UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

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MONITORIZACIÓN DEL PROCESO DE SOLDADURA ELÉCTRICA POR PUNTOS

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TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: Monitoring of resistante spot welding process

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Abstract

Trabajo Fin de Grado desarrollado con el propósito de monitorizar y controlar, en tiempo real, los diferentes parámetros del proceso de soldadura eléctrica por puntos (RSW) en aceros de alta resistencia.

El documento se compone de varias partes, que abarcan desde los principios teóricos de la soldadura por puntos hasta los resultados de los test realizados para dicho tipo de soldadura en una empresa real.

En los primeros capítulos se presenta el estudio de las características, funciones y usos de los diferentes sensores que tuve la oportunidad de utilizar, así como su implantación en un ordenador a través del software LabVIEW.

A continuación se explican los archivos de LabVIEW utilizados para la adquisición de datos a través de los sensores, así como los procedimientos para salvar datos y poder estudiarlos posteriormente.

Una vez los principios del RSW y los procedimientos para la monitorización del proceso son conocidos, se presentan los resultados de los ensayos realizados en los talleres de la universidad, así como los datos experimentales obtenidos en la industria FIAT, en su sede en Turín.

En definitiva, este proyecto se llevó a cabo para conocer mejor las características más importantes de los procesos de soldadura por puntos, monitorizar dichas variables y crear una herramienta eficaz para detectar posibles fallos en los puntos de soldadura resultantes. Del mismo modo pretende ser un manual para que futuros alumnos de la universidad sean capaces de realizar dichos experimentos.

Keywords

MONITORIZACIÓN, RSW, SOLDADURA POR PUNTOS, ACEROS ALTA RESISTENCIA, LabVIEW

INDEX

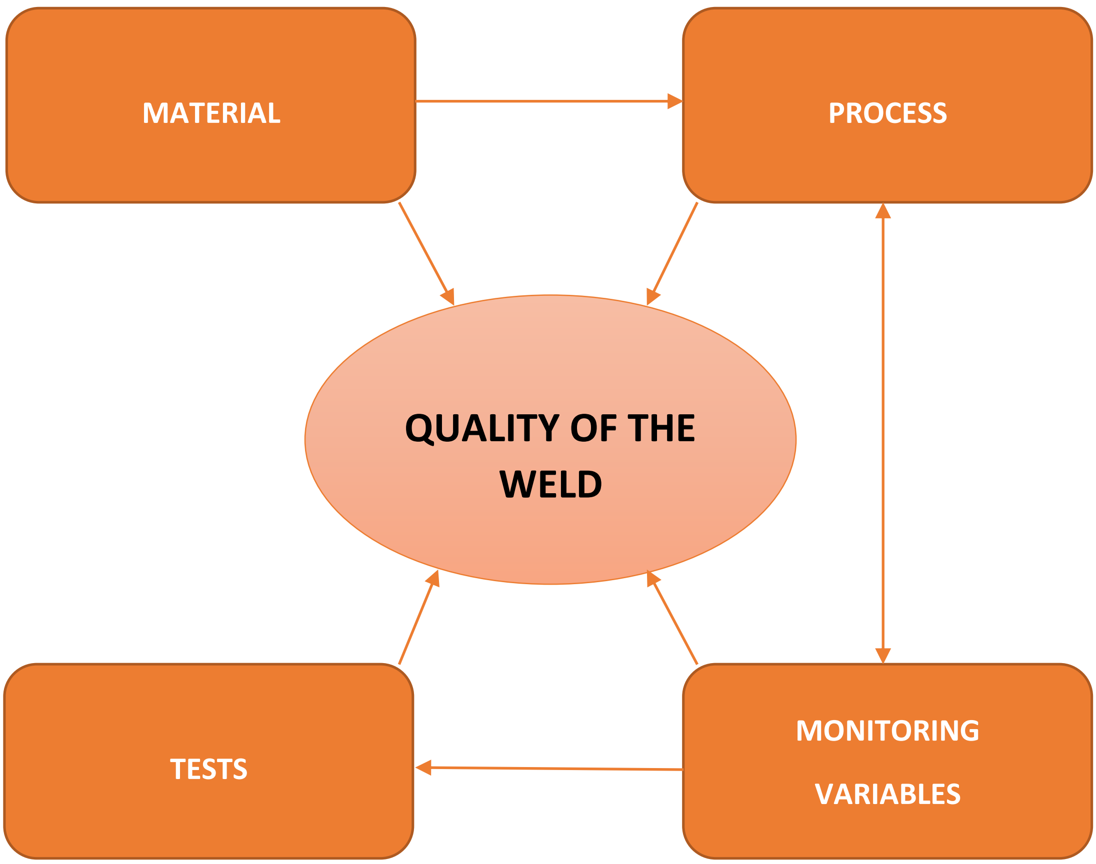
1. Introduction

The purpose of this master thesis is to monitoring the main parameters in the Resistant Spot Welding (RSW) Process. It is the continuation of a previous thesis developed by a Politécnico di Torino's student last year.

RSW process is used for the union of two or more thin steel sheets, which make it really appropriated for the construction of car bodies. The final aim of this thesis is to monitoring, with the sensors, hardware and software explained on it, the real RSW carried out in a real factory.

In order to make this purpose possible, the main parameters of RSW will be described, as well as the hardware needed to monitoring them. The procedure to acquire and treat data from the sensor and their implementation into a computer software will be deeply explained in order to make easy the process for future tests.

Monitoring of the variables in RSW process is one of the main steps to study the quality of the weld, according to the next illustration.



Monitoring variables is our principal goal, but it is intimately related with the other parameters, that is why along this thesis, all of them will appear and will be explained one way or another.

This master thesis is divided in four main chapters, beginning from the most basic information about RSW and finishing with the tests made in industry.

More deeply, the structure of this thesis is the next one:

In the first part, the Resistant Spot Welding process is introduced. On it, is possible to read about the physical principles of RSW, as well as a detailed description of his main parameters. The test for determinate the quality and properties of this kind of welds will be also described in this part, making easier the reading of the next chapters of this document.

In the second part of this thesis, the hardware used for the elaboration of the tests and essays is explained. There is possible to find all the information about what kind of sensors are used, his properties and the results that can provide. In the same way, the hardware necessary to import the data form the sensors into a computer is presented, totally necessary to study and treat the data from experiments.

Once the hardware is explained, the third part of this document will explain how to use the sensors, how to acquire data into the computer, how to manipulate de acquisition parameters… definitely, the process to be able to work with them and obtain satisfactory results.

In the last part of this this master thesis, the tests conducted are deeply explained, including the materials to work, the machines used on them and the structure of the tests. The real results of this tests are presented in two Appendix at the end of this inform, where is possible to see the graphical data obtained from the sensors and the posterior test made for check the quality of the welded point.

2. Resistance Spot Welding

2.1 Process description

The RSW is a common process for steel sheets welding. His principle is to produce a large heat quantity due to a high current which travels between two electrodes through the material for a short period of time. A high pressure existing between the electrodes keep them together while the process, and makes easier a uniform welding nugget.

Resistance spot welding is a widely used joining process for fabricating sheet metal assemblies such as automobiles, truck cabins, rail vehicles and home applications due to its advantages in welding efficiency and suitability for automation. (1)

It may be performed manually, robotically or by a dedicated spot welding machine. The similar spot welds having same property can be obtained in high production speeds by controlling welding current, electrode force and weld time automatically. The required low voltage (5–20 V) and high current intensity (2000–15,000 A) for welding process is obtained from transformer and the pressure is obtained from hydraulic, mechanic and pneumatic devices.

The produced heat is based in Joule's Law, and is able to create a welding nugget between the two metal pieces, which physical and metallurgical properties really similar to the base metals.

$$W = R * I^2 * t = \frac{V^2 t}{R}$$

Joule's law:

W *= Energy (J)*

I *= amperage/current (A)*

R *= resistance (Ω)*

V *=Voltage (V)*

T *=time (s)*

The RSW cycle is divided in six steps, from the placing of the sheets to the result of the process. This steps are explained in the next illustration: (2)

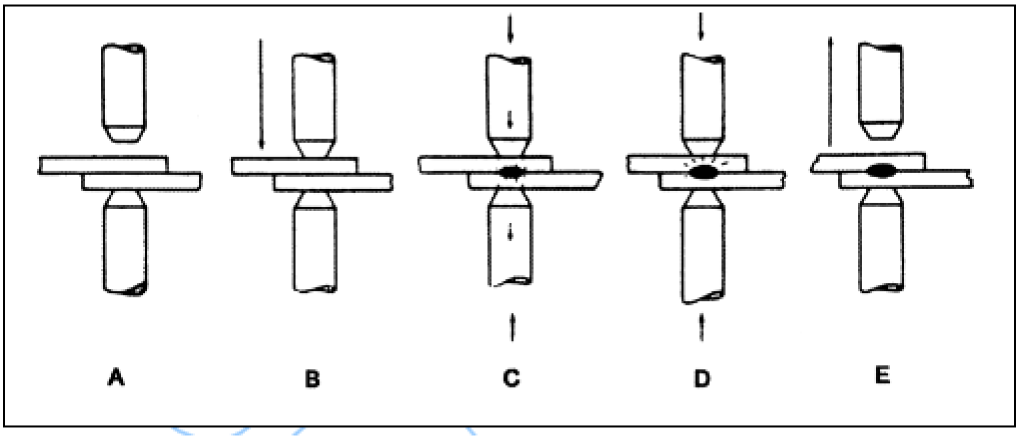


Illustration 1 Scheme of the six steps in a ERW process

A. Elements to be welded, placed one above the other.
B. Descent of the upper electrode.
C. Start of the welding current.
D. End of the welding current, but the electrodes continues making pressure in the sheets.
E. End of the pressure. Separation of the electrodes.

This process is developed in a resistance spot welding machine. At present, there are a lot of companies which produce this kind of machines, making their own models. Anyway, the principles and elements are common in all of them: (2)

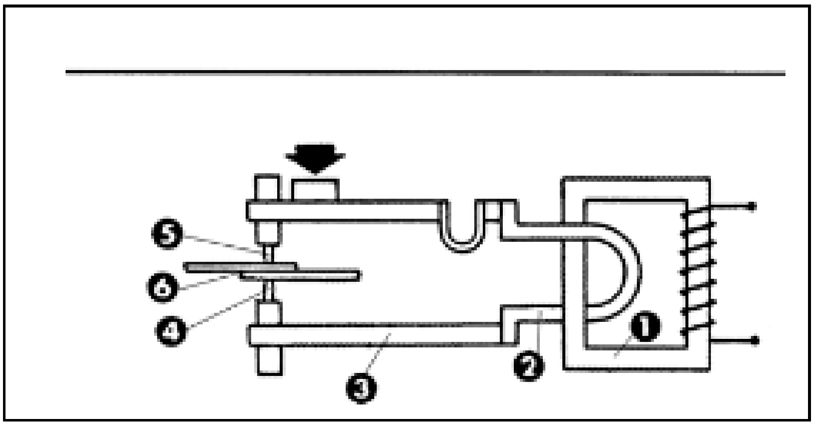


Illustration 2 Scheme of a ERSW machine

1. Primary transformer.
2. Secondary transformer.
3. Secondary outside circuit.
4. Lower electrode.
5. Upper electrode.
6. Pieces to weld.

This RSW process has a big advantage, the automatization, which makes the process suitable for line work, with a lower cost and higher efficiency. In any case, this is not the only advantage of the process. Another important points in favor for this welding process are the next: (3)

- Short process time.
- Easy manipulation of the main parameters.
- Consumables are not needed, such as materials or welding rods.
- Safe operation due to the low voltage values.
- Clean and ecology.
- The result is an electro-mechanical safe union.

2.2 Main Parameters

Quality and properties of the welding point are highly influence for the input parameters, and the variation of one or several of them can change notably the mechanical properties of the welding point.

It is convenient to remember that the principle of ERSW is Joule's Law, where is patent the influence of the Resistance, Intensity and time, but they are not the only ones.

$$W = R * I^2 * t = \frac{V^2 t}{R}$$

Next, this parameters, and some other will be explained deeply.

2.2.1 Resistance

Resistance is one important parameter in the spot welding process. That is why is important to avoid some situations (4):

- Surfaces of the plates not clean, with oils, water or lubricants.
- Circuit loses in the conductor material, usually copper. These loses are impossible to eliminate, but we can make it lower if we maintain the circuit cool. When the welding works the circuit is warning up and in these conditions the conductivity of copper fall down, increasing the resistance and the power loses.
- Not having enough pressure between the electrodes and the plates. The pressure helps to have a better contact between plate-electrode.
- Not changing the electrodes when they are deformed by a lot of use. Also the geometry of the electrode, if the contact section is higher, the resistance is lower.
- Loses in the secondly circuit of the machine

2.2.2 Welding time

It has to be specially controlled, because it has to be enough to can have the best rate of material fusion with the best penetration, but also the lower possible. This is because is important to increase the production and avoid an elevate fusion rate in the surface.

The order of Welding Time in ERW is of the order of the hundreds of mille-seconds (mS). (5)

2.2.3 Current /amperage

The current is the most important parameter in welding, not only in ERW. When the welding is made with lower current as should have, the deeply of the union is not enough. This happens for example when we fix the energy rate and the voltage has a high value.

If we make the union with too much current we have better penetration but less mechanical resistance. For these reasons are important to control the current and has the first priority in our working parameters.

The current in the ERW is very high, to the order or thousands of amps, between 2.000 A and 15.000 A. (2)

Current is one of the parameters which will be monitored for the redaction of this Thesis.

2.2.4 Voltage

The voltage is important when we fix the energy rate. If we use lower voltage as we might, we will have low fusion rate. If we use higher voltage, we will have higher fusion rate and less penetration because all the fusion will be in the surface welding.

The voltage in the ERW is very low, to the order or a few V, in a range of 5-20 V, for example. (2)

Due to his importance in ERW process, is needed to study the Voltage during the welding process.

2.2.5 Displacement

In spite of displacement does not appear in Joule's law, is one of the most important parameters in ERW. To monitoring the displacement of the coupons while the welding process is on-going, can provide us a lot off information about the welding result. (6)

Pressure, another of the main important parameters in ERW, is directly related to displacement.

2.2.6 Other important parameters

The parameters showed above have a high importance in the welding process, but some other parameters have to be studied before the welding process too, because of their important influence in the final result.

- The materials of the electrode
- The material of the plates that we are going to weld. The steel that is composed by ferrite is harder to weld with this technique. Also, the steel very allowed is difficult to weld.
- The geometry of the electrode that is changing all the time when we use them. The electrode has a finer point at the start than after a long time use.
- The resistance between the plates, that have to be as close as can to the total resistance of the circuit. Remember that this kind of welding is based on the law of Joule, and we need the maximum heat in the welding with the less electric energy, for give to the process a better yield.
- The pressure of the electrodes, for principally two reasons: The first one to fix the resistance point, the second one for reduce the resistance of the total circuit and make it closer to the weld resistance, that it is which will give to the plates the heat to make the weld.
- The cooling system of the electrode. In the welding we have high temperatures and we have to cool the plates quickly to have a better production. Also the cooling speedy of the electrode gives us different heat treatments, so it is an important parameter. (7)

2.3 Test for RSW

There are two different methods of destructive testing use in lab, Quantitative Evaluation Tests

- Lap-shear test
- Cross-tension test

For the development of this thesis, the Cross Tension test was the destructive test chose for the study of the welding points. Politécnico di Torino is able to adapt his tensile testing machine to the required standard for the elaboration of the tests.

The international standard for the Specimen dimensions and procedure for cross tension testing of resistance spot and embossed projection welds is ISO 10273.

Cross tension test is a kind of essay in which two steel sheets are placed, welded and posteriorly studied in the next way:

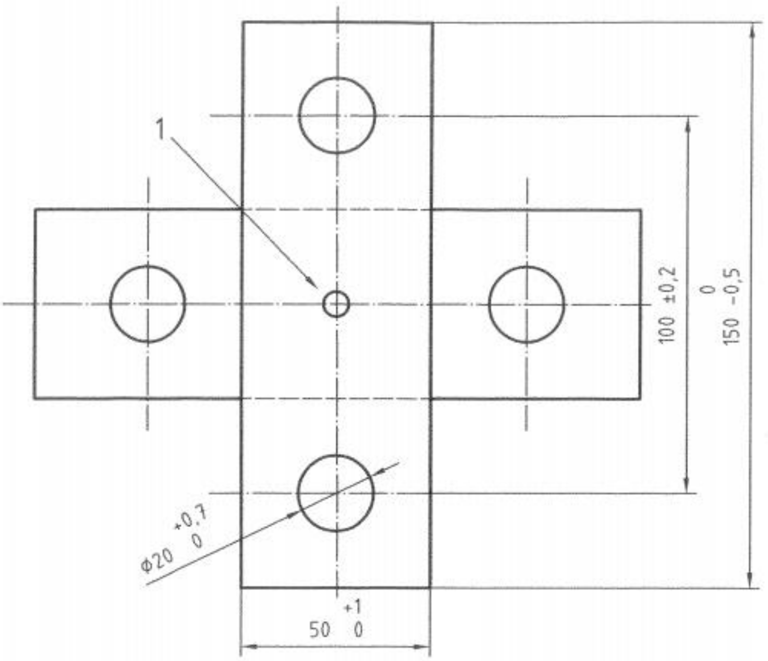


Illustration 3 ISO standard for Cross tension test

The welded union, also called coupon, is placed in a typical tensile testing machine using a standard fixture system. After being located in the correct way, is possible to begin with the test.

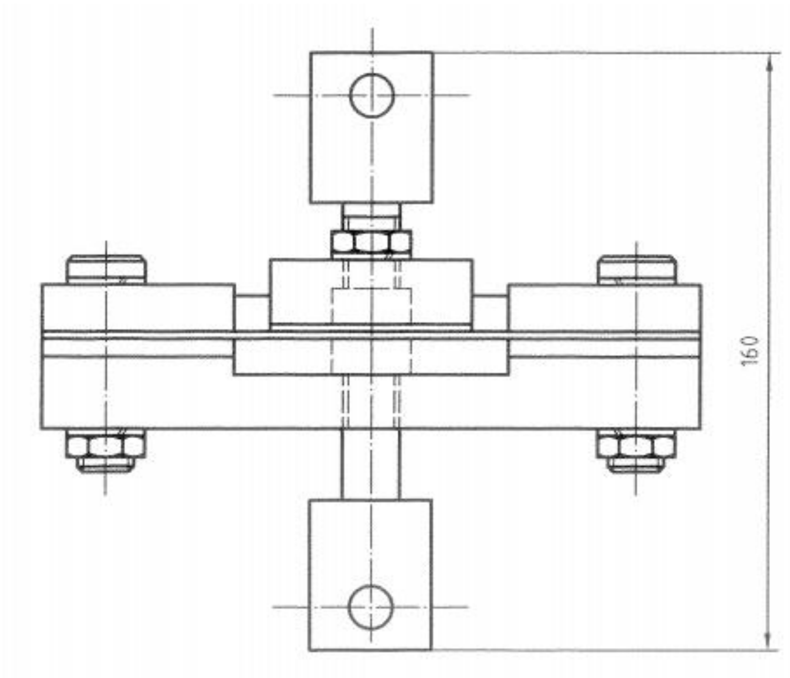


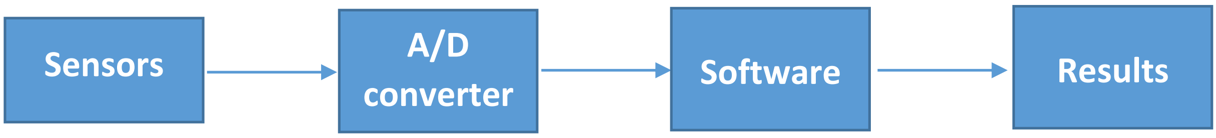
Illustration 4 ISO fixture for Cross tension test

The tests begin with a null displacement and force value in the parameters of the tensile strength machine, finishing the test once the coupon fails and his two specimens are totally separated.

This is the destructive method, along with other ones, is one of the Standard test to measure the characteristics of a welded point. It is especially important for us, due to is used for the development of this thesis.

3. Hardware used for monitoring of Resistance Spot Welding

The main purpose of this Master Thesis is to monitoring the most important parameters during the RSW process. This will be made using two kind of sensors (Rogowski coil and Fiberoptic measurement sensor), which purpose is to acquire the data while the RSW process is made and transform his data into a Voltage value. After that, an Analogical to Digital converter will be used in order to convert the output data form the sensors into suitable data which is possible to work using a computer software. A simple scheme about how the process will be done is showed now:



In this chapter, the different sensors, and the Analogical to Digital converter will be deeply explained, showing their main features and the advantages of their implementation in the RSW monitoring process.

As was said before, for the elaboration of this thesis, a Current sensor and a Displacement sensor will be used. They were chosen because current and displacement (which is directly related with Pressure) are two of the most important parameters in the RSW process. With their measure in each moment, is possible to know all the physics variables and an estimation of the properties of the final welding point can be made.

The sensors chosen to develop this thesis are the next ones:

- **Current sensor.** Rogowski current transducer PEM CWT 30/4/700.
- **Measure Sensor.** Fiberoptic D100-C1E1PR2T2

Is needed an Analogical-To-Digital data converter to read the data with a computer. In this study the next one will be used:

- **A/D converter:** Native Instruments USB-6216.

