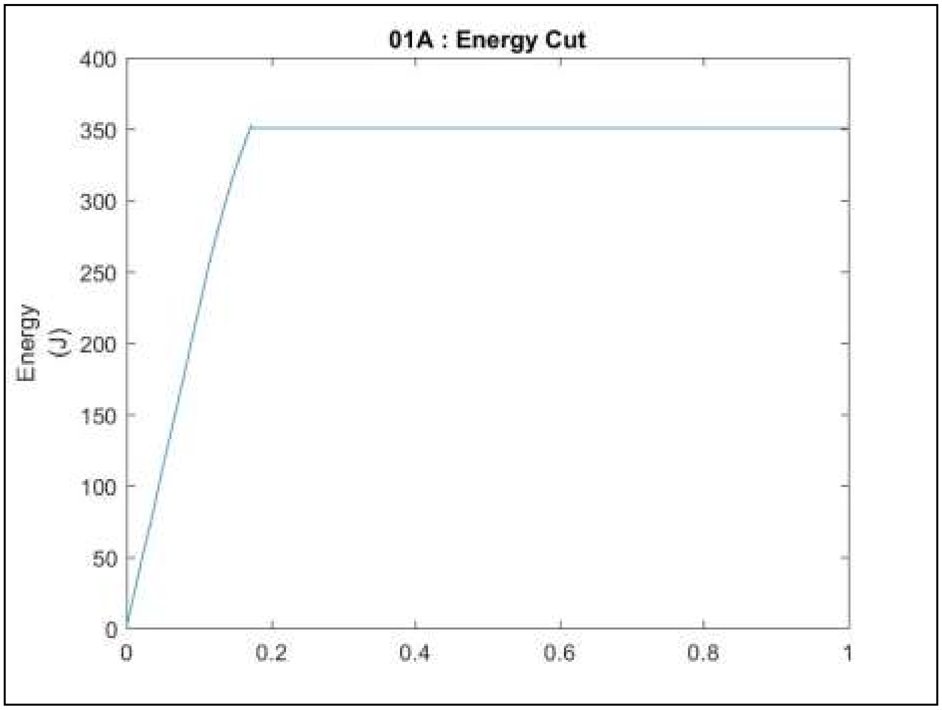


Figure 19: Energy Cut

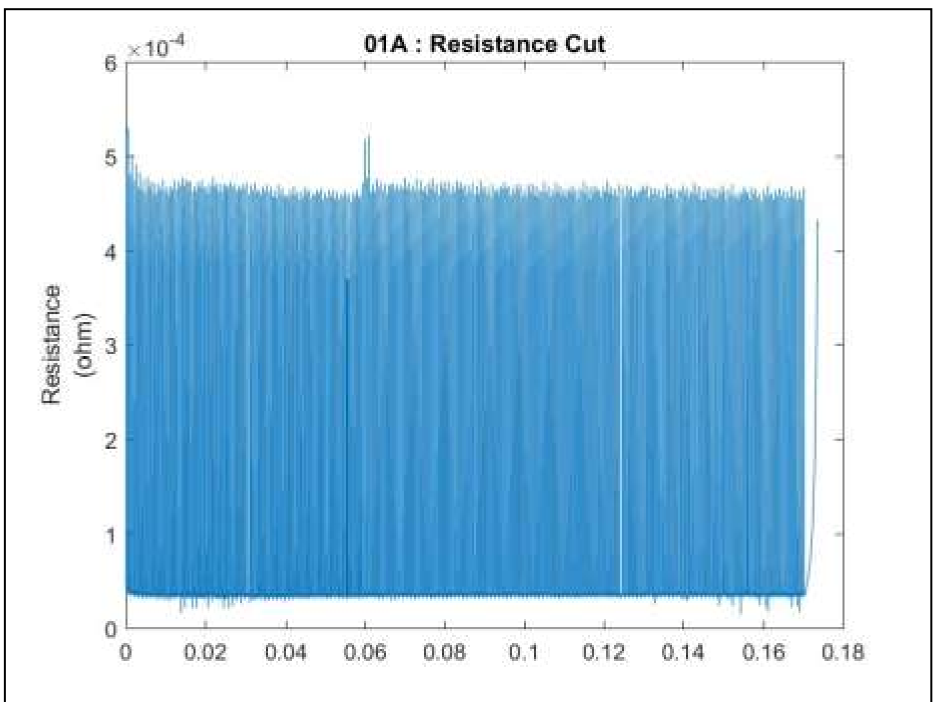


Figure 20: Resistance Cut

Even after the graphs obtained above the data visualization is not clear, to solve this problem already cut graphs have been further smoothen, by taking the root mean square values locally. This has been done using the local RMS function in matlab. The interval is set 20 80, which means that for all the 80 consecutive values a RMS value has been taken, and all the graphs have been re plotted using only the RMS values. In the following RMS graphs during active interval for secondary voltage, secondary current, energy and resistance are shown:

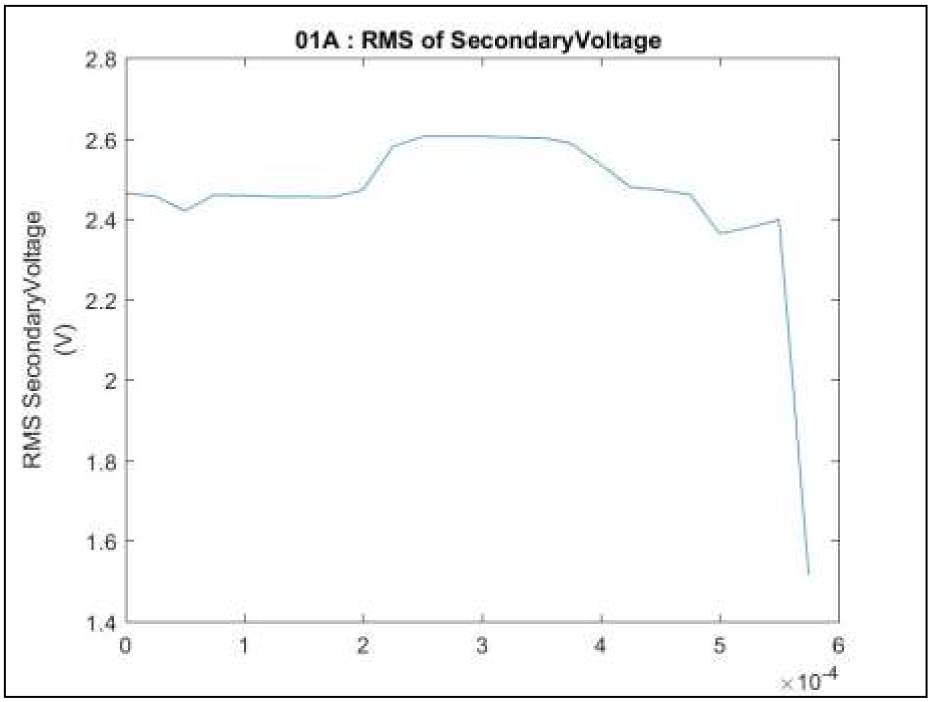


Figure 21: Secodary Voltage

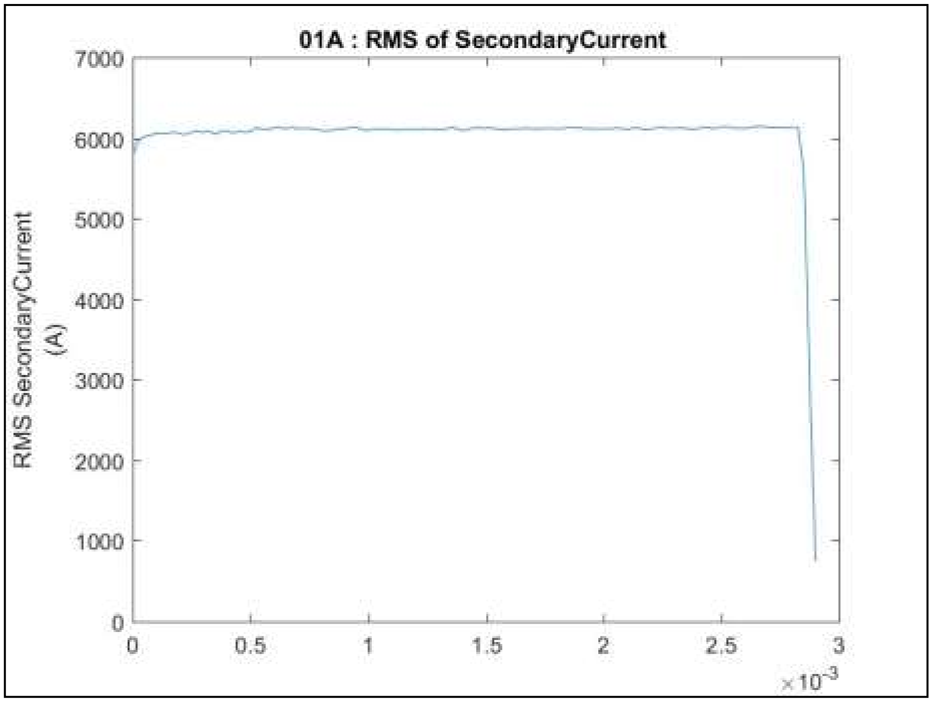


Figure 22: Secondary Current

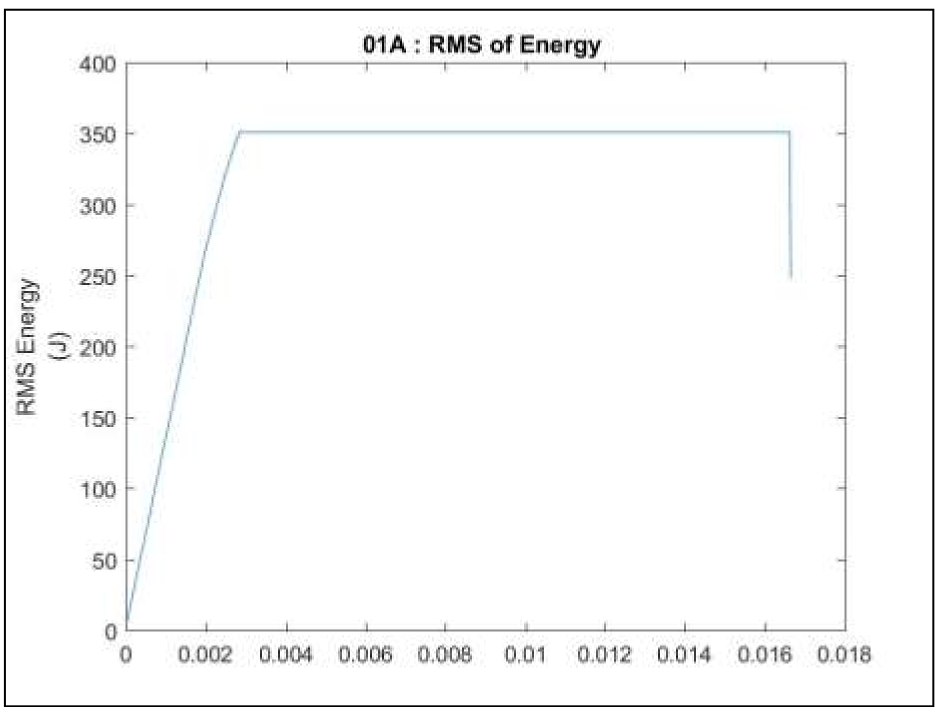


Figure 23: Energy

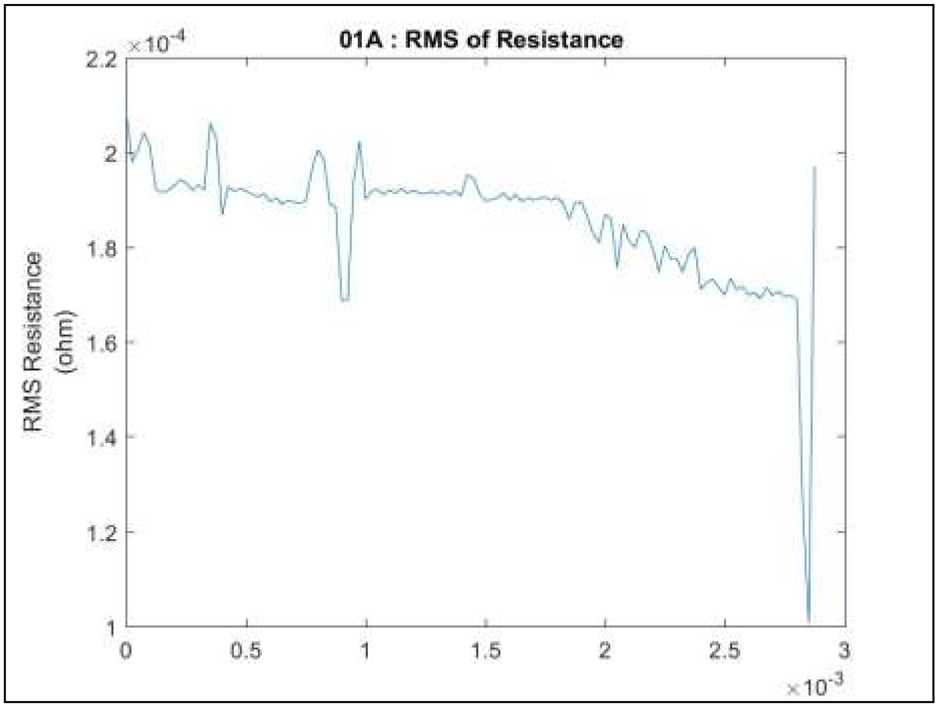


Figure 24: resistance

As evident from the graphs, all of them represent the parameters for weld test 01A. In order to verify the strength of weld performed using these parameters, shear test is performed according to American National Standard AWS D8.1M:2013. The results obtained are acquired using the data acquisition system; this data is extracted on a text file. Then by opening this file in matlab software, graphs are plotted for displacement and Force. An example of shear test performed can be seen in figure 25.

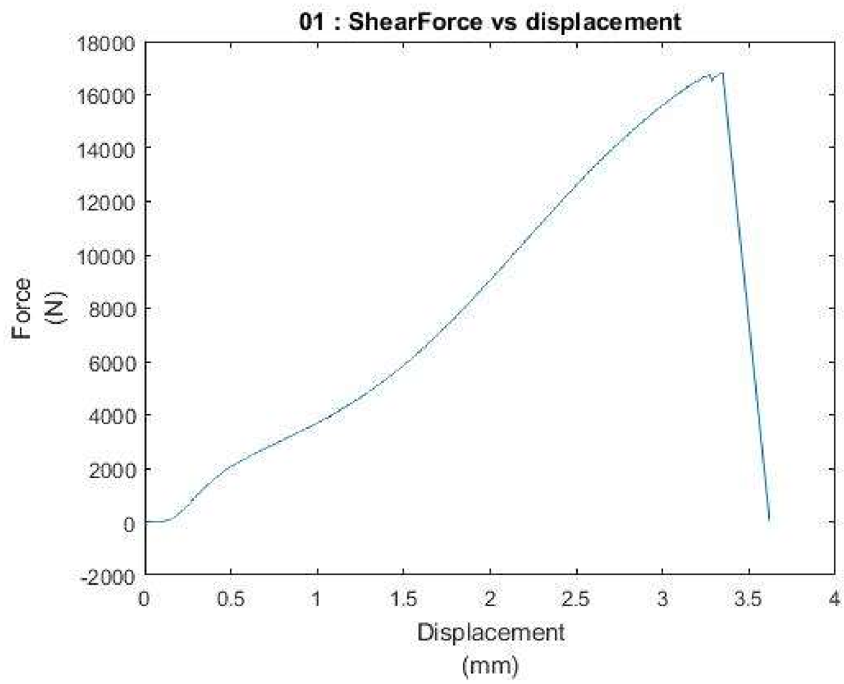


Figure 25: Shear test SF_01

To carry out the analysis 27 sets of weld were performed, each set contained 3 weld tests, where all three welds are performed using same weld parameters. During these 27 sets mainly secondary current and electrode force are modified.

As each set contains the weld performed using same process parameters, in order to compare the weld quality with process parameters, all the graphs for parameters and shear tests are re-plotted, so that all the three plots for one parameter are shown in a single plot together. Below you can see the combined plots for parameters and shear tests.

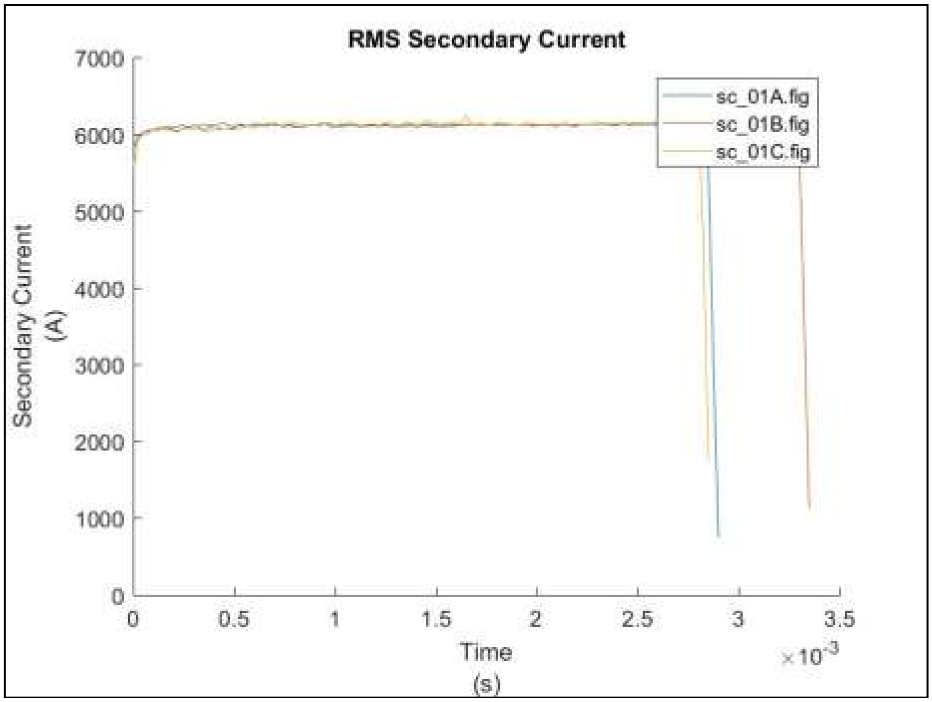


Figure 26: A combined plot containing graphs of secondary Currents for all three replications.

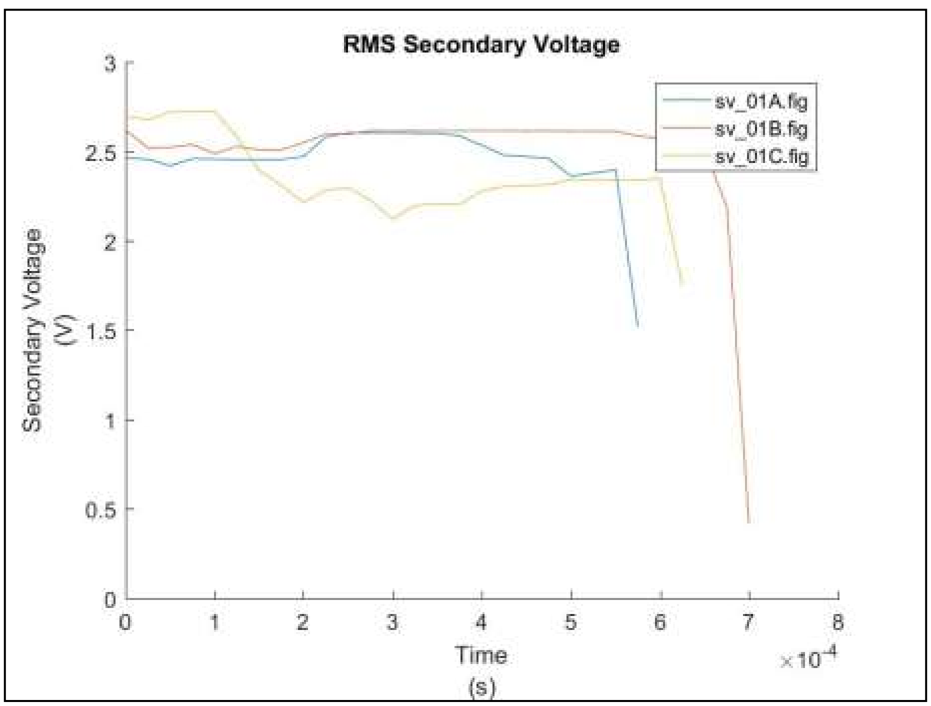


Figure 27: A combined plot containing graphs of Secondary Voltage for all three replications.

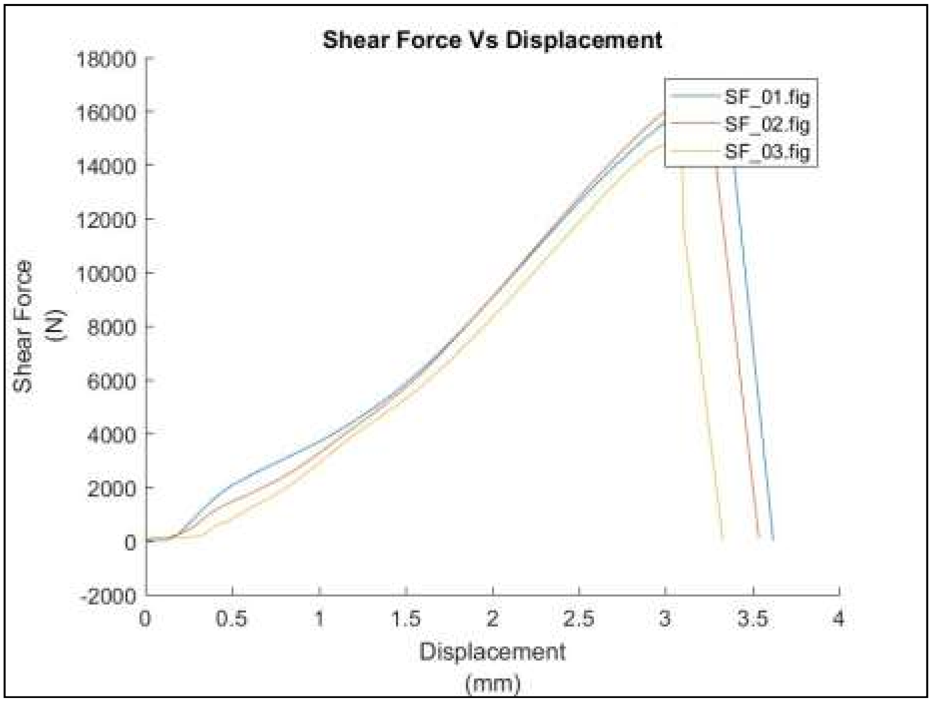


Figure 28: A combined plot containing graphs of Shear test for all three replications.

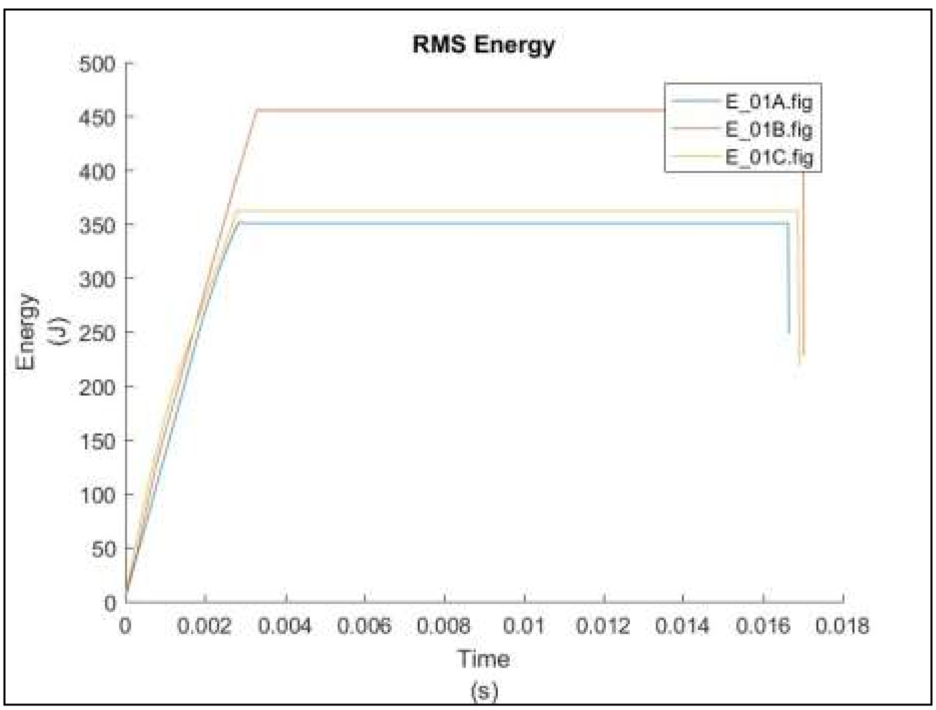


Figure 29: A combined plot containing graphs of Energy for all three replications.

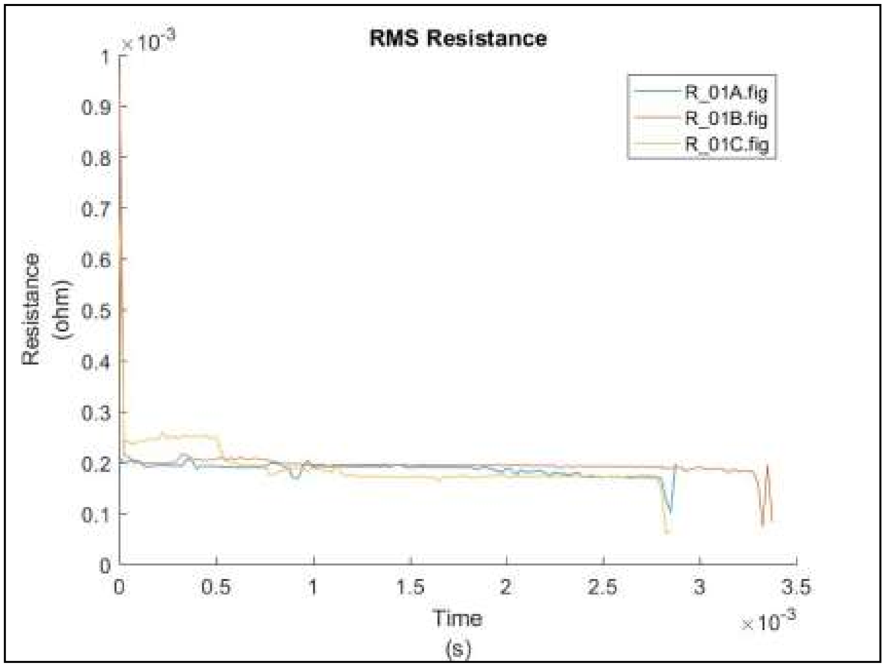


Figure 30: A combined plot containing graphs of Resistance for all three replications of test 01.

Below are the graphs for test 24:

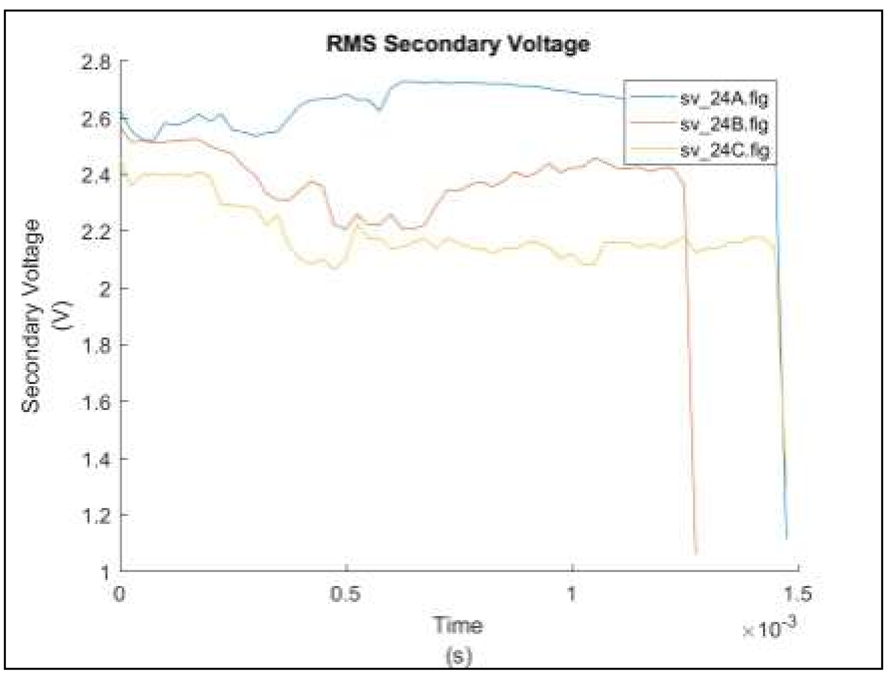


Figure 31: A combined plot containing graphs of Voltage for all three replications of test 24.

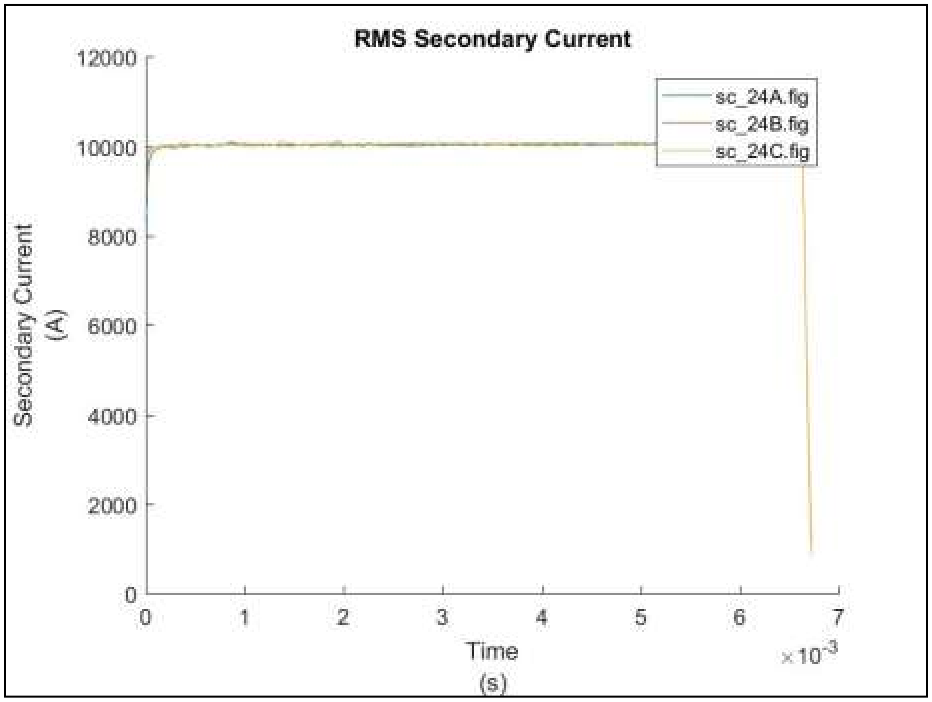


Figure 32: A combined plot containing graphs of Current for all three replications of test 24.