With this three instruments, we are capable to make an intensive study about the influence of the different parameters on the RSW. We can identify the current which is been used to produce the welding nugget as well as the displacement of the electrode in that process.

Then, the most important features and parameters of this sensors will be explained.

3.1 Rogowski coil

Current is one of the most important parameters in RSW processes. Almost all the interesting ERW are made with alternating current (AC) with and inverter to produce DC, but needing a secondary circuit with DC. Rogowski coil is able to measure both kind of currents (AC and DC), which make it really polyvalent.

Other of the main advantages of Rogowski coil is his capacity to measure a big range of current, form a small one (from 15A) to a high current (more than 300KA).

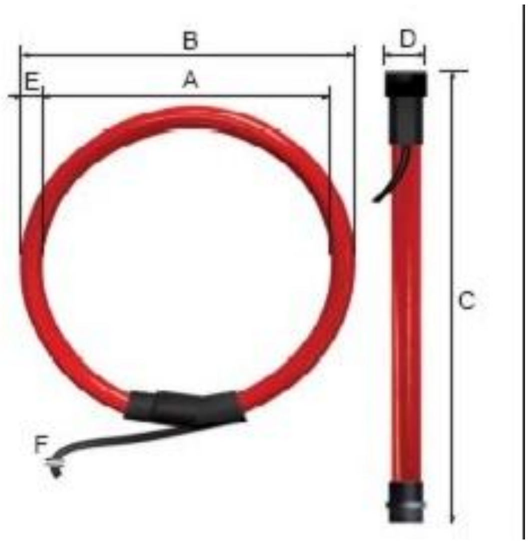


Illustration 5 Rogowski coil

Rogowski coil operates as follows:

An alternating or pulsed current in a conductor develops a magnetic field and the interaction of this magnetic field and the Rogowski coil local to the field gives rise to an induced voltage within the coil which is proportional to the rate of change of the current being measured.

For use the Rogowski coil is needed a transducer of signal. With the coil we take the information of the variables that give to us the capacity of knows the exactly current, but it is the transducer the instrument which makes the transformation.

The voltage induced in a Rogowski coil is proportional to the **rate of change** of current enclosed by the coil-loop. It is therefore necessary to **integrate** the coil voltage in order to produce a voltage proportional to the current. (8)

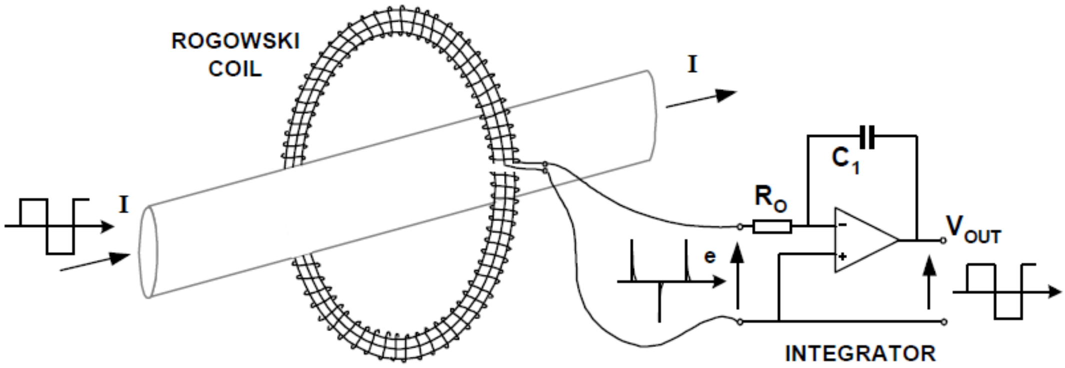


Illustration 6 Integrator Scheme

The wires of the circuit have to pass thought the sensor. As the sensor works as a coil, has to be perpendicular to the circuit to have the best measures. So, in this case we have two different factors which can divert the real measure; the incertitude of the magnetic measure of the sensor and the position of the Rogowski sensor (if it is not totally perpendicular to the circuit). (9)

The advantages of this method are the high linearity and fast response of the sensor which enable it to register high frequency current pulses and the easy and simple installation of the measure system.

In the other hand, it is equipment very susceptible to external noises.

The coil is uniformly wound with ***N*** turns/m on a non-magnetic former of constant cross section area ***A*** m2. If formed into a closed loop then the voltage **e** induced in the coil is given by the equation

$$\boldsymbol{e} = \mu_0 \boldsymbol{NA}\frac{\boldsymbol{di}}{\boldsymbol{dt}} = \boldsymbol{H}\frac{\boldsymbol{di}}{\boldsymbol{dt}}$$

Where

$$\boldsymbol{H}\left(\frac{\boldsymbol{Vs}}{\boldsymbol{A}}\right) \textit{is the coil sensibility}$$

$$\boldsymbol{I} \textit{ is the current to be measured passing through the loop}$$

The loop does not need to be circular and ***e*** is independent of the current position in the loop. To reproduce the current waveform as a measurement signal which can be displayed on an oscilloscope or quantified using a DVM, all that is required is means for accurately integrating the coil voltage, such that

$$V_{out} = 1/T_i \int e.dt = R_{SH} * I$$

Where the next equations are the transducer sensitivity in (mV/A)

$$\boldsymbol{T_i} = R_0 C_1$$

$$\boldsymbol{R_{SH}} = H/T_i$$

The relationship $\mathbf{V_{out}}$ proportional to **I** is valid throughout the transducer bandwidth. The bandwidth is defined as the range of frequencies from $\mathbf{f_L}$ to $\mathbf{f_H}$ for which sinusoidal currents can be measured to within 3dB of the specified sensitivity $\mathbf{R_{sh}}$.

At low frequencies the integrator gain increases and in theory will become infinite as the frequency approaches zero. This would result in unacceptable dc drift and low frequency noise; hence the integrator gain has to be limited at low frequencies. This limitation is achieved by placing a low pass filter in parallel with the integrating capacitor. The low pass filter sets the low frequency bandwidth $\mathbf{f_L}$, typically this is less than 1Hz. (8)

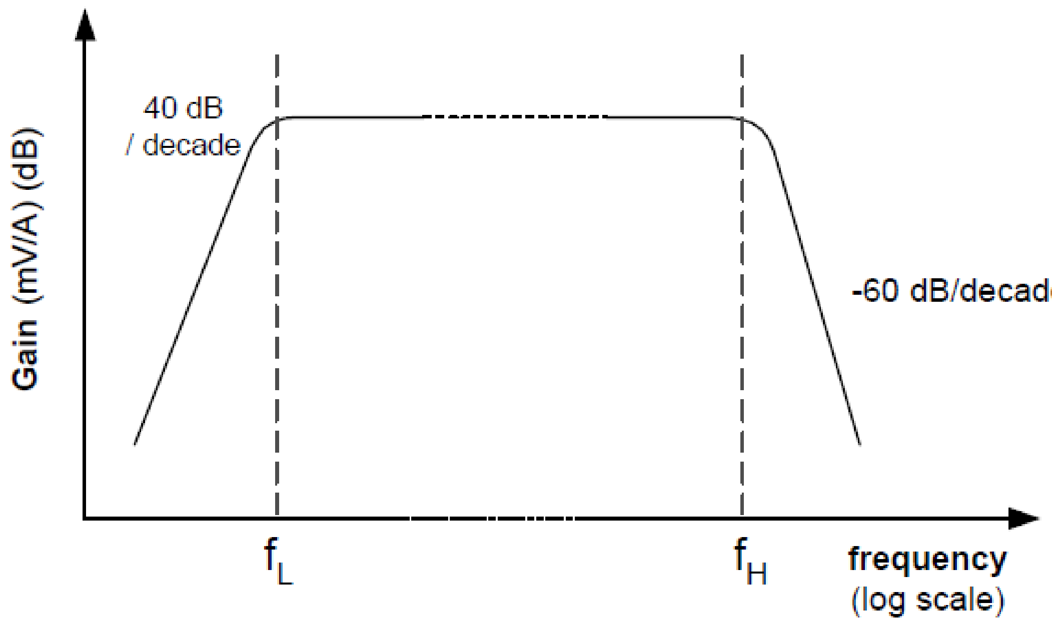


Illustration 7 Rogowski Coil Bandwidth

According to the features of the Rogowski coil, his large measure range and the ease to obtain results, makes it suitable for the purpose of this thesis.

As a resume, a list of advantages and disadvantages of this sensor is presented here (10):

- **Can measure large currents without saturating**. The size of the Rogowski coil required remains the same despite the size of current. This is unlike other current transducers which become bulkier as the current magnitude increases.
- **Are easy to use** - the coil is thin and flexible and easy to insert around a current carrying device.
- **Are non-intrusive**. They draw no power from the main circuit carrying the current to be measured.
- Have a very wide bandwidth extending from typically 0.1Hz up to 17MHz.
- **Provide an isolated measurement at ground potential** similar to other current transducers (except co-axial shunts) i.e. there is no direct electrical connection to the main circuit.
- **Can measure AC signals superimposed on large DC**. The transducer does not measure direct currents - as a result it can measure small AC currents in the presence of a large DC component
- **Can measure changes of current as fast as 40,000A/µs.**

3.1.1 Rogowski coil PEM CWT B 15/4/500 Features

The Rogowski coil that has been used for monitoring the ERW process in this Thesis is **PEM CWT B 15/4/500.** His features are the following:

- **Sensitivity** 0.2 mV/A.
- **Peak current** 30 kA.
- **Peak di/dt** 40 kA/µS.
- **Noise MAX** 3 mV.
- **Droop** 0.2%/mS.
- **LF (3dB) bandwidth** 0.2 Hz.
- **Phase lead at 50Hz** 0.3 deg.
- **HF (3dB) bandwidth** 10MHz.
- **Typical accuracy** From ±0.2% in the centre of the coil to ±1% in the coil loop.

The letter and numbers after CWT name has the following meaning:

- **B** Battery Power Supply (4 x 1.5V).
- **4** Cable Length. 4 meters.
- **500** Coil Circumference. 500 mm.

Illustration 8 Rogowski coil PEM CWT B/4/500

3.2 Fiberoptic sensor Philtec D100

For the measurement of the displacement between the electrodes along the RSW process, Philtec maker was chosen, concretely their PHILTEC D100 model.

It is of a reflective type and it utilizes bundled glass fibers to receive and transmit light to and from target surfaces. This method could be considerate non contacted sensor, which means that the sensor does not interference in the process. This kind of sensor has not a magnetic influence as result of the high welding current of ERW, which will not distort the data, and can measure the displacement without interference in the welding process. (7)

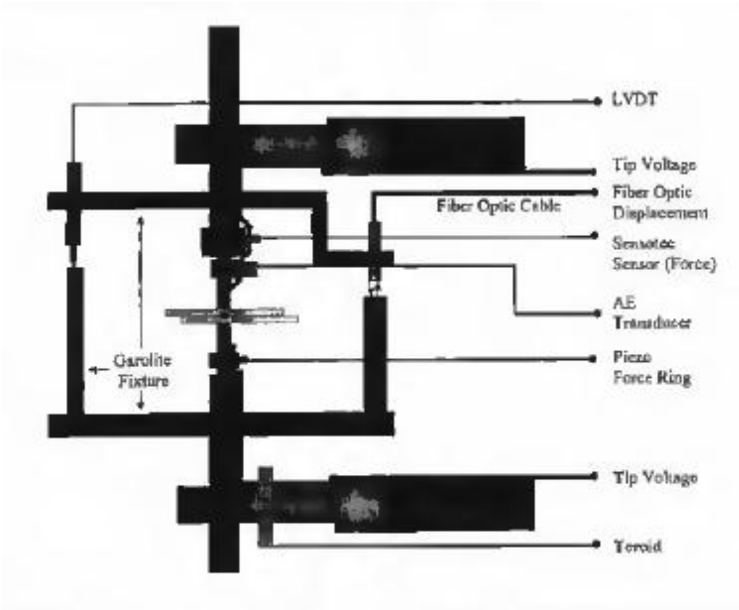


Illustration 9 ERW scheme

As is showed in the previous illustration, with the right fixturing system, is possible to hold the sensor in a parallel surface with the welding machine, making the data acquisition easier and better.

Some of the general advantages and disadvantages of the fiber optic sensor are: (11)

- They can be used on most materials, irrespective of the color or conductivity.
- The measure surface can be not directly the surface of work. This make that the sensor will not make interference with the welding process.
- The sensor filters better the magnetic fields as consequence of the high current in the welding process.
- The installation of the sensor it is not so easy than in the LVDT sensor, but, in the other hand, we do not need to make a hole in the pieces that we are to weld.
- The model “D100 Product” uses a kind of light in the measure that minimizes the influences of highs temperatures that we can have in ERW.

Philtec is one of the companies leading manufacturer of Fiberoptic Sensor. It provides to the costumer a big customizability for their products.

3.2.1 Philtec D100-C1E1PR2T2 Features.

The main characteristics of the Fiberoptic sensor used in this Thesis are the next ones (12):

Reflectance Dependent Output with Dual Functions: Far Side/Near Side

- Ø 2.54 mm Target Spot Size (0.100 inch)
- 10 mm Total Operating Range (0.400 inch)
- 0.7 mv/µm Far Side Sensitivity (18 mv/mil)
- 35 mv/µm Near Side Sensitivity (900 mv/mil)

FEATURE	mm	inch
Tip Outer Diameter, Ø C	3.18	0.125
Fiberoptic Diameter	2.54	0.100
Tip Length, C	76.2	3
Collar Length, B	12.7	0.5
Collar Diameter, Ø B	6.35	0.25
Cable Length, A	914	36
Cable Diameter, Ø A	5.7	0.225
Cable Min. Bend Radius	25	1

Philtec D100 has a special graph to show the displacement, as all the models of this kind of sensors. It was provided by the distributor and is shown and explained here:

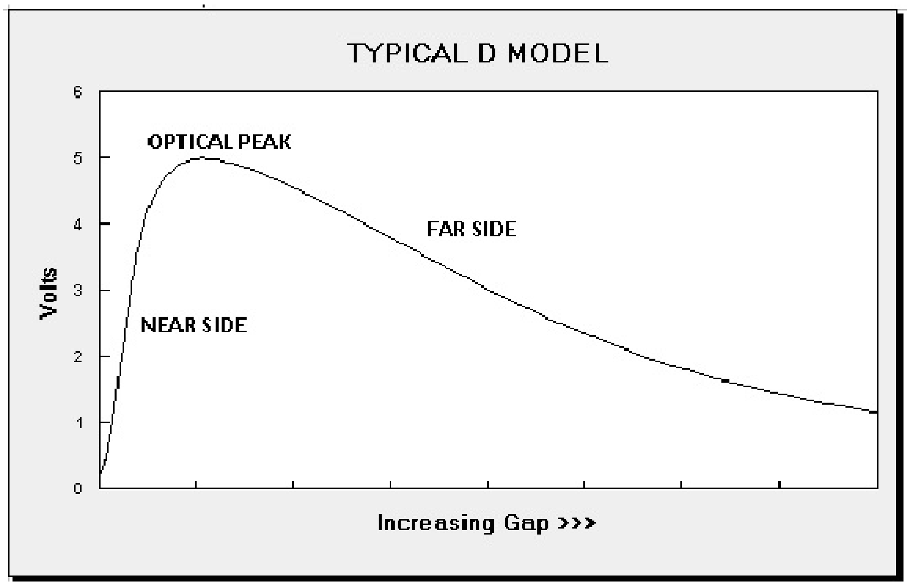


Illustration 10 Phiberoptic D model graph

As is shown in the illustration above, the graph has two different parts, depending of the measured distance. They are called Near Side and Far Side, and are different for each Philtec model. In this case, for Philtec D100, the particular graphs are the following.

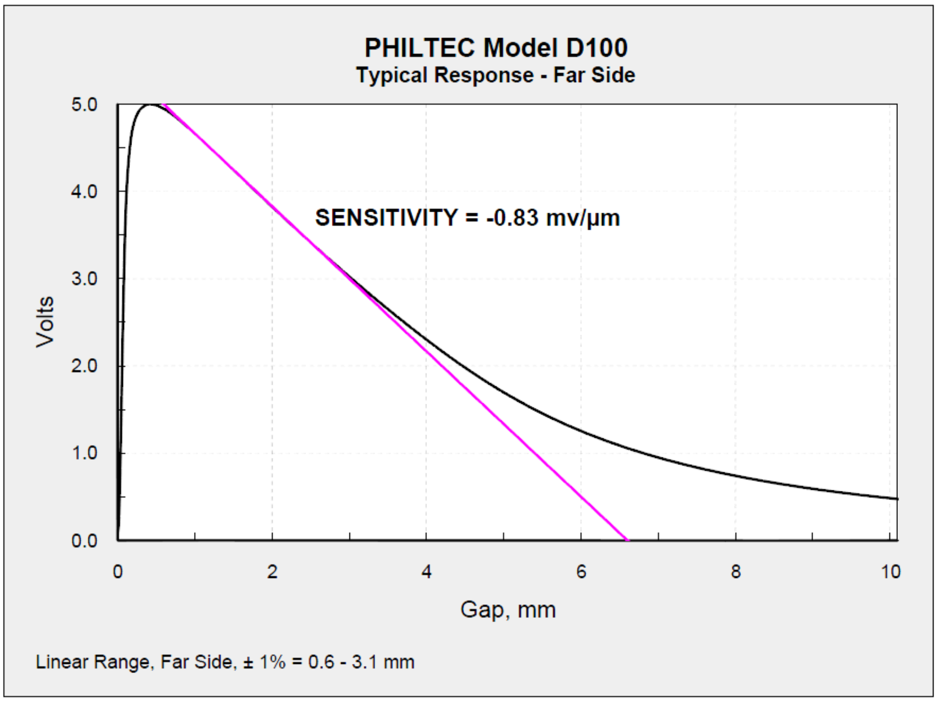


Illustration 11 Typical response Far Side

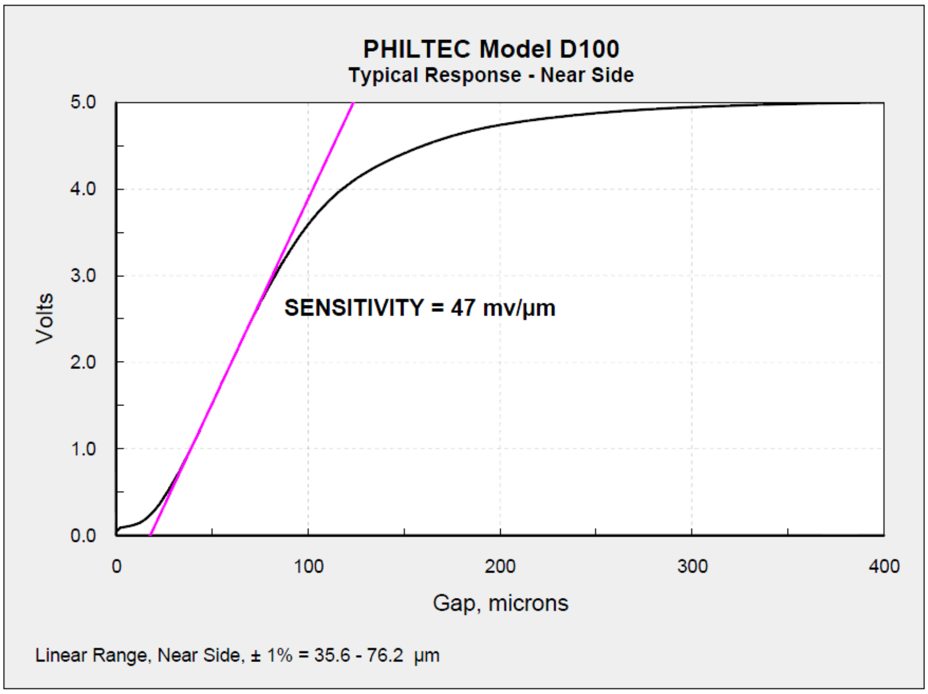


Illustration 12 Typical response Near Side

Using this graphs, is possible to transform the Output Voltage of Philtec Sensor into a Measure value, which is the real purpose of the test.

Once the main properties of the sensor are shown, is needed to explain the particular features of PHILTEC D100-C1E1PR2T2 sensor. PHILTEC allows you to customize the sensor, choosing specific features for it, making easier working with it, and adapting it to the customer needs.

The special features of each sensor are indicated in the own name, with the letters C, E, P, R and T. The meaning of them, for PHILTEC D100-C1E1PR2T2 sensor are the following ones:

3.2.1.1 C1 Option

Interlocking Stainless Steel with a Temperature Range from -270 to +340 C, with maximum strength and temperature range, and good flexibility.

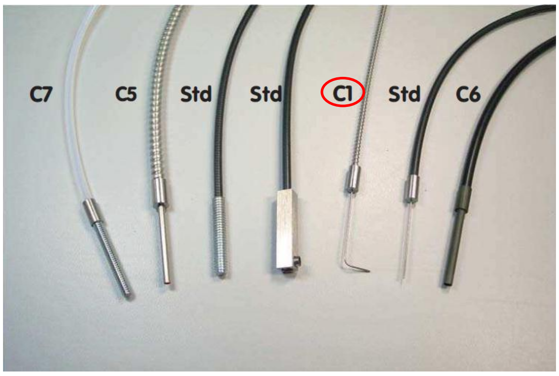


Illustration 13 C option

3.2.1.2 E1 Option

Extra length cable. Length of E1 Option cable: 2m.

3.2.1.3 P Option.

For most of this kind of sensor, a calibration chart is provided with each sensor giving the voltage output response to distance. There are three ways to derive accurate distance measurements: (13)

- Within the bounds of the linear range, convert the change in voltage output as follows: Distance = Δ milliVolts ÷ Sensitivity = µm
- Over the non-linear range, create a lookup table using the XY calibration data points
- Use a polynomial curve fit to accurately map the sensor’s output function.

Linear ranges of Philtec’s fiberoptic sensors vary from approximately 10% to 30% of the total operating ranges. Option P can extend the range of calibrated operations beyond the bounds of linear ranges via polynomial curve fitting.

When P option is available, is possible to get the real distance using only the Polynomial provided for each case, making the work easier.

In this specific case, the polynomial curve provided by the maker for Far Side is the shown on the next illustration. In our study, this equation has been used because his measuring range is more appropriated for monitoring the RSW process.

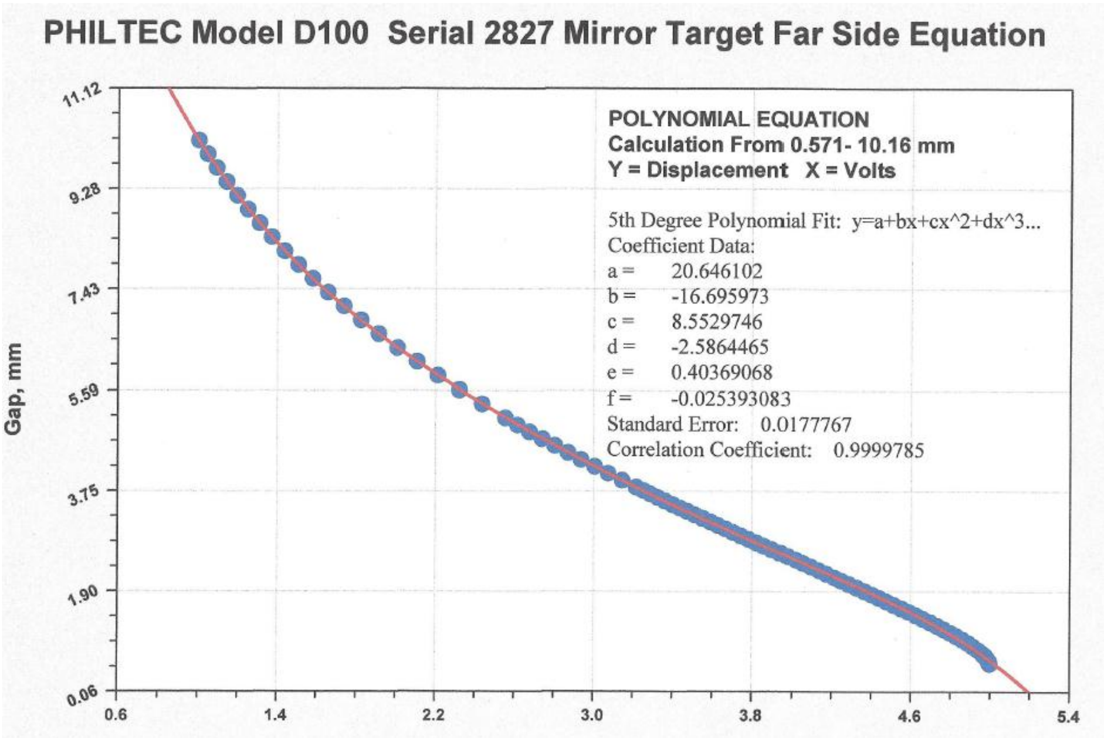


Illustration 14 Far side Polynomial

Attending to the values that appear in the graph, the polynomial curve that has to be used is:

$$y = 20.646102 - 16.695973x + 8.5529746x^2 - 2.5864465x^3 + 0.40369068x^4 - 0.025393083x^5$$

Where:

$$y = Real\ displacement, mm$$
$$x = Volts, DC$$

This is the equation that is going to be used in the integration of the sensor into computer software.

If is needed to measure distances smaller than 0.571mm, is possible to use the next equation for near side. The polynomial is more complex but their implantation follows the same process than for Far side.

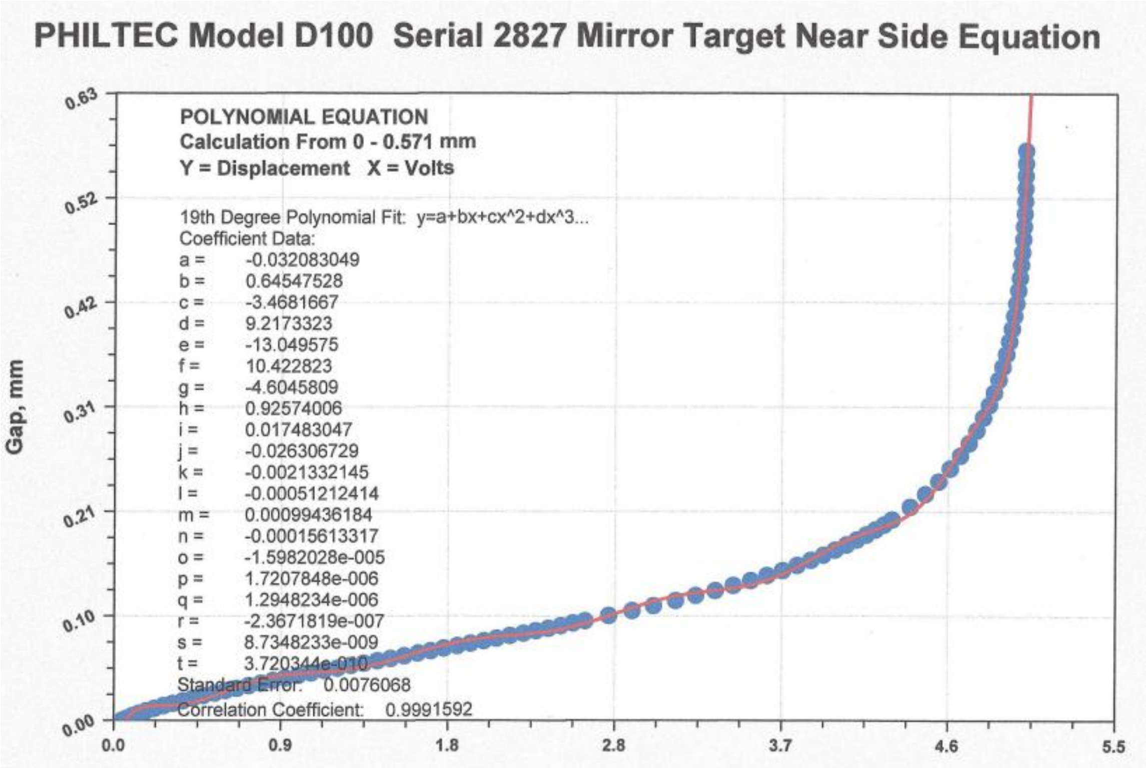


Illustration 15 Near side polynomial

3.2.1.4 R2 Option

Ambient light rejection. These devices operate with continuous light emission. Standard units are subjected to ambient light pickup. In environments where lights is a problem, ambient light pickup can be 50 to 100 times smaller when option R is used.

3.2.1.5 T2 Option

This option provides the sensor a threated head, in order to make easier the fixture to the machine. In our case, the sensor has M8x1.5 threat.

Illustration 16 T2 Option

3.3 National Instruments USB-6216

The previously explained sensors are needed to acquire data for the Welding Process, but that data have to be read by a computer. Here is where the National Instruments analogic to digital converter appears. With this hardware is possible to receive the data from the sensors, convert them into a digital output, and use them in the LabVIEW software.

We have chosen the NI USB-6216 converter, which specifications are this ones: (14) (15)

- **Connector**: Screw/68-pin SCSI.
- **Analog inputs:** 16.
  - **Resolution (bits):** 16.
  - **Max rate (kS/s):** 400.
- **Analog outputs**: 2.
  - **Resolution (bits):** 16.
  - **Max rate (kS/s):** 250.
- **Digital I/O:** 24 or 32 DIO.
- **Isolation:** 60V, CAT I.
- **BUS Interface:** USB 2.0 High speed.

This features are perfect for working with our Philtec Fiberoptic and Rogowski Coil Sensor. The sensors specifications are compatible with NI, and makes them able to work together.

NI USB-6216 allows the user to use a lot of inputs and outputs simultaneously, but in our case we have used, at most, two Analog Inputs (One for each sensor), and the USB output. In any case, this hardware is really versatile and can be used for other purposes or tests in the future.

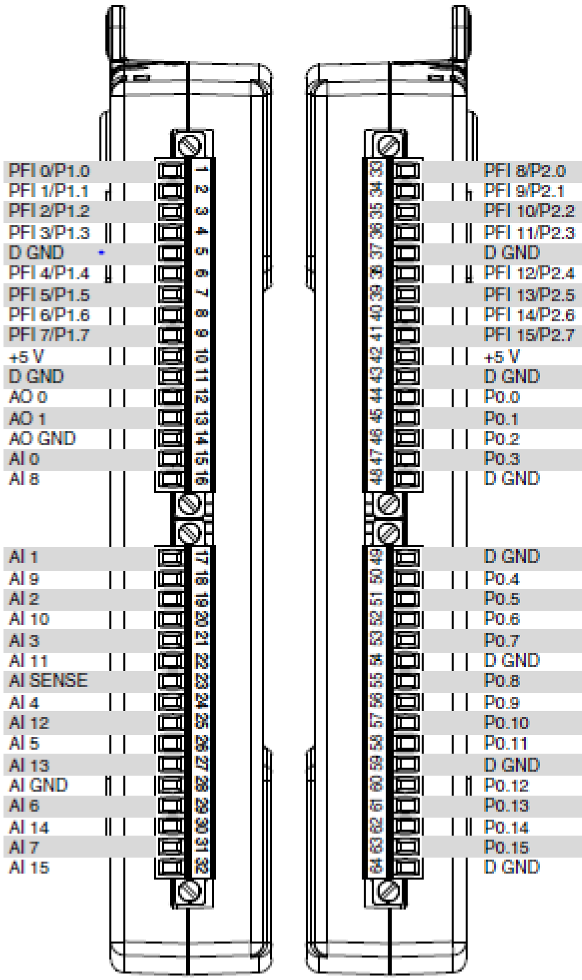


Illustration 17 USB-6216 Connection diagram

In the Illustration above the Analog/Digital Inputs and Outputs are shown, to ease the user the utilization of this Hardware.

In our case, as was said before, only two Analog outputs are needed, one for each sensor. The chosen Inputs have been AI1 and AO2.

The digital output is the same for all cases, an universal USB cable, making the sensor suitable for work with all kind of laptops.

Once the hardware is known, is possible to begin with the software. As is known, for the elaboration of this Thesis, LabVIEW 2013 was the software chosen. In the following sheets of this report, the steps to integrate the Hardware into the computer will be explained.

In any case, the first stage to acquire and process data from the sensors, is to know exactly how to use LabVIEW, and what is needed to do. The next part of this thesis will solve all this problems and answer all the questions.

4. Implementation of the hardware

Once the hardware to use is deeply studied and explained, is possible to begin with the software. In this thesis, as it is definitely known, LabVIEW 2013 will be used.

LabVIEW is a really powerful and easy to use computer software. It is not necessary any knowledge about any programming language (C, C++, Java…) to work with it. That is why LabVIEW is not a classic programming software, it is a GRAPH programming software.

Due to our Analogic-to-Digital converter comes from Native Instruments, we have decided to use LabVIEW, what is developed for the same company. Politecnico di Torino has got a license for the LabVIEW 2013 version, so it is easier to use this software.

Create a new program is easier than with other software. It works with a Block diagram, where the components of the main program appears, making the understanding of it simple and really intuitive. With a basic knowledge about programming and math, everybody is able to create a program with a high degree of difficulty.

In addition to the Block diagram that was mentioned above, LabVIEW uses a Front Panel, where is shown the results of the program made in the Block Diagram. In this screen, is possible to watch all kind of Graphs, indicators, controls for the program and many other useful data. Here is where really appears the program that was created, and is the interface which the user is going to work.

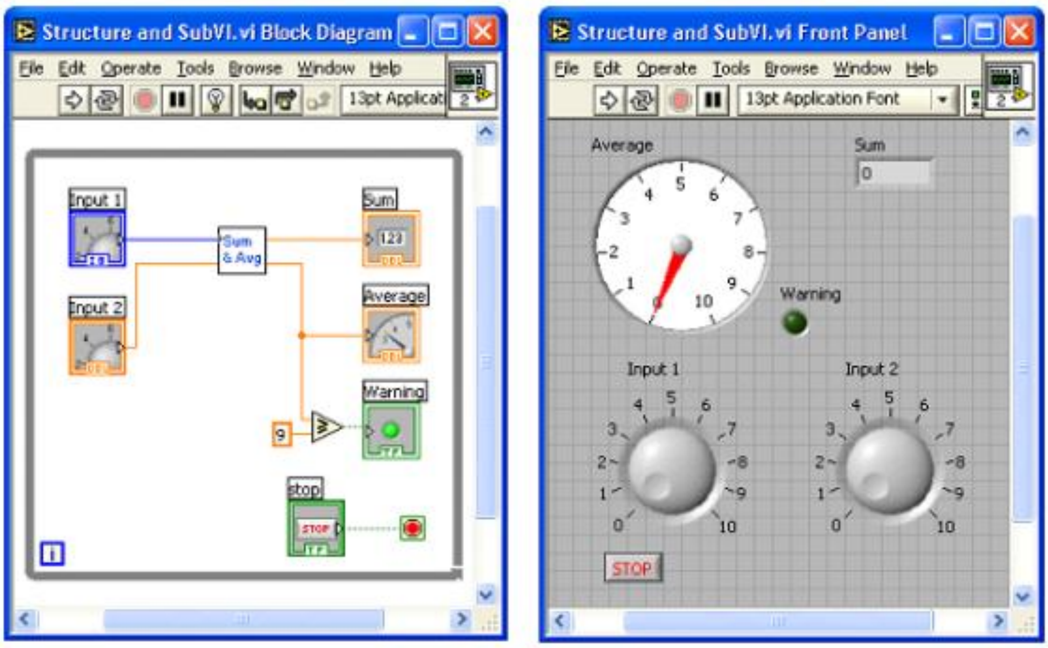


Illustration 18 LabVIEW Block Diagram and Front Panel

As first step to begin using LabVIEW, is recommended to study the manual of this software, as well as practice with the examples and tutorials which are available on the National Instruments website. They are really useful and provides the user the capacity of working with LabVIEW. The Manual and the tutorials are available in the next websites:

- LabVIEW Manual: http://www.ni.com/pdf/manuals/320999e.pdf
- LabVIEW online Tutorial: http://www.ni.com/academic/students/learn-labview/

After acquire some basic and intermediate level skills with the software, the next step is to integrate the Native Instruments analogic-to-digital converter in the computer.

To learn some LabVIEW skills is totally indispensable, due to is the interface which allows the user to acquire, read, and treat the data provided for the sensors.

Once the user is able to use in a basic level this software is possible to take the next step, **how to integrate NI USB-6216 in LabVIEW.**

4.1 Integration of NI with LabVIEW

For the elaboration of this thesis, is needed to use some computer software to take the signals form the sensors. Due to our Analogic-to-Digital converter comes from Native Instruments, we have decided to use LabVIEW, which is developed for the same company.

LabVIEW is a complete, intuitive and easy to use software. At first, I did not had any knowledge about this program, but an on-line course was enough to begin using it, making me able to use this software for our test.

Is needed, as well, a specific software to connect our NI converter to LabVIEW. We found it on the webpage of National Instruments. At first there was some compatibility problems between LabVIEW and the drivers form the Converter, but with some deep study we could correct them and begin to work.

Then, it will be shown the process to connect the NI converter to the computer, and how to be able to work with the data received from it.

In this thesis, we will work with a **NI USB-6216**.

4.1.1 Connect the sensor to computer

First of all, is needed to download the drivers for the converter. For our NI model, we need the NI-DAQmx software, which includes all the necessary to work with it.

The software that has been used to connect the Hardware, is NI MAX, included in the NI DAQmx installer. Here is possible to test all the devices, and see if they are working properly.

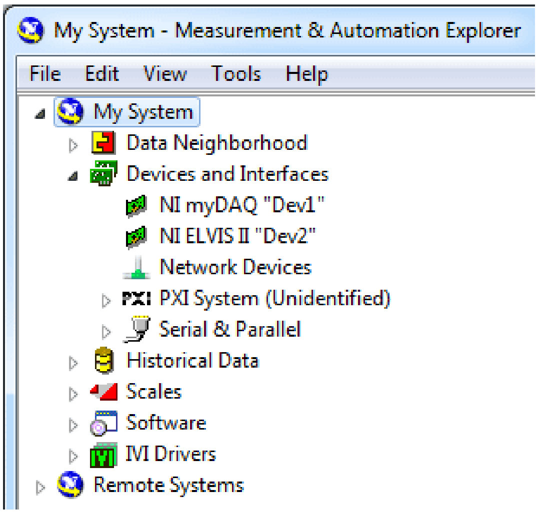


Illustration 19 NI MAX Menu

In this picture, is shown the left menu form NI MAX. In Devices and Interfaces, you can see which devices are connected to the computer. In our case it was NI myDAQ, because is the software that we are using.

Clicking with the right button on the name of our device, appears a menu when we can do a lot of operations with our hardware. It will appear this window:

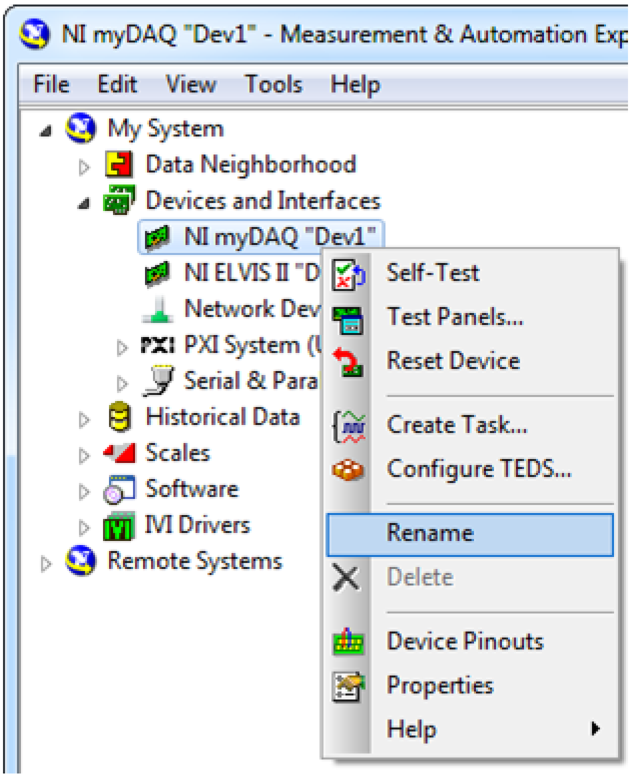


Illustration 20 NI MAX Options

It’s highly recommended to do the Self-Test, and Reset the device before work with LabVIEW. If we click on Test Panels, we will be able to check if the computer is getting some signal from the hardware, who means that is working properly.

If exists doubts about the Inputs-Outputs of the device, we can click on Device Pinouts, when will appear a scheme of our Hardware, really useful at first.

There are a lot of options in addition of the explained before, but which are explained here are enough for us.

Once the device is connected and sending signal to the computer, we can begin acquiring data from it on LabVIEW.

4.1.2 Data acquisition

Here will be shown the step by step process to acquire data from the Hardware. Is really useful to follow this steps in order to make the first test with LabVIEW. (16)

1. Connect the USB DAQ device to your PC

2. Connect the signal of interest to the analog input channel 0 (ai0) terminal of your device

   a) You can locate the device pinouts for your DAQ device by searching for your device online at ni.com
   b) The user guide and specifications contain this diagram
   c) Right-click your device in NI Measurement & Automation Explorer (MAX) and select Device Pinouts

3. Create a new VI in LabVIEW a. Open LabVIEW and select File >> New VI

4. Place a DAQ Assistant on the block diagram

   a. Right-click on the block diagram and select Express >> Input >> DAQ Assistant
   b. Place the DAQ Assistant on the block diagram by left-clicking.