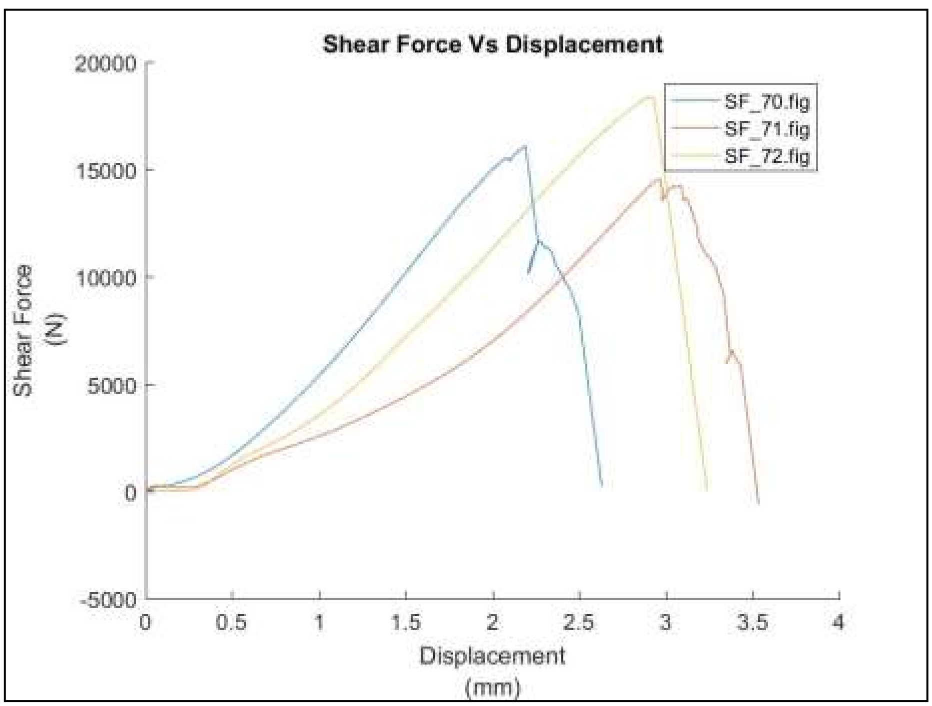


Figure 33: A combined plot containing graphs of Shear test for all three replications of test 24.

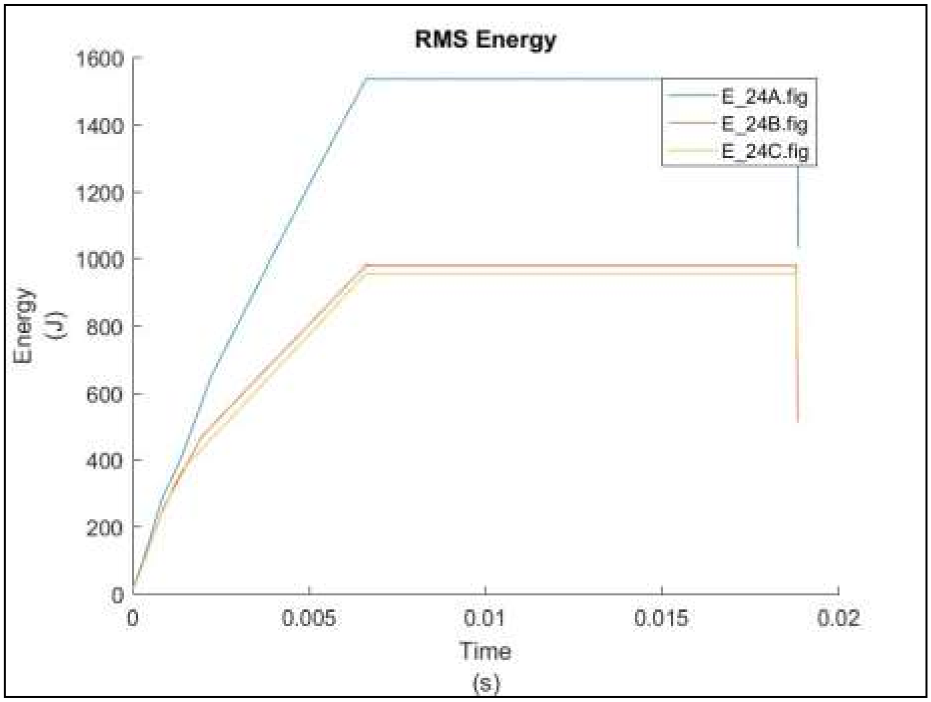


Figure 34: A combined plot containing graphs of Energy for all three replications of test 24.

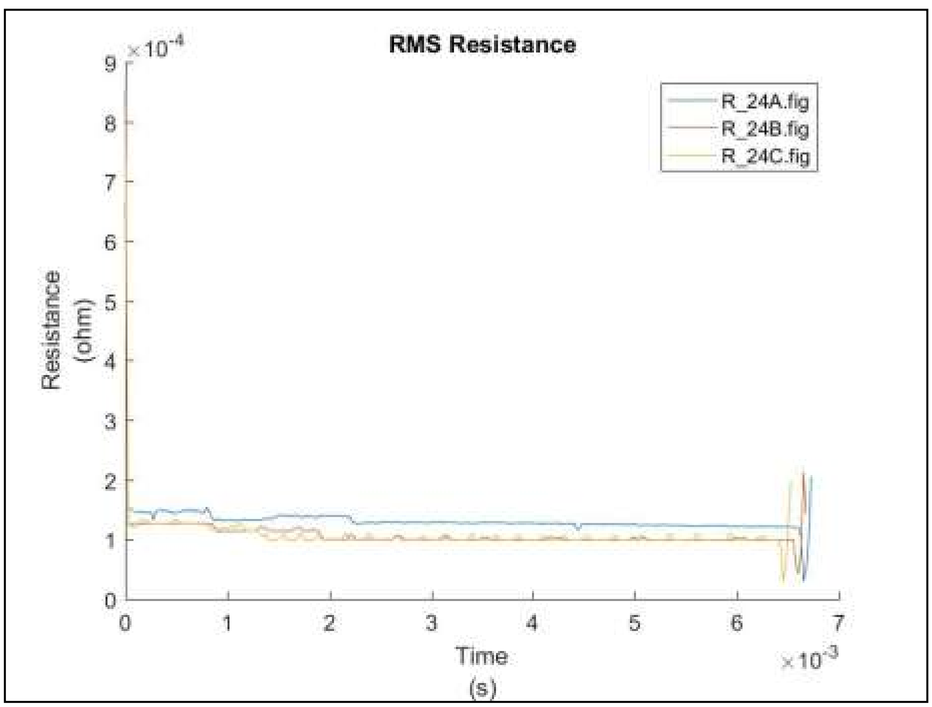


Figure 35: A combined plot containing graphs of Resistance for all three replications of test 24.

All the graphs of parameters (secondary voltage, secondary current, Energy, Resistance) and their relative shear tests can be found in Appendix 1.

In order to analyze the data and obtain the respective graphs, a matlab script has been written, which is to be used during this thesis, and also for all the tests to be performed in the future. These scripts can be found in Appendix 2.

CHAPTER 4

CONCLUSION

Monitoring of Resistance spot welding parameters done during this thesis has enabled us to find out the affect of various weld parameters on weld quality. Then with the help of data acquisition system, this data can be extracted and further analyzed. In order to facilitate and accelerate the analysis, matlab scripts given in Appendix 2 are used. The work done in this thesis is the base of further analysis to be done for studying the affect of different parameters, material surface condition, and surface treatment on the weld quality. The other objective is to compare the measured parameter values to the values that were imposed. This can help find the discrepancies and losses in the system, and help prepare a preventive maintenance plan for the system. On the basis of data obtained effect of each process parameter will be evaluated on weld quality and also it will be assessed whether the parameters imposed are energy efficient or not, if not then try to achieve the required weld quality with less energy and time consumption.