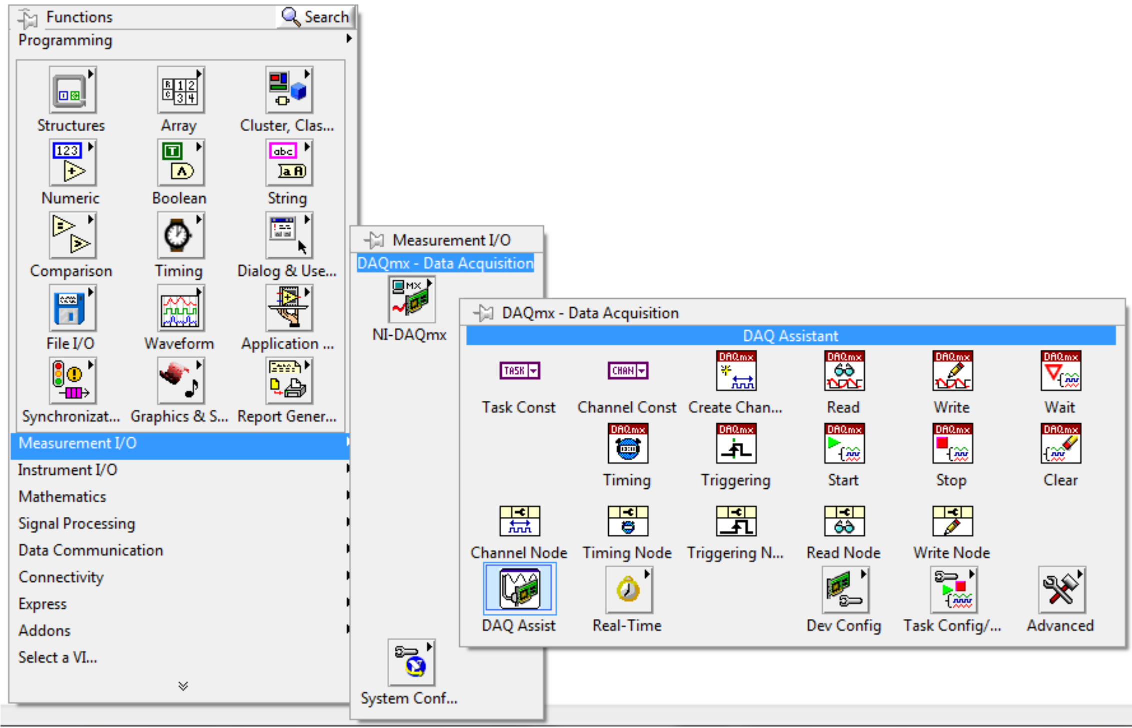


Illustration 21 How to insert DAQ assistant

5. Configure DAQ Assistant type

   a. Select Acquire Signals
   b. Select Analog Input
   c. Select Voltage
   d. Select Dev1 (or the name of your device if not Dev1)
   e. Select aiX, where "X" is the number of the selected input

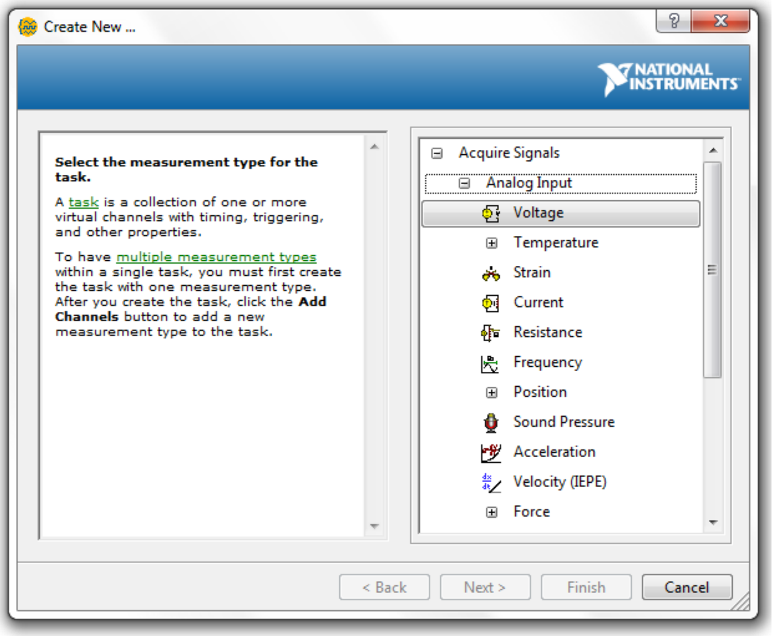


Illustration 22 Configure DAQ Assistant

6. Configure acquisition settings

a. Enter 1000 (Case study: 300kS) for Number of Samples
b. Enter 10k (Case study: 100kHz) for Sample Rate
c. Click Run to test your settings
d. Click OK to finish the DAQ Assistant

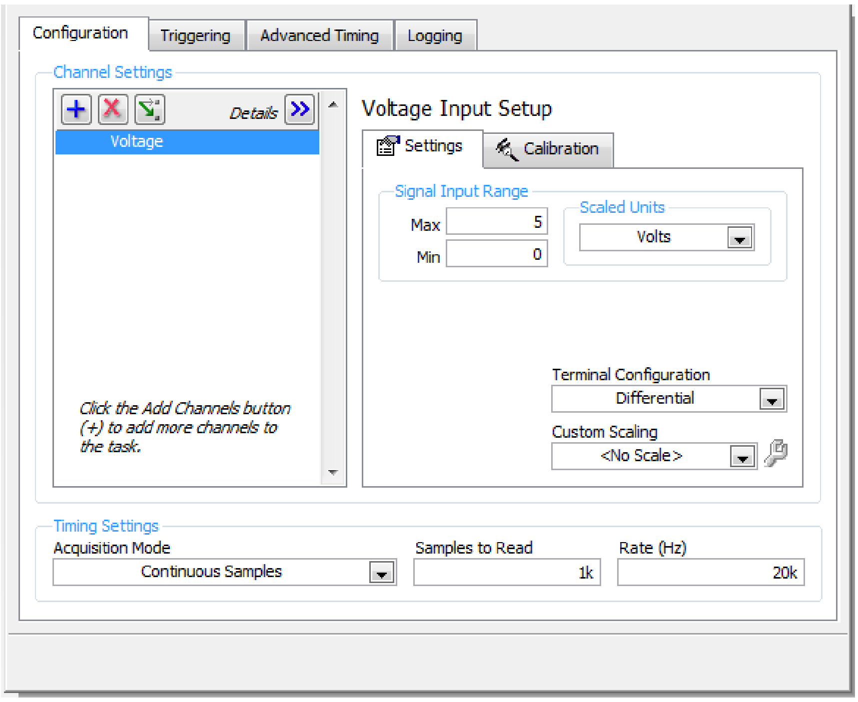


Illustration 23 Data acquisition settings

7. Create the graph indicator to view data

a. Right-click on the Data output terminal of the DAQ Assistant
b. Select Create >> Graph Indicator
c. Run the VI by pressing the Run button and visualize the results
d. Adjust Graph Indicator appearance as desired

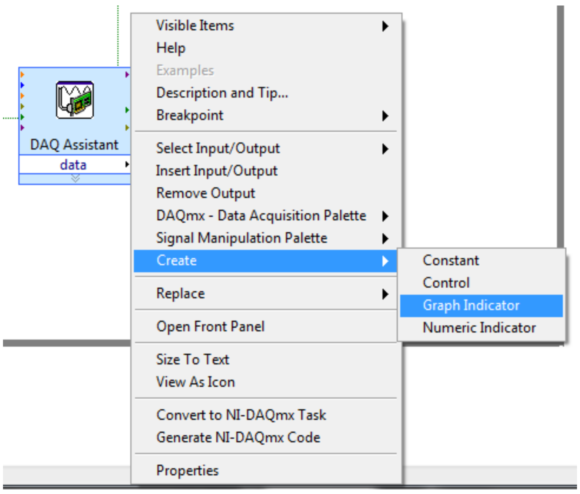


Illustration 24 Create Graph indicator

8. Change acquisition mode to Continuous (in case of continuous data acquisition required)

a. Double-click the DAQ Assistant
b. Change Acquisition Mode from N Samples (Finite) to Continuous
c. Select OK to finish the DAQ Assistant
d. Select Yes to auto place the While Loop around the DAQ Assistant

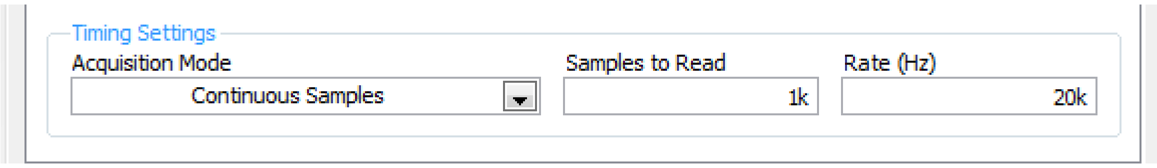


Illustration 25 Continuous Samples

9. Create the stop condition to include when the Stop button is pressed or an error is detected

a. Unwire the Conditional Terminal from the Stopped output terminal of the analog input DAQ Assistant
b. Right-click the block diagram and select Programming >> Boolean >> Or
c. Wire the output from the Stop button control to the bottom input of the Or Boolean function
d. Right-click the block diagram, select Programming >> Cluster, Class, & Variant >> Unbundle by Name, and place this to the right of the analog input DAQ Assistant
e. Wire the Error Out output terminal of the analog input DAQ Assistant to the input of the Unbundle by Name function and ensure Status is selected to be unbundled
f. Wire the output of the Unbundle by Name function to the top input of the Or function
g. Wire the output of the Or function to the input of the Conditional Terminal

10. Run the VI to visualize the data on the front panel .

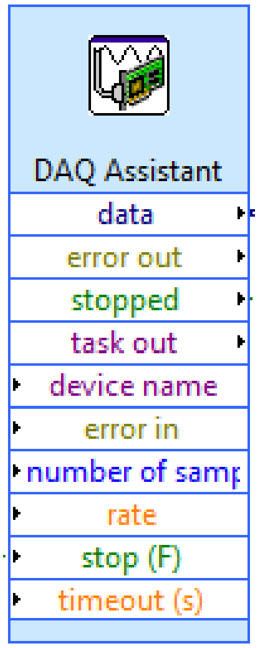


Illustration 26 DAQ Assistan icon

Once the previous process has been made, an icon like the previous one will be shown on the block diagram, making possible to change some of the most important features of the data acquisition. The meaning of the most important, and the useful for us are this:

- **Data**: Digital output. Here the Charts will be connected to watch the results.
- **Error out:** Choose a value for the Output error.
- **Device name:** Changes the name of the device.
- **Number of samples:** Allows the user to select the amount of data acquired by the sensor.
- **Rate:** Selects the Rate in Hz of data acquisition.
- **Timeout (s):** Specifies the amount of time in seconds to wait for samples to become available

It is possible to select and choose some of the properties of the data acquisition in this way, but some others are only available by clicking in the DAQ block, which will show the next window, where is possible to change some parameters:

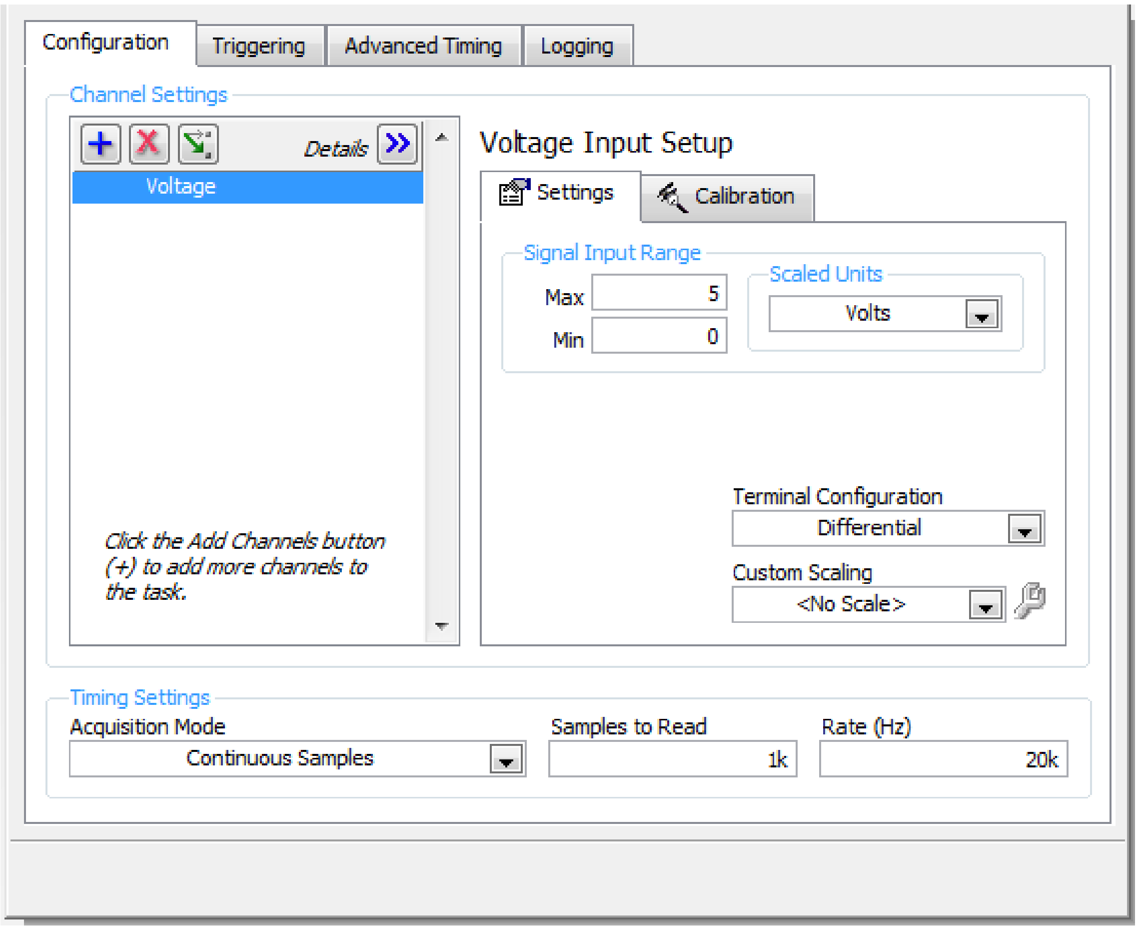


Illustration 27 DAQ Assistant Options

Some of the changes that can be made here are the next ones:

- **Signal Input Range**. We will change the Max an Min values to adapt them to the Output range of the sensor that is going to be used.
- **Timing settings.** Here are shown the parameters that can be modified.
    - <u>Acquisition Mode.</u> We will select Continuous Samples. This means that the computer will be having data from the sensor as much time as we want. We only have to push "Run" to begin the data acquisition and click on the "Stop" button to finish it.
    - <u>Samples to read and Rate (Hz).</u> Will be selected the proper values that our sensor can provide us.

4.1.3 Generating graphic and numeric data results.

Once the sensor is correctly connected, and is possible to acquire data from it, it is possible to view our results on a Graph in real time, and as numerical data when the data acquisition process is ended.

There are two ways to results to be shown: Waveform Chart and Waveform Graph.

- **Waveform Chart.** This kind of Waveform shows the voltage measurements in real time, but it does not save the previous results. It means that you can check the actual measure but not all the measures from the whole process. This kind of chart is not appropriated for us.

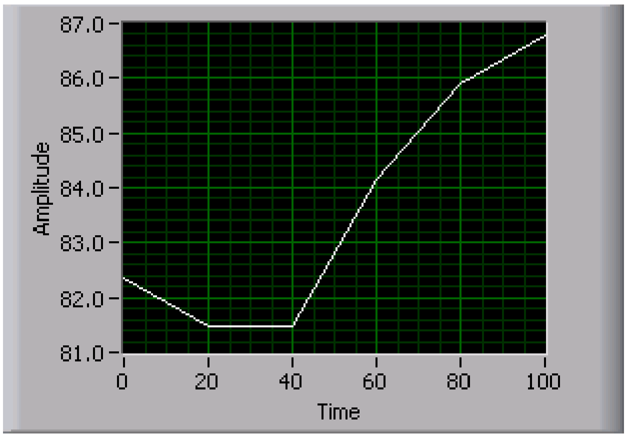


Illustration 28 Waveform Chart example

- **Case study: Waveform Graph.** In this case, the graph will show the actual measure, and the previous measures, showing all of them in the same graph. This is really useful for us, because we can the progress of the measure, from the beginning until the end of the test.

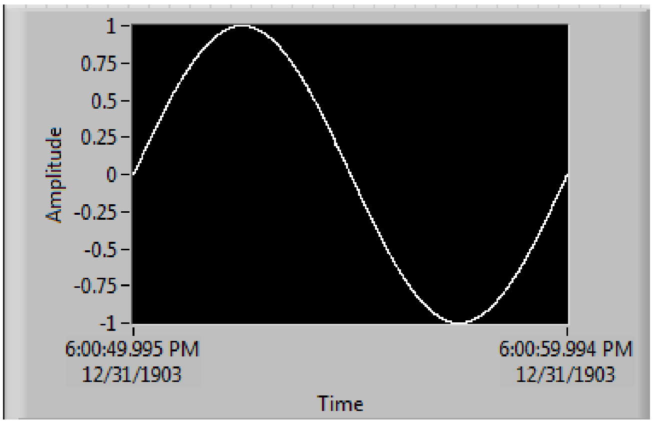


Illustration 29 Waveform Graph example

LabVIEW allows us to export the numeric results of the measurement into an Excel or .txt file, which is useful if is needed to study the data deeply. Clicking with right button on the Graph->Export->Export data to Excel, LabVIEW will create a new file with the time, and the measure form the graph.

The previous process is simple to make, but not totally recommendable, because takes a lot of time and is not possible to adapt the data to our needs, that is why we used another method for acquiring data from LabVIEW, the "**Write to Measurement File**" tool.

Write to Measurement File tool allows the user to enable the automatic data saving, in a desired directory and with an appropriate kind of file. It is faster and more safety to save data this way, that is why is highly recommended to implement this "box" into the LabVIEW Virtual Instrument.

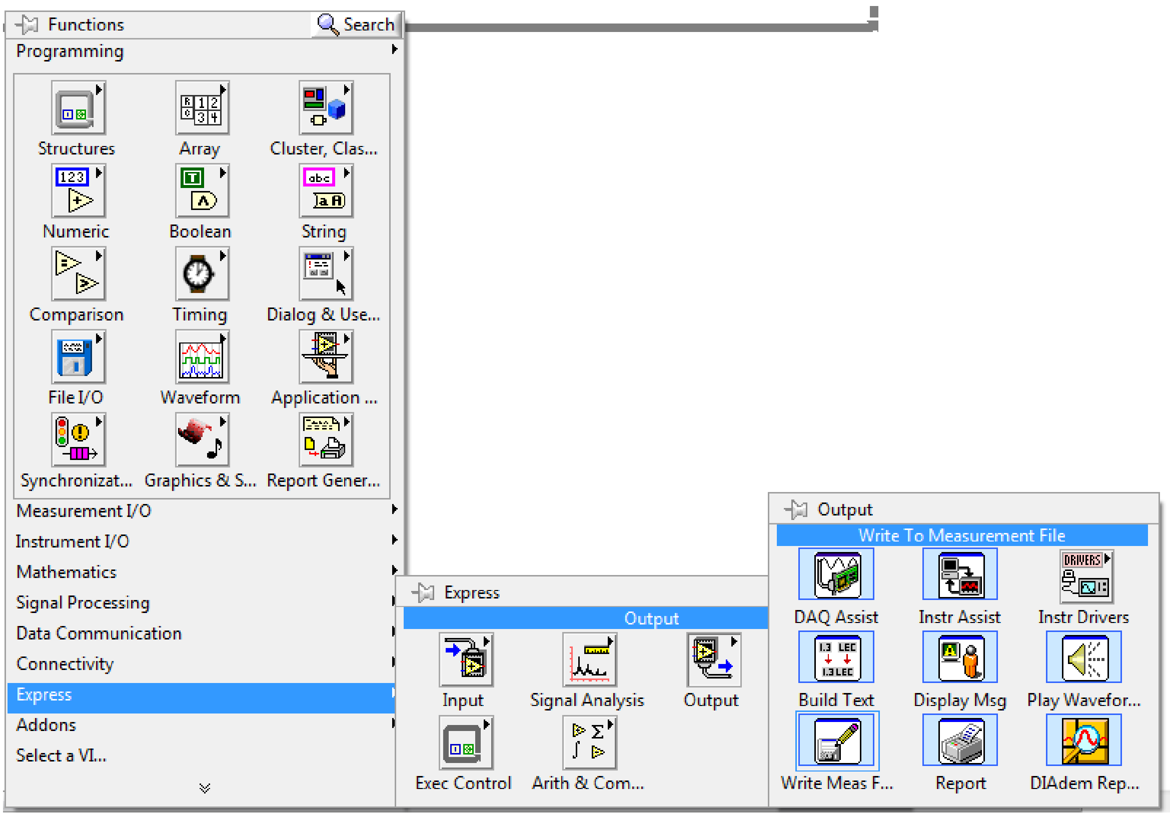


Illustration 30 How to implement "Write to Measurement File" tool

This box allows the user to select a lot of different options, where the most important for us are the next ones:

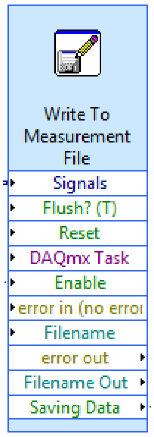


Illustration 31 Write to Measurement box

- **Signals**: Select the input data which are going to be saved.
- **Reset**: Restarts the device.
- **Enable**: Allows the user the option of begin/end the data acquisition without finishing the application.
- **Filename**: Select the name of the file where the data will be saved.
- **Saving data**: Light indicator. On when data is saving.