APPENDIX 1

Test 1

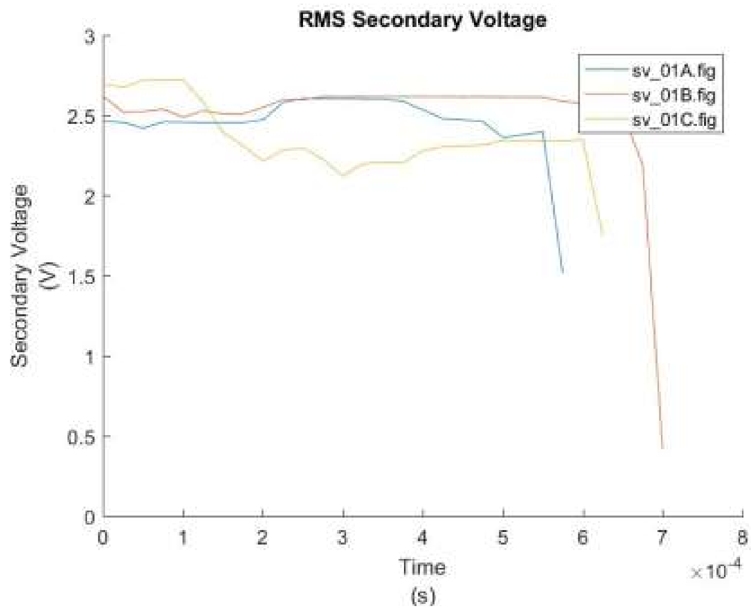


Figure: Secondary Voltage Test 1

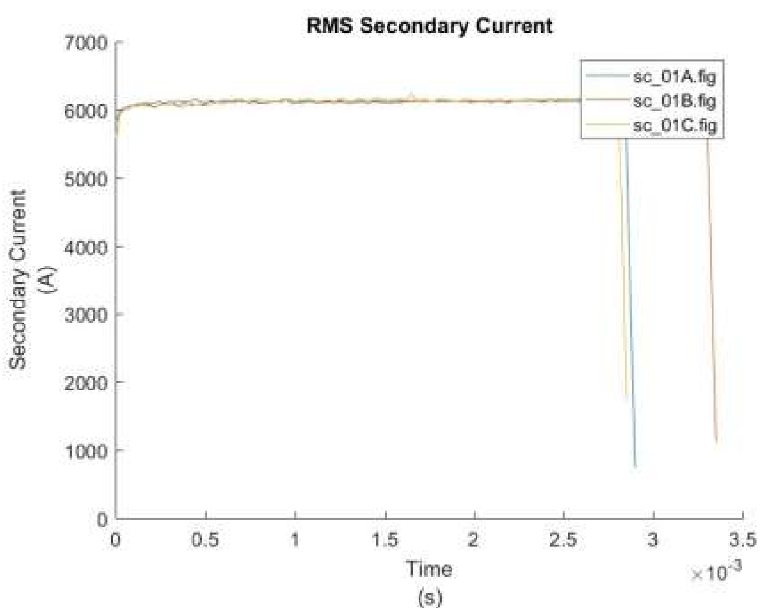


Figure: Secondary Current Test 1

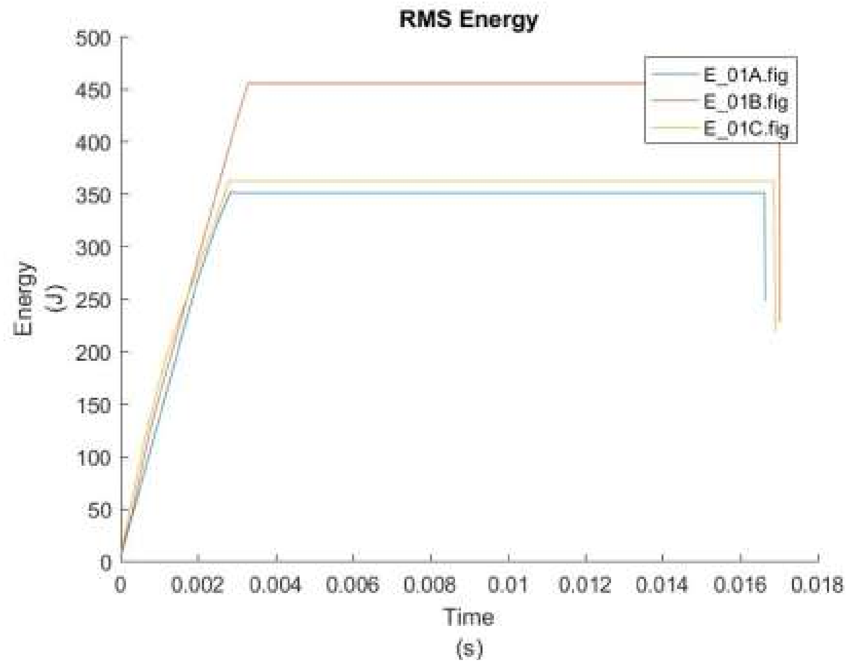


Figure: Energy Test 1

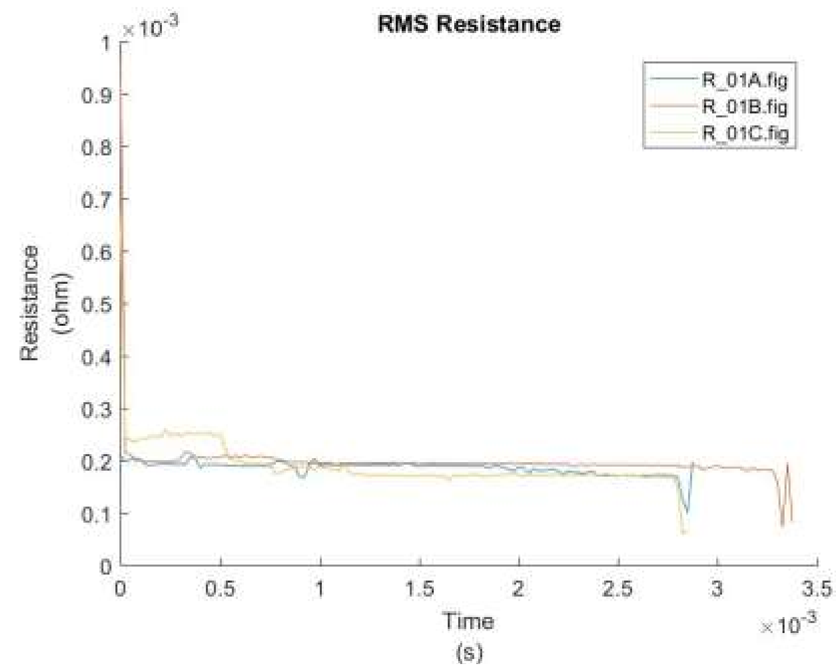


Figure: Resistance Test 1

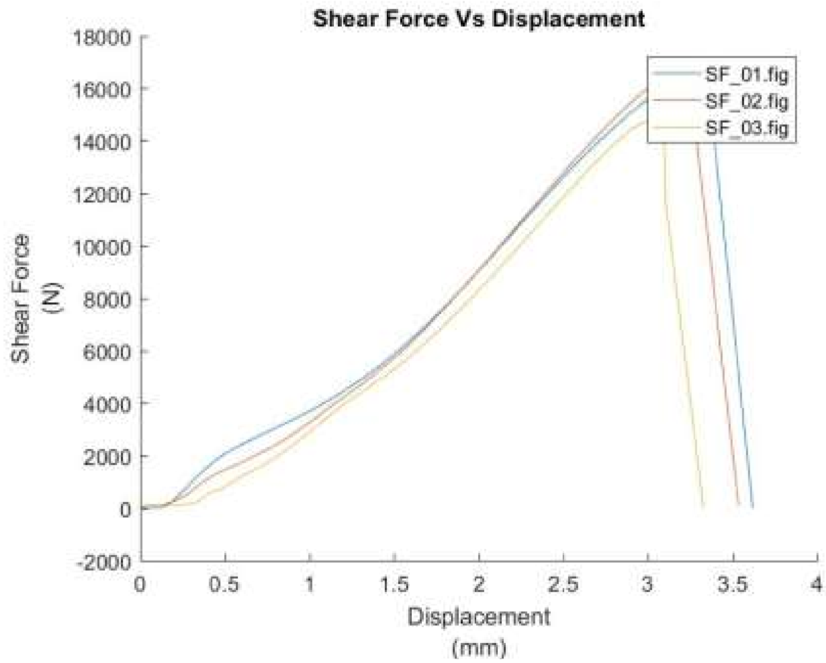


Figure: Shear tension test 1

Test 2

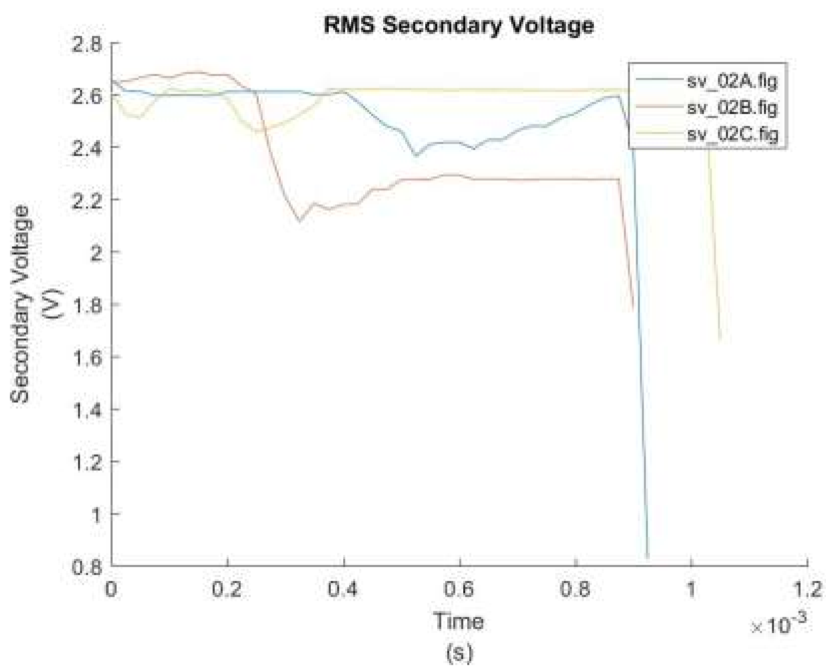


Figure: Secondary Voltage Test 2

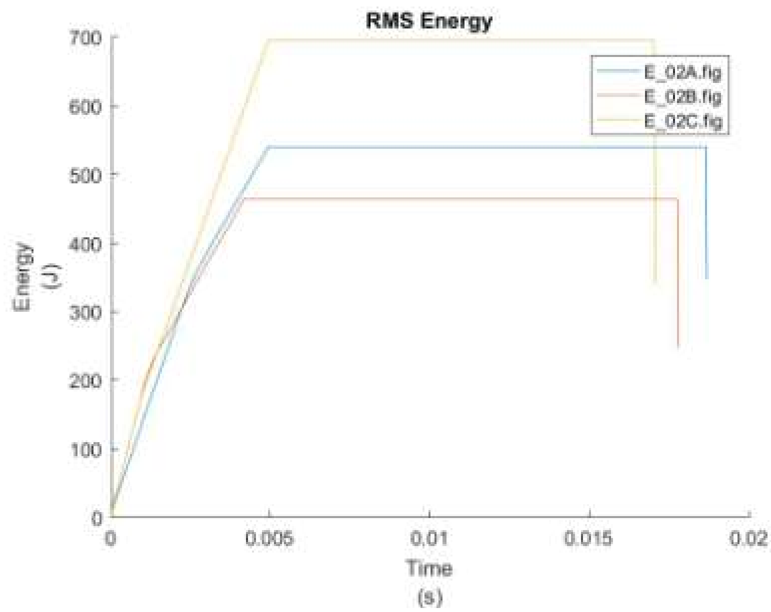


Figure: Energy Test 2

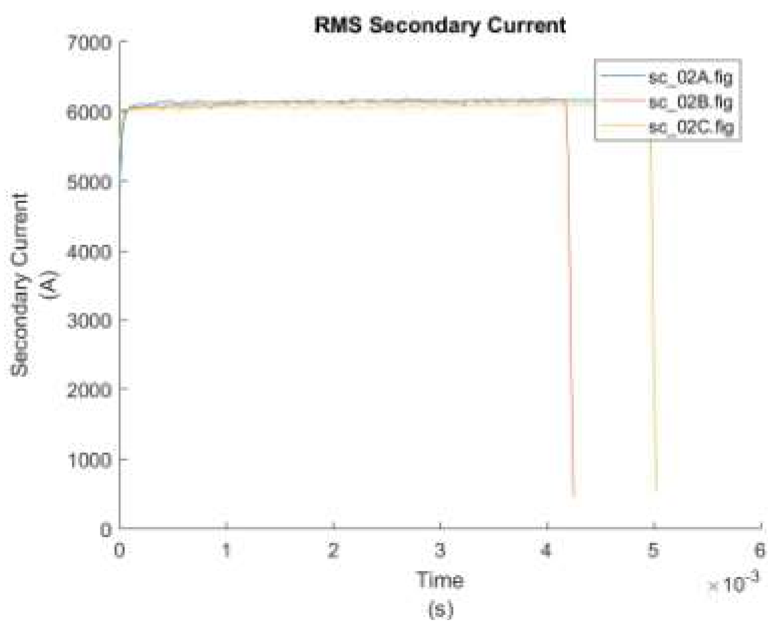


Figure: Secondary Current Test 2

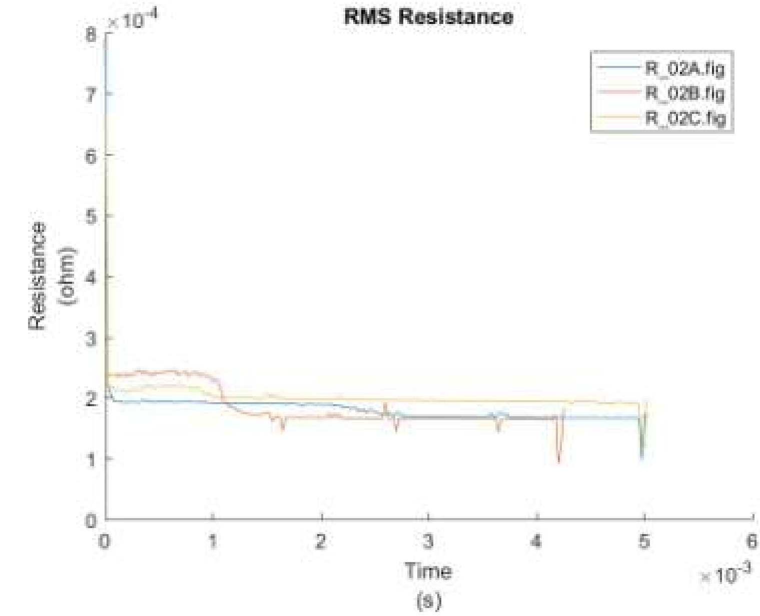


Figure: Resistance Test 2

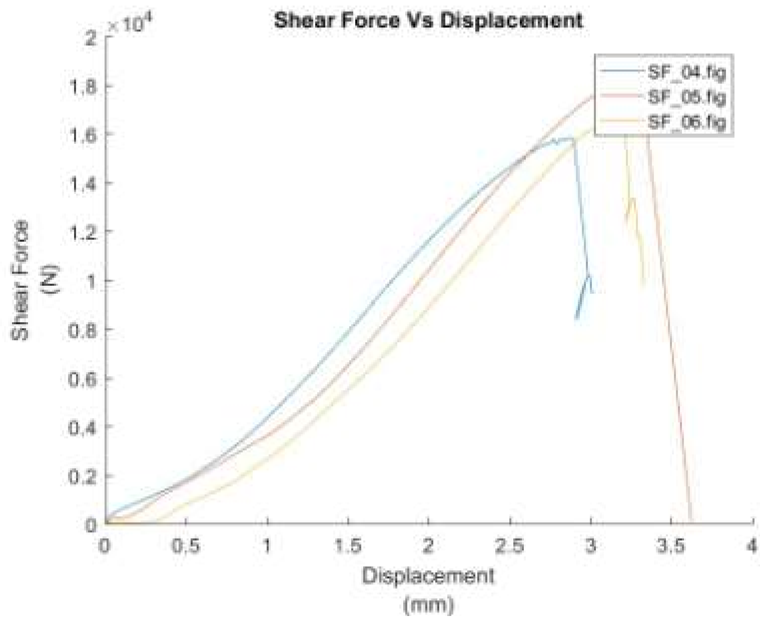


Figure: Shear tension test 2

Test 3

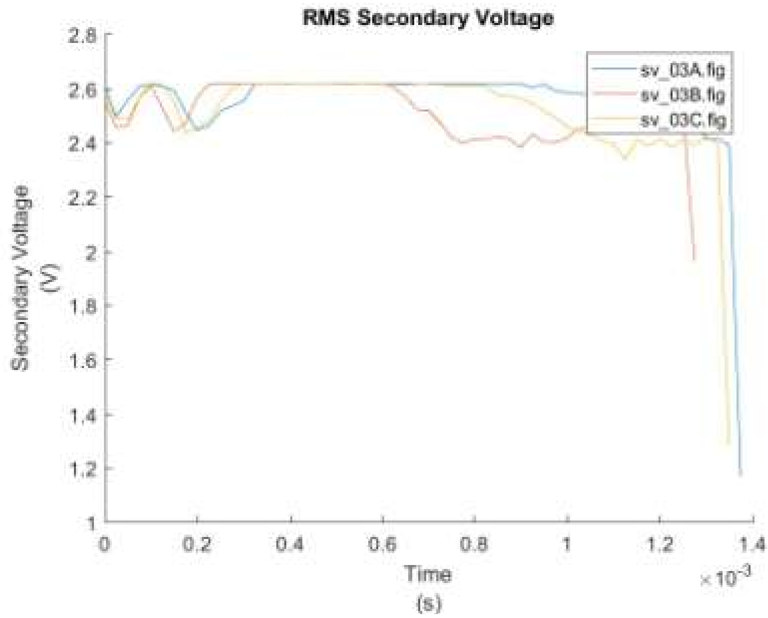


Figure: Secondary Voltage Test 3

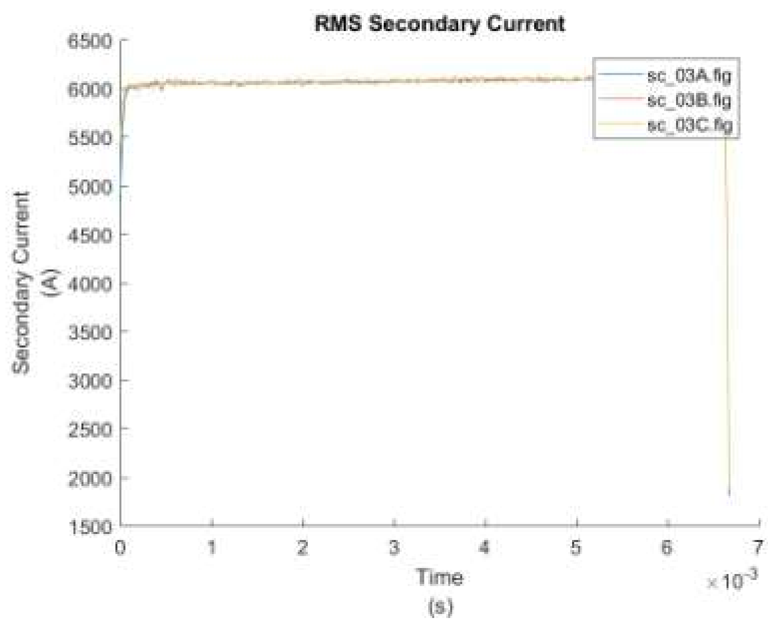


Figure: Secondary Current Test 3

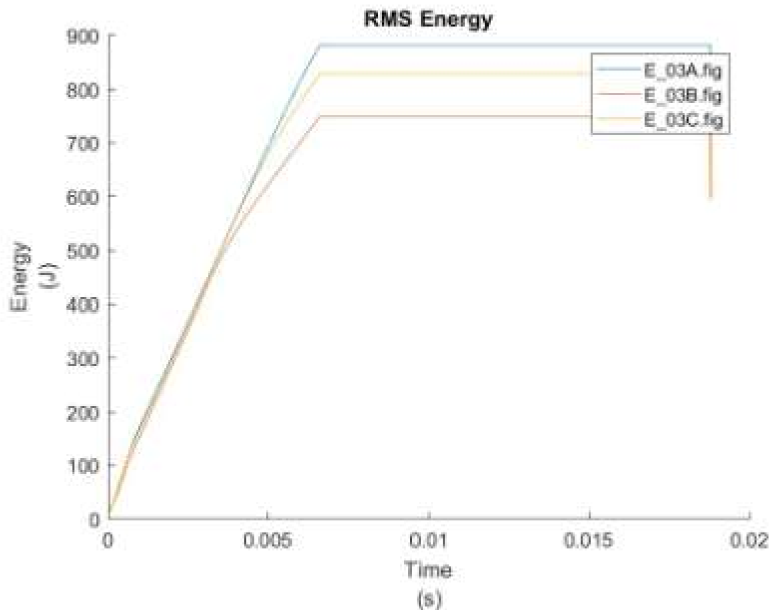


Figure: Energy Test 3

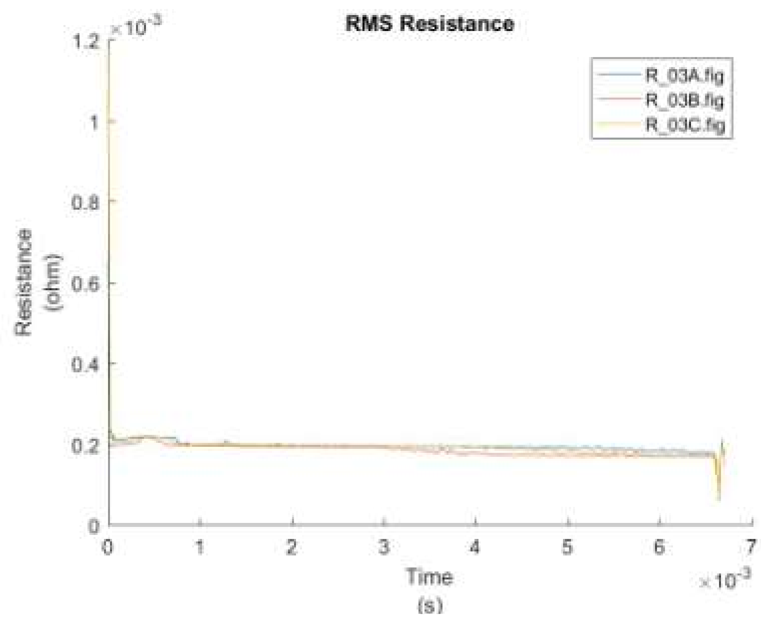


Figure: Resistance Test 3

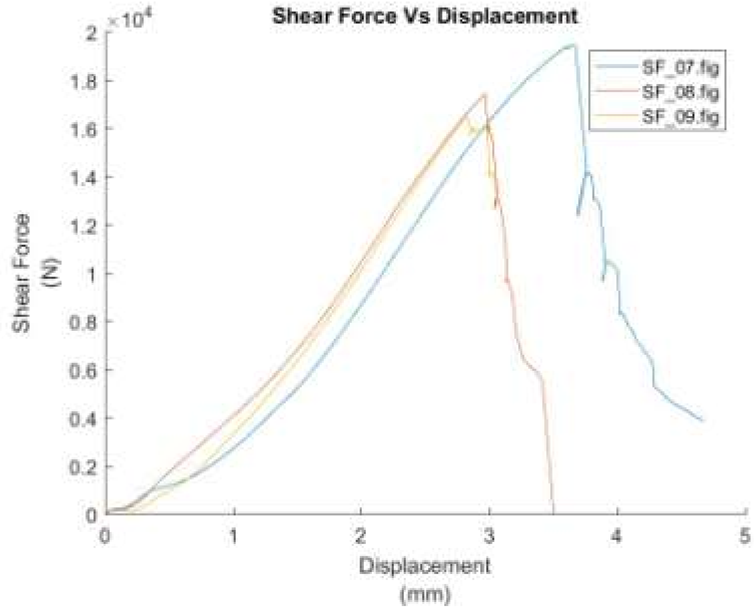


Figure: Shear tension test 3

Test 4

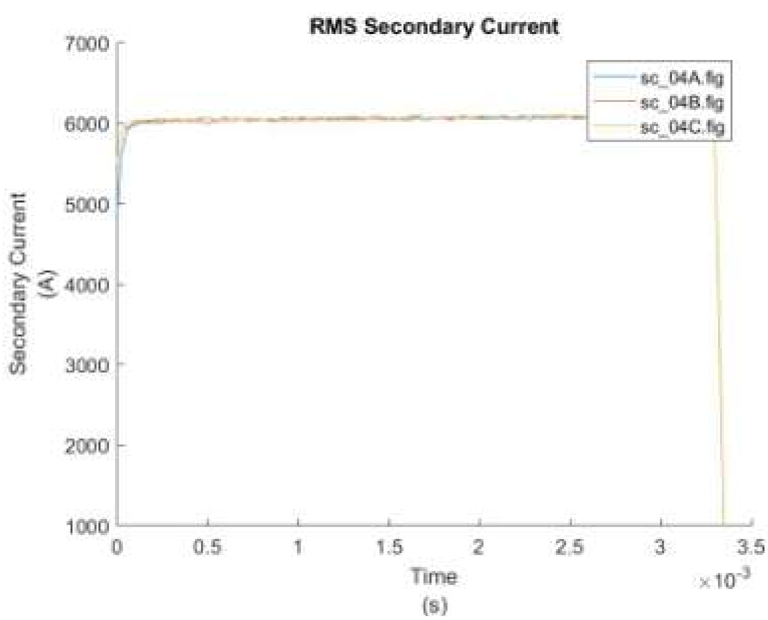


Figure: Secondary Current Test 4

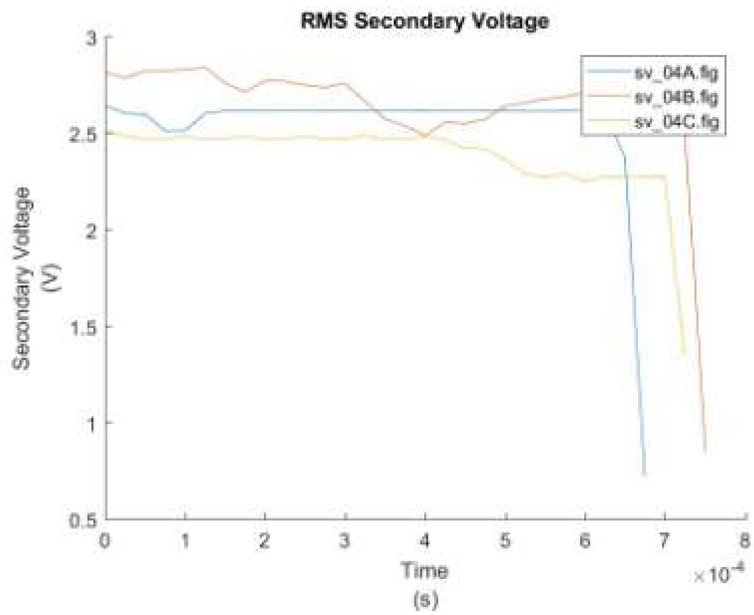


Figure: Secondary Voltage Test 4

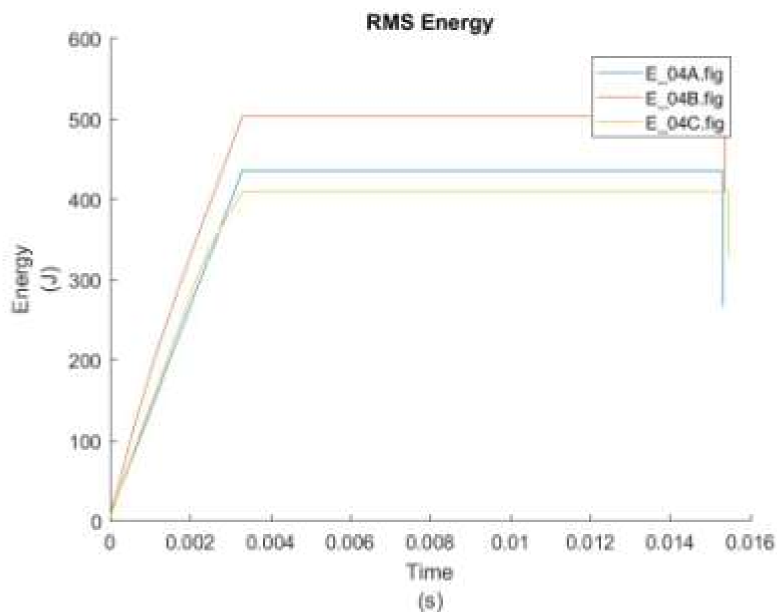


Figure: Energy Test 4

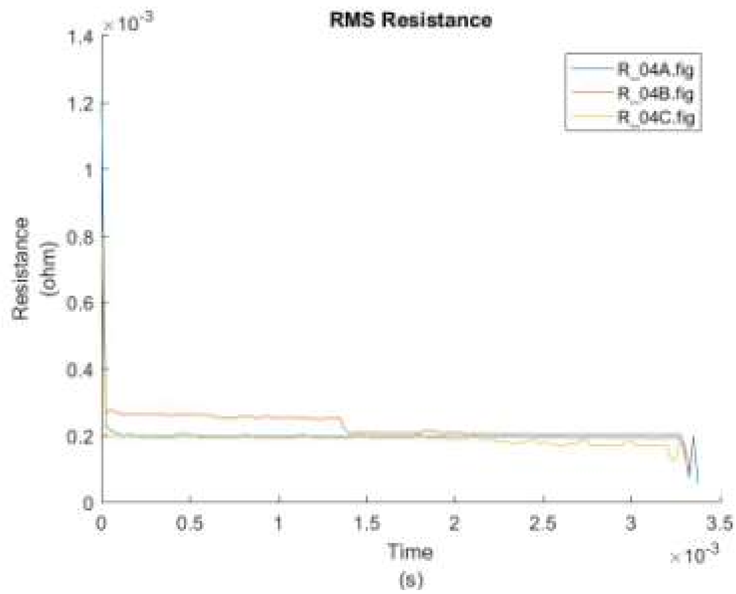


Figure: Resistance Test 4

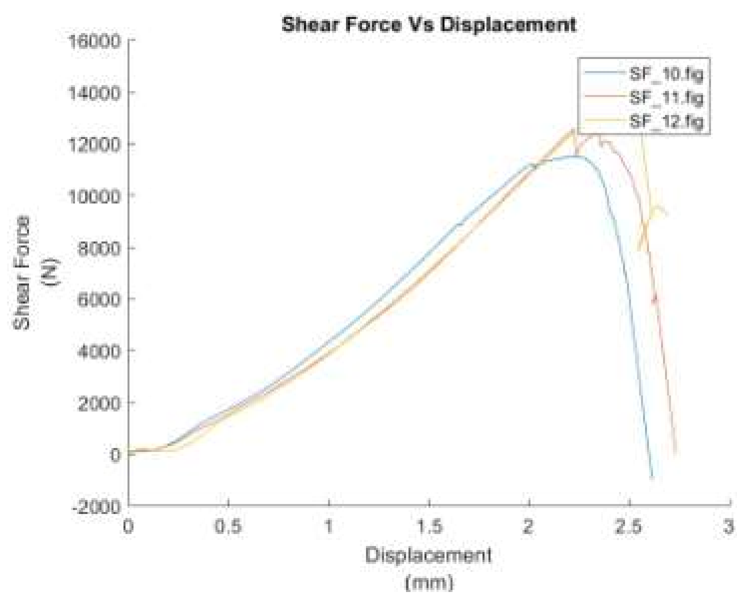


Figure: Shear tension test 4

Test 5

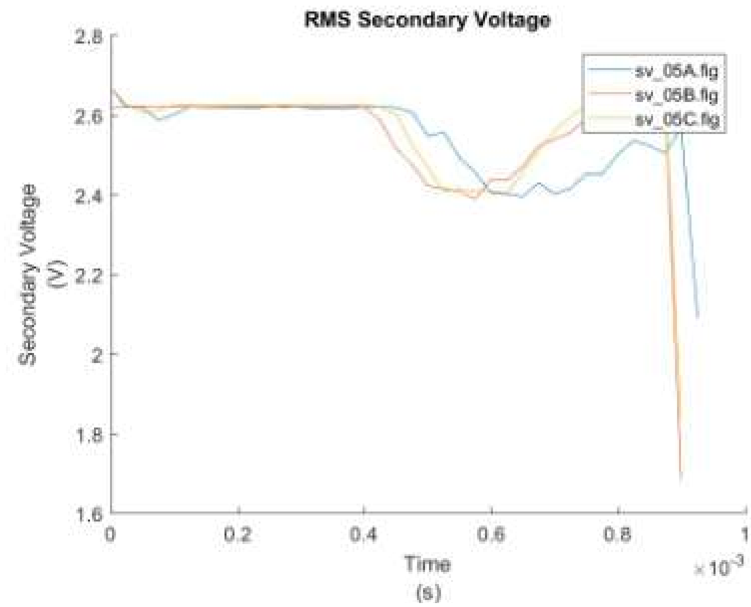


Figure: Secondary Voltage Test 5

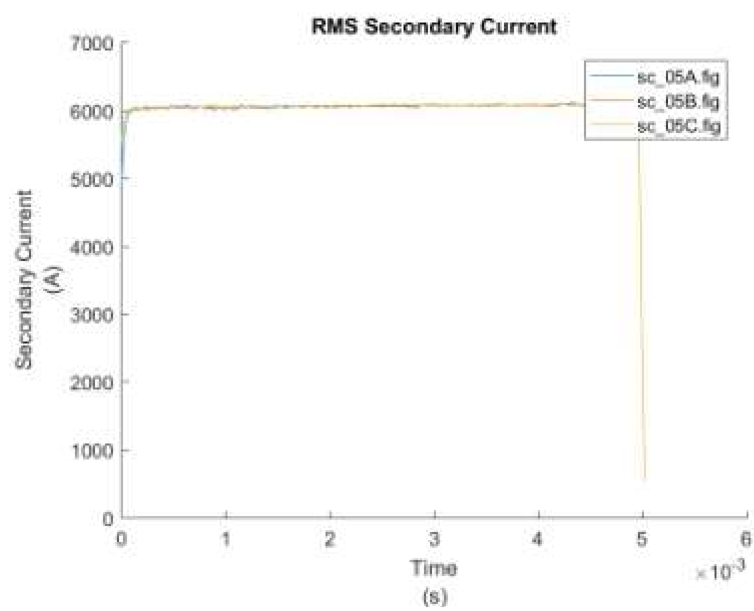


Figure: Secondary Current Test 5

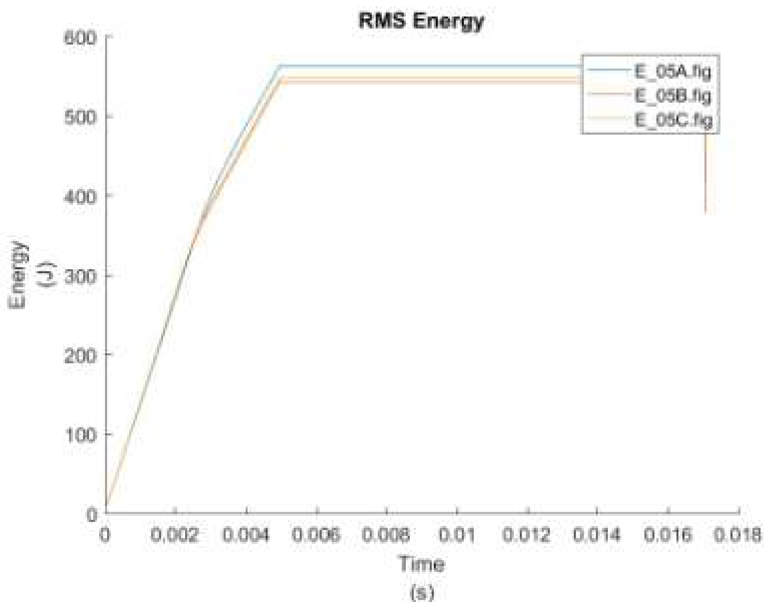


Figure: Energy Test 5

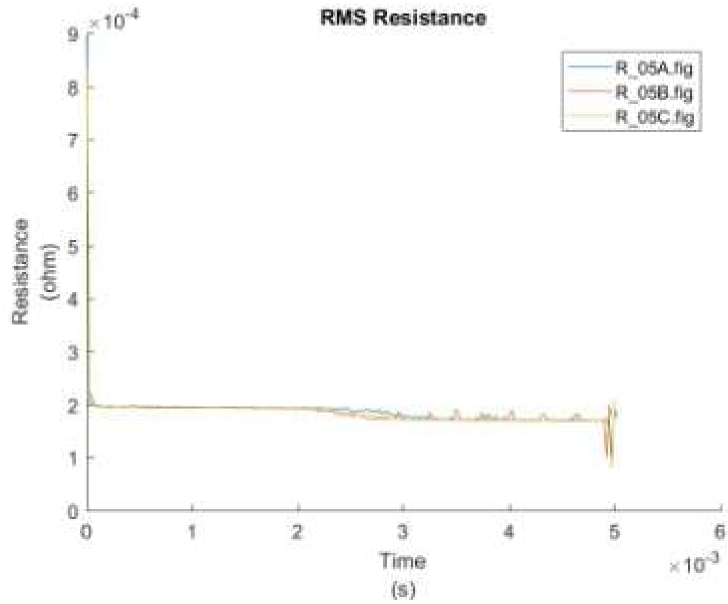


Figure: Resistance Test 5

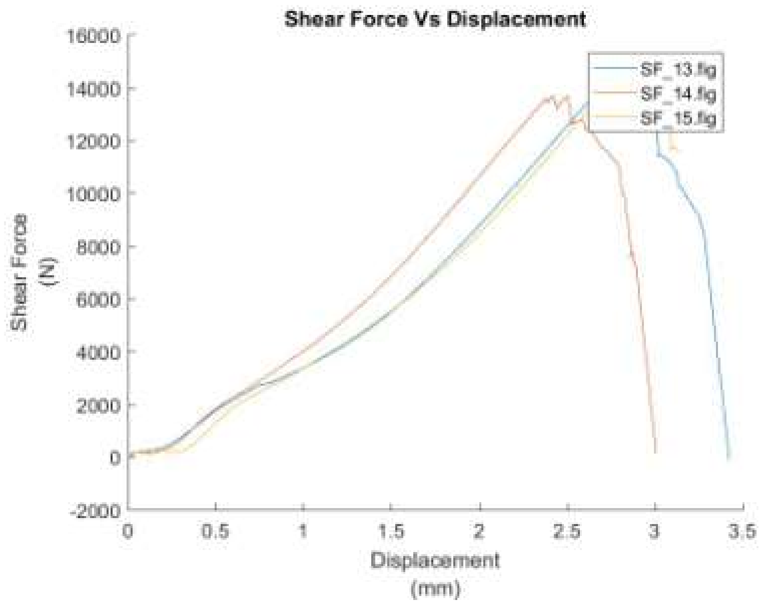


Figure: Shear tension test 5

Test 6

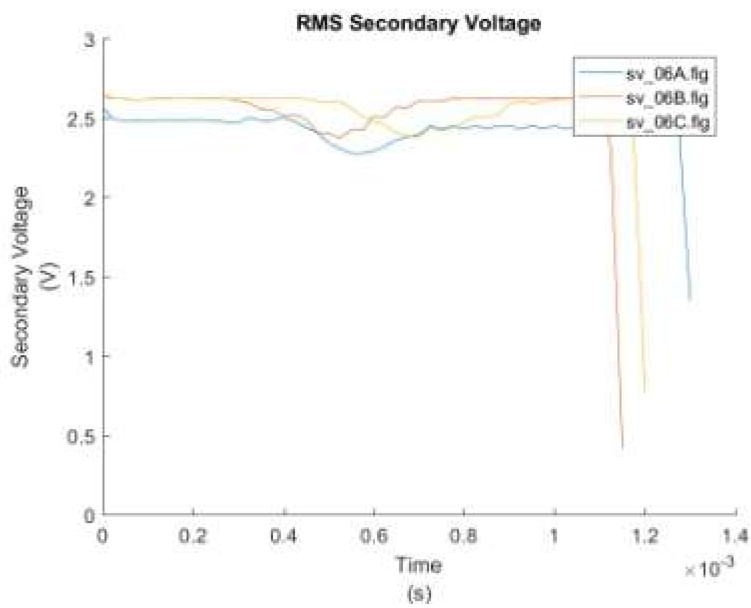


Figure: Secondary Voltage Test 6

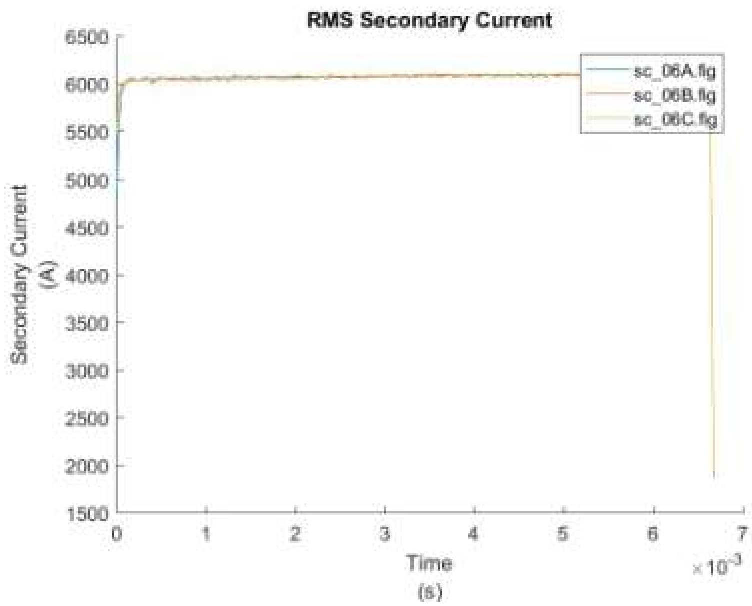


Figure: Secondary Current Test 6

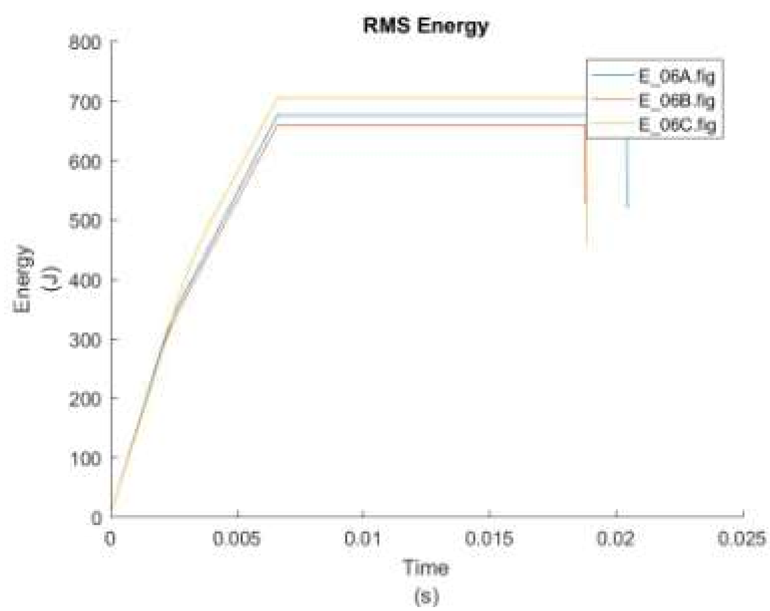


Figure: Energy Test 6

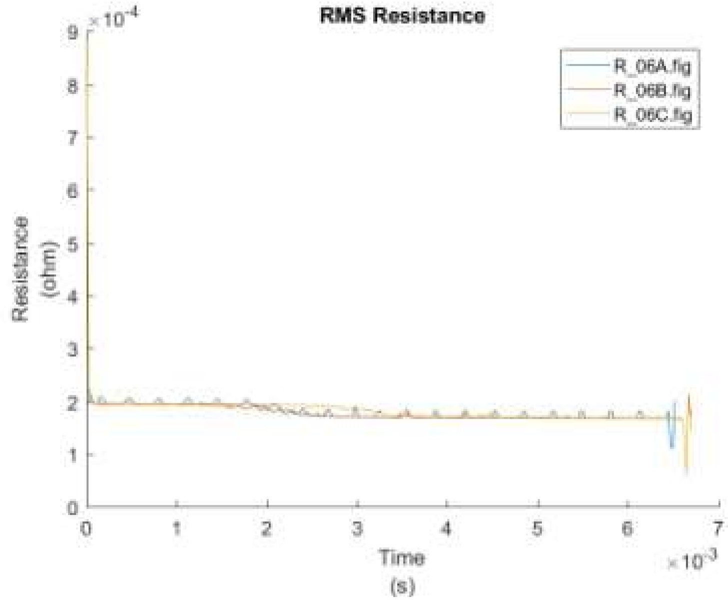


Figure: Resistance Test 6

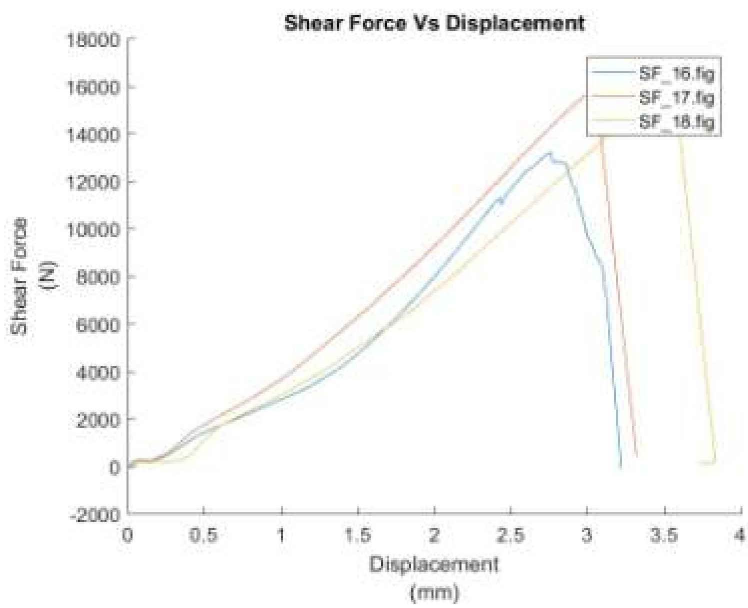


Figure: Shear tension test 6

Test 7

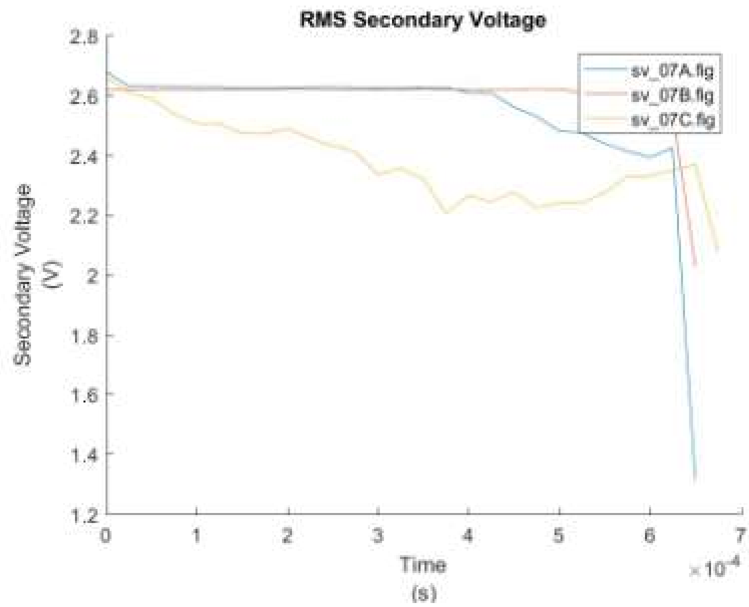


Figure: Secondary Voltage Test 7

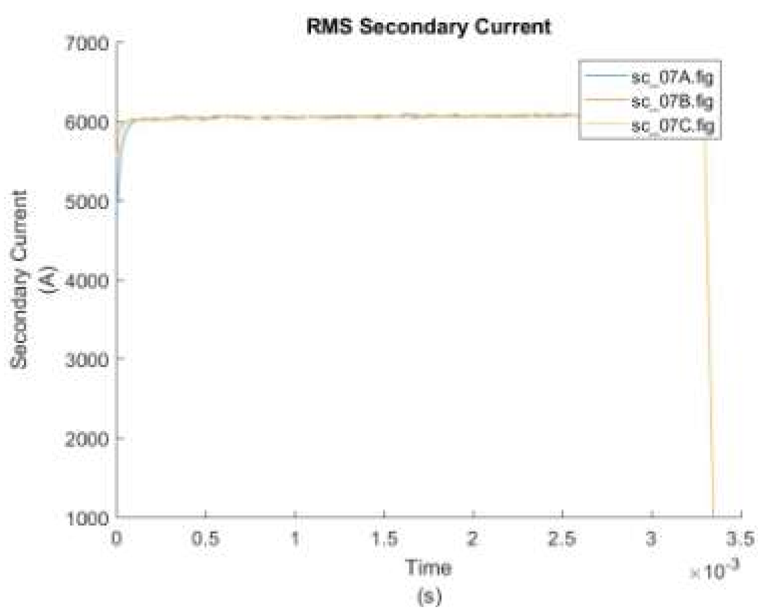


Figure: Secondary Current Test 7

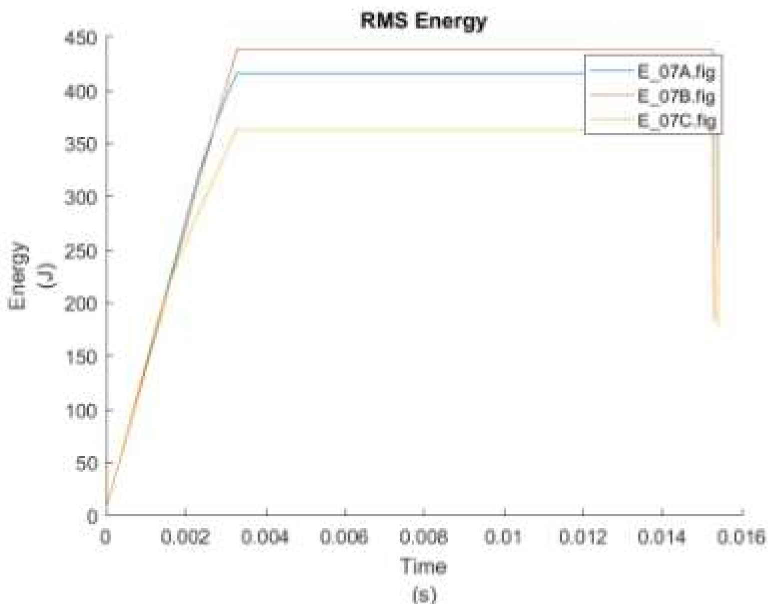


Figure: Energy Test 7

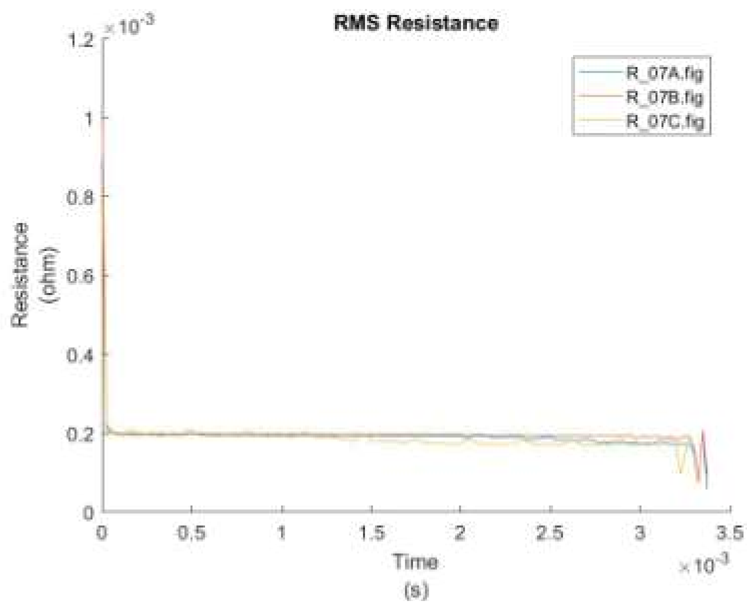


Figure: Resistance Test 7

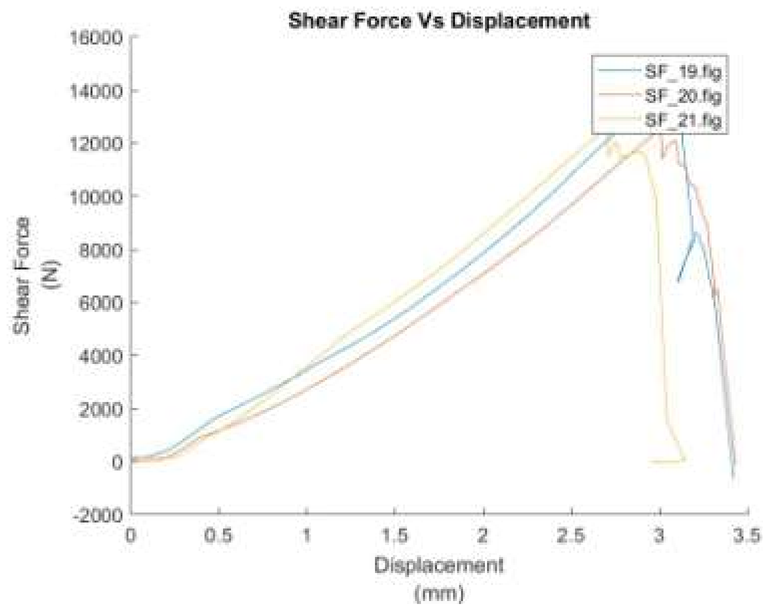


Figure: Shear tension test 7

Test 8

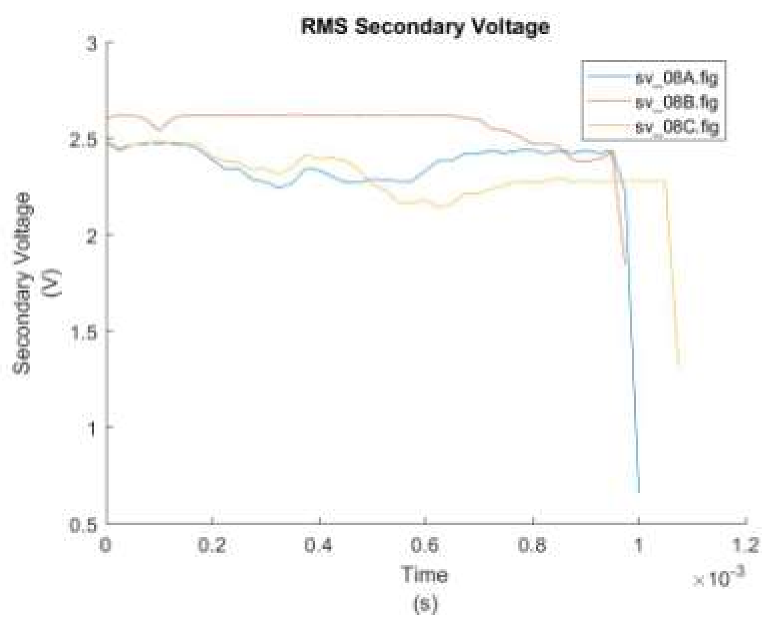


Figure: Secondary Voltage Test 8

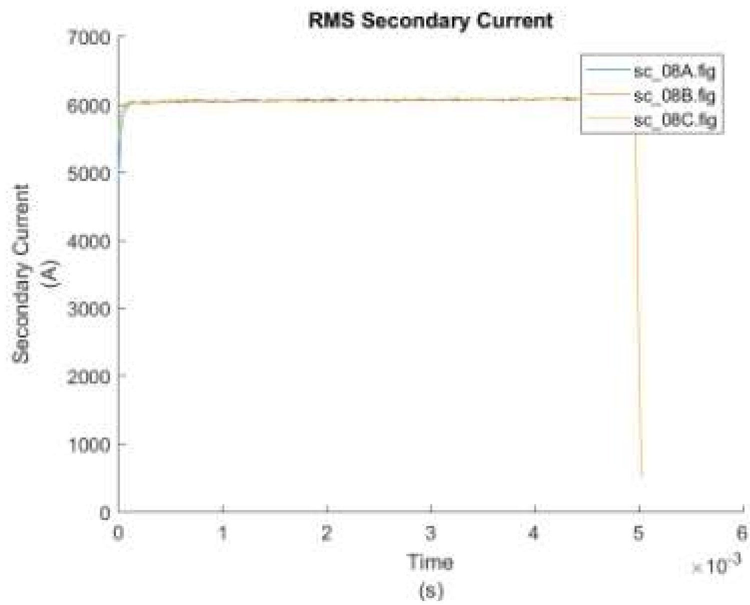


Figure: Secondary Current Test 8

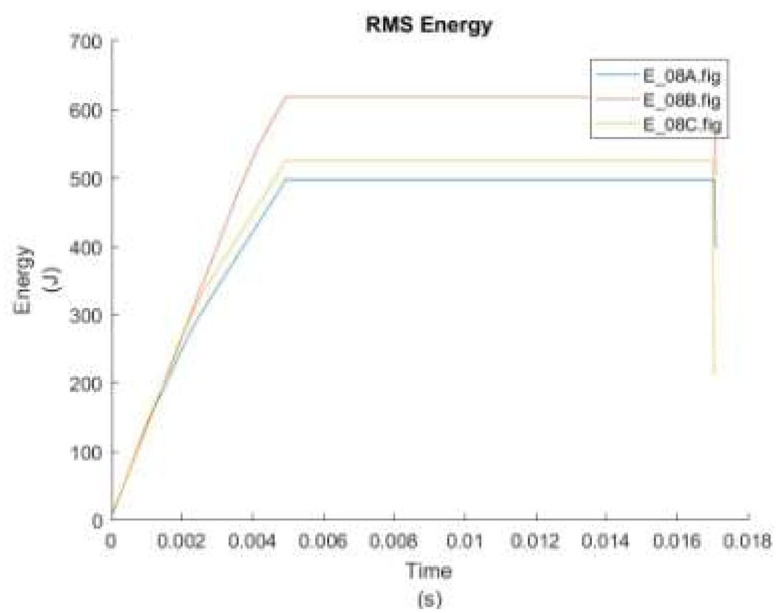


Figure: Energy Test 8

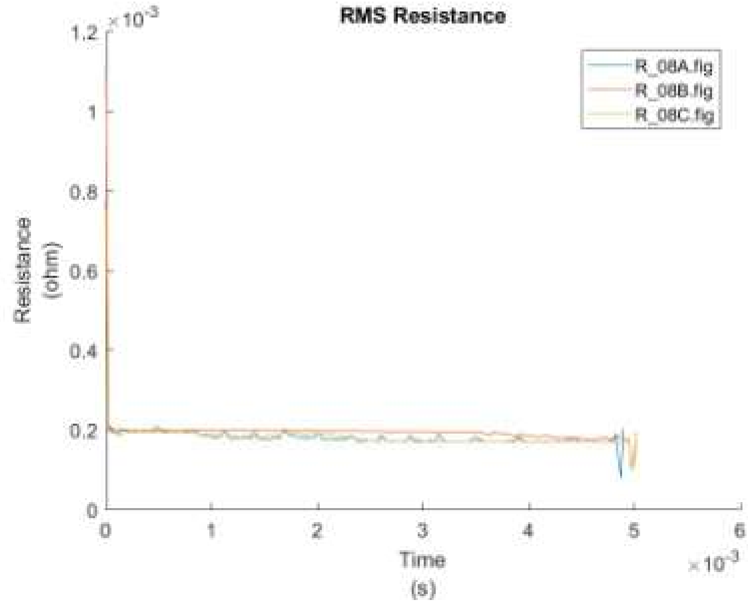


Figure: Resistance Test 8

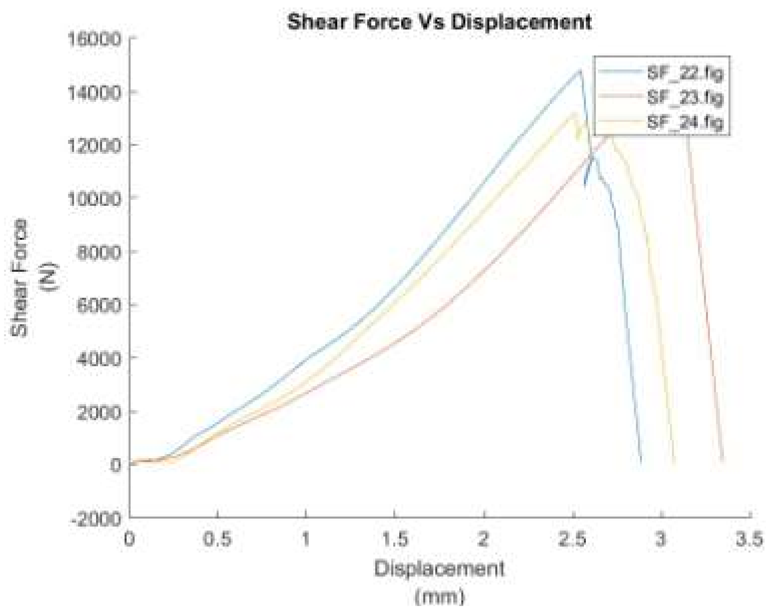


Figure: Shear tension test 8

Test 9

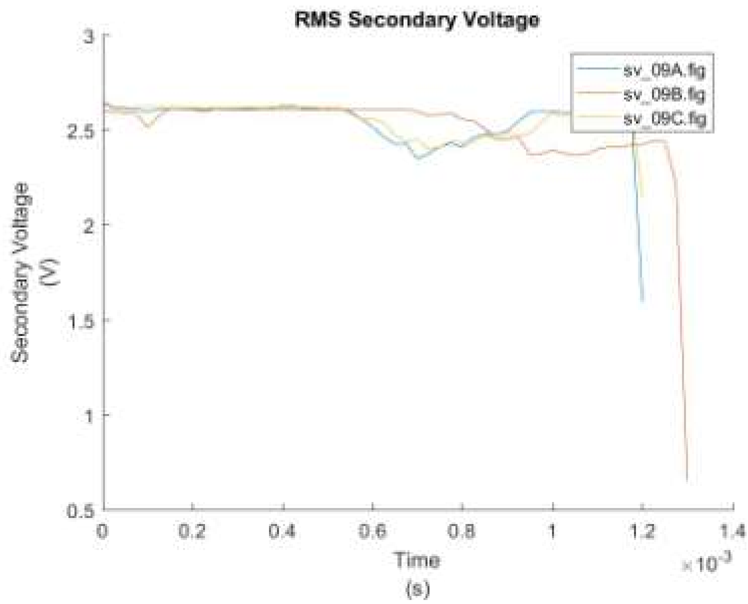


Figure: Secondary Voltage Test 9

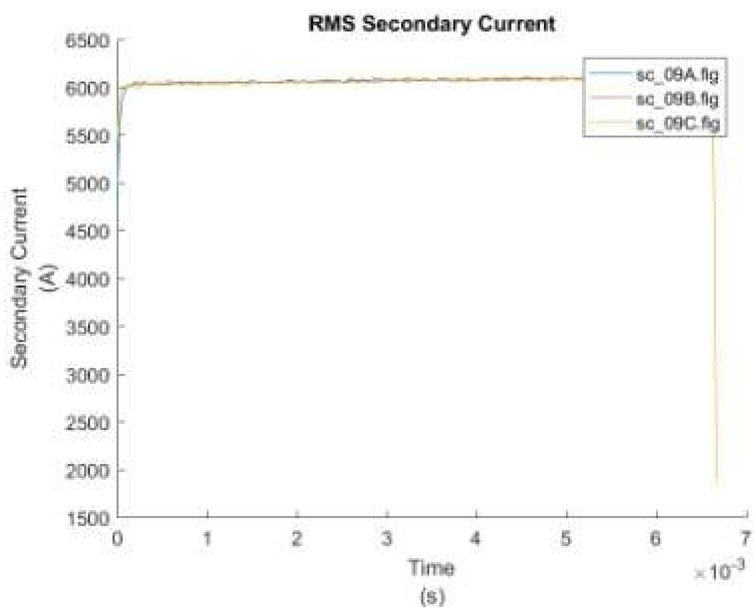


Figure: Secondary Current Test 9

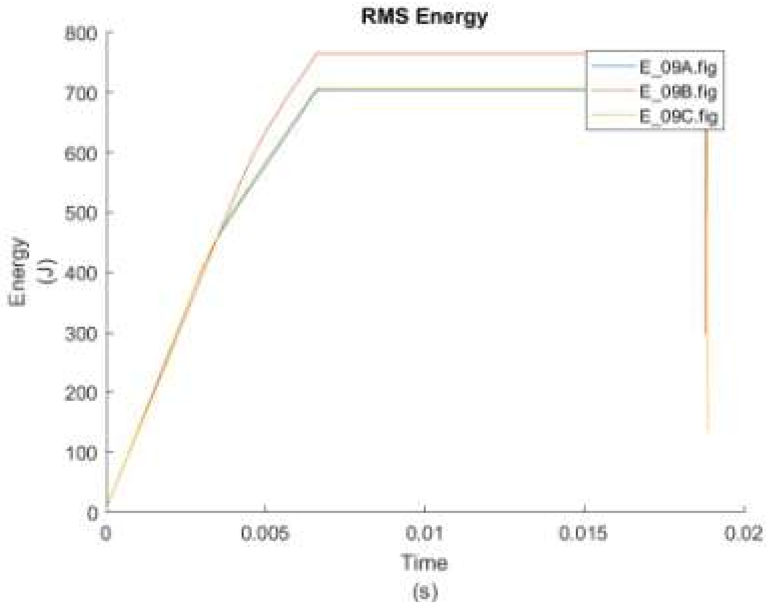


Figure: Energy Test 9

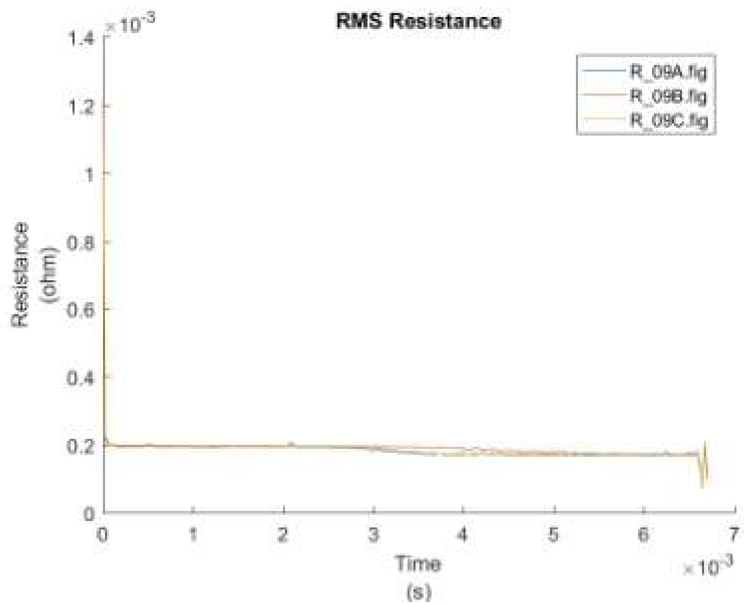


Figure: Resistance Test 9

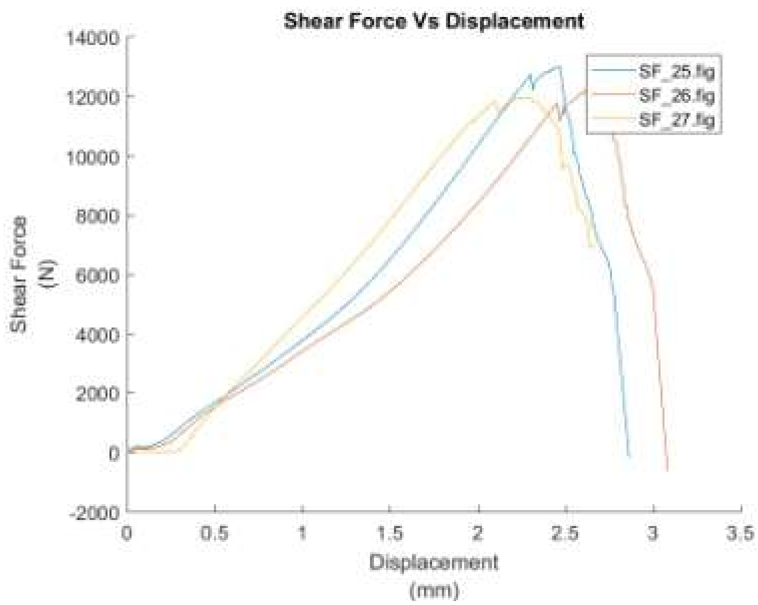


Figure: Shear tension test 9

Test 10

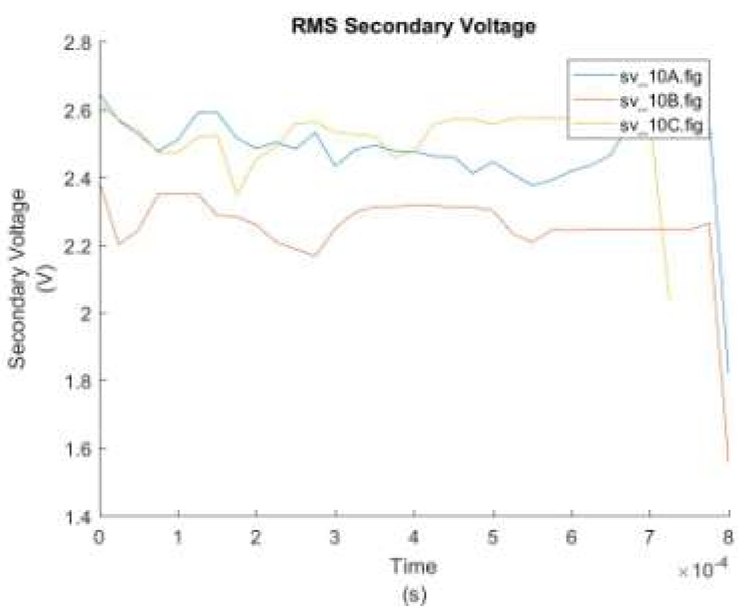


Figure: Secondary Voltage Test 10

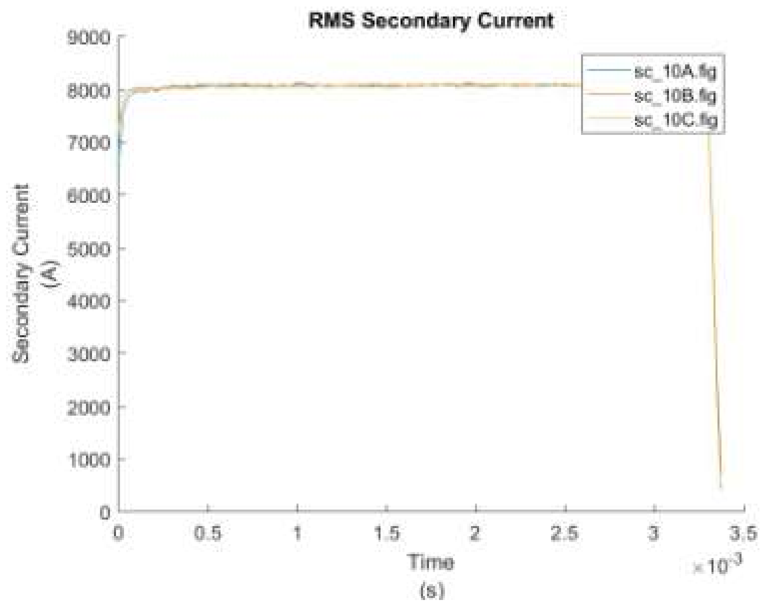


Figure: Secondary Current Test 10

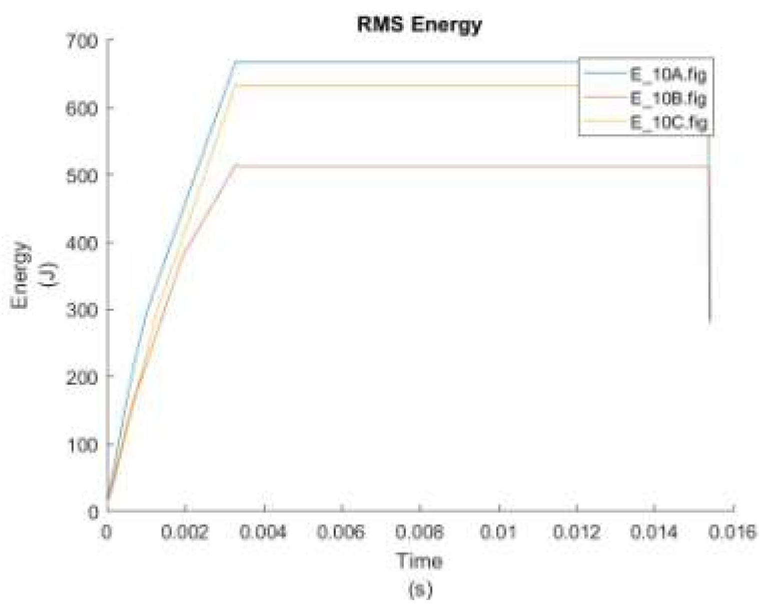


Figure: Energy Test 10

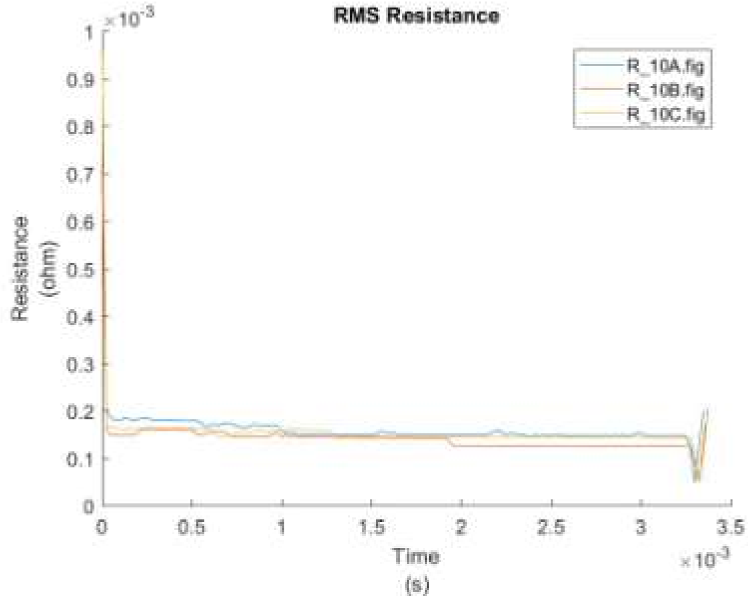


Figure: Resistance Test 10