Double click in the box opens a new window, when is possible to choose a lot of properties for the destination file, such as the next:

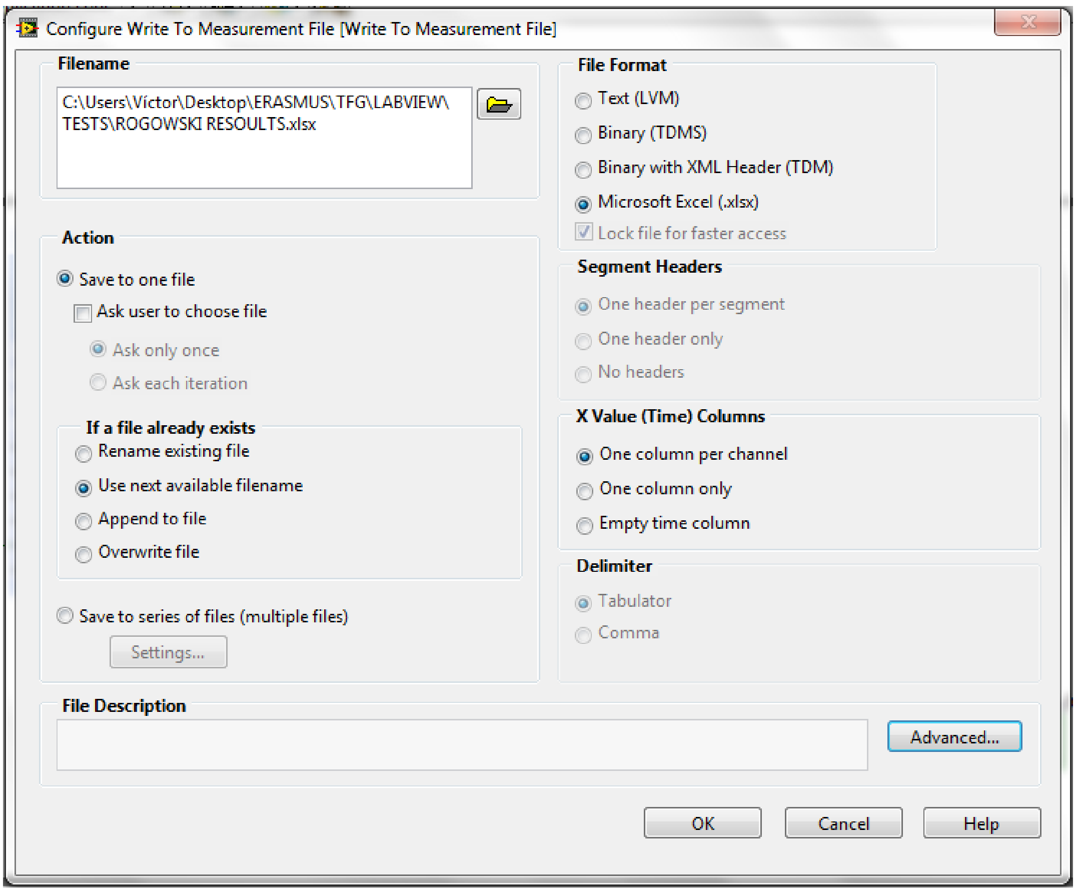


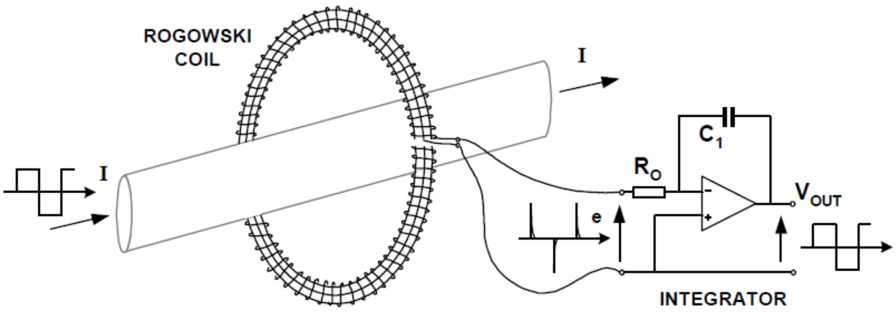
Illustration 32 Write to Measurement File Configuration

Once the "Connect the hardware" and "Generate and save data" are known, is possible to begin to work with the different sensors, and create an appropriate LabVIEW VI for each one. In the next point this will be explained.

4.2 Integration of Rogowski coil.

For our purpose of monitoring the current in ERW process, PEM CWT 150B / 4 / 500 was chosen. The integration of this sensor is simpler than the Philtec D100 sensor. This is because this CWT 150 model is compound by: (8)

- A typical Rogowski Coil.
- An integrator, to convert Current Input into Voltage Output.



The integrator makes the measuring process simple, according with the next equation, is possible to know the real current in the wire from the output voltage.

$$\boldsymbol{V_{out}} = 1/T_i \int e.dt = \boldsymbol{R_{SH}} * \boldsymbol{I}$$

Where the next equations are the transducer sensitivity in (mV/A)

$$\boldsymbol{T_i} = R_0 C_1$$

$$\boldsymbol{R_{SH}} = H/T_i$$

According to the documentation provided by the maker, CWT 150B / 4 / 500 has a sensibility of exactly 0.2 mV/A. This value will be used to the conversion from Voltage to real Current in the coil, through the equation above. To get the real measure in Amperes existing in the coil, is needed to modify that equation, according to the next:

$$\boldsymbol{I_{coil}} = \frac{\boldsymbol{V_{out}}}{\boldsymbol{R_{SH}}} = \frac{\boldsymbol{V_{out}}[\boldsymbol{V}]}{\boldsymbol{0.2}[\boldsymbol{mV/A}]} = \frac{\boldsymbol{V_{out}}[\boldsymbol{V}]}{\boldsymbol{0.0002}[\boldsymbol{V/A}]} = \boldsymbol{I_{coil}}[\boldsymbol{A}]$$

This provide us enough information to implement the Rogowski coil into LabVIEW. Just like explained in the Fiberoptic LabVIEW program, the data acquisition is integrated in a While Loop, which will take data from the sensor until the user clicks the STOP button.

The data treatment is simpler that with Fiberoptic, due to the equation above is the only one needed. The LabVIEW VI follows the next Block Diagram:

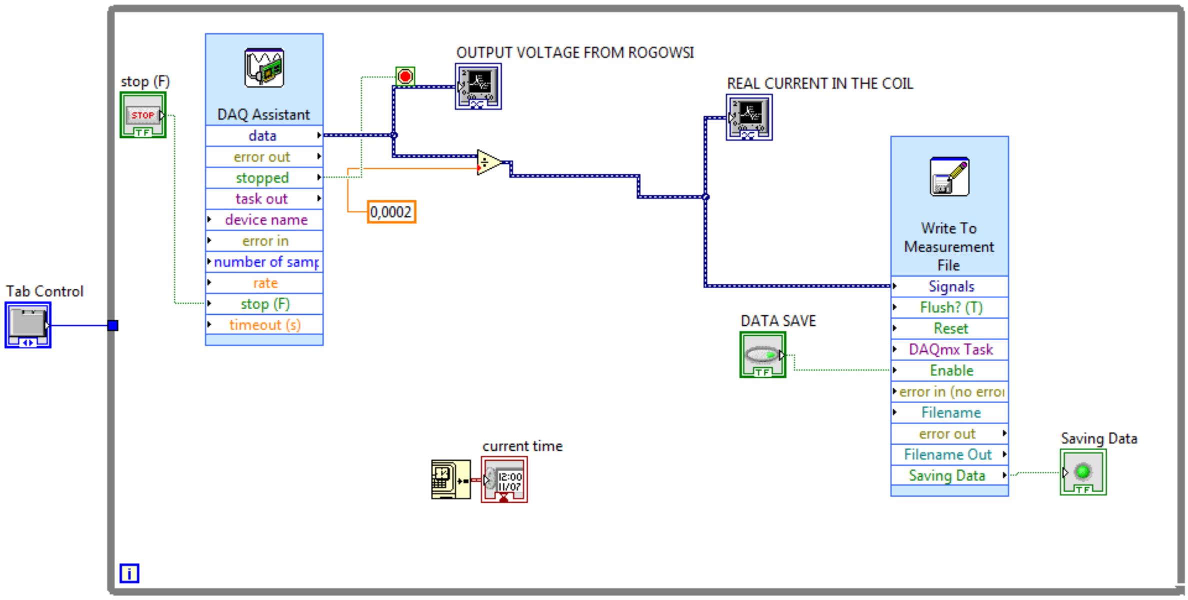


Illustration 33 Rogowski Block Diagram

The explanation of the different elements of this VI is the next one:

- **Grey square surrounding the block diagram**: Represents a While loop.
- **Tab control**: Provides a special interface to the Front Panel.
- **DAQ Assistant**: Take the data form the Rogowski coil and convert it into numerical data.
  - **Data**: Output numerical data. Will be plotted later.
  - **Stopped**: Created automatically for the DAQ assistant. Is the condition to stop the While loop
  - **Stop (F)**: Button which stops the application.
  - **Number of samples. Case study:** 300kS
  - **Rate. Case study:** 100kHz
- **Output Voltage from Rogowski Chart**: Plot the real data in Voltage from the sensor.
- **Math operation**: Transforms the Voltage values into Real current values.
- **Numeric constant** : The value of the Sensitivity of the Rogowski coil (0.0002mV/A)
- **Real current in the coil Chart:** Plots the real current values in the Rogowski coil.

- **Write to measurement file:** Save the data of the real current into a Excel (.xls) file.
    - **Signals:** Provides the data which have to be saved in the .xls file.
    - **Data save:** Button that enables/disables the data saving.
    - **Saving data**: Light that shows if data is being correctly saved.
- **Current time**: Shows the real world time, according to a global clock.

As usual, a Front panel with the block diagram features exists. There is possible to see all the buttons, graphs, indicators… explained above.

Illustration 34 Front Panel for Rogoswki

- **Output voltage from rogowski**: Shows the voltage provided for the Rogowski Coil, in a range from 0 to 6V.
- **Real current in the coil:** Shows the real Current in the coil, applying before the convenient adjustment to convert the signal from Volts to Amperes. This one is the really important for our purpose.
- **Stop button**: Finishes the program and the data acquisition.
- **Current time**: Shows the real time while the measuring are made.
- **Data Save**: Creates the Excel file and begin/stops the saving of the measures.
- **Saving data**: If the light is on, the data save is working properly.

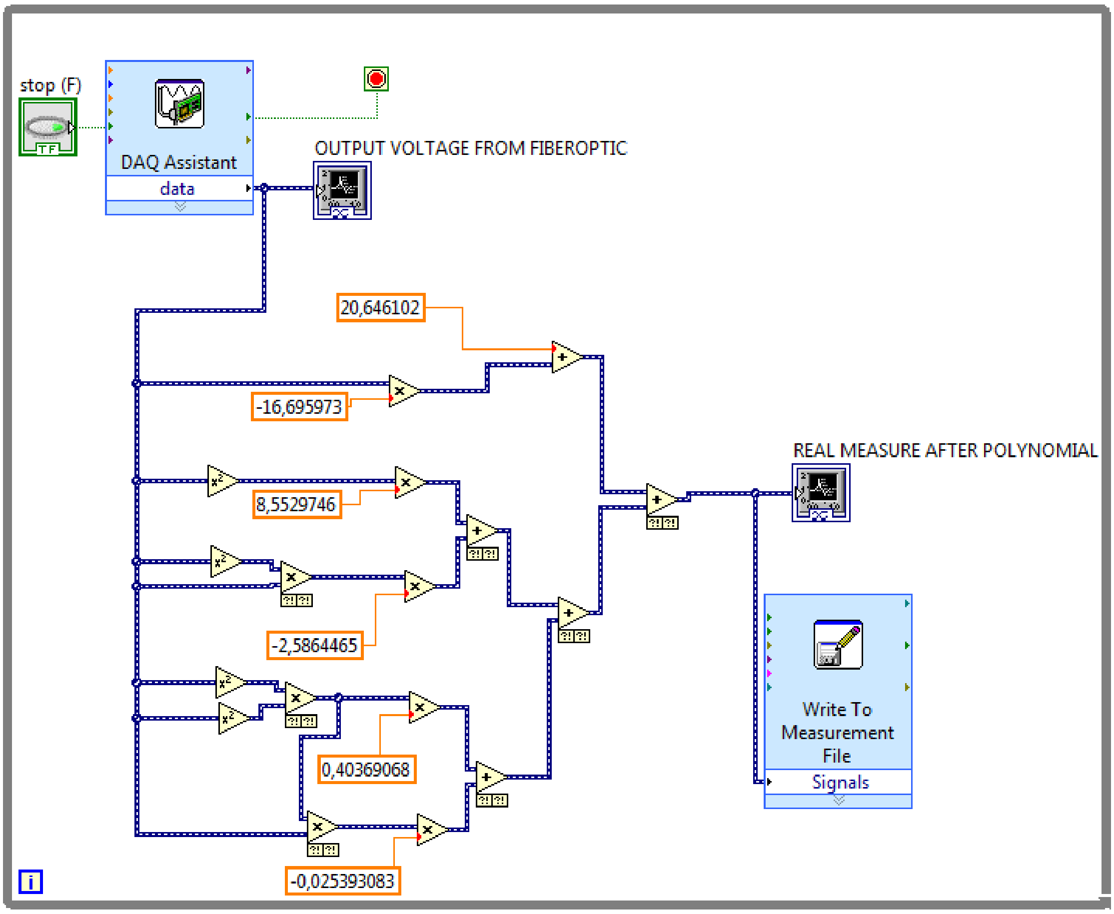
4.3 Integration of Philtec D100-C1E1PR2T2

4.3.1 Creation of LabVIEW software

Philtec **D100-C1E1PR2T2** is the sensor choose to monitoring the displacement in the ERW process. As we said, is a really precise instrument, with an operate range from 0mm to up to 10mm, making it suitable for the welding process.

The first step for monitoring the measurement data in the computer is to create the LabVIEW Virtual Instrument (VI) program. The maker of this instrument provided us a Polynomial Curve, which was used to program the LabVIEW VI and made possible the integration of the sensor into the computer.

In the next illustration is shown the LabVIEW VI which was programmed for acquiring data from Fiberoptic, and convert it into real distance values through the polynomial curve. The main scheme of the Block Diagram is the next:



The Block Diagram above it's made up for the next components:

- **Grey square surronding blocks**: Means that the block diagram is into a While Loop.

- **DAQ Assistant**: Take the data form the Fiberoptic sensor and convert it into numerical data.
    - **Data**: Output numerical data. Will be plotted later.
    - **Stopped**: Created automatically for the DAQ assistant. Is the condition to stop the While loop
    - **Stop (F)**: Button which stops the application.

- **Output Voltage For Fiberoptic Chart:** Shows the real voltage values measured by the sensor. It is really useful to have a chart like this for calibrate the sensor at the beginning of the test, and to check if is working properly while that tests. How to calibrate the sensor will be shown later, after the explanation of the VI program. This graph must show a curse similar to this one:

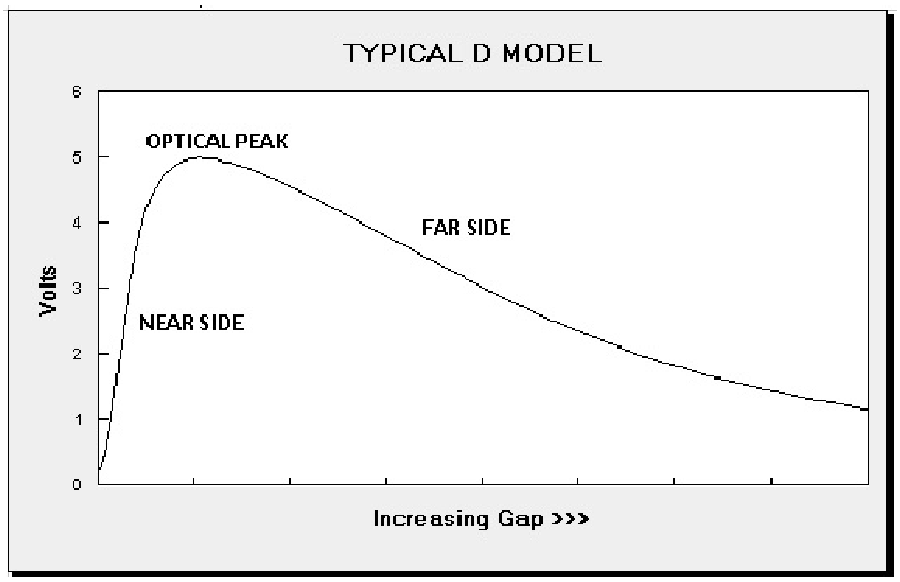


Illustration 35 Typical D Model Graph

- **Integrator:** The output signal from DAQ Assistant is treated with the polynomial curve to get the real measure value. The polynomial used for our case is the next one:

$$y = 20.646102 - 16.695973x + 8.5529746x^2 - 2.5864465x^3 + 0.40369068x^4 - 0.025393083x^5$$

Where:

$$y = Real\ displacement, mm$$
$$x = Volts, DC$$

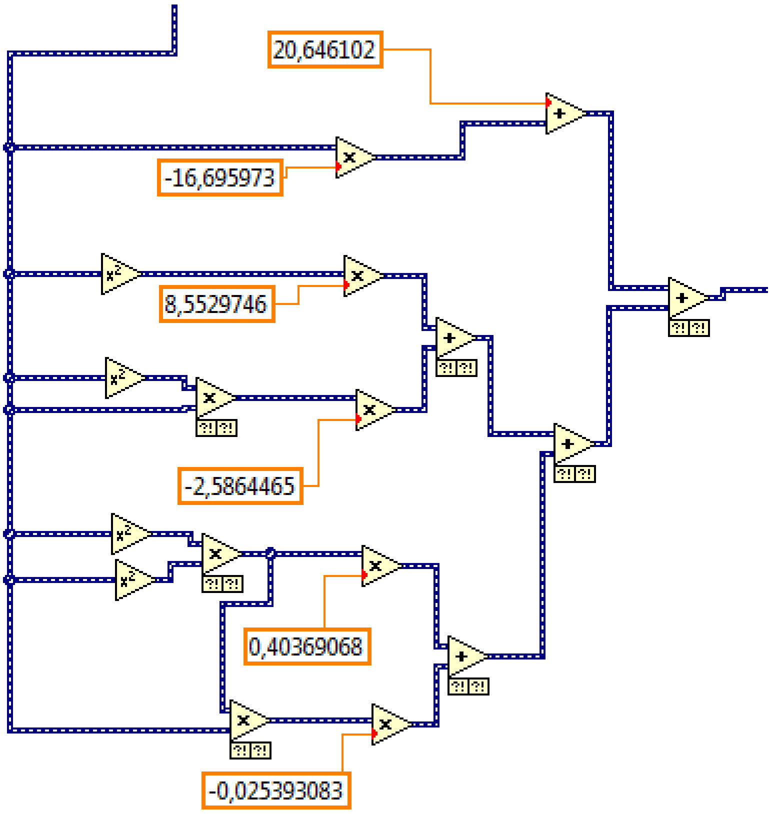


Illustration 36 Polynomial Values

In the picture above, the different constants are multiplied for the voltage value (x) with its suitable exponent (x^2, x^3, x^4…) and later added or subtracted with the other polynomial components, creating the desired polynomial equation

- **Real Measure After Polynomial Chart:** Shows the real measure between the sensor and the mirror target. This is the graph more interesting for us, because is actually the monitoring of the distance sought.
- **Write to measurement file:** Save the data of the real current into a Excel (.xls) file.
    - **Signals:** Provides the data which have to be saved in the .xls file.
    - **Data save:** Button that enables/disables the data saving.
    - **Saving data**: Light that shows if data is being correctly saved.

As known, this is the “hidden part” of the LabVIEW VI. The interface that will appear to the user when the LabVIEW file is opened (the Front Panel), and the really useful for the data acquisition in the test is the next one:

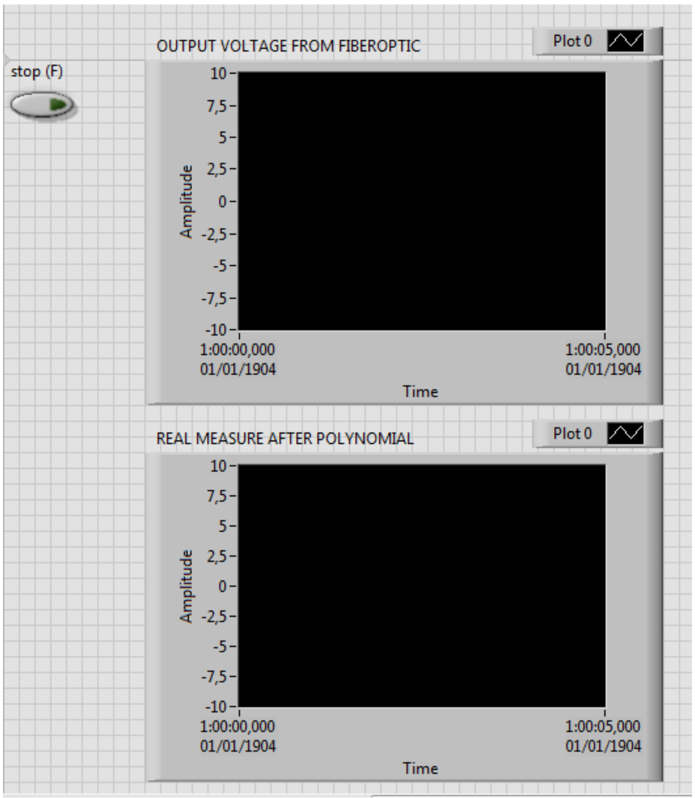


Illustration 37 Fiberoptic Front Panel

If, for any reason, the Write to Measurement tool is not working as desired, or the user prefers another data saving method, is possible do the process by the next way:

Clicking the right mouse button, it is allowed to Export the data from the graph into numerical values.