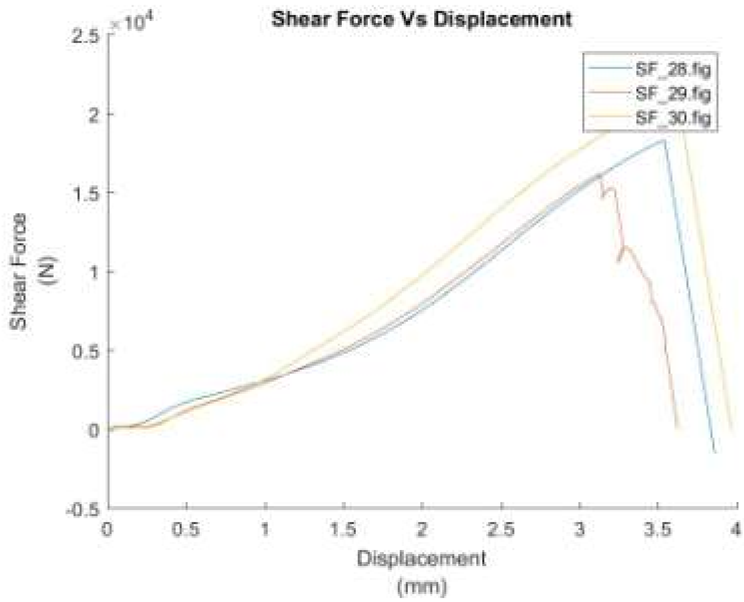


Figure: Shear tension test 10

Test 11

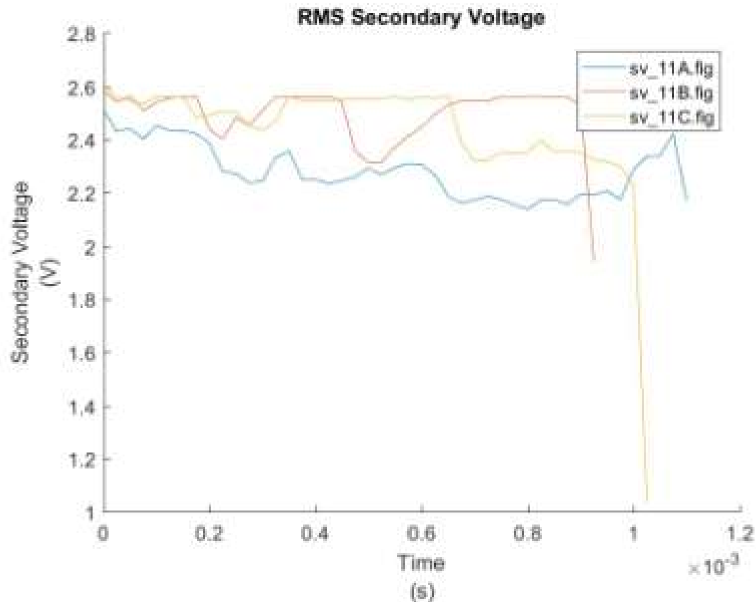


Figure: Secondary Voltage Test 11

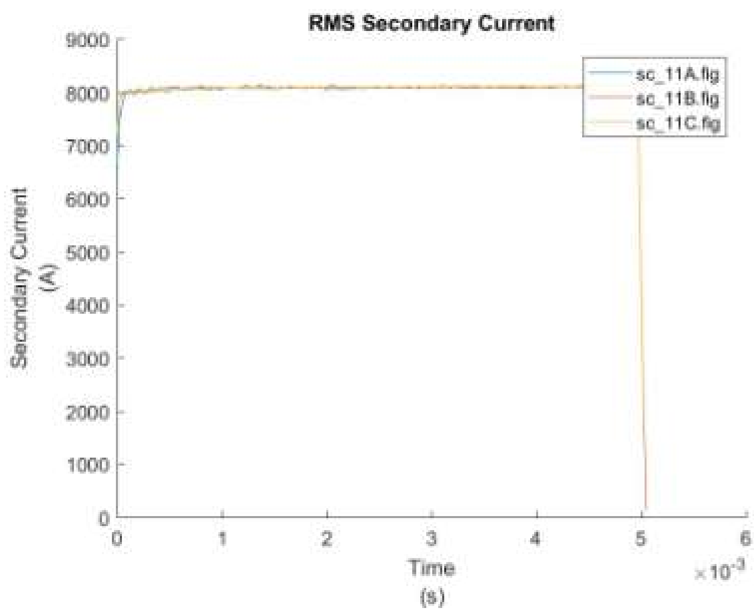


Figure: Secondary Current Test 11

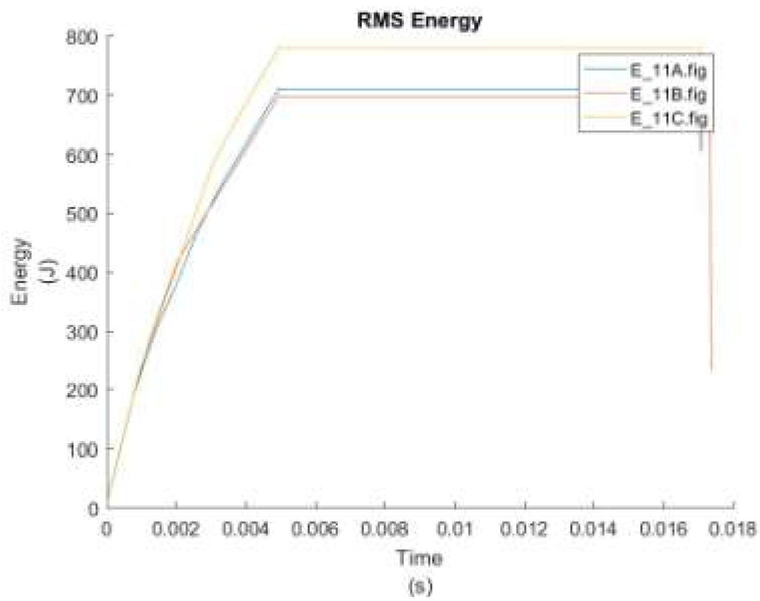


Figure: Energy Test 11

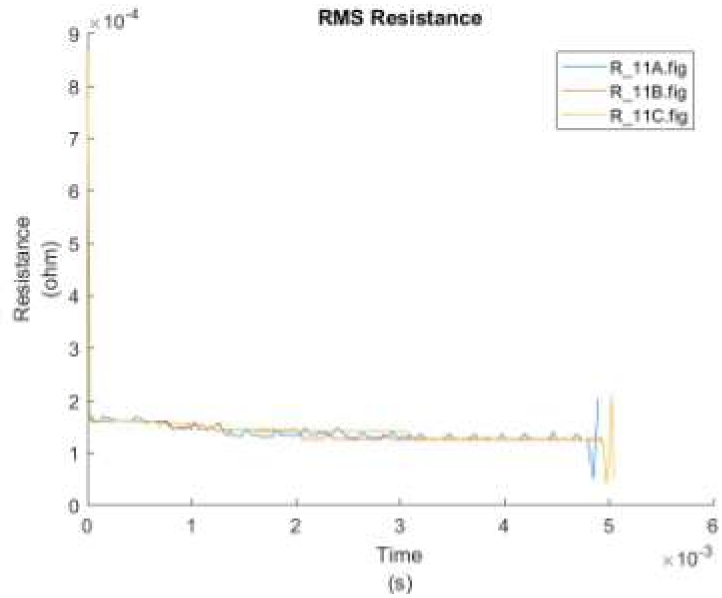


Figure: Resistance Test 11

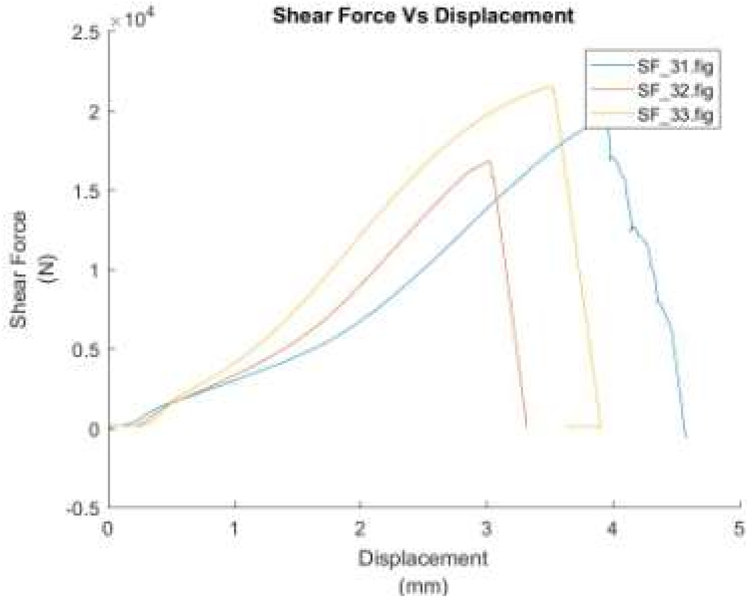


Figure: Shear tension test 11

Test 12

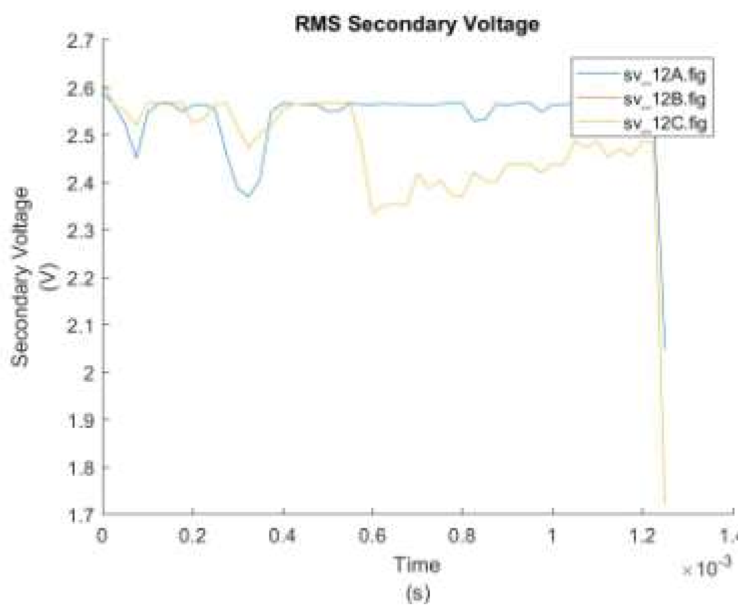


Figure: Secondary Voltage Test 12

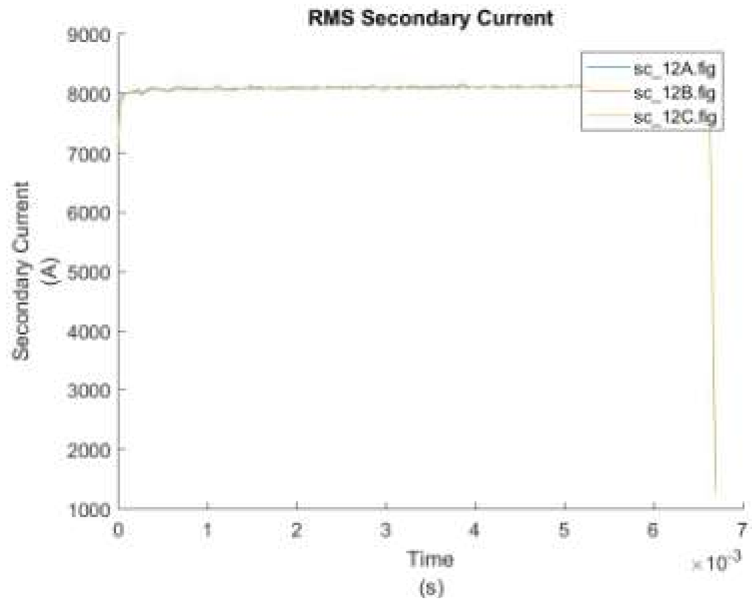


Figure: Secondary Current Test 12

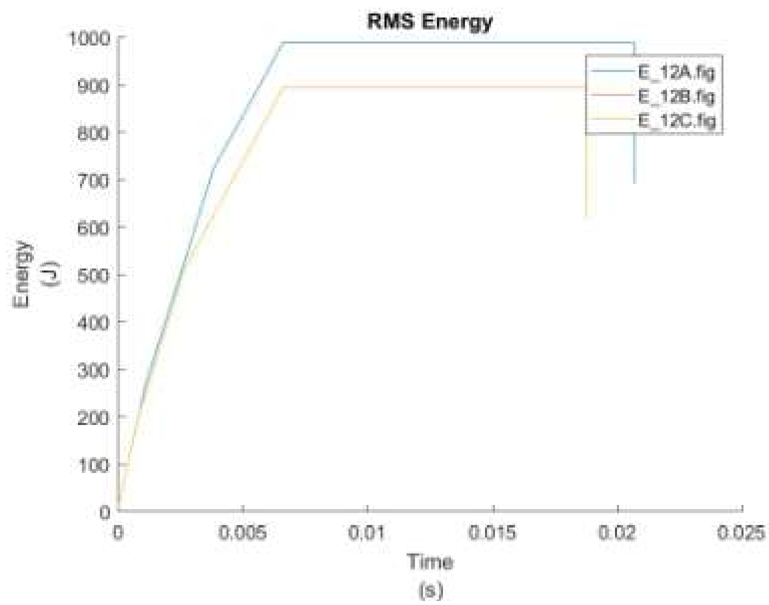


Figure: Energy Test 12

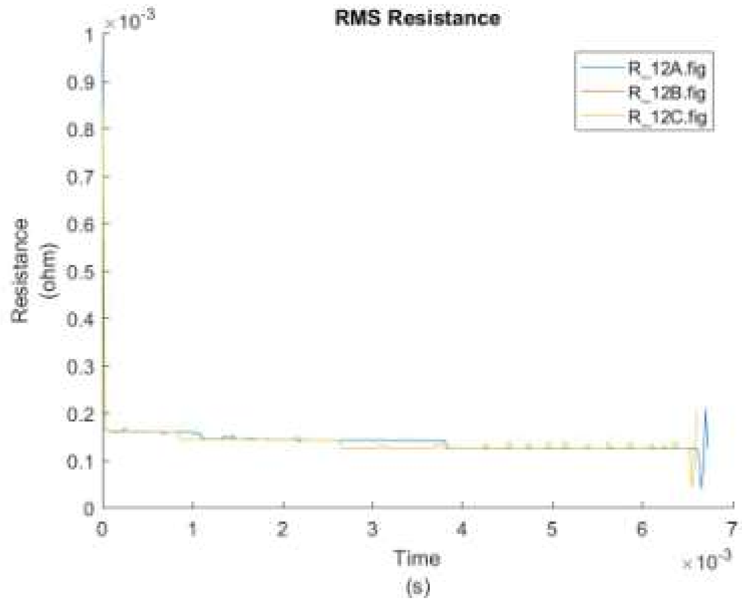


Figure: Resistance Test 12

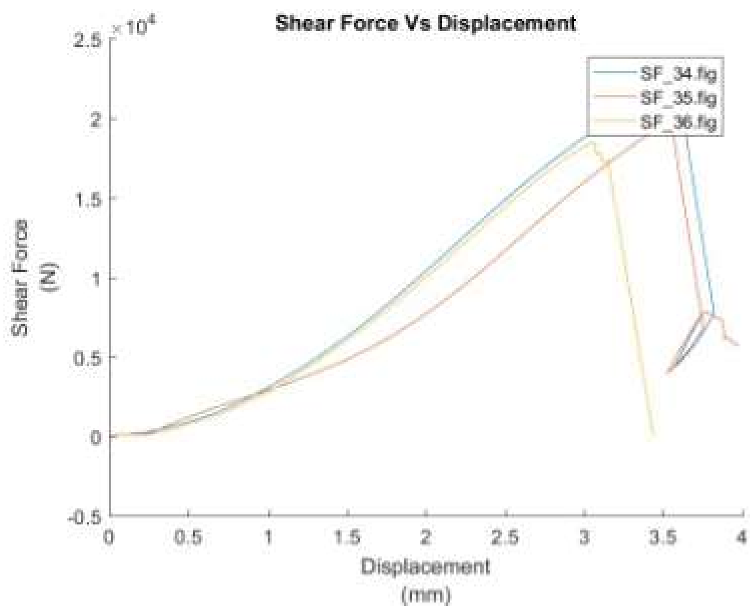


Figure: Shear tension test 12

Test 14

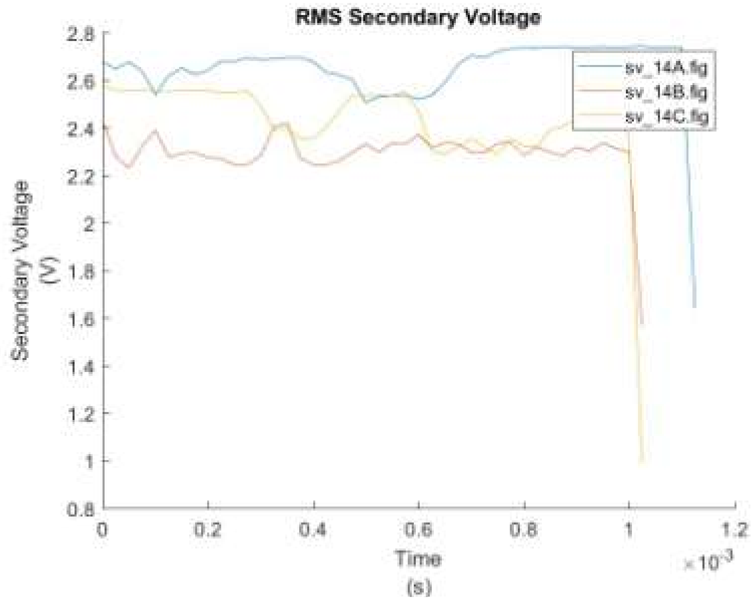
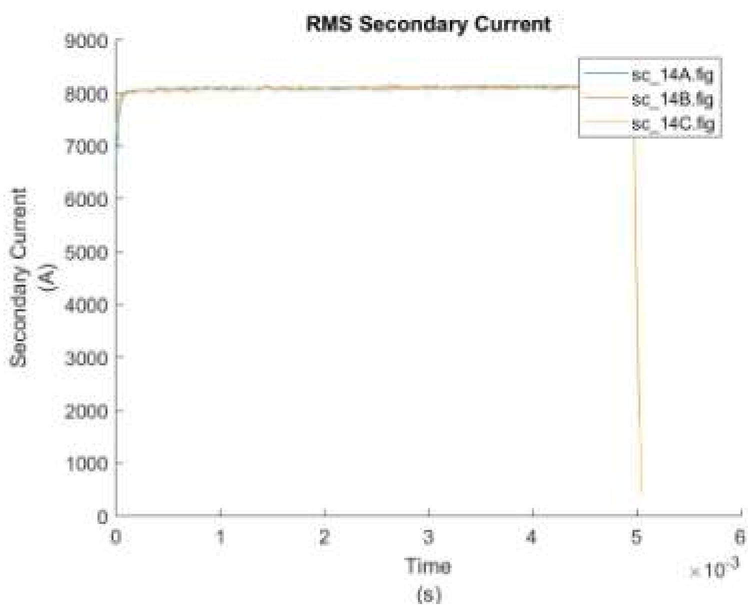


Figure: Secondary Voltage Test 14



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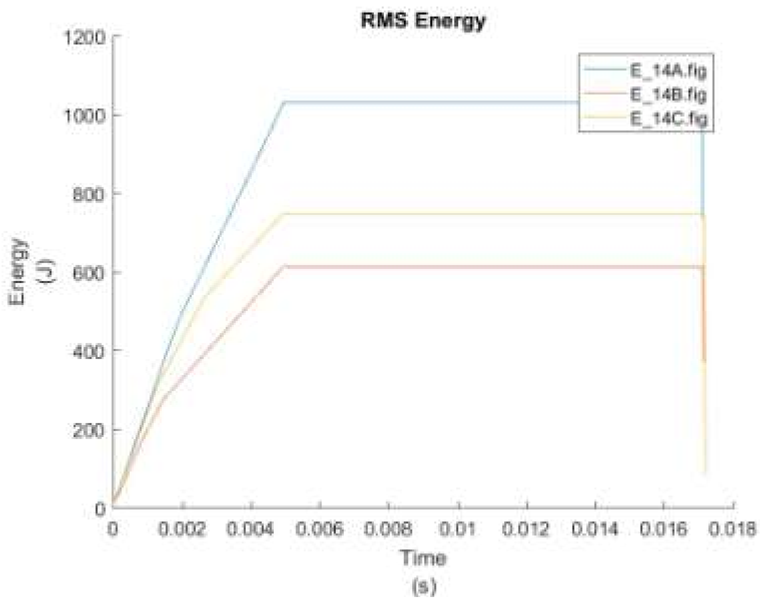

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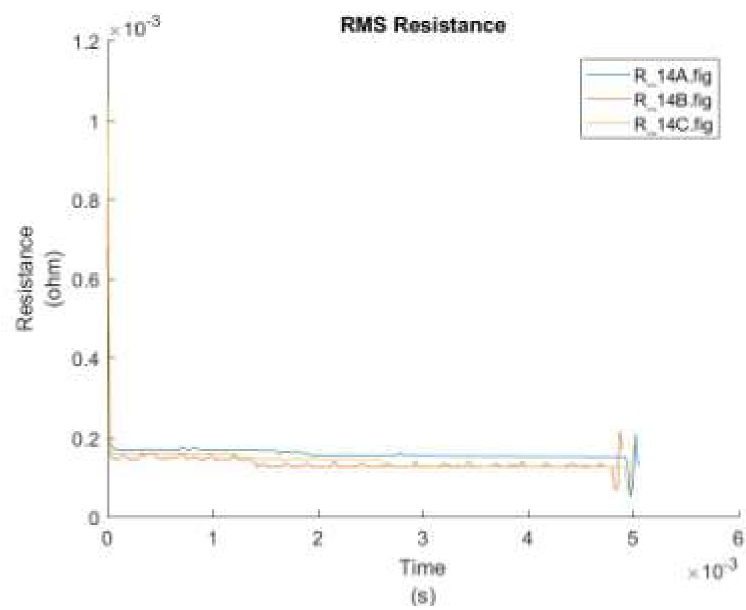


Figure: Resistance Test 14

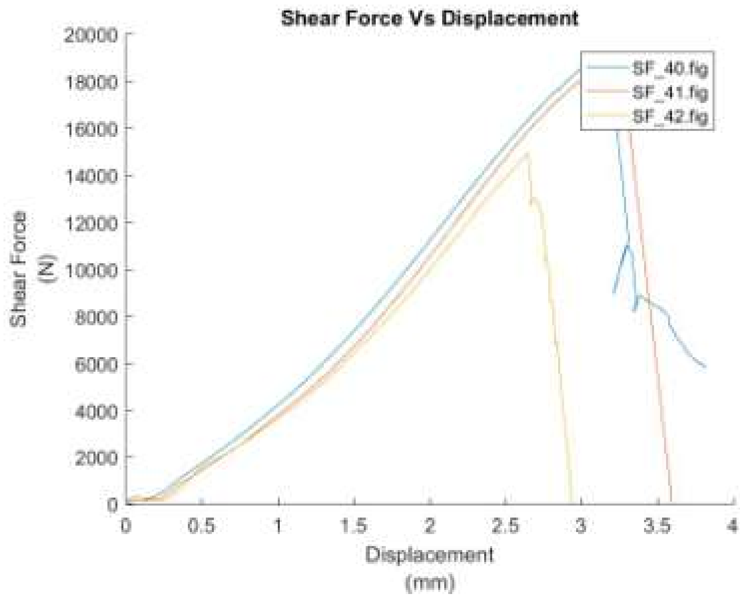


Figure: Shear tension test 14

Test 15

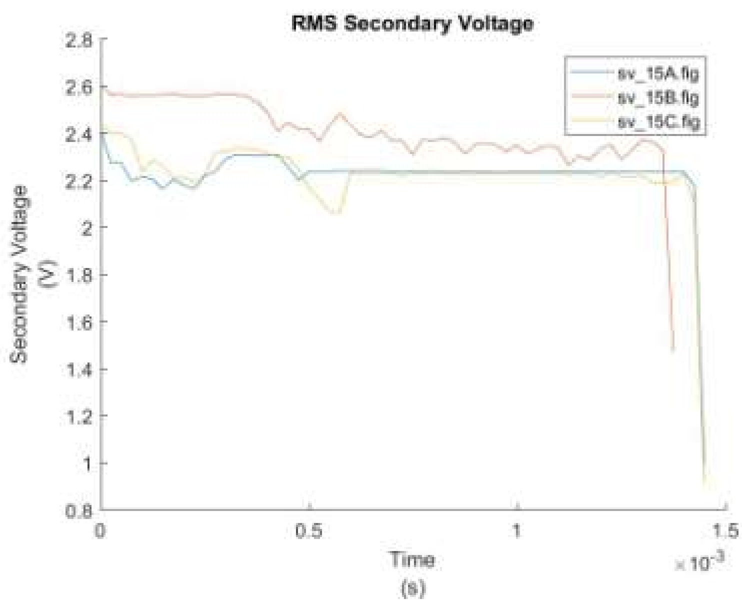


Figure: Secondary Voltage Test 15

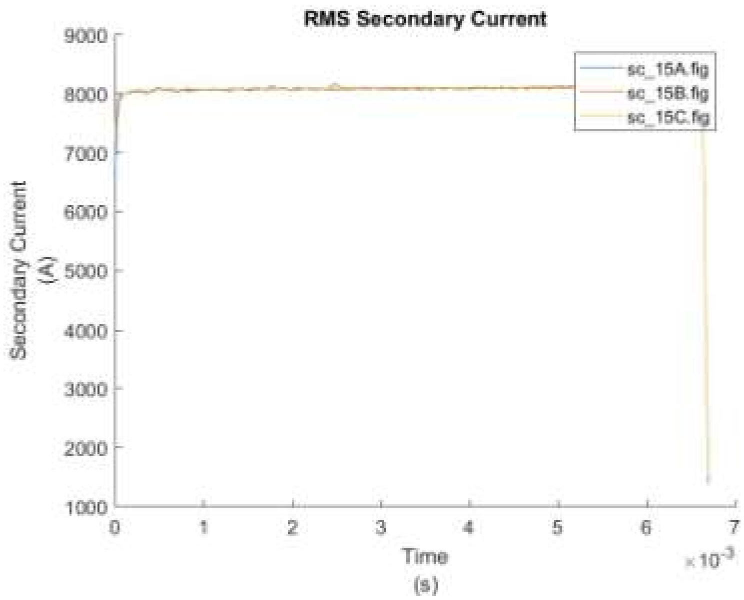


Figure: Secondary Current Test 15

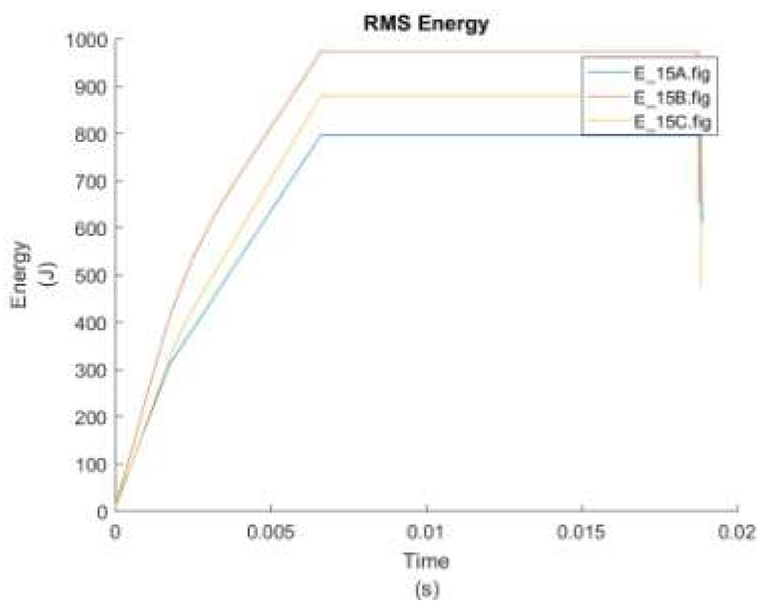


Figure: Energy Test 15

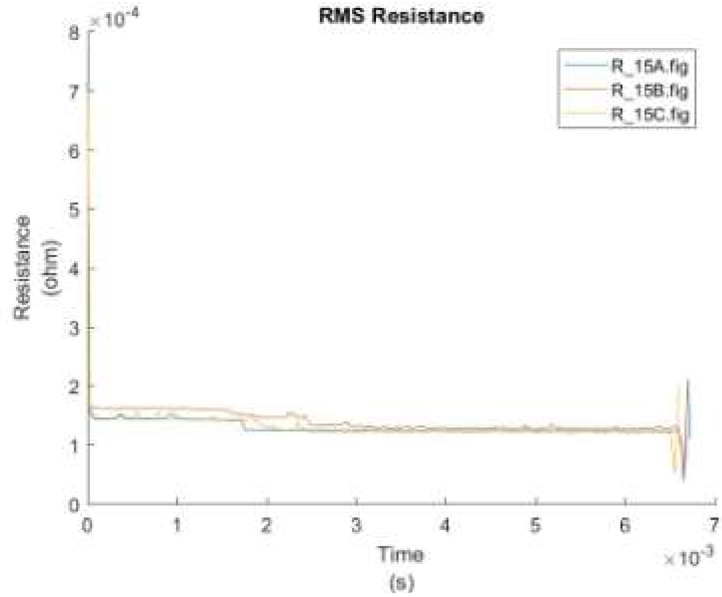


Figure: Resistance Test 15

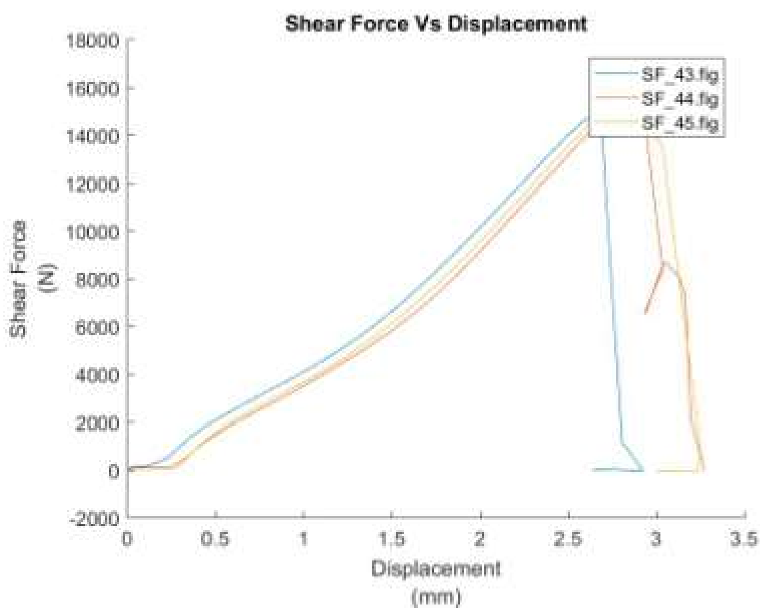


Figure: Shear tension test 15

Test 16

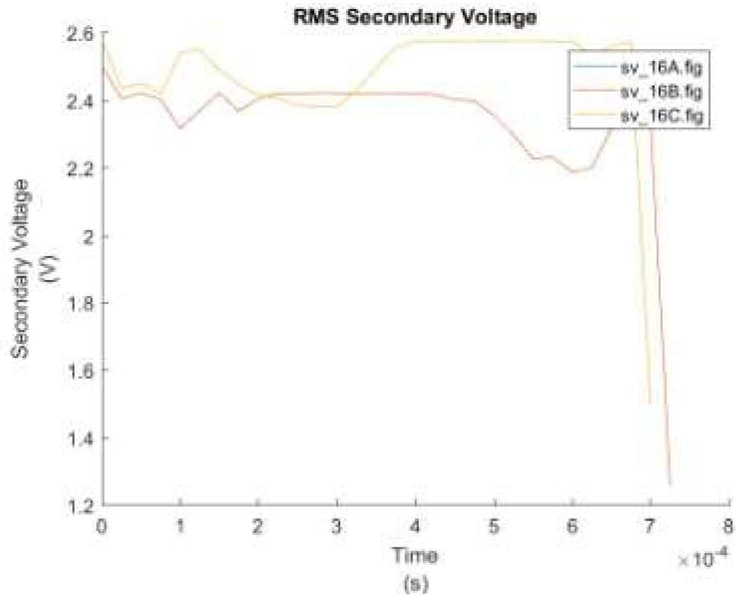
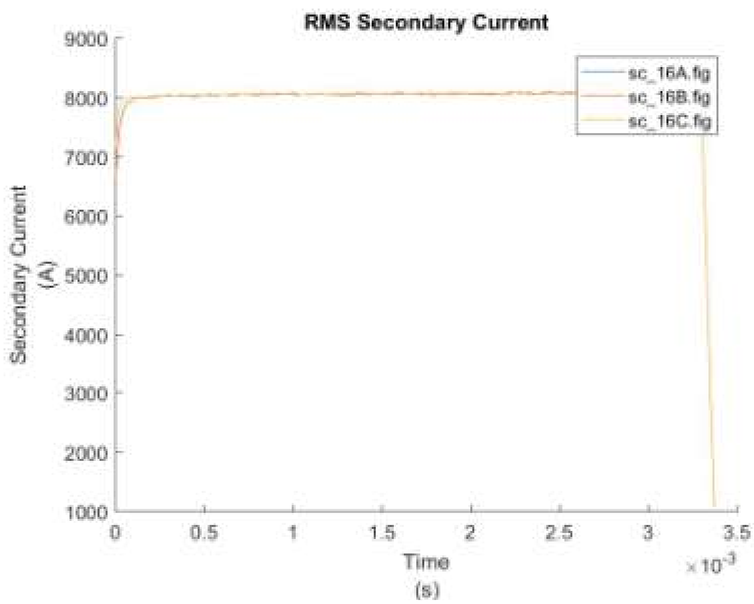


Figure: Secondary Voltage Test 16



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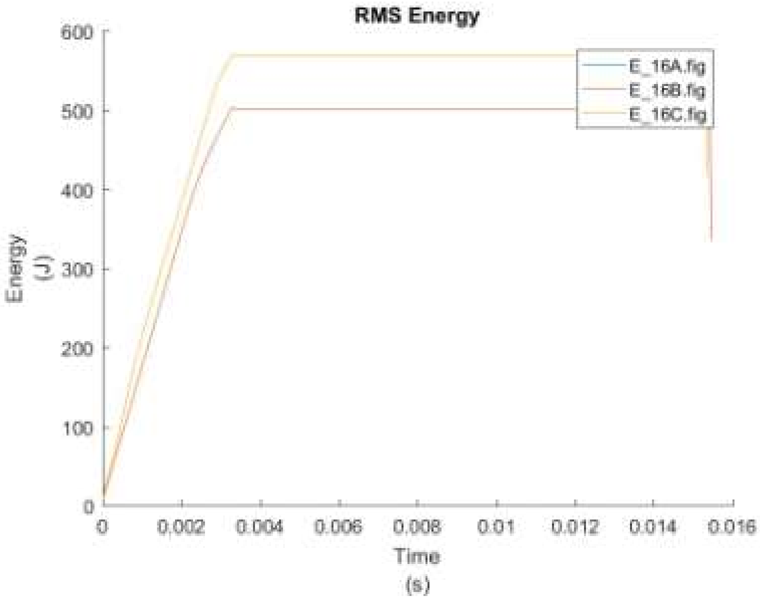