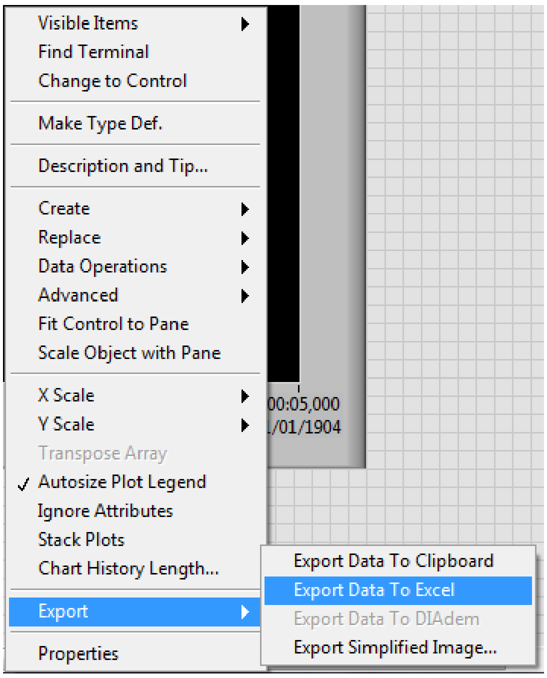


Illustration 38 How to export data to Excel

LabVIEW will open automatically an Excel file with the time and value of all the measures performed during the welding process.

Once the data acquisition and treatment has been explained, is needed to know how to begin working with the sensor, and the main step is to calibrate it before make the measure. This process have to be realized always before using the sensor, in order to check if is working properly or is needed to make any adjustments.

RESULTS example

4.3.2 Philtec D100-C1E1PR2T2 calibration.

In order to make the sensor work properly, is highly recommended to do the next steps always before using the sensor. It guarantees the highest perpendicularity and the best placement of the sensor. (17)

1. Mount the sensor so that it is perpendicular to the target surface. Perpendicularity can be established by holding the sensor against the target surface while adjusting its contact angle until a minimum voltage reading is obtained. The output voltage should read close to zero. Generally, at best perpendicularity, the output should read less than 250 millivolts.
2. While maintaining perpendicularity, move the sensor away from the target until the maximum output level is attained. At that position, adjust the GAIN controls (coarse and fine) until the output voltage reads 5.000 Volts.
3. Reposition the sensor gap to the desired operational set point on either the near side or on the far side (refer to the factory supplied calibration curves).

Gain controls are located on the side of the sensor, and is needed a little screwdriver to manipulate them.

Illustration 39 Phiberoptic D100 controls

Coarse screw is used to get closer the higher value with low precision, while Fine screw allows the user adjust the sensor with higher accuracy.

4.3.3 Fixture System

In order to implement the Fiberoptic sensor into the welding machine, a fixture system is totally necessary. A support has been designed according to the sensor and RSW machine dimensions, taking another important factors into account:

- High temperature can interference the measurement.
- Electromagnetism can influence the measuring process.
- The sensor has to be enough separated from the welding process, with the puropose of protect it.

The first version of the fixture system will be made in Acrylonitrile Butadiene Styrene plastic, but in the future, will be preferable his manufacturing into steel or aluminum.

In the next illustration, a scheme of the designed fixture system is shown.

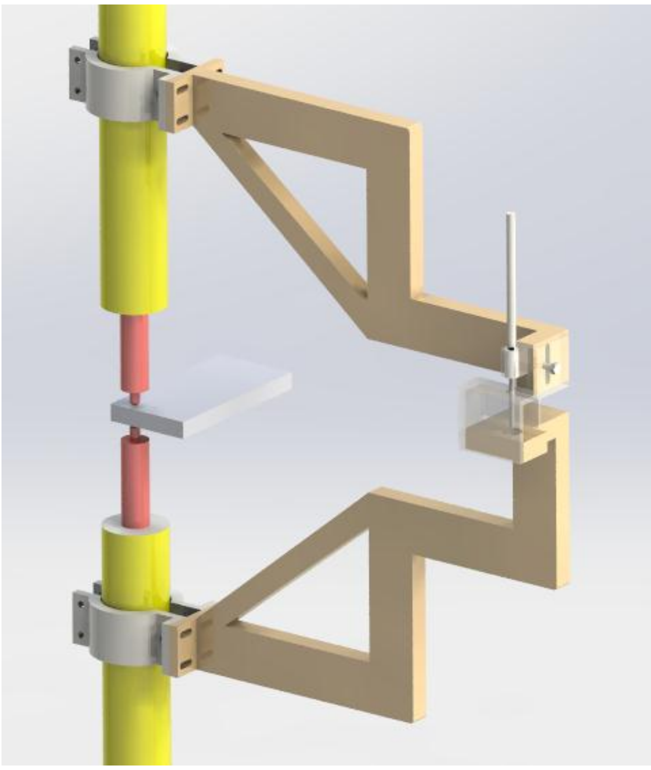


Illustration 40 Fixture system

In the next chapters, the main parameters for the manufacturing of this fixture system will be presented, as well as a Finite Elements analysis to test the correct behavior under the RSW process conditions.

4.3.3.1 Fastening part

This part of the assembly is designed to be replaceable in case of necessity; in case of fracture or if an RSW process test is needed in another welding machine.

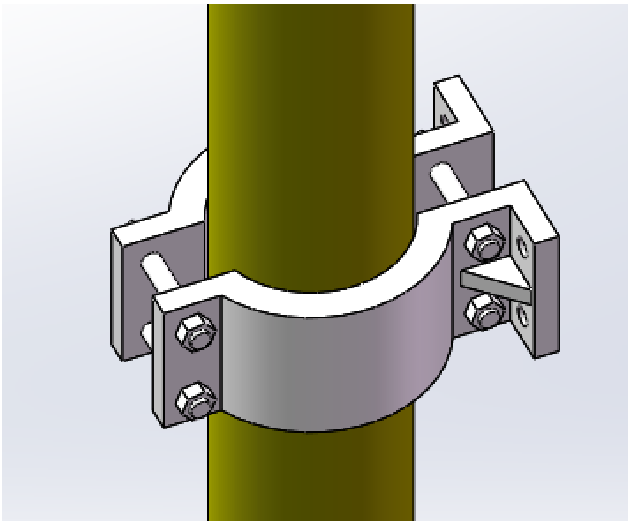


Illustration 41 Fastening Part

The main dimension parameters are shown in the next illustration. Is important to let clear than the radius of fastening part is 1mm larger than the column of welding machine. It is because pipe clamp structure would generate its fastening friction with deformation.

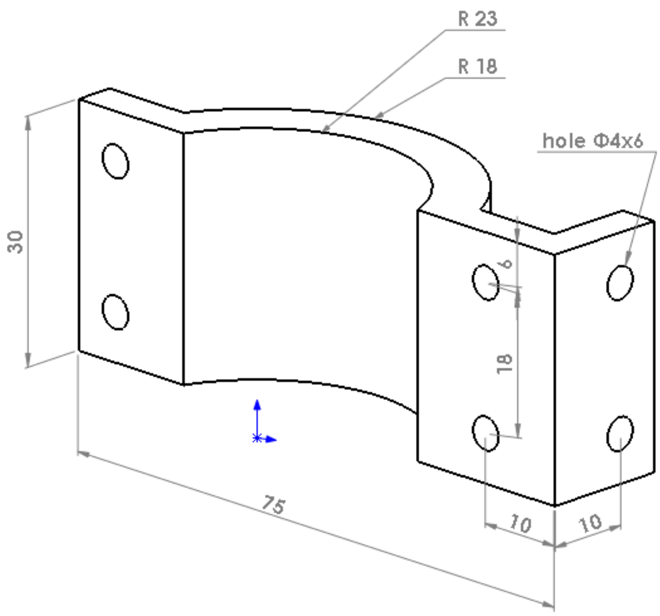


Illustration 42 Fastening part main dimension

4.3.3.2 Cross Arm

Is necessary to let separated the sensor form the welding process. That is why this arms were designed. They are made to minimize the vibration of the welding machine.

One of the arms has an adaptor for placing the sensor, and in the other one a little hole is manufactured, with the purpose of situate the Mirror objective on it.

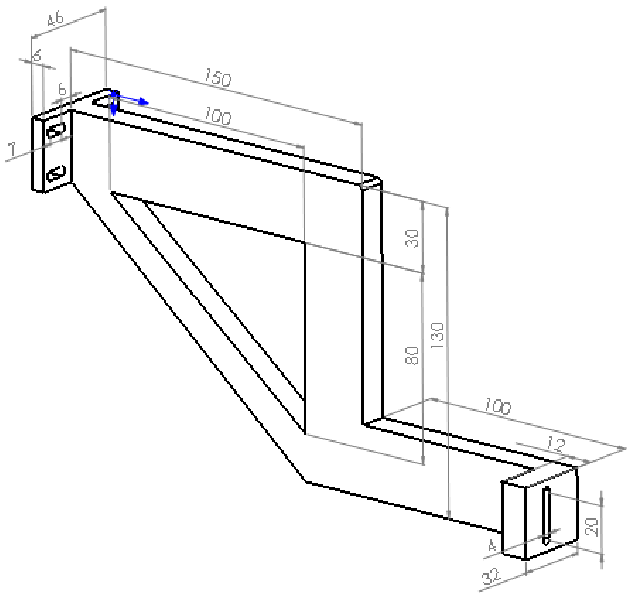


Illustration 43 Upper arm

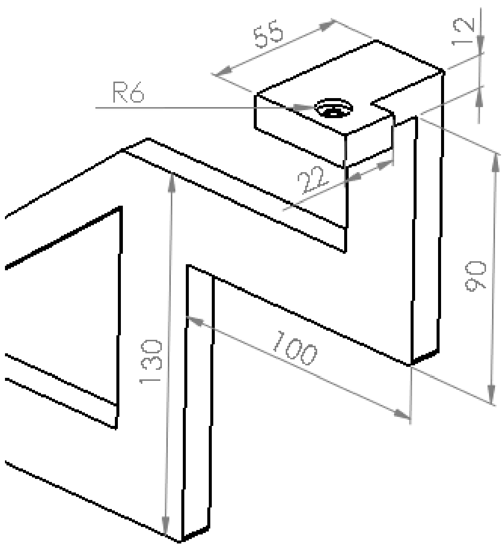


Illustration 44 Lower arm

Though a FEM software, a stress study was made, showing the next results.

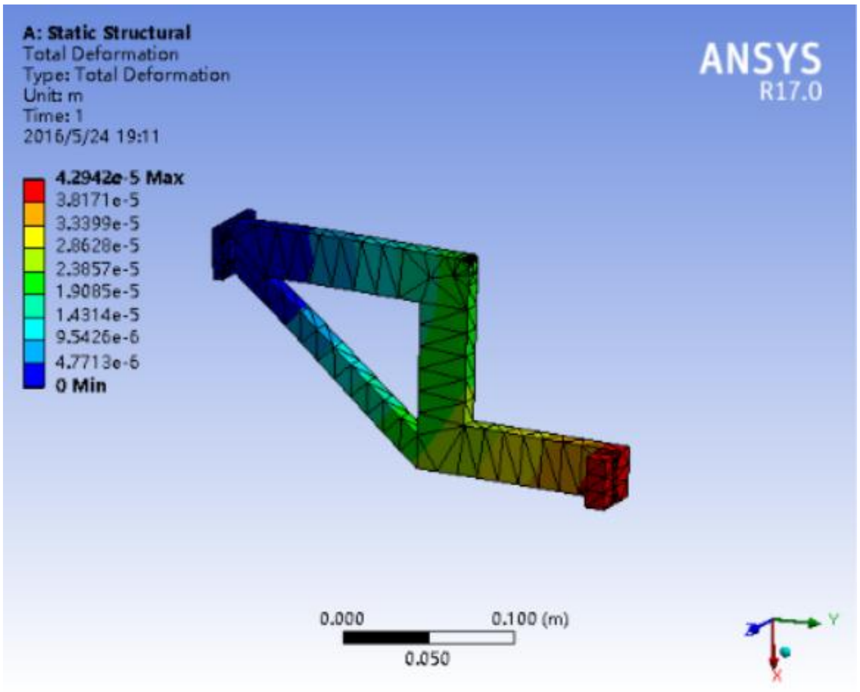


Illustration 45 FEM study (I)

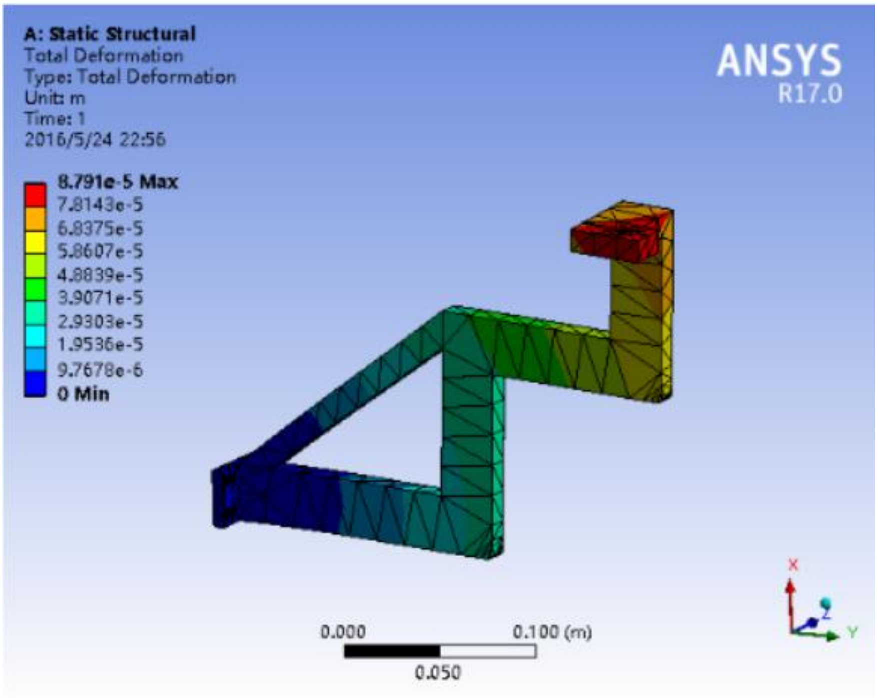


Illustration 46 FEM study (II)

The maximum deformation of the arms has a low value, which made them suitable for the main purpose.

4.3.3.2 Probe mounting part

According to the dimensions of the sensor's thread (M8x16mm), the probe mounting part was designed. Is made with the purpose of modify his position on Y axis in order to place the sensor into his suitable measuring range.

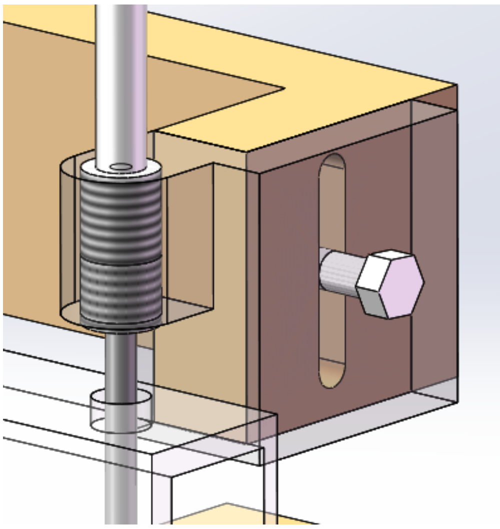


Illustration 47 Probe mounting part

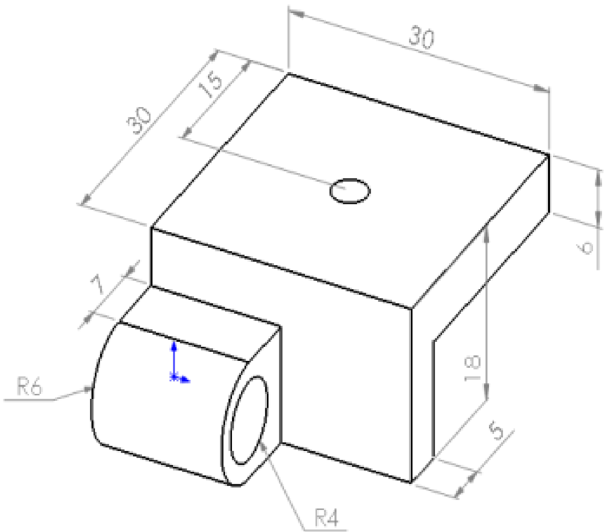


Illustration 48 Main dimensions of probe mounting part

4.3.3.2 Protective shield

During the welding process, a lot of liquid steel is usually projected from the welding point. If one of this small drops contacts with the sensor, it could be seriously damaged. That is why some protection is needed.

This protective shield is showed below. It meets his purpose without interference in the welding process or in the measuring process, so it is suitable to work with.

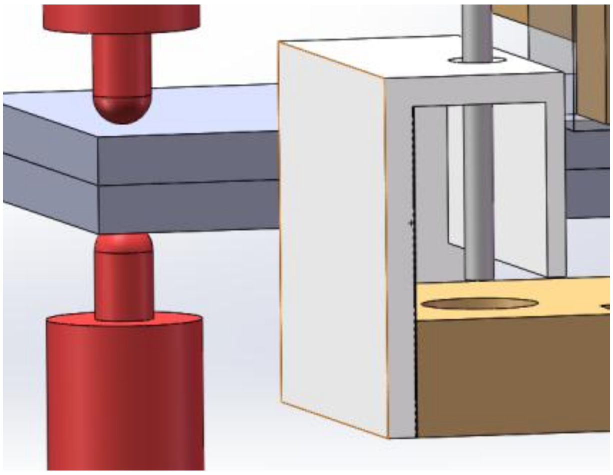


Illustration 49 Protective Shield

5 Tests

5.1 CRF test

The test for Rogowski coil (measuring of current) were developed at Centro Ricerche FIAT (CRF), at its headquarters in Torino. They lent us a RSW machine and one of their workers for the elaboration of the welds, in order to make possible the monitoring of the current while the RSW process were made.

After a brief introduction, in this chapter will be explained all the relevant aspects which were important for the elaboration of the test, including the materials and the machine used, the test structure and the final results.

5.1.1 Resistance Spot Welding

The main purpose of this Master Thesis is to monitoring the RSW process in real time and save the data for their further study. As known, a Rogowski coil and a Fiberoptic measurement sensor will be used to this end.

Politécnico di Torino does not have a welding machine with the desired features for made this tests. That is why, for data acquisition and test of the devices, was necessary to go to a big industry, in this case Fiat.

The RSW will be made for two new generation steels, TRIP and Q&P. Welding each time two specimens, one of each kind of steel, to understand better their behavior under stress.

This specimens will be later tested in a cross tension test, and will provide information about the welding process and the features of both materials.

5.1.2 Materials

The requirements on mechanical properties of steels are constantly increasing and new heat and thermomechanical treatment processes for such steels are being developed. High-strength low alloyed steels, as a group of steels, offer favorable proportion of strength, elongation and toughness. The level of ultimate tensile strength required in these materials, upon suitable heat treatment, reaches 1,500 MPa. Their elongation should be around 15%, while the maximum content of alloying and residual elements should not exceed five weight per-cent. (18).

Automotive industry is not an exception, and the most important companies are always searching for best results in their car bodies, attending mainly to the safety of the people inside the car and a good fuel efficiency. That is why high quality steels are used or the production of this car bodies.

Each one of the different kind of steels has his own features, that is why is important to know what are the requirements for the manufacturing of car bodies.

The main purpose for the manufacturing of car bodies is a good relation between economic costs, mechanical resistance and the energy absorber capacity in case of hit. There are several types of steels with this properties, such as:

- **TWIP** Twinning induced plasticity.
- **DP** Dual Phase.
- **TRIP** Transformation Induced Plasticity.
- **Q&P** Quenching and Partitioning.

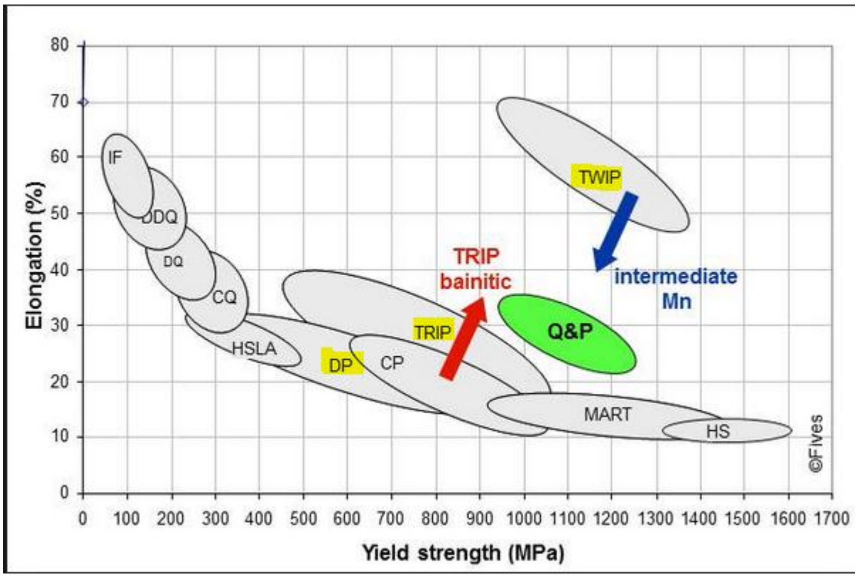


Illustration 50 Elongation (%) vs Yield Strenght for different Steels

In this thesis, the tests have been made for the TRIP and Q&P advanced high-strength steels, in order to improve the knowledge of their properties and their behavior under stress while the cross tension tests. In the graph below, the different kinds of steel are shown, according to their Elongation and their Yield strength. (19)

The TRIP steel provides a good Elongation-Yield strength relation, but not as well as Q&P in some cases.