Figure: Energy Test 16

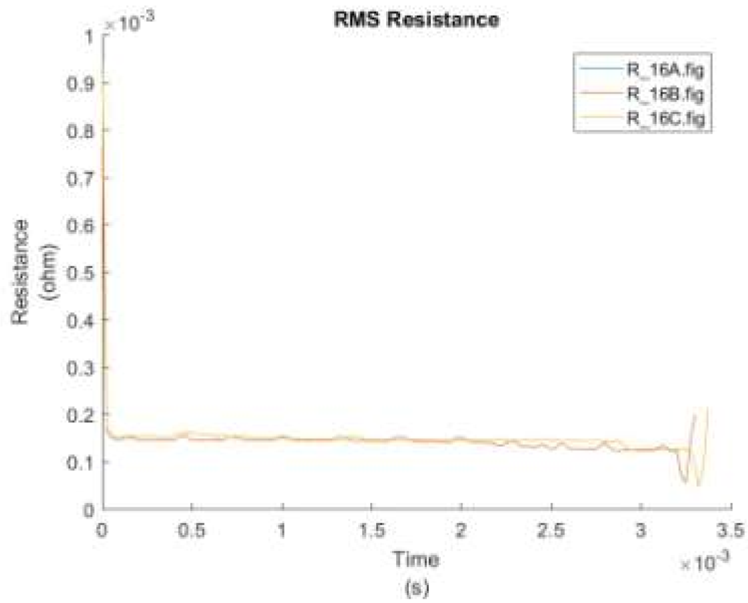


Figure: Resistance Test 16

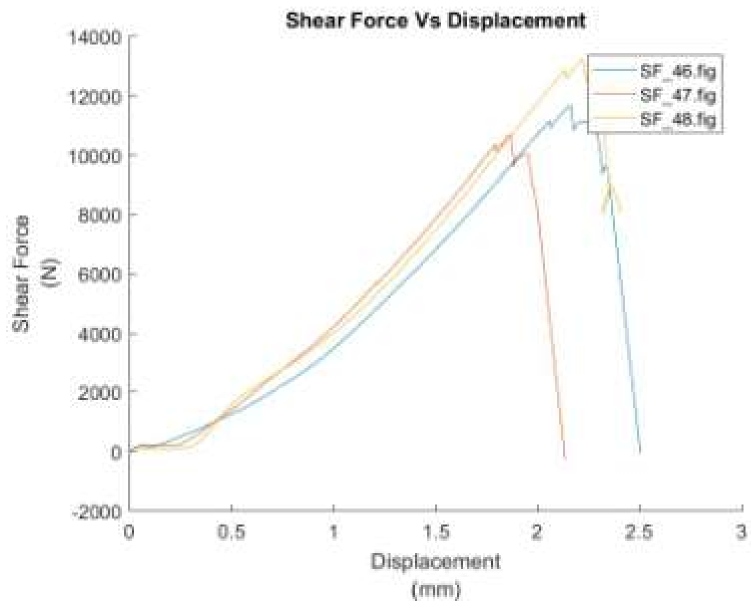


Figure: Shear tension test 16

Test 17

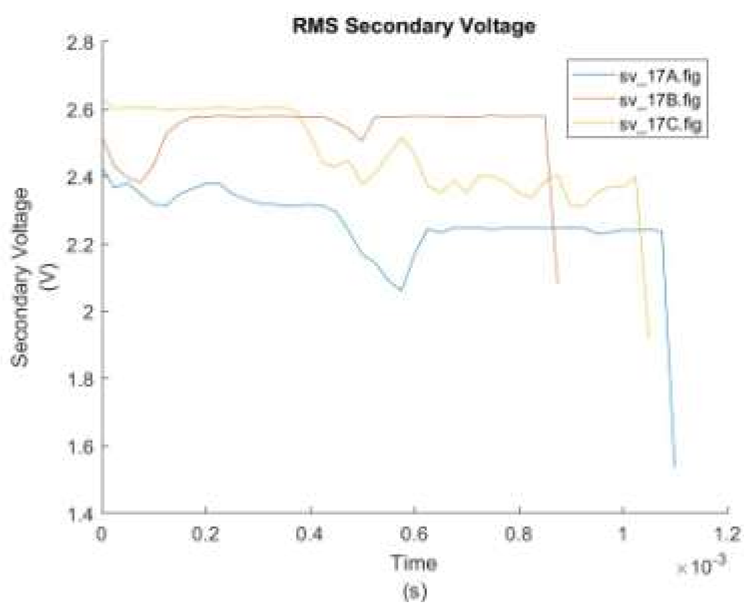
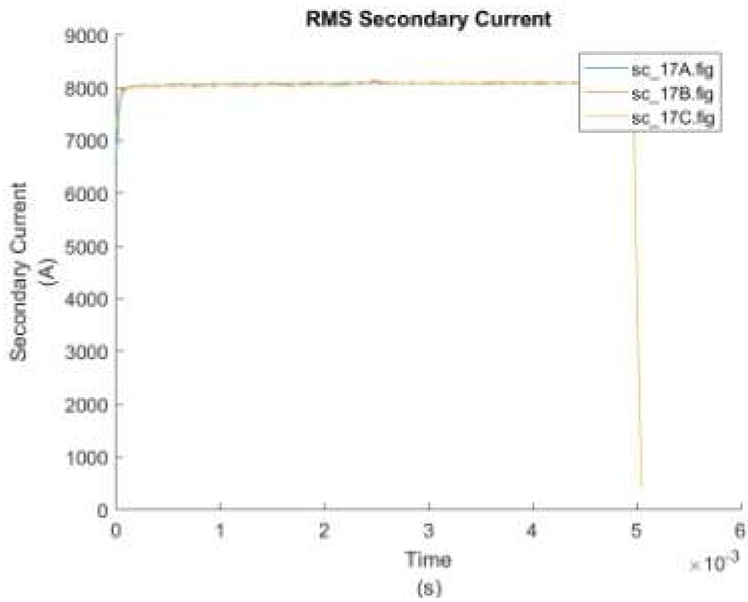


Figure: Secondary Voltage Test 17



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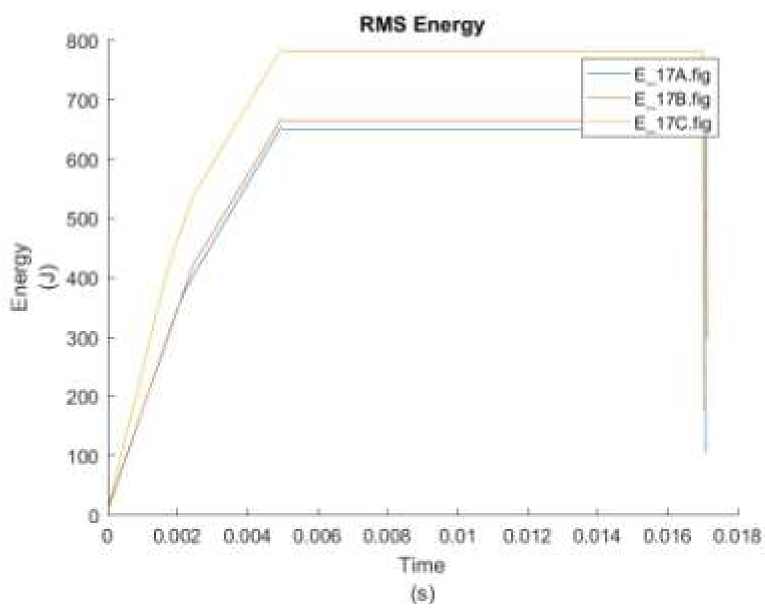

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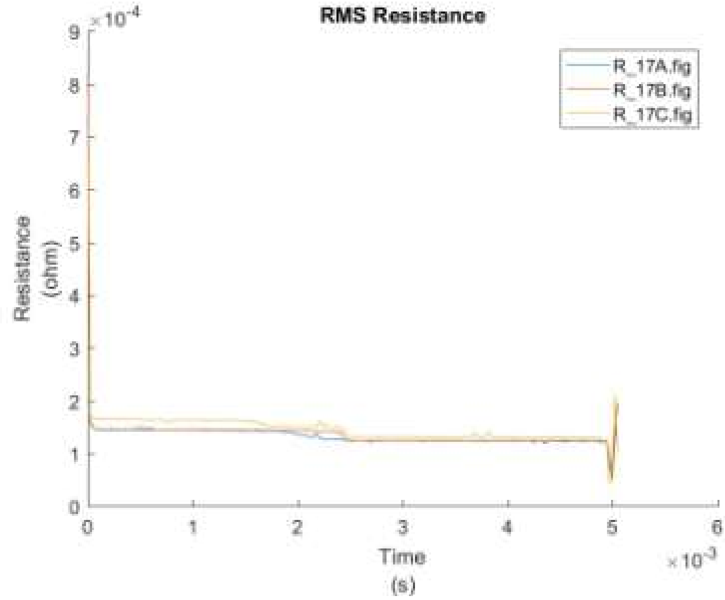


Figure: Resistance Test 17

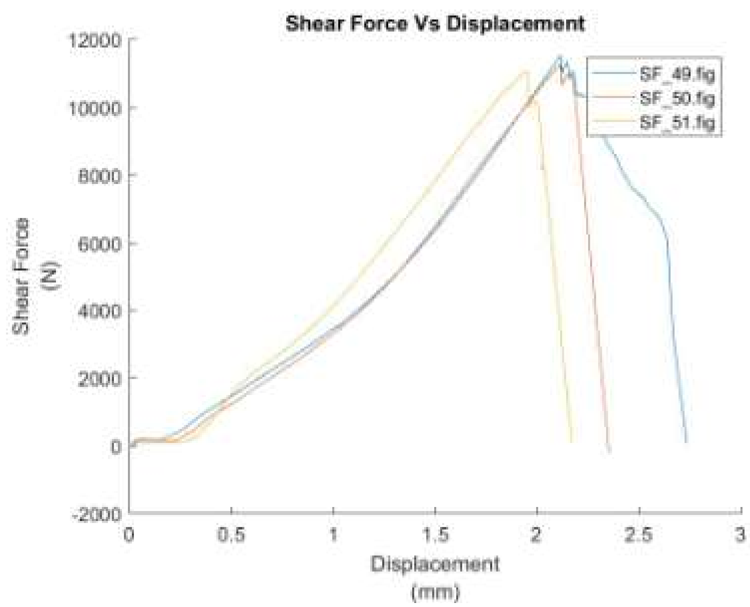


Figure: Shear tension test 17

Test 18

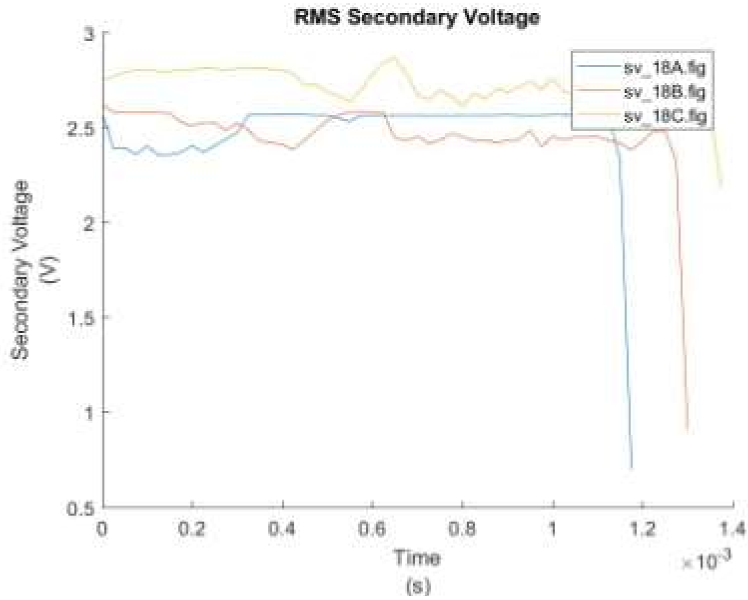
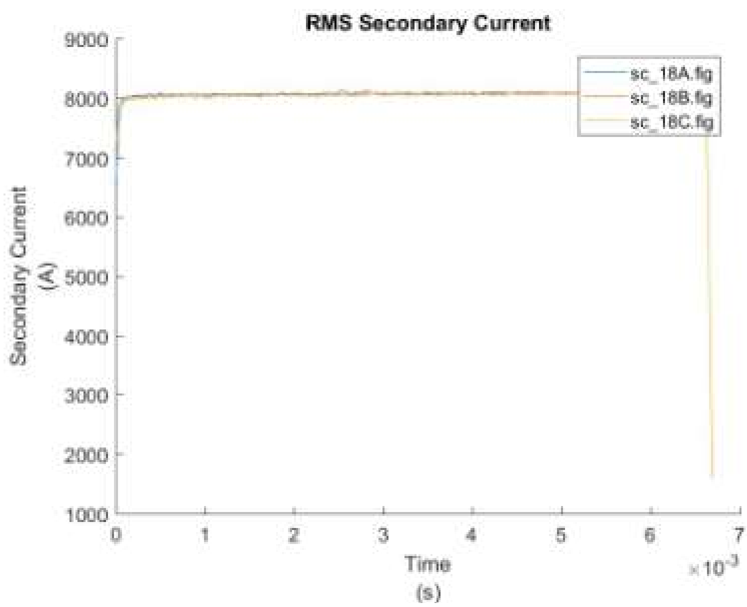


Figure: Secondary Voltage Test 18



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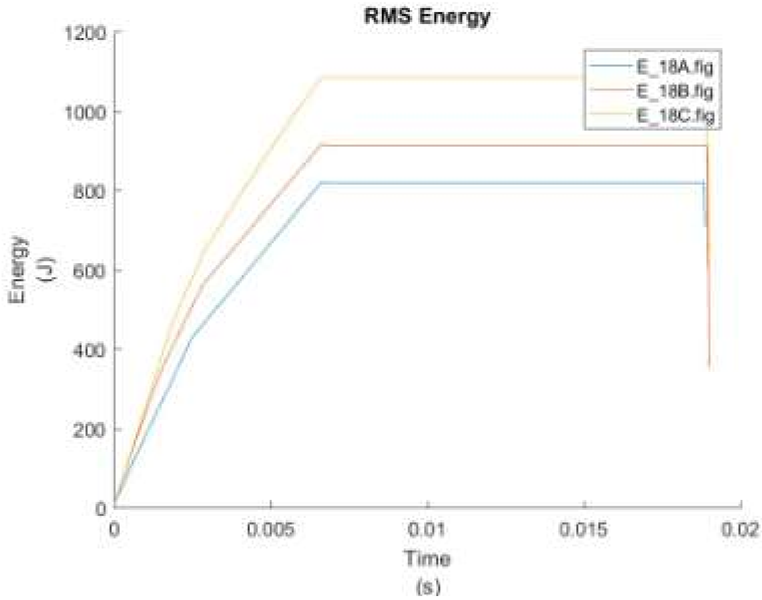

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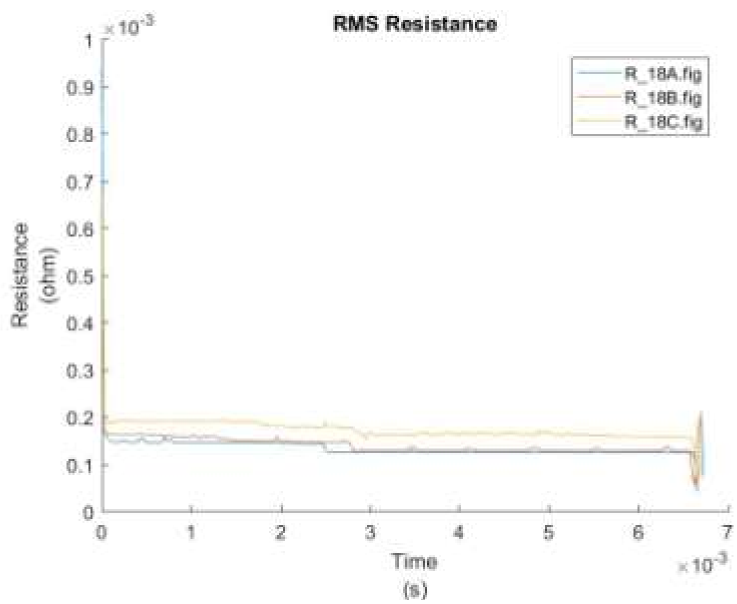


Figure: Resistance Test 18

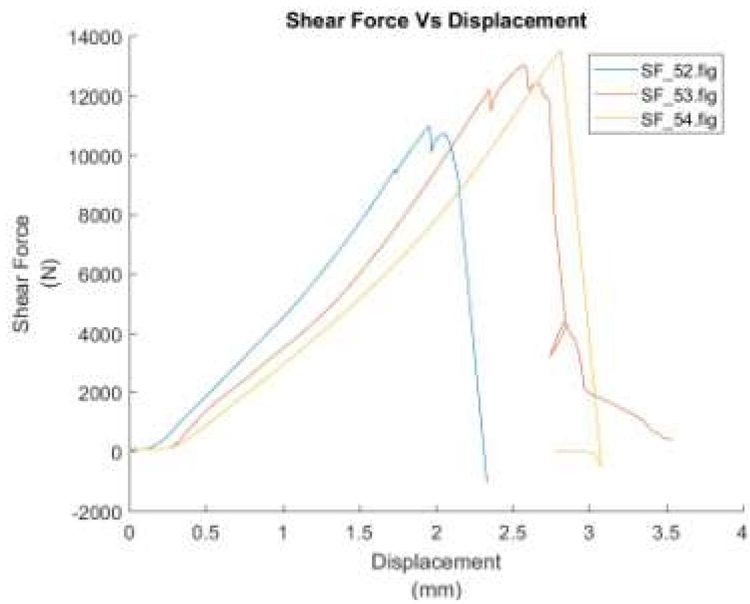


Figure: Shear tension test 18

Test 19

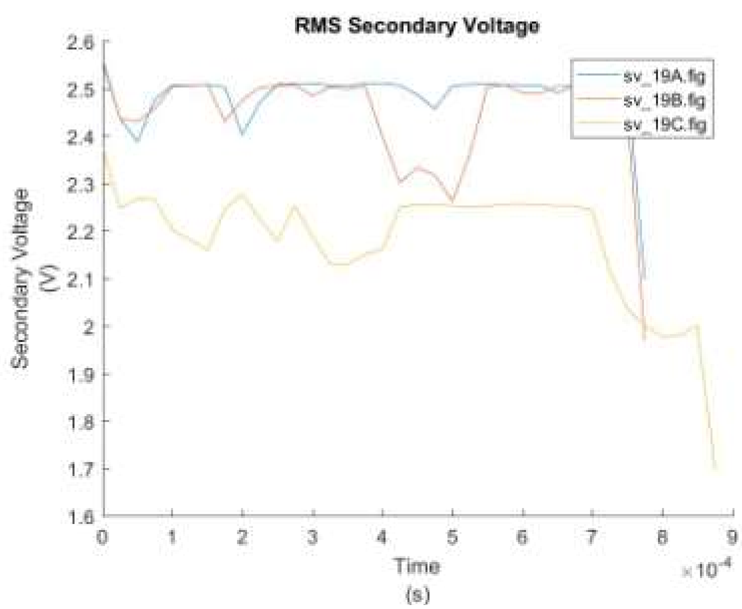
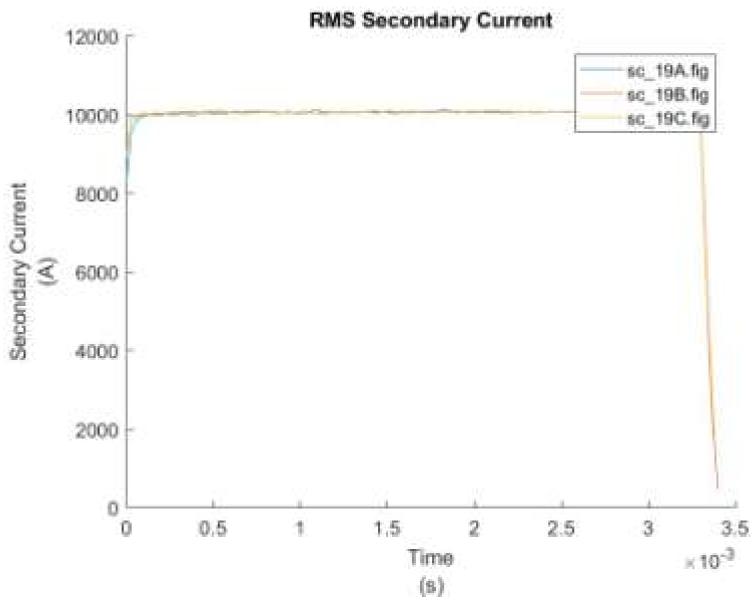


Figure: Secondary Voltage Test 19



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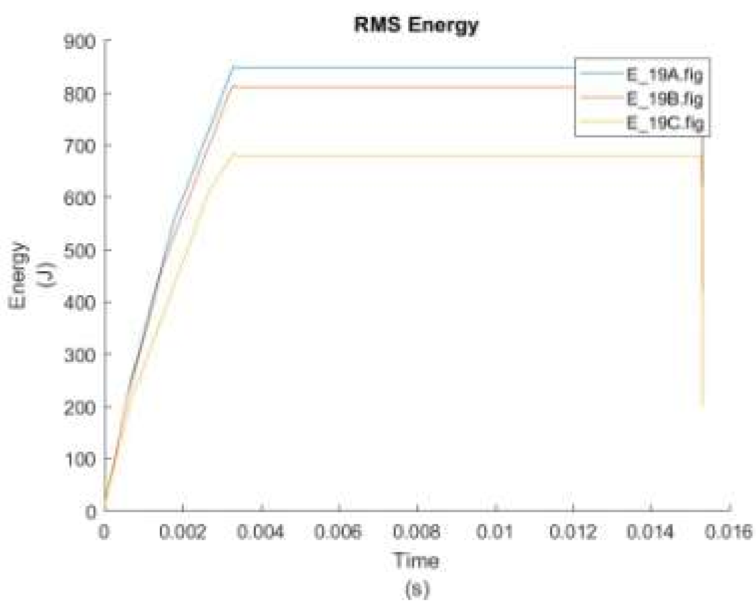


Figure: Energy Test 19

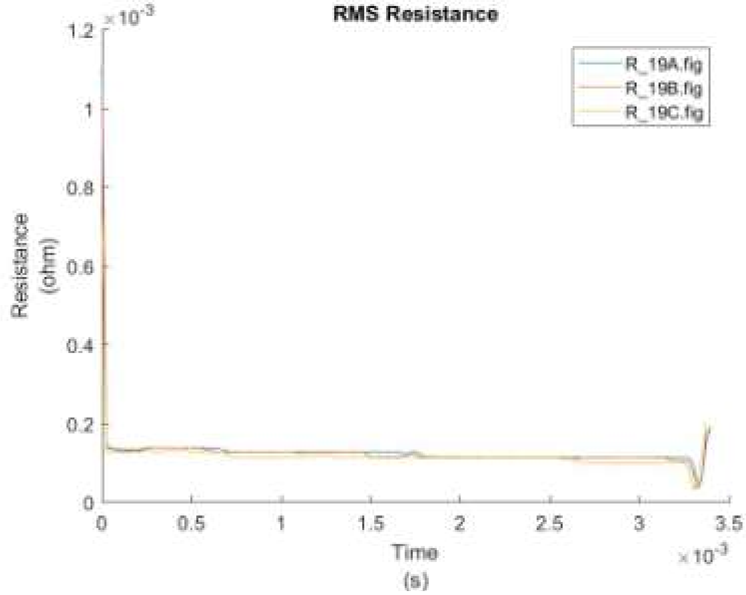


Figure: Resistance Test 19

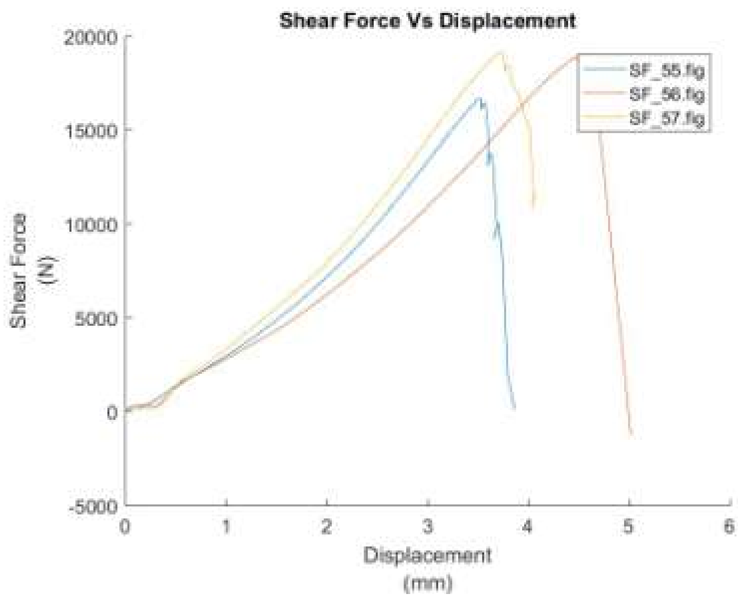


Figure: Shear tension test 19

Test 20

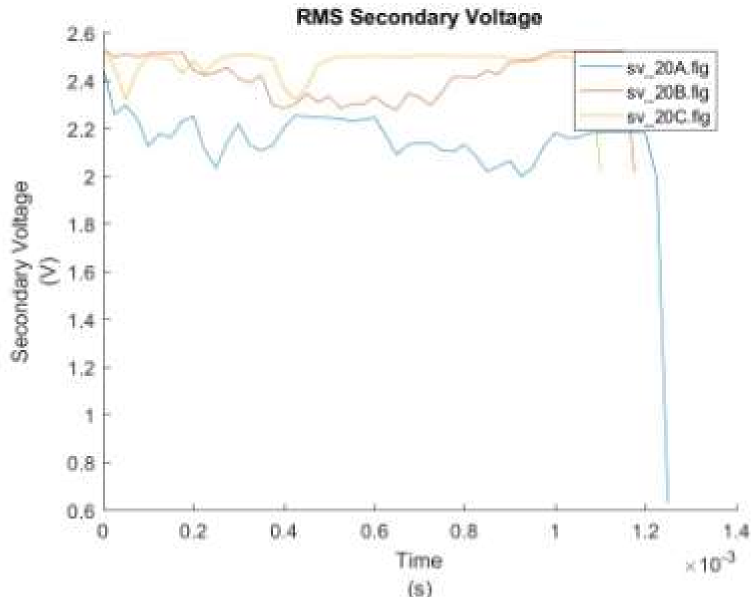


Figure: Secondary Voltage Test 20

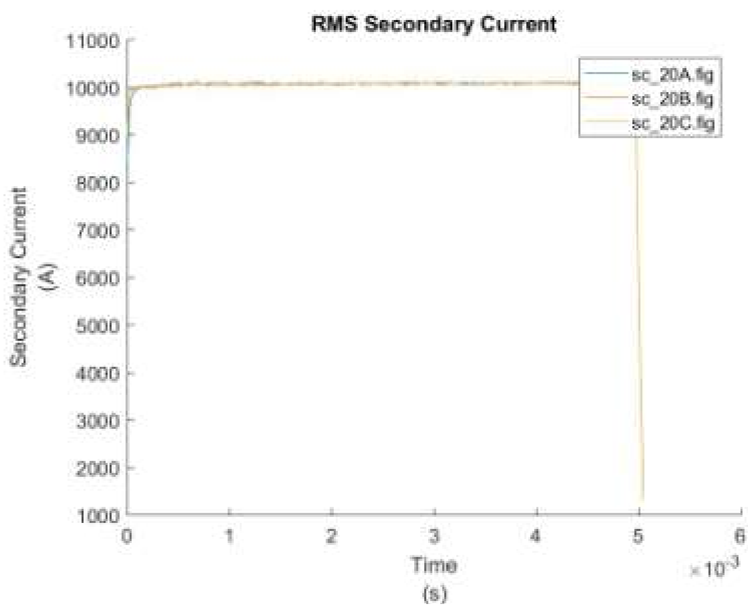


Figure: Secondary Current Test 20

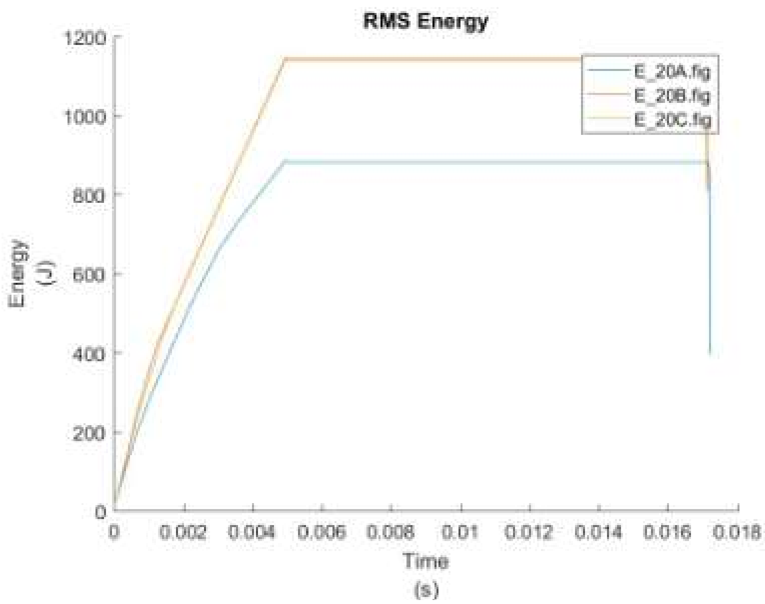


Figure: Energy Test 20

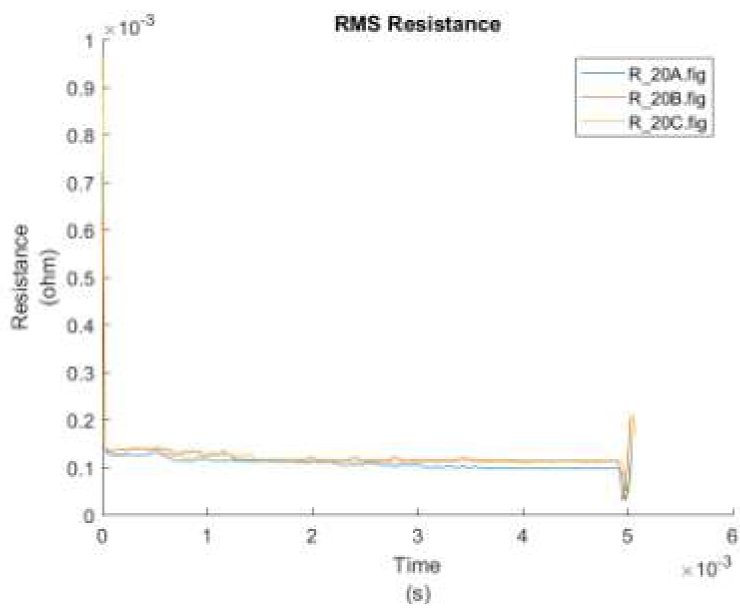


Figure: Resistance Test 20

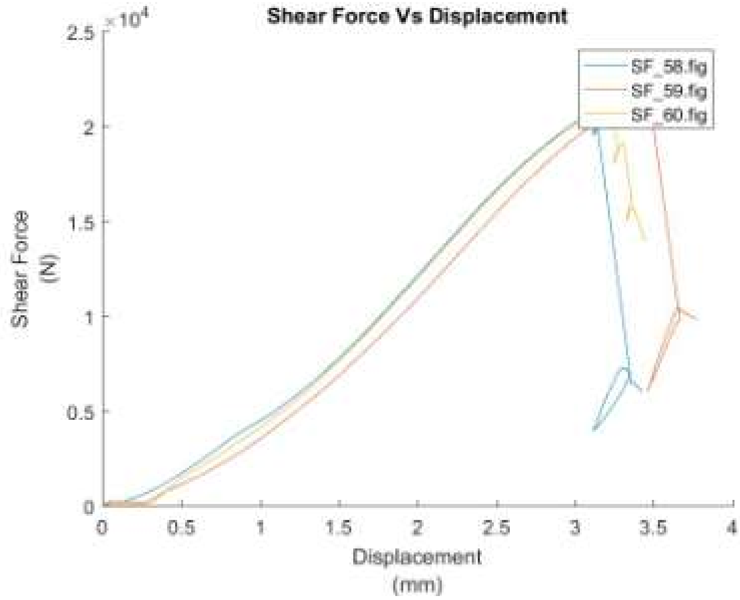


Figure: Shear tension test 20

Test 21

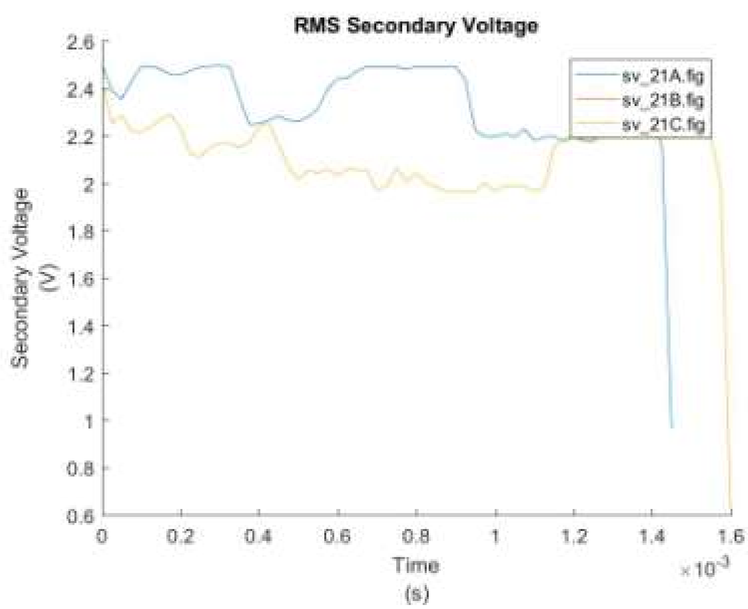


Figure: Secondary Voltage Test 21

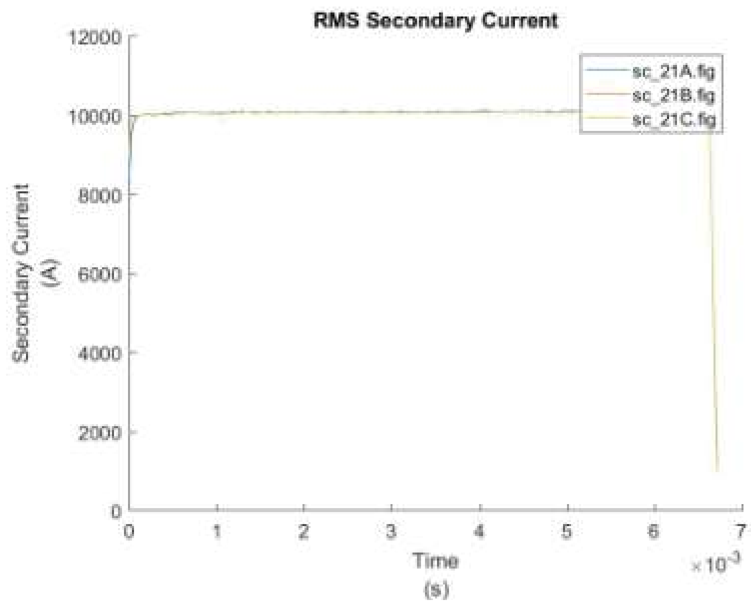


Figure: Secondary Current Test 21

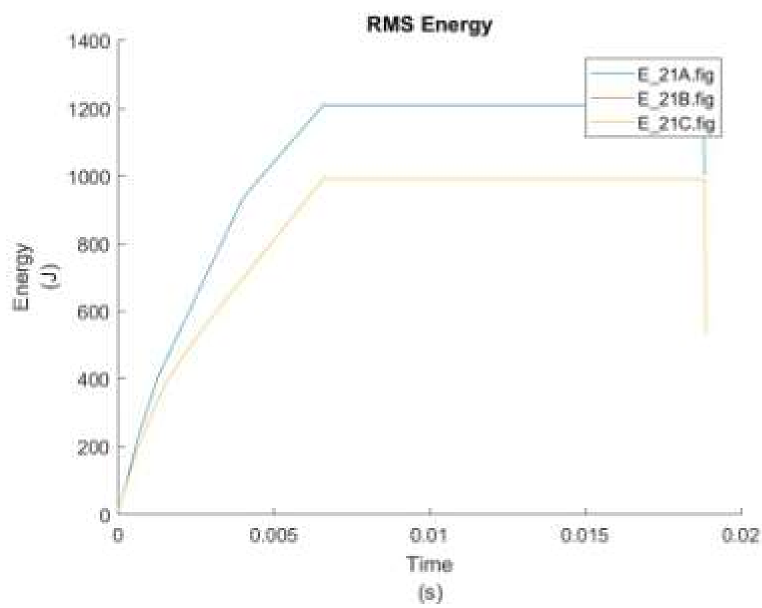


Figure: Energy Test 21

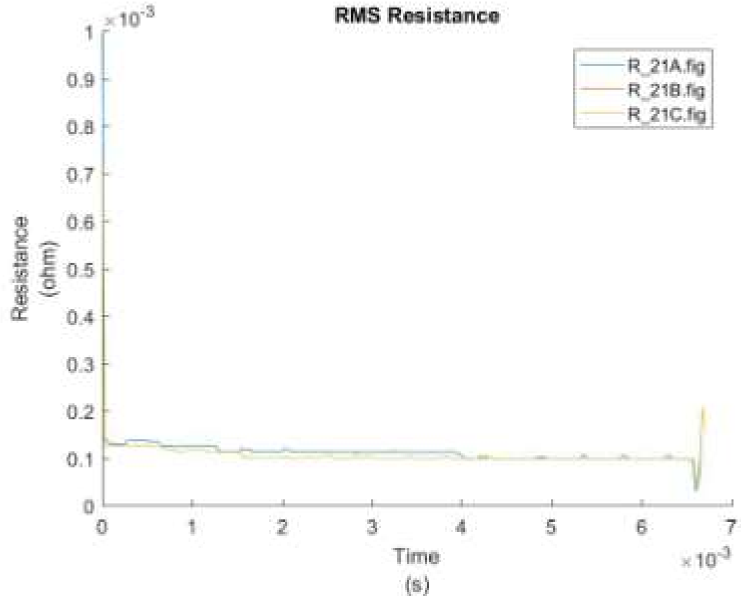


Figure: Resistance Test 21

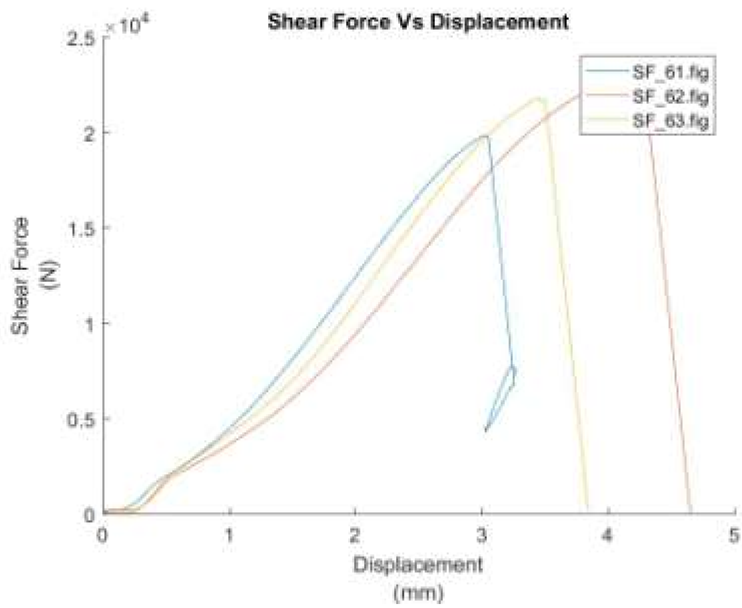
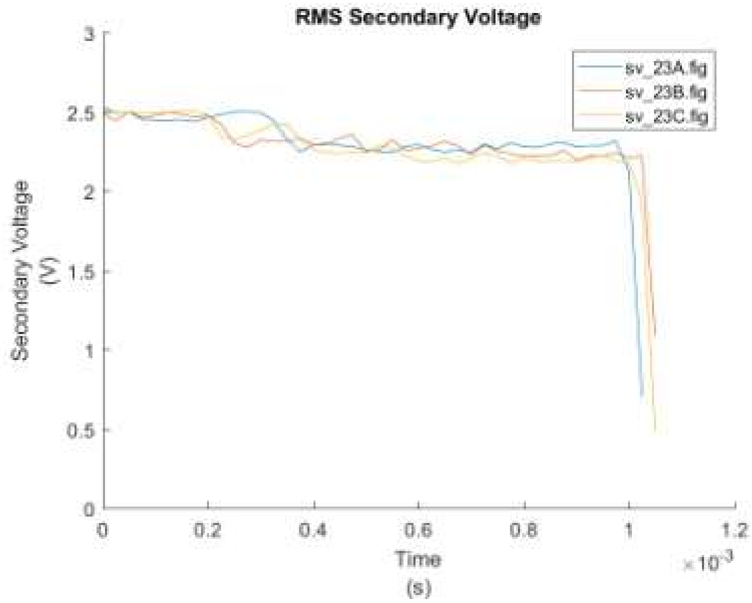


Figure: Shear tension test 21

Test 23



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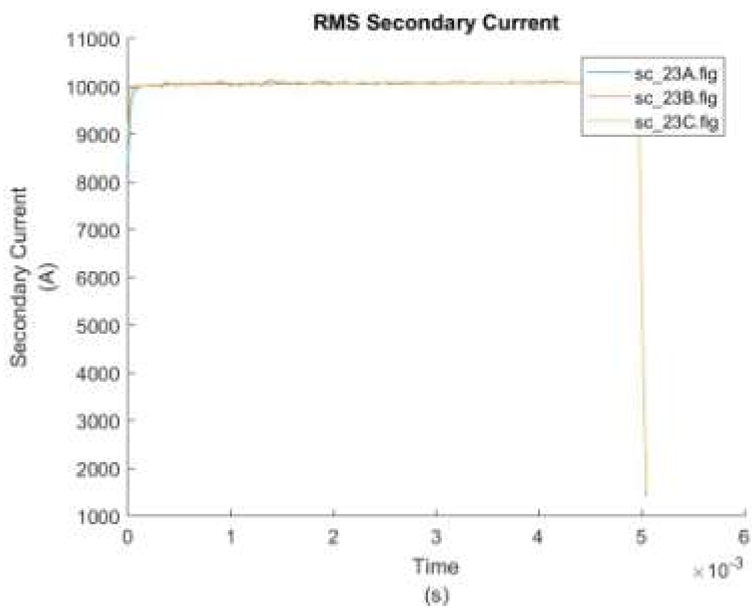