In the next illustration will be shown the relation between elongation and Ultimate Tensile Strength for the steels under study. (20)

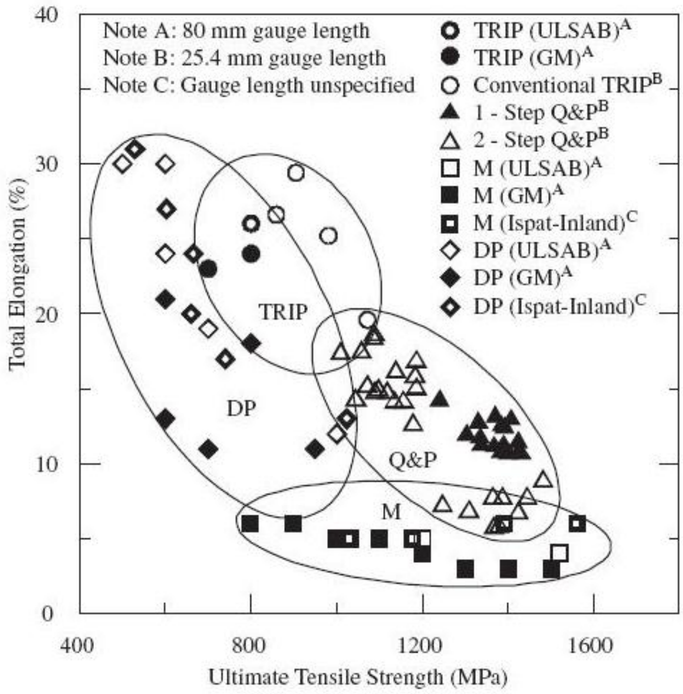


Illustration 51 Elongation (%) vs Ultimate Tensile Strength (MPa)

5.1.2.1 TRIP: Transformation Induced plasticity

TRIP is a no conventional steel. It has a really good comportment to the hits and can absorb a lot of energy when is deformed, which makes it progressively harder. The explanation of this fact is the next one:

TRIP is composed by bainite, ferrite and austenitic grans, which becomes martensitic grans when the steel is deformed, which endows a progressive increase of his hardness.

There are several compositions for this kind of steel, but most of them has some things in common:

- The percent of carbon in TRIP is, usually, between 0,2-0,77%.
- The manganese percent is lower than 2%.

In the next table, some of the usual composition of TRIP commercial steel are showed:

Acciai TRIP PF (% in massa)					
C	Mn	Si	Al	Nb	Altri
0.2	1.5	1.5	-	-	-
0.2	1.5	0.1	1.8	-	-
0.3	1.5	0.3	1.2	-	-
0.15	1.5	0.6	-	-	P:0.1

0.15	1.5	0.1	1.0	-	Cu,Ni
0.2	1.5	1.5	-	0.04	-
0.2	1.5	1.1	-	0.04	Mo:0.3

Illustration 52 TRIP commercial steels (21)

TRIP steel has a special heat treatment for acquire his properties. The typical microstructure contains 50% of ferrite, 30-35% of bainite and 15-20% of retained austenite.

This treatments begins with a fast heating of the steel, maintaining the higher temperature for some minutes (until 30 min) and follows by a high decrease of the temperature. This temperature will be stable for about 8 minutes and, after that, the TRIP steel is cooled in a natural way, with an water flux.

The graph representation of this heat treatment, and the properties of each step,are presented in the next illustration (22):

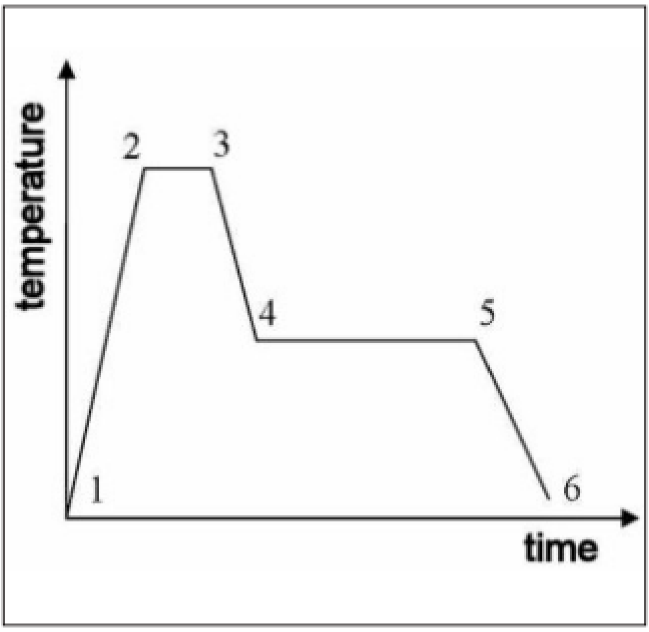


Illustration 53 Heat treatment for TRIP steels

- **1-2 Heating:** Recrystalization, carbide precipitation, cementite dissolution.
- **2-3 Delay (810ºC/30min):** pearlite and ferrite transformation to austenite, carbon segregation, grain grow th, precipitation of carbides.
- **3-4 Cooling from austenite temperature:** transformation to ferrite.
- **4-5 Bainitic holding time:** quenching salt 410°C, 430°C/3 to 8 minutes. Transformation to bainite, cementite precipitation

- **5-6 Ambient temperature cooling (water)**. Part of austenite transforms to martensite.

Is possible to vary the time and the temperature of the different part of the process, providing the steel different properties. This have a big influence in the mechanical properties of TRIP, which is evidenced in the next tables:

Heat Preatment Procedure	Proof Stress [MPa]	UTS [MPa]	Ductility [%]
810°C/30 min+ 410 °C/3 min	469 430	1032 1022	21 22
830°C/30 min+ 410 °C/3 min	457 473	993 984	20 20
850°C/30 min+ 410 °C/3 min	457 473	944 948	23 23

Illustration 54 Dependency of mechanical properties on austenitizing temperature

Heat Preatment	Proof Stress [MPa]	UTS [MPa]	Ductility [%]
810°C/430°C-4 min	466	1082	17
810°C/430°C-5 min	458	1065	20
810°C/430°C-8 min	539	1001	26
810°C/410°C-3 min	522	1095	17
810°C/410°C-5 min	470	1021	23
810°C/410°C-8 min	519	976	26

Illustration 55 Mechanical properties depending of the bainite transformation holding time

As a result of their very high tensile strength, TRIP steels are particularly suitable for parts designed to absorb energy in an impact. In the graph below the mass reduction potential compared to that of an HSLA 380 (High strength low alloy) steel is shown. (23)

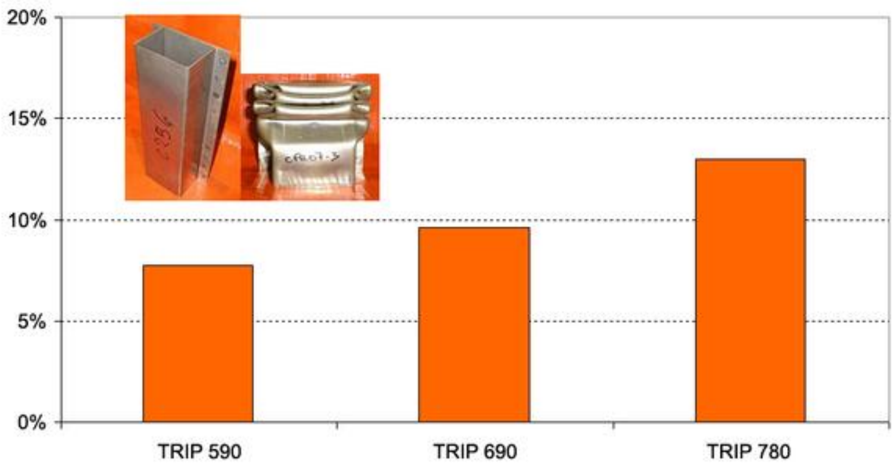


Illustration 56 Mass reduction potential of different TRIP steels

The properties of this kind of TRIP steels are the next ones (24)

	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Ti	Nb
TRIP590	0.15	1.57	1.02	0.018	0.028	0.08	0.02	0.02	0.043	-	-
TRIP690	0.14	1.57	1.45	0.014	0.027	0.04	0.02	0.02	0.04	0.019	0.042
TRIP780	0.19	1.58	1.6	0.013	0.025	0.07	0.02	0.02	0.036	0.027	0.038

Illustration 57 Steels' chemical composition

Steel	UTS, MPa	Elongation, %	YS, MPa	thickness, mm
TRIP590	617	17.6	394	2
TRIP690	699	14.7	400	2
TRIP780	792	18.0	471	2

Illustration 58 Mechanical Properties of TRIP steels

5.1.2.2 Q&P: Quenching and Partitioning

Quenching and Patitioning, also called Q&P, is a modern steel treatment which **has as purpose** to produce very fine martensite with retained austenite between martensite plates. After austenitizing, the steel should be quenched (Q-P) to a specific temperature calculated in such a way as to produce a pre-defined ratio of martensite and non-transformed austenite.

Subsequently, the temperature of the material should be raised to the **partitioning** level (PT). The carbon will diffuse to the existing austenite and increase its stability to the level where it does not transform upon cooling to ambient temperature. As the austenite becomes enriched in carbon during the partitioning stage, its actual Ms-Mf temperatures decrease. Full stabilization requires that the Ms temperature is depressed to or below room temperature to prevent martensitic or bainitic transformation of insufficiently stabilized austenite during final cooling. (18) (25)

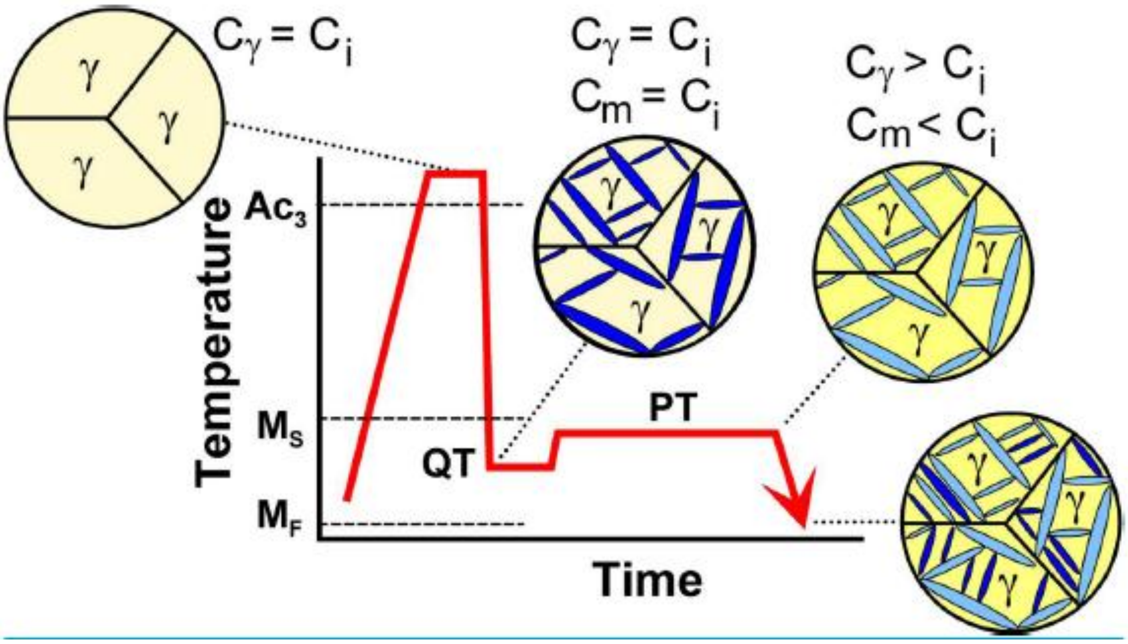


Illustration 59 Time-temperature profile of the Q&P process, and how the steel's structure

In the illustration above, is schematically presented the Q&P process, and shows the multi-step thermal processing route. The two main steps that follows the Q&P process are the next ones: (26)

1. After heating so as to obtain a fully austenitic or intercritical microstructure, the steel is quenched to a suitable pre-determinated temperature (Quenching temperature,QT) below the martensite starts (Ms) but above the martensite finish (Mf) temperatures in order to form a pre-defined amount of martensite. The microstructure at this QT consists of martensite and untransformed austenite if it was fully austenized or contains additional ferrite if it was intercritically annealed.
2. Then, the steel is either isothermally held at this QT (one step Q&P) or brought to a higher (two steps Q&P) partitioning temperature (PT). The aim of the latter step is to carbon-enrich the untransformed austenite remaining at the QT through carbon depletion of the carbon supersaturated martensite. In this way, after final quenching to room temperature, metastable Retained Austenite (RA) is obtained.

There is not fixed values for the principal parameters of Q&P, and the properties of the steel varies according to that parameters. This properties are highly influenced by the microstructure of the steel, which obviously, changes with the variation of the heat treatment parameters.

To show the variation in the properties of the Q&P steels, according to the values of their parameters, some graphs will be shown. In the next table are written the different values for QT, PT and Pt (Partitioning time). (26)

Specimen		QT (°C)	PT (°C)	Pt (s)
QP-0.25-	1	224	350	500
	2	244	300	500
	3	244	350	500
	4	244	400	100
	5	244	400	500
	6	244	400	1000
	7	264	350	500

Illustration 60 Different Q&P steel

As was said above, the microstructure of this steels have a capital importance in the behavior of the steel. Here is possible to appreciate the differences in many measures:

Specimen		Tempered martensite (TM) (μm)		Retained austenite (RA) (μm)	
QP-0.25-	1	2.7	± 0.3	0.5	± 0.1
	2	2.3	± 0.1	0.4	± 0.1
	3	2.2	± 0.4	0.6	± 0.1
	4	2.2	± 0.2	0.5	± 0.2
	5	2.2	± 0.3	0.7	± 0.1
	6	2.4	± 0.1	0.7	± 0.2
	7	2.5	± 0.3	0.5	± 0.1

Illustration 61 Average grain size

Specimen		Retained Austenite (RA)		Untempered Martensite (UM)	Tempered Martensite (TM)
		(%)	%C (wt.)		
QP-0.25-	1	14.2	0.91	13.8	72
	2	14.7	1.05	17.7	67.6
	3	14.4	0.99	14.1	71.5
	4	18.3	0.84	9.9	71.8
	5	17.9	1.03	12.2	69.9
	6	20.2	1.01	10.5	69.3
	7	13.5	1.11	15.8	70.7

Illustration 62 Volume fraction and carbon content (wt. %) of RA and volume fraction of UM and TM

And the mechanical properties of the specimens according to their microstructure:

Specimen		$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)	ε_U (%)	ε_f (%)	n
QP-0.25-	1	900	1357	10	22	0.19
	2	721	1419	10	21	0.25
	3	803	1471	11	21	0.26
	4	621	1462	17	26	0.24
	5	821	1267	16	28	0.19
	6	681	1275	16	29	0.20
	7	761	1354	13	24	0.24

Illustration 63 Tensile and deformation values for the different specimens

5.1.2.3 Composition of Materials used in the tests

The composition of the TRIP and Q&P steels can vary according to the needs along his life. The chemical compositions (in %wt.) of our steel coupons are the following ones:

Chemical composition [%wt.]					
	C	*Mn*	*Si*	*Al*	*Ti*
Q&P	0.2	0.2	1.5	-	-
TRIP	0.2	2.2	0.48	0.81	0.01

5.1.3 Resistance Spot Welding Machine

The monitoring of Fiat test were made in one of their welding machines in their laboratories. The features of the welding machine used for the elaboration of the tests are quite similar to the next ones, belonging to a TECNA machine:

- **Supply voltage:** 400V
- **Supply frequency:** 50Hz
- **Phases:** 3
- **Nominal power at 50% duty cicle:** 98kVA
- **Max. Welding power:** 300kVA
- **Sec. Nominal Voltage:** 9.4V
- **Max. Wekding current:** 32KA
- **Max. Force:** 736daN
- **Water cooling:** 10l/min
- **Supply pressure:** 6.5bar
- **Net weight:** 490kg

The main features were appropriated to make the test, and was possible to modify some parameters to obtain different welding points and compare them later.

As was said, each welding was made between to sheets of different material (Q&P and TRIP), and in two different ways (for cross tension test and for lap sheat test).

For the data acquisition, the Rogowski coil was placed in the fixed electrode of the welding machine, and matching the electrode with the center of the coil, in order to make minimal the error in the measures.

5.1.4 Current Monitoring phase results

5.1.4.1 Test structure

For the elaboration of the welds, Taguchi method was used.

Taguchi is a design of experiments method which are based on well defined guidelines. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulates the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. The crux of the orthogonal arrays method lies in choosing the level combinations of the input design variables for each experiment. (27)

The design of an experiment involves the following steps

1. Selection of independent variables
2. Selection of number of level settings for each independent variable
3. Selection of orthogonal array
4. Assigning the independent variables to each column
5. Conducting the experiments
6. Analyzing the data
7. Inference

For the realization of the test, Taguchi L9 method was chose. Their characteristics were the following ones:

- Independent Variables:
    - Welding time
    - Current
    - Force
- Number of levels for each variable: 3

Once the variables and the number of levels for each one were chosen, to make the orthogonal array for the experiment was possible. The selected method was Taguchi L9, and the array used is the next one:

Test	Current	Force	Time
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Being the different values for the independent variables the following ones:

	1	2	3
Current (kA)	6	7,5	9
Force (kN)	2	3	4
Time (ms)	200	325	450

As additional information, the diameter of the electrodes were 6mm, and the electrodes remained exerting pressure for 500ms.

For each configuration, six welding points were made and monitored, making a total amount of 54 samples. 36 of that samples were for lap shear test, and the 18 remaining for cross tension test.

5.1.4.2 Test Results

The implementation of Philtec Fiberoptic sensor was not possible to made, due to the absence of a suitable fixture system. The fixture system designed in Chapter 4.3.3 has to be manufactured, and used in the future to the implementation of Fiberoptic sensor in the way was explained before.

Therefore, the test in industry were made for the monitoring on current, using the Rogowski coil introduced in Chapter 3.1. The characteristic of the current were correct to use to Rogowski coil (Current range from 15A to 300KA).

The results of the welding test elaborated at Fiat factory were saved, studied and cleaned, allowing to know the current in every moment along the welding process.

For each one of the nine different configurations, this procedure was followed. The real results were also plotted to make easier their posterior study and to give an explanation of the possible failures in the welded unions.

The treated data will be presented according to the input values in the welding process, given them numbers from 1 to 9, and for each number letters from A to F., and are presented in the Appendix 1.

It is important to make clear that the purpose of this thesis is to monitoring the real results provided for the devices, leaving their correction for future studies. In any case, the theoretical way to correct them is the next.

5.1.4.2.1 Data Correction

In this case study, when the current in the coil is a **Pulsed Current** with a duration higher than 100ms, the behavior of the Rogowski coil, and the correction method is the showed below.

Rogowski coil has an offset when the measuring of the current is made. Is possible to realize about that seeing the next illustration: (8)

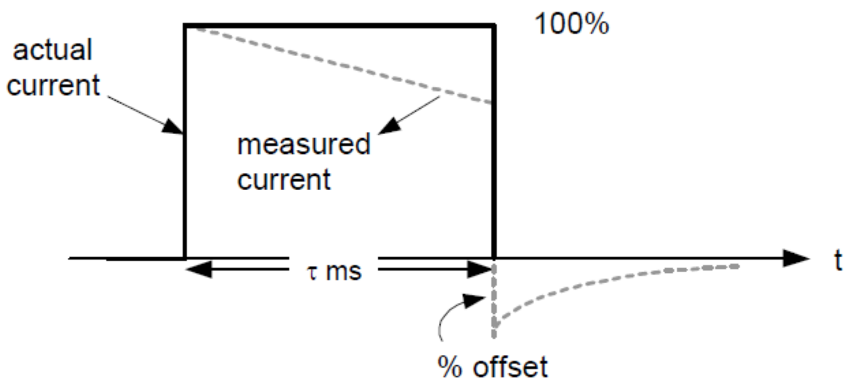


Illustration 64 Rogowski coil Offset

The offset produced by the pulsed current in the coil can be corrected with the next equation: (8)

$$\% \text{ offset } = \tau \text{ x (mean value / peak value) x (droop in } \%/\text{ms)}$$

For the best precision in the study of the data, this operation should be done for each test.

5.1.5 Verification phase results

For the verification of the results, Cross Tension Test (introduced on Chapter 2.3) has been made for each one of the coupons named with letters E and F.

All the results of the Cross tension test are showed in the Appendix II, along with some results of another kind of test, Shear Test, provided for one of the associate professor (for number 6 coupons).

In this appendix is also possible to see a table with the comparative of the maximum values of displacement and force for each test.