Figure: Secondary Current Test 23

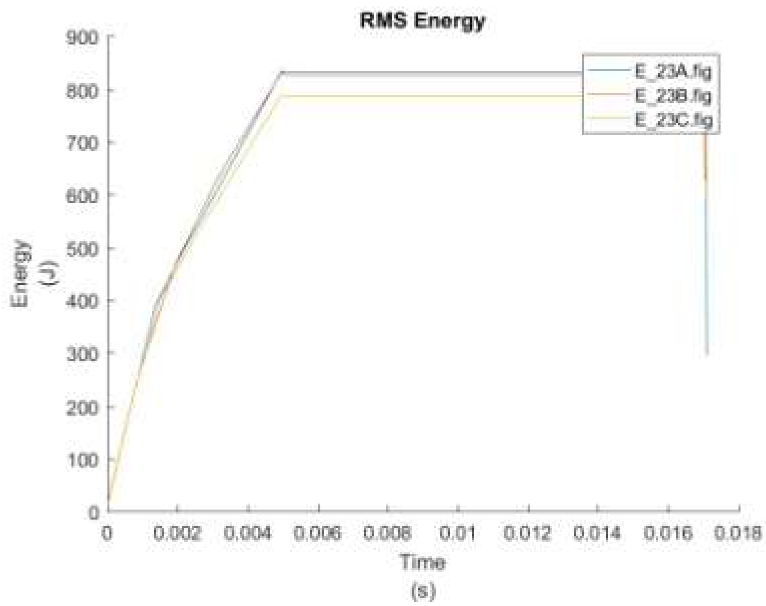

Figure: Energy Test 23

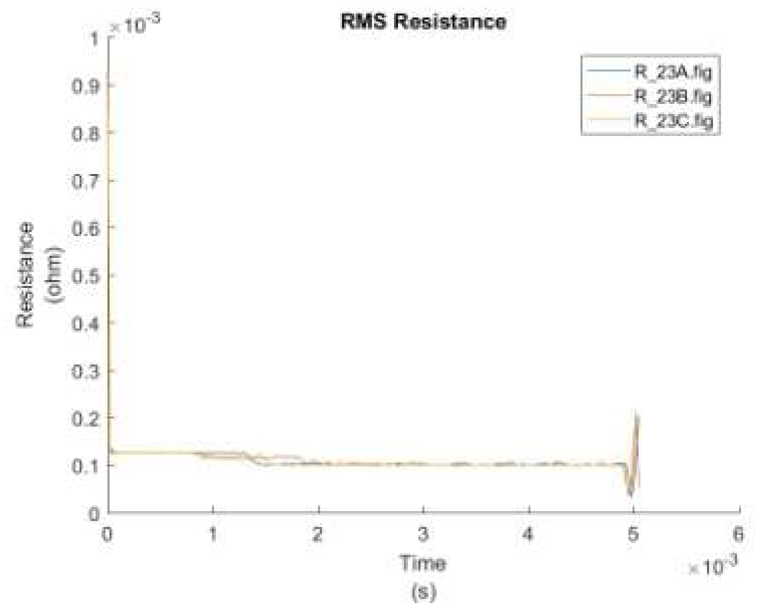

Figure: Resistance Test 23

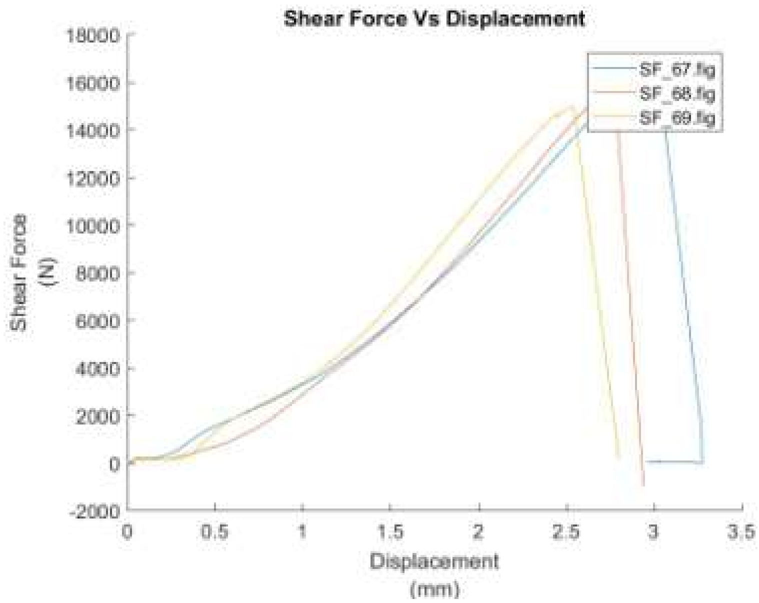

Figure: Shear tension test 23

Test 24

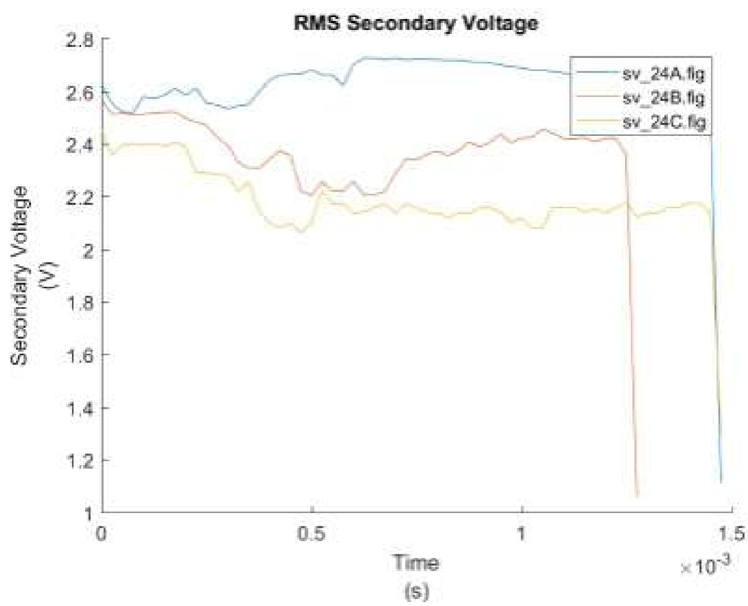

Figure: Secondary Voltage Test 24

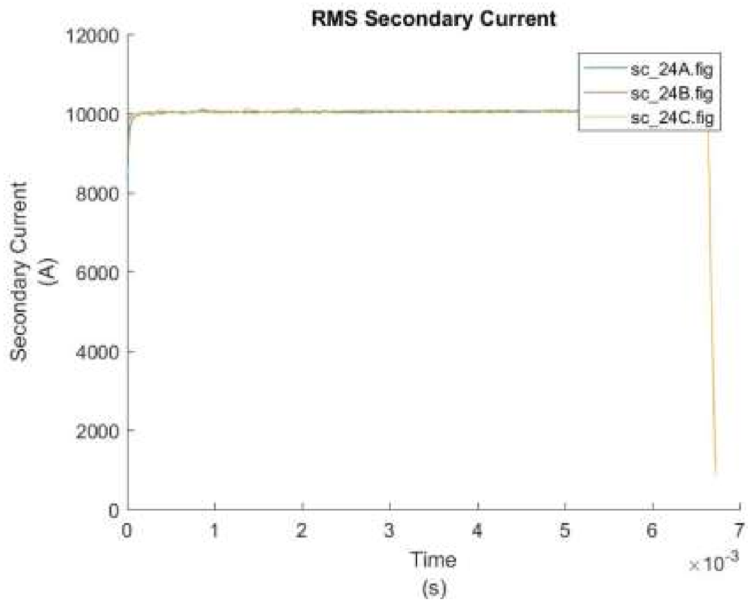

Figure: Secondary Current Test 24

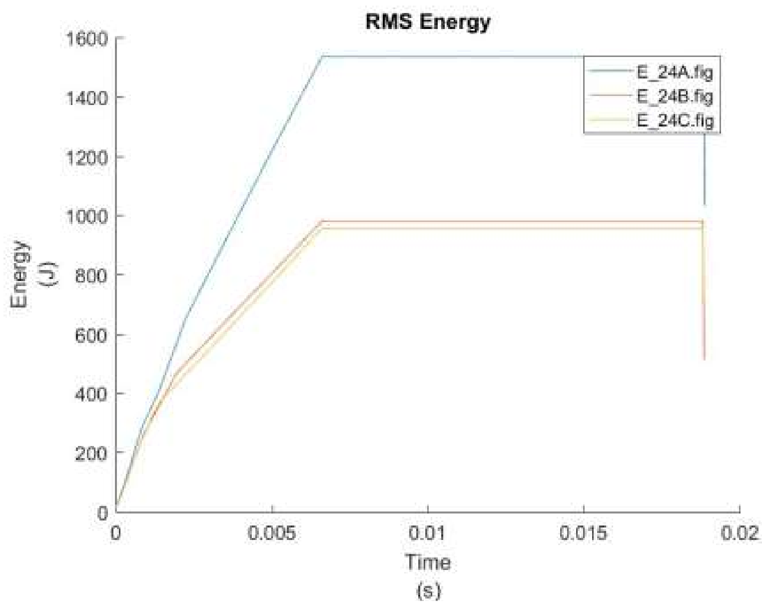

Figure: Energy Test 24

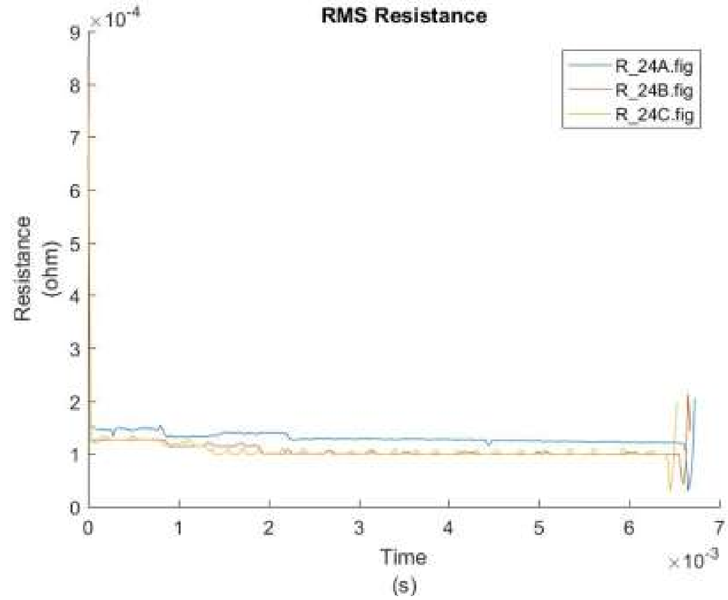

Figure: Resistance Test 24

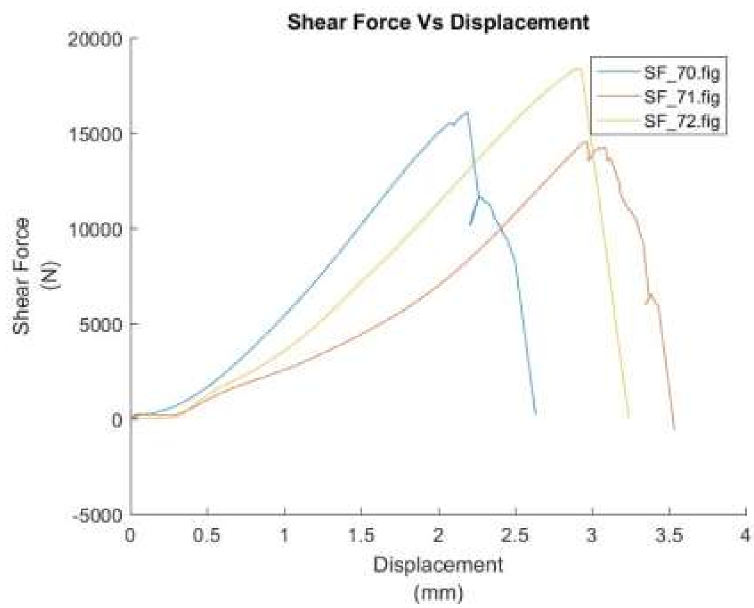

Figure: Shear tension test 24

Test 25

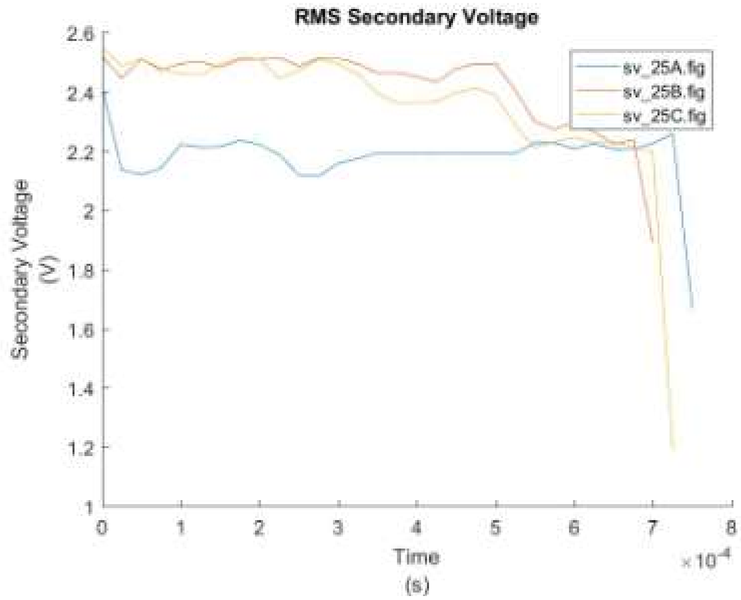

Figure: Secondary Voltage Test 25

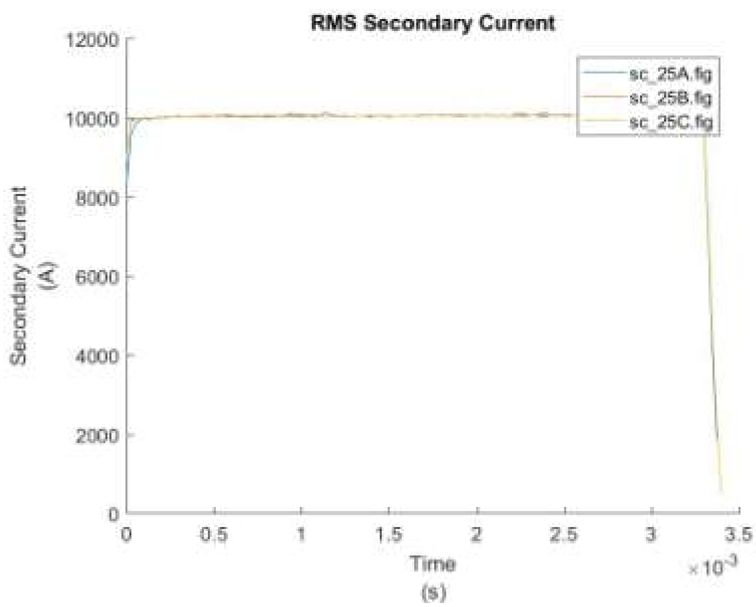

Figure: Secondary Current Test 25

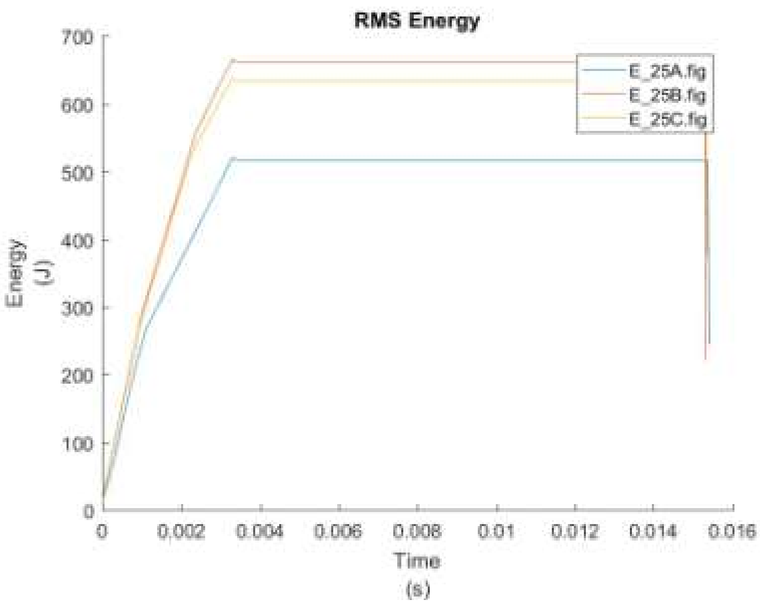

Figure: Energy Test 25

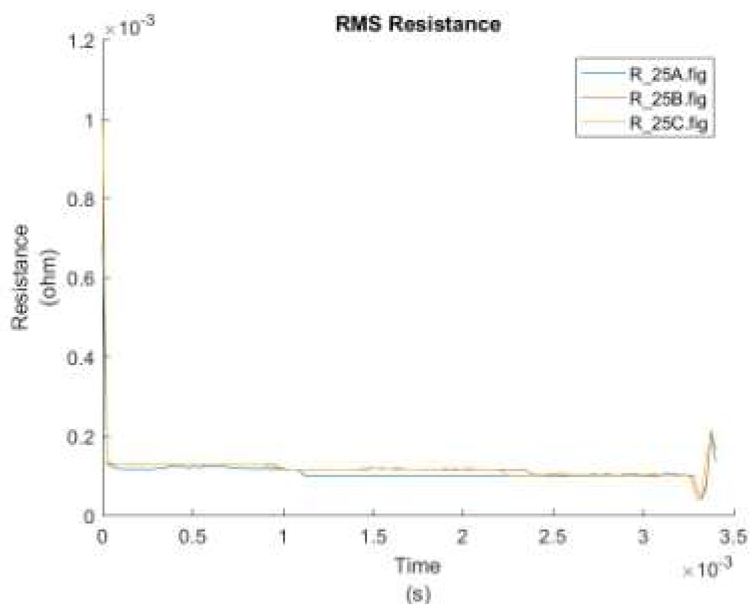

Figure: Resistance Test 25

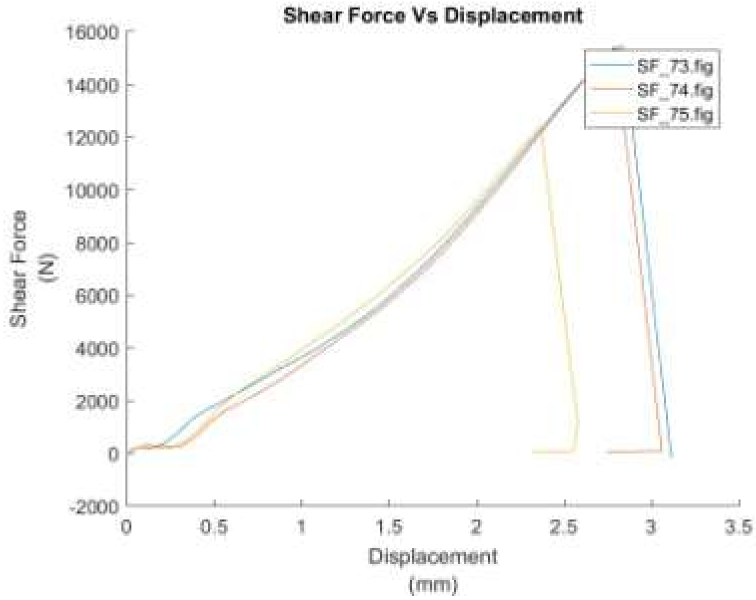

Figure: Shear tension test 25

Test 26

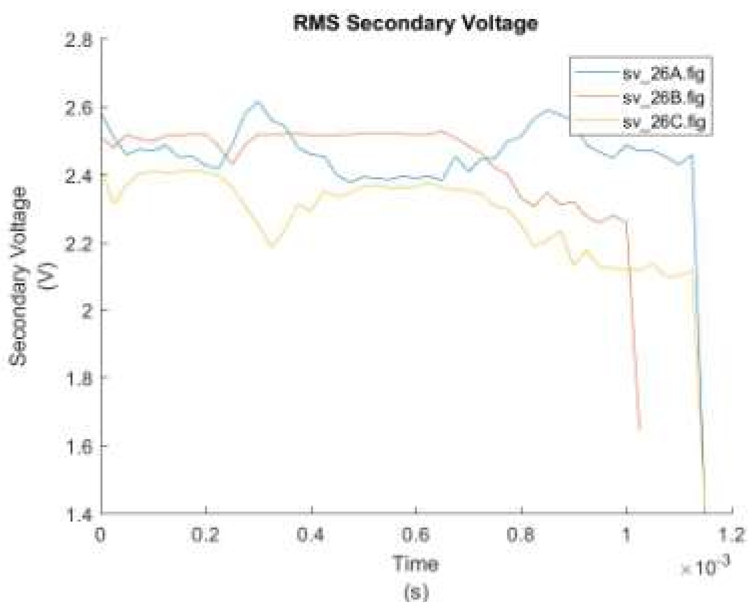

Figure: Secondary Voltage Test 26

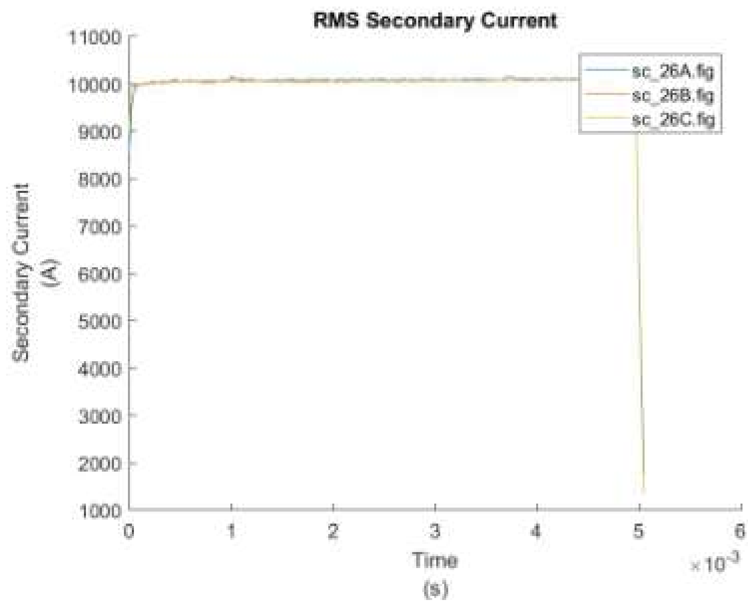

Figure: Secondary Current Test 26

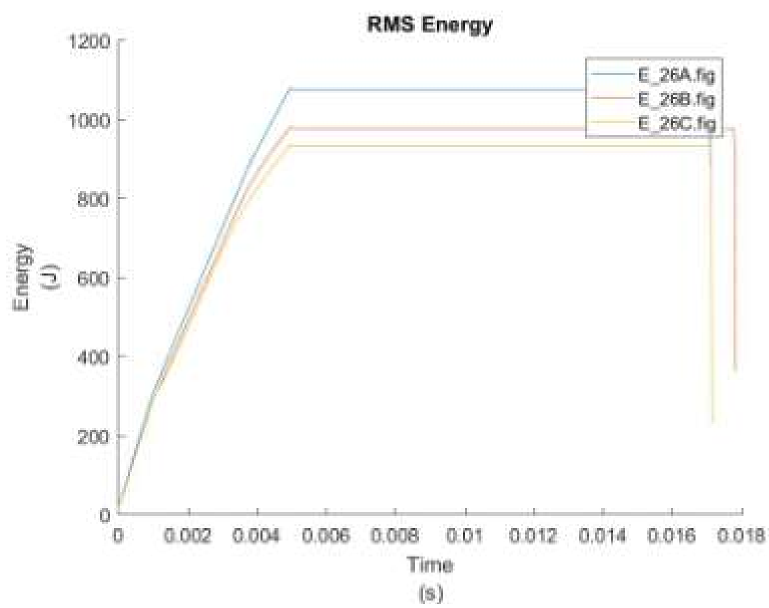

Figure: Energy Test 26

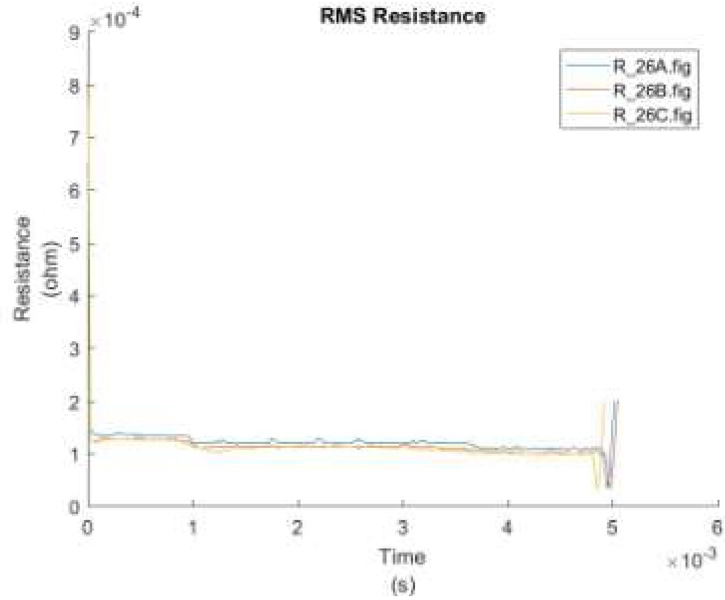

Figure: Resistance Test 26

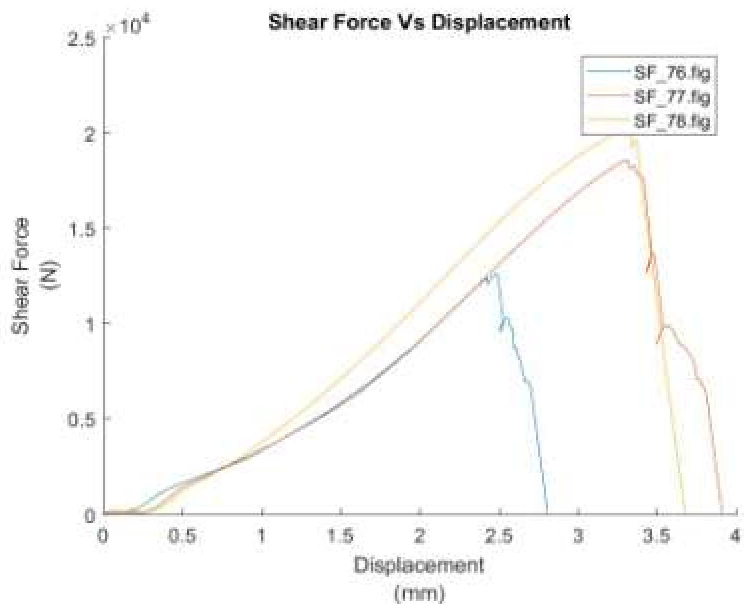

Figure: Shear tension test 26

Test 27

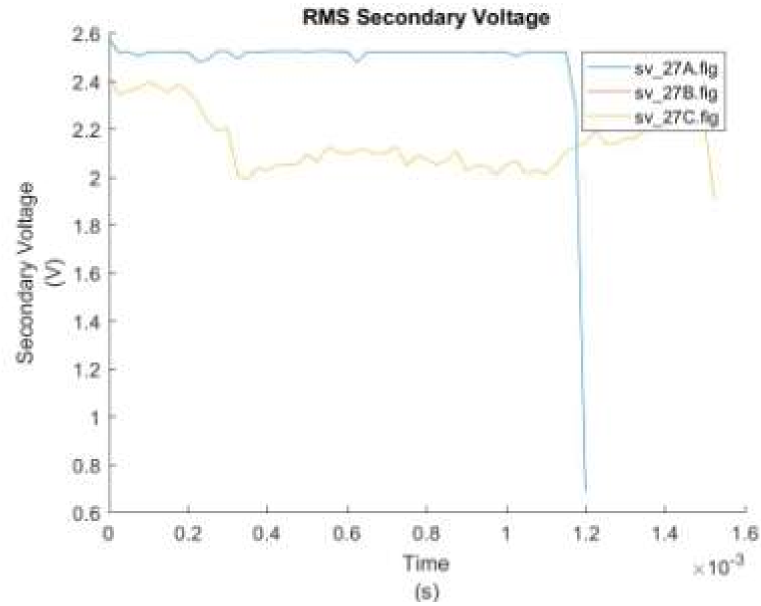

Figure: Secondary Voltage Test 27

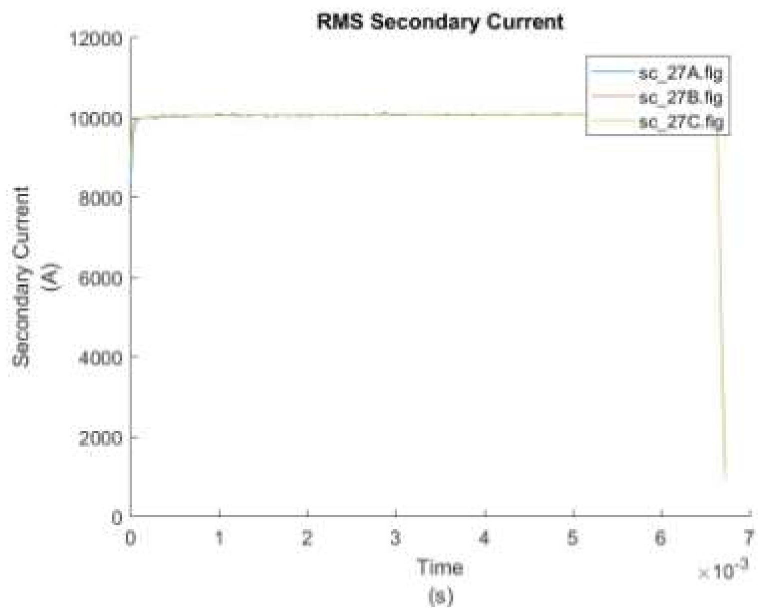

Figure: Secondary Current Test 27

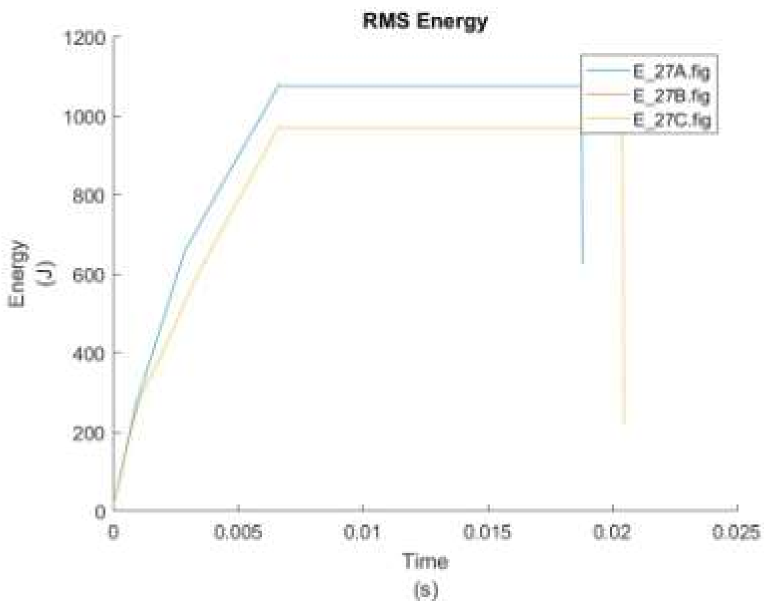

Figure: Energy Test 27

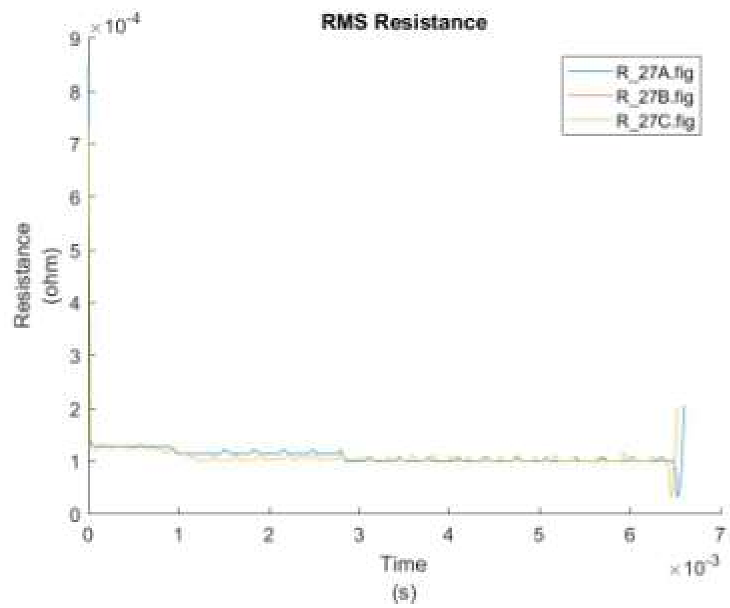

Figure: Resistance Test 27

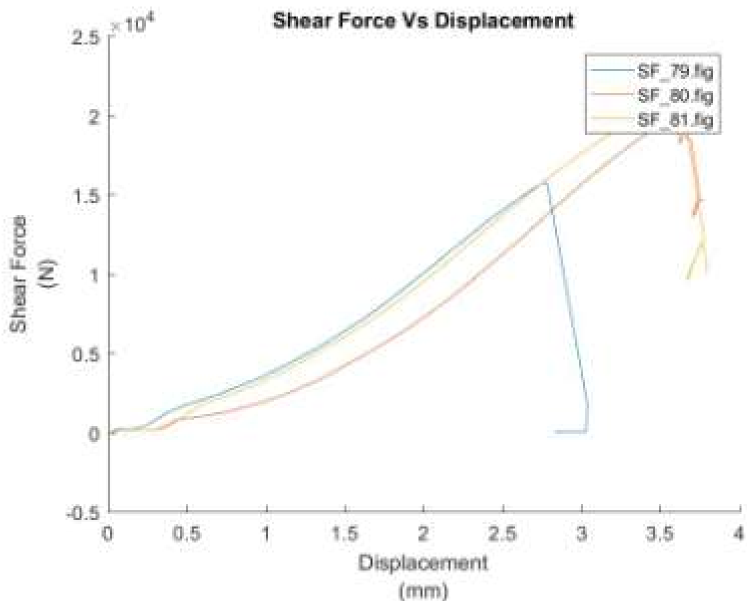

Figure: Shear tension test 27

APPENDIX 2

```
%% Initialize variables.
filename = 'D:\Thesis\WAVEnew\01A.dat';
file_name = '01A';
delimiter = '\t';
startRow = 24;

%% Read columns of data as strings:
formatSpec = '%*s%*s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%[^\n\r]';

%% Open the text file.
fileID = fopen(filename,'r');

%% Read columns of data according to format string.
textscan(fileID, '%[^\n\r]', startRow-1, 'WhiteSpace', '',
'ReturnOnError', false);
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter,
'ReturnOnError', false);

%% Close the text file.
fclose(fileID);

%% Convert the contents of columns containing numeric strings to
numbers.
raw = repmat({''},length(dataArray{1}),length(dataArray)-1);
for col=1:length(dataArray)-1
    raw(1:length(dataArray{col}),col) = dataArray{col};
end
numericData = NaN(size(dataArray{1},1),size(dataArray,2));

for col=[1,2,3,4,5,6,7,8,9,10,11,12,13,14]
    % Converts strings in the input cell array to numbers. Replaced
non-numeric
    % strings with NaN.
    rawData = dataArray{col};
    for row=1:size(rawData, 1);
        % Create a regular expression to detect and remove non-numeric
prefixes and
        % suffixes.
        regexstr = '(?<prefix>.*?)(?<numbers>([-
]*(\d+[\.]*)+[\,]{0,1}\d*[eEdD]{0,1}[-+]*\d*[i]{0,1})|([-
]*(\d+[\.]*)*[\,]{1,1}\d+[eEdD]{0,1}[-+]*\d*[i]{0,1}))(?<suffix>.*)';
        try
            result = regexp(rawData{row}, regexstr, 'names');
            numbers = result.numbers;

            % Detected commas in non-thousand locations.
            invalidThousandsSeparator = false;
            if any(numbers=='.');
                thousandsRegExp = '^\d+?(\.\d{3})*\,{0,1}\d*$';
                if isempty(regexp(numbers, thousandsRegExp, 'once'));
                    numbers = NaN;
```

```
                    invalidThousandsSeparator = true;
                end
            end
            % Convert numeric strings to numbers.
            if ~invalidThousandsSeparator;
                numbers = strrep(numbers, '.', '');
                numbers = strrep(numbers, ',', '.');
                numbers = textscan(numbers, '%f');
                numericData(row, col) = numbers{1};
                raw{row, col} = numbers{1};
            end
        catch me
        end
    end
end


%% Allocate imported array to column variable names
VPhaseR = cell2mat(raw(:, 1));
VPhaseS = cell2mat(raw(:, 2));
VPhaseT = cell2mat(raw(:, 3));
IPhaseR = cell2mat(raw(:, 4));
IPhaseS = cell2mat(raw(:, 5));
IPhaseT = cell2mat(raw(:, 6));
Force = cell2mat(raw(:, 7));
AirPressure = cell2mat(raw(:, 8));
SecondaryVoltage = cell2mat(raw(:, 9));
SecondaryCurrent = cell2mat(raw(:, 10));
Displacement = cell2mat(raw(:, 11));
Temperature = cell2mat(raw(:, 12));
Energy = cell2mat(raw(:, 13));
Resistance = cell2mat(raw(:, 14));

delta = 0.000025;

%%Force
% fig_Force = figure('Name','Force','NumberTitle','off');
% t = (0: delta : (((length(Force)-1)) * delta) )';
% plot(t, Force)
% title(sprintf('%s : Force', file_name));
% ylabel({'Force','(daN)'})
% fig_Force_cut = figure('Name','Force Cut','NumberTitle','off');
% Force_cut = Force((Force > 10 | Force < -10),:);
% t_cut = (0: delta : (((length(Force_cut)-1)) * delta) )';
% plot(t_cut, Force_cut)
% title(sprintf('%s : Force Cut', file_name));
% ylabel({'Force Cut','(daN)'})
% fig_Force_rms = figure('Name','Force RMS','NumberTitle','off');
% Force_rms = rms(Force_cut, 80, 20, 1);
% t_rms = (0: delta : (((length(Force_rms)-1)) * delta) )';
% plot(t_rms, Force_rms)
% title(sprintf('%s : RMS of Force ', file_name));
% ylabel({'Force RMS','(daN)'})

%%Secondary Voltage
```

```
fig_SecondaryVoltage = figure('Name','Secondary
Voltage','NumberTitle','off');
t_SecondaryVoltage = (0: delta : (((length(SecondaryVoltage)-1)) *
delta) )';
plot(t_SecondaryVoltage, SecondaryVoltage)
title(sprintf('%s : SecondaryVoltage', file_name));
ylabel({'SecondaryVoltage','(V)'})
fig_SecondaryVoltage_cut = figure('Name','SecondaryVoltage
Cut','NumberTitle','off');
SecondaryVoltage_cut = SecondaryVoltage((SecondaryVoltage > 0.00005 |
SecondaryVoltage < -0.5),:);
t_SecondaryVoltage_cut = (0: delta : (((length(SecondaryVoltage_cut)-
1)) * delta) )';
plot(t_SecondaryVoltage_cut, SecondaryVoltage_cut)
title(sprintf('%s : SecondaryVoltage Cut ', file_name));
ylabel({'SecondaryVoltage','(V)'})
fnm = sprintf('svc_%s.fig',file_name);
savefig(fnm)

% saveas(gcf, 'sv.m');

fig_SecondaryVoltage_rms = figure('Name','SecondaryVoltage
RMS','NumberTitle','off');
SecondaryVoltage_rms = rms(SecondaryVoltage_cut, 80, 20, 1);
t_SecondaryVoltage_rms = (0: delta : (((length(SecondaryVoltage_rms)-
1)) * delta) )';
plot(t_SecondaryVoltage_rms, SecondaryVoltage_rms)
title(sprintf('%s : RMS of SecondaryVoltage ', file_name));
ylabel({'RMS SecondaryVoltage','(V)'})
fnm1 = sprintf('sv_%s.fig',file_name);
savefig(fnm1)


%%Secondary Current
fig_SecondaryCurrent = figure('Name','Secondary
Current','NumberTitle','off');
t_SecondaryCurrent = (0: delta : (((length(SecondaryCurrent)-1)) *
delta) )';
plot(t_SecondaryCurrent, SecondaryCurrent)
title(sprintf('%s : SecondaryCurrent', file_name));
ylabel({'SecondaryCurrent','(A)'})
fig_SecondaryCurrent_cut = figure('Name','SecondaryCurrent
Cut','NumberTitle','off');
SecondaryCurrent_cut = SecondaryCurrent(SecondaryCurrent > 1200 );
t_SecondaryCurrent_cut = (0: delta : (((length(SecondaryCurrent_cut)-
1)) * delta) )';
plot(t_SecondaryCurrent_cut, SecondaryCurrent_cut)
title(sprintf('%s : SecondaryCurrent Cut', file_name));
ylabel({'SecondaryCurrent','(A)'})
fnm2 = sprintf('scc_%s.fig',file_name);
savefig(fnm2)
fig_SecondaryCurrent_rms = figure('Name','SecondaryCurrent
RMS','NumberTitle','off');
SecondaryCurrent_rms = rms(SecondaryCurrent_cut, 80, 20, 1);
t_SecondaryCurrent_rms = (0: delta : (((length(SecondaryCurrent_rms)-
1)) * delta) )';
```

```
plot(t_SecondaryCurrent_rms, SecondaryCurrent_rms)
title(sprintf('%s : RMS of SecondaryCurrent ', file_name));
ylabel({'RMS SecondaryCurrent','(A)'})
fnm3 = sprintf('sc_%s.fig',file_name);
savefig(fnm3)
%%Energy
fig_Energy = figure('Name','Energy','NumberTitle','off');
t_Energy = (0: delta : (((length(Energy)-1)) * delta) )';
plot(t_Energy, Energy)
title(sprintf('%s : Energy', file_name));
ylabel({'Energy','(J)'})
fig_Energy_cut = figure('Name','Energy Cut','NumberTitle','off');
Energy_cut = Energy((Energy > 0.5 | Energy < -0.5),:);
t_Energy_cut = (0: delta : (((length(Energy_cut)-1)) * delta) )';
plot(t_Energy_cut, Energy_cut)
title(sprintf('%s : Energy Cut', file_name));
ylabel({'Energy','(J)'})
fnm4 = sprintf('Ec_%s.fig',file_name);
savefig(fnm4)
fig_Energy_rms = figure('Name','Energy RMS','NumberTitle','off');
Energy_rms = rms(Energy_cut, 80, 20, 1);
t_Energy_rms = (0: delta : (((length(Energy_rms)-1)) * delta) )';
plot(t_Energy_rms, Energy_rms)
title(sprintf('%s : RMS of Energy ', file_name));
ylabel({'RMS Energy','(J)'})
fnm5 = sprintf('E_%s.fig',file_name);
savefig(fnm5)
%Resistance
fig_Resistance = figure('Name','Resistance','NumberTitle','off');
t_Resistance = (0: delta : (((length(Resistance)-1)) * delta) )';
plot(t_Resistance, Resistance)
title(sprintf('%s : Resistance', file_name));
ylabel({'Resistance','(ohm)'})
fig_Resistance_cut = figure('Name','Resistance
Cut','NumberTitle','off');
Resistance_cut = Resistance((Resistance > 0.0000035 | Resistance < -
0.00335),:);
t_Resistance_cut = (0: delta : (((length(Resistance_cut)-1)) * delta)
)';
plot(t_Resistance_cut, Resistance_cut)
title(sprintf('%s : Resistance Cut', file_name));
ylabel({'Resistance','(ohm)'})
fnm6 = sprintf('Rc_%s.fig',file_name);
savefig(fnm6)
fig_Resistance_rms = figure('Name','Resistance
RMS','NumberTitle','off');
Resistance_rms = rms(Resistance_cut, 80, 20, 1);
t_Resistance_rms = (0: delta : (((length(Resistance_rms)-1)) * delta)
)';
plot(t_Resistance_rms, Resistance_rms)
title(sprintf('%s : RMS of Resistance ', file_name));
ylabel({'RMS Resistance','(ohm)'})
fnm7 = sprintf('R_%s.fig',file_name);
savefig(fnm7)

%% Clear temporary variables
```

```
clearvars filename delimiter startRow formatSpec fileID dataArray ans
raw col numericData rawData row regexstr result numbers
invalidThousandsSeparator thousandsRegExp me;




%% DECLARATIONS AND INITIALIZATIONS

% Calculates windowed (over- and non-overlapping) RMS of a signal using
the specified windowlength
% y = rms(signal, windowlength, overlap, zeropad)
% signal is a 1-D vector
% windowlength is an integer length of the RMS window in samples
% overlap is the number of samples to overlap adjacent windows (enter 0
to use non-overlapping windows)
% zeropad is a flag for zero padding the end of your data...(0 for NO,
1 for YES)
% ex. y=rms(mysignal, 30, 10, 1).  Calculate RMS with window of length
30 samples, overlapped by 10 samples each, and zeropad the last window
if necessary
% ex. y=rms(mysignal, 30, 0, 0).  Calculate RMS with window of length
30 samples, no overlapping samples, and do not zeropad the last window


function y = rms(signal, windowlength, overlap, zeropad)

delta = windowlength - overlap;

%% CALCULATE RMS

indices = 1:delta:length(signal);
% Zeropad signal
if length(signal) - indices(end) + 1 < windowlength
    if zeropad
        signal(end+1:indices(end)+windowlength-1) = 0;
    else
        indices = indices(1:find(indices+windowlength-1 <=
length(signal), 1, 'last'));
    end
end

y = zeros(1, length(indices));
% Square the samples
signal = signal.^2;

index = 0;
for i = indices
    index = index+1;
    % Average and take the square root of each window
    y(index) = sqrt(mean(signal(i:i+windowlength-1)));
end
```

```
%% Initialize variables.
filename = 'D:\Thesis\spot welding\shear tensione test\Replication
2\dati\44.txt';
file_name = '44';
delimiter = '\t';
startRow = 105;

%% Format string for each line of text:
%   column1: double (%f)
%   column2: text (%s)
%   column3: text (%s)
% For more information, see the TEXTSCAN documentation.
formatSpec = '%f%f%f%*s%*s%*s%*s%*s%*s%[^\n\r]';

%% Open the text file.
fileID = fopen(filename,'r');

%% Read columns of data according to format string.
% This call is based on the structure of the file used to generate this
% code. If an error occurs for a different file, try regenerating the
code
% from the Import Tool.
textscan(fileID, '%[^\n\r]', startRow-1, 'WhiteSpace', '',
'ReturnOnError', false);
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter,
'ReturnOnError', false);

%% Close the text file.
fclose(fileID);

%% Post processing for unimportable data.
% No unimportable data rules were applied during the import, so no post
% processing code is included. To generate code which works for
% unimportable data, select unimportable cells in a file and regenerate
the
% script.

%% Allocate imported array to column variable names
Results = dataArray{:, 1};
VarName2 = dataArray{:, 2};
VarName3 = dataArray{:, 3};

Time = Results;
Displacement = VarName2;
ShearForce = VarName3;

%%Force
fig_Force = figure('Name','Shear Test','NumberTitle','off');
plot(Displacement,ShearForce)
title(sprintf('%s : ShearForce vs displacement', file_name));
ylabel({'Force','(N)'})
xlabel({'Displacement' , ' (mm) '})
fnm = sprintf('SF_%s.fig',file_name);
savefig(fnm)
```

```
%[val, SV] = max(Displacement);
%hold on
%text(t_SecondaryVoltage_rms(SV), val, sprintf('Max RMS Value =
%6.3f',val))
%fill(t_SecondaryVoltage_rms, SecondaryVoltage_rms(:,SV),'g');
%hold off
%saveas(gcf, 'sv.m');

%cfg = sprintf('SF_%s.jpg',file_name);
%savefig(cfg,SF_01,'jpg')



%% Clear temporary variables
clearvars filename delimiter startRow formatSpec fileID dataArray ans;
```

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