5.2 DIGEIP Tests

5.2.1 Test description.

For the Philtec D100-C1E1PR2T2 tests, a Coordinate Measuring Machine (CMM) was used at the DIGEIP workshop. There was possible to fix the Fiberoptic sensor into the CMM head and compare both results in order to check the correct behavior of the sensor.

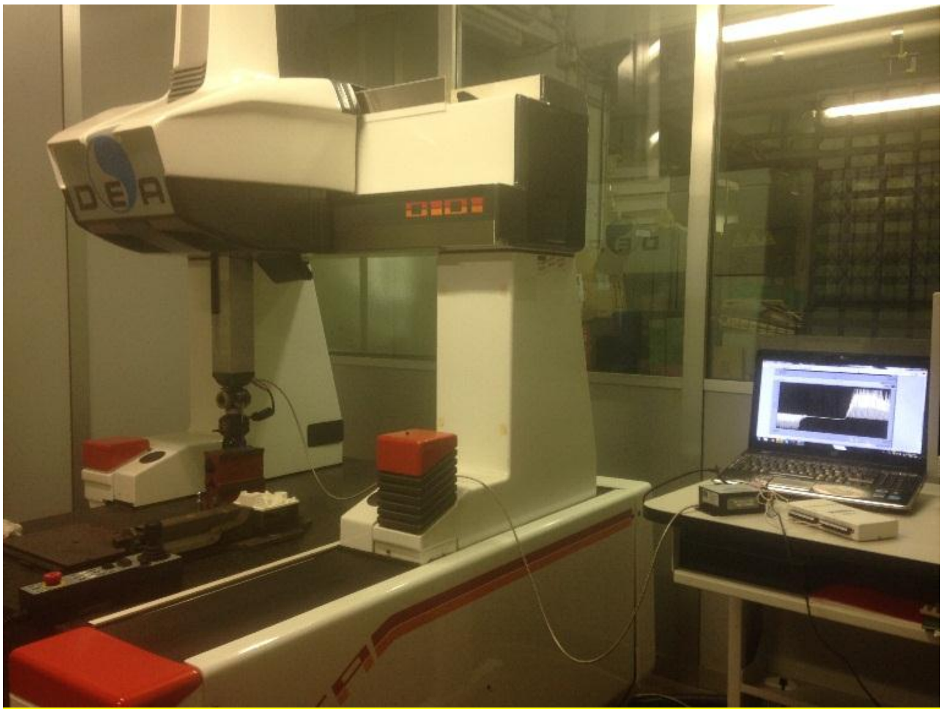


Illustration 65 Implementation of Fiberoptic sensor into CMM

While the development of the test, all the steps indicated by the manufactured were followed. Is possible to describe, schematically, the steps for the sensor's correct operation:

- **Connect the sensor and wait for about 30 minutes.** (Time needed to warm up the sensor).

- **Check perpendicularity.** With the head of Fiberoptic sensor in touch with the mirror target, the output voltage should show a value near to 250mV. If output voltage value is higher than 250mV, is necessary to adjust the perpendicularity of the sensor.

- **Adjust maximum value.** After the perpendicularity test, is necessary to calibrate the sensor properly. The procedure is to find the maximum value that the sensor can provide (it shall correspond to a distance near to 1mm) and adjust it with the "Coarse screws". Probably the maximum value, at first, will be higher than 5V, so is necessary to manipulate the screws until the maximum value reaches the value 5V. (This procedure is deeply explained at Chapter 4.3.2).

- **Begin with the tests.**

Along this test, some important guidelines were discovered. The main important conclusions about the use of Philtec D100-C1E1PR2T2 sensor are the following ones:

- The most perpendicularity corresponds with the best output values.
- The mirror target provided by maker have to be clean and correctly placed to get the best results.
- To use another surface as target is possible, but not recommended due to an important lack of precision.
- For calibration, the sensor has to be as close as possible to the target, even in touch, to check the best perpendicularity.
- Is needed a warm up of the sensor for about 30 minutes.
- Is possible to change the angle in which the light reflects on the target, applying some corrections. (Not recommended).
- The best rate of the sensor, in Hz, should be minor than 6KHz, in order not to have an important output Gain (db).

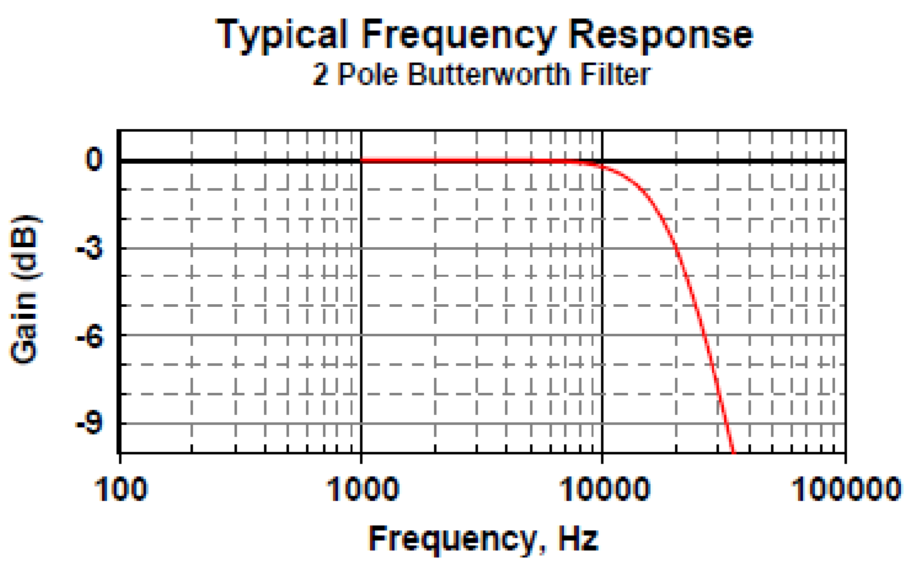


Illustration 66 Typical frequency response

5.2.2 Test Results

In this chapter some results of Fiberoptic sensor tests are shown.

It is a good beginning to start with a comparative between the Theoretical voltage curve and the real curve measured in the experiments.

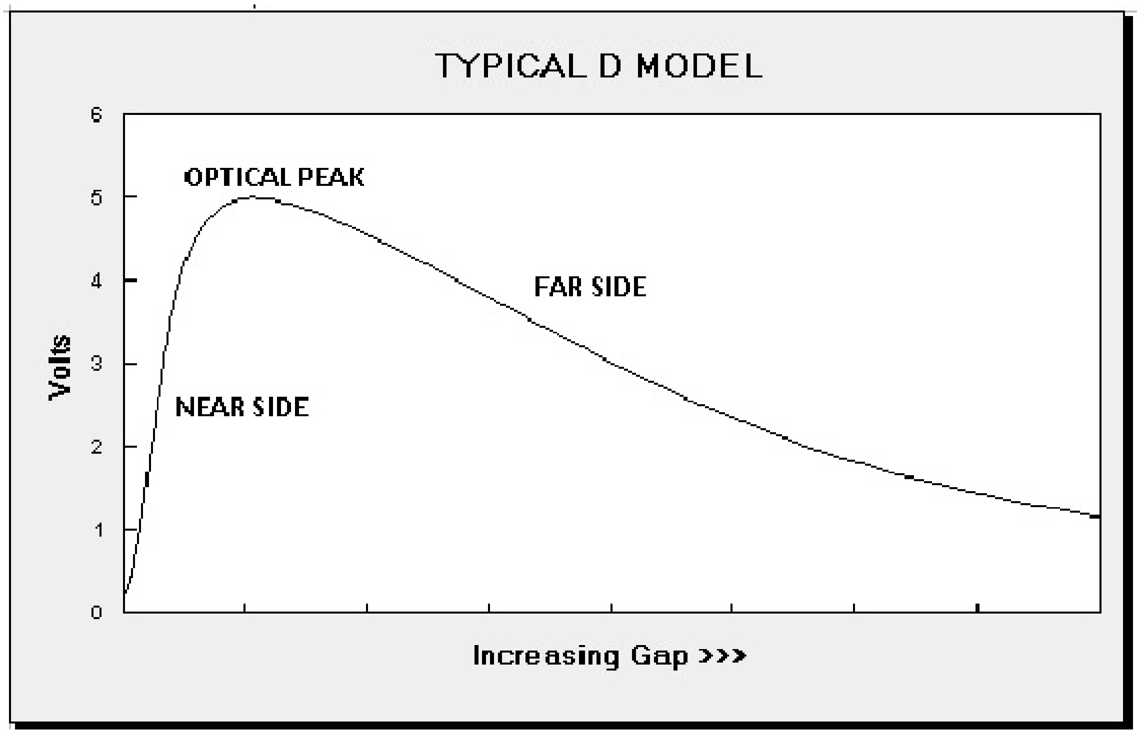


Illustration 67 Theoretical voltage curve

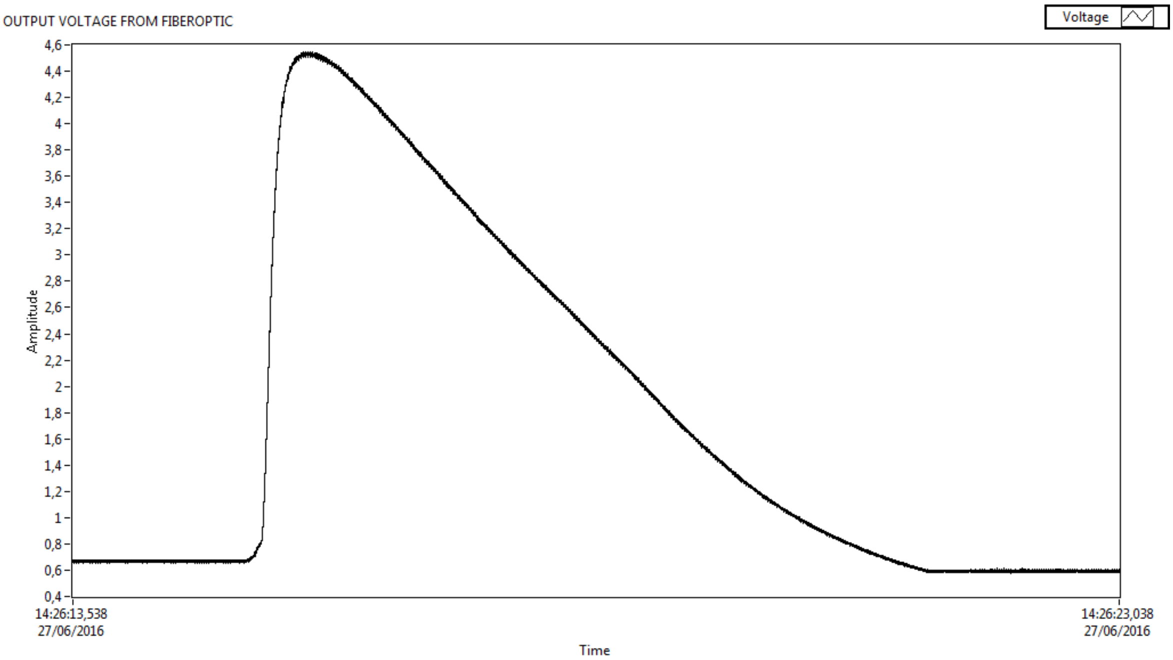


Illustration 68 Experimental curve

As is possible to appreciate in the illustrations above, the trend of both graphs are really similar, which indicate that the sensor is working properly.

Despite of that, the lower and higher value of the voltage in the experimental curve are not the ideals. The maximum value corresponds to 4.55V (It should be 5V) and the minimum is about 0.65V (It should be near 0.25V).

This facts are caused for a bad calibration and placement of the sensor. It indicates that it is not totally perpendicular and the maximum value was not correctly adjusted.

Next, a comparative of CMM and Fiberoptic sensor measures will be presented. As is obvious, exists some error in the results due to aspects explained in the paragraph above. Anyway is clear that the sensor is working properly and, with a correct fixture system and a good calibration, the results will be really precise.

Initial CMM value	Final CMM value	CMM measure	Fiberoptic Measure	Error
-247,25	-243,127	-4,123	4,96	0,20301
-247,69	-241,81	-5,88	6,4	0,08844
-247,89	-240,59	-7,3	7,73	0,0589
-248,29	-242,47	-5,82	6,31	0,08419
-277,68	-271,52	-6,16	6,92	0,12338
-278,19	-268,63	-9,56	9,78	0,02301

6 Conclusions

In this Master Thesis, the process for monitoring the parameters of Resistant Spot Welding Process has been described and explained deeply, form beginning to end.

The main purpose of this Master Thesis was to know the features of RSW process, study the sensors and hardware needed to monitor it, implement them into a computer and be able to study the real data from the process.

For his redaction, I have to study European and American standards and a lot of documentation about the different sensors and their implementation and behavior under different situations.

After acquire sufficient knowledge about the hardware, was necessary to implement them into a computer. This process was made with LabVIEW software, creating an own LabVIEW program (.vi) for each one of the sensors and adapting them according to the specifications of the experiment.

In order to check the correct operation of the hardware and software, several experiments were developed at DIGEP workshop in the Politécnico di Torino before make the final test at FIAT factory.

The suitable behavior of the sensors and the software made possible the acquisition of a big quantity of data along the test in FIAT factory, which made this experiment really useful for the study of the quality and possible failures of the welded points.

After the elaboration of this studies and tests, I develop a Technical Report for future applications of the sensors in future projects or future studies of Politécnico di Torino, making possible to continue this thesis with new tests, new information and even new sensors.

Regarding my personal development, the redaction of this thesis provided me a lot of new skills about electronics devices and welding process and gave me the chance to work in a field almost unknown for me. Now, I know I am able to begin a new project almost from zero, and bring it to fruition obtaining good results in his real purpose, as it became clear in the experimental results of this Master Thesis.

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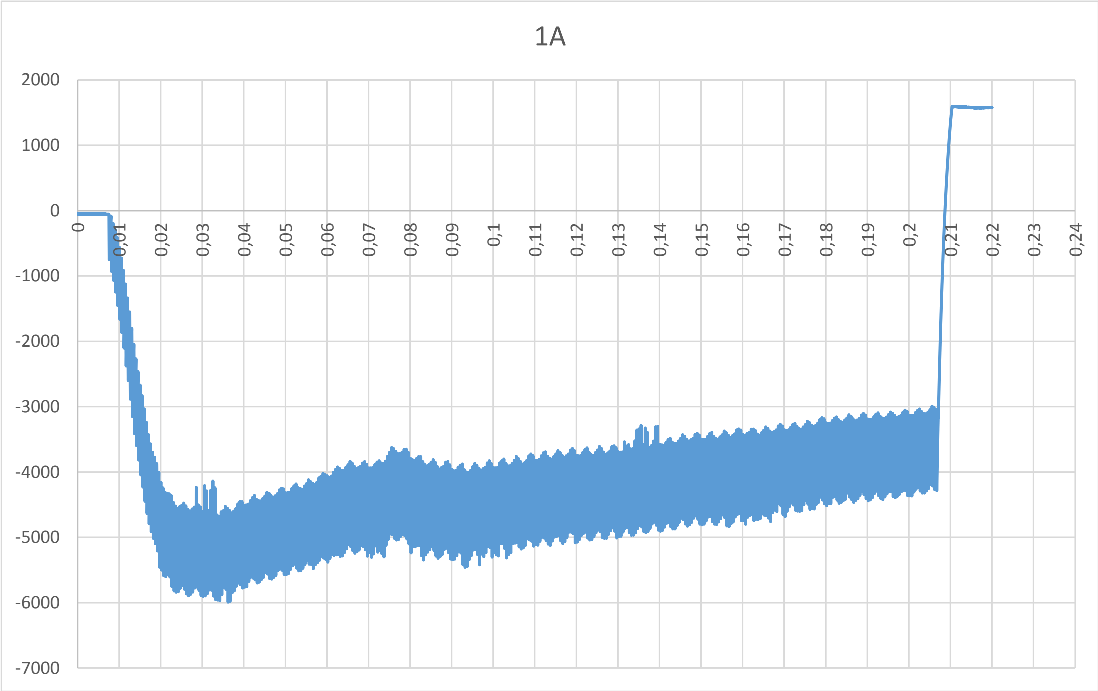
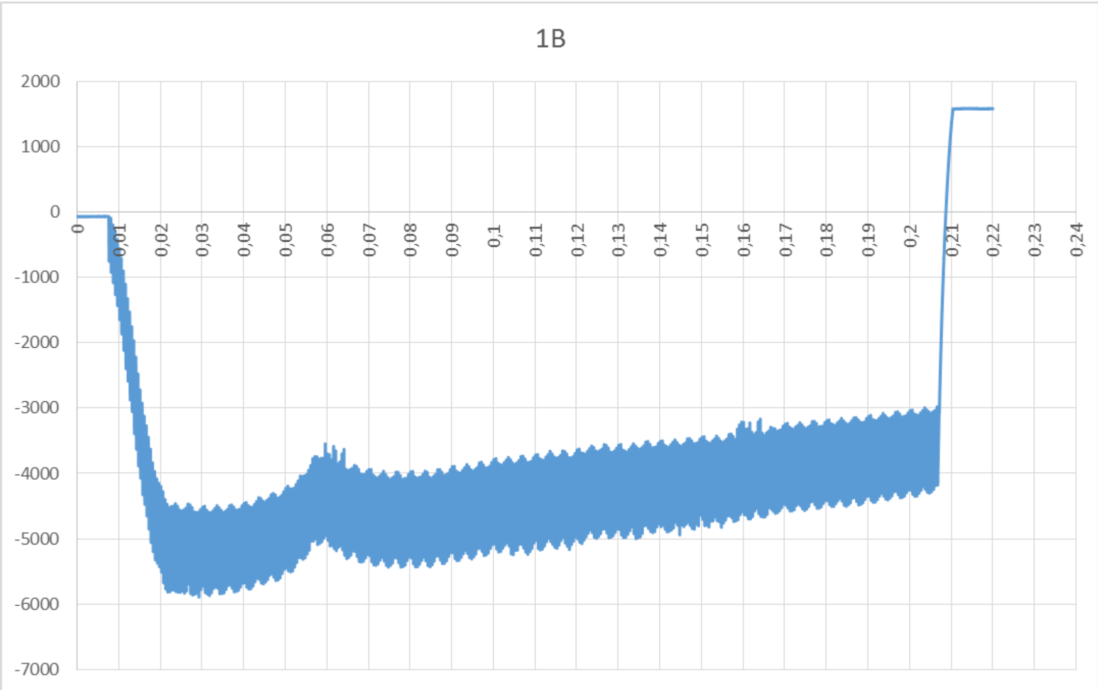
APPENDIX I ROGOWSKI TEST DATA RESULTS

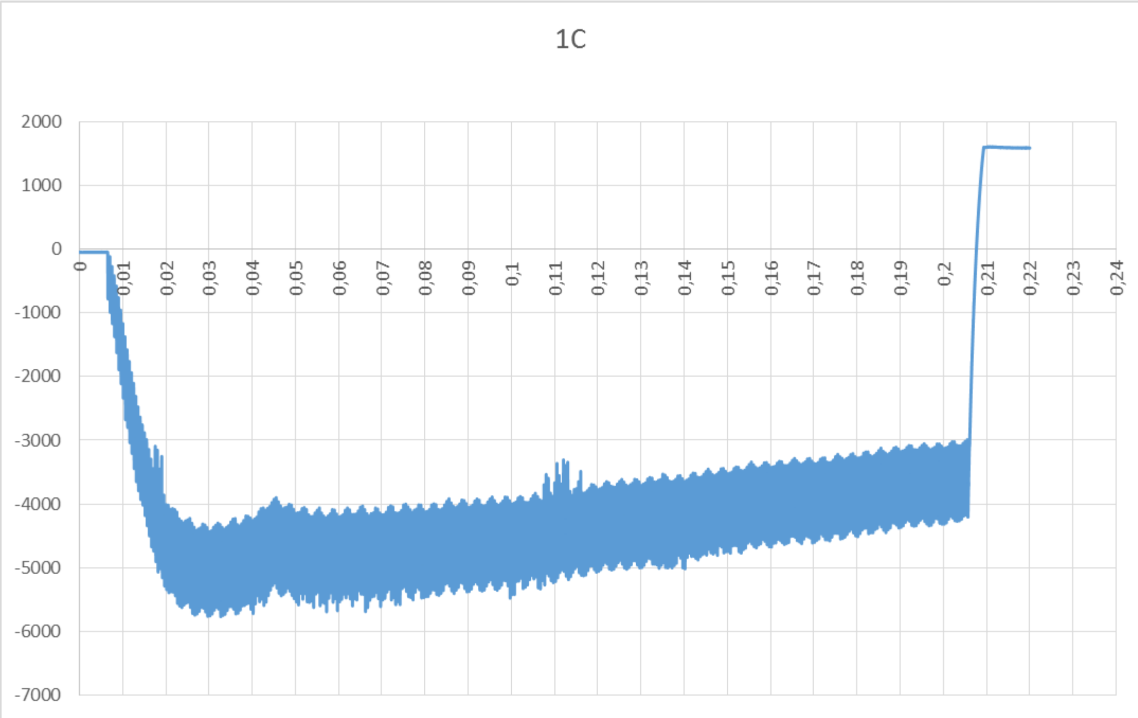
First configuration

Input values for this configuration:

- Current (KA): 6
- Force (KN): 2
- Welding time (ms): 200



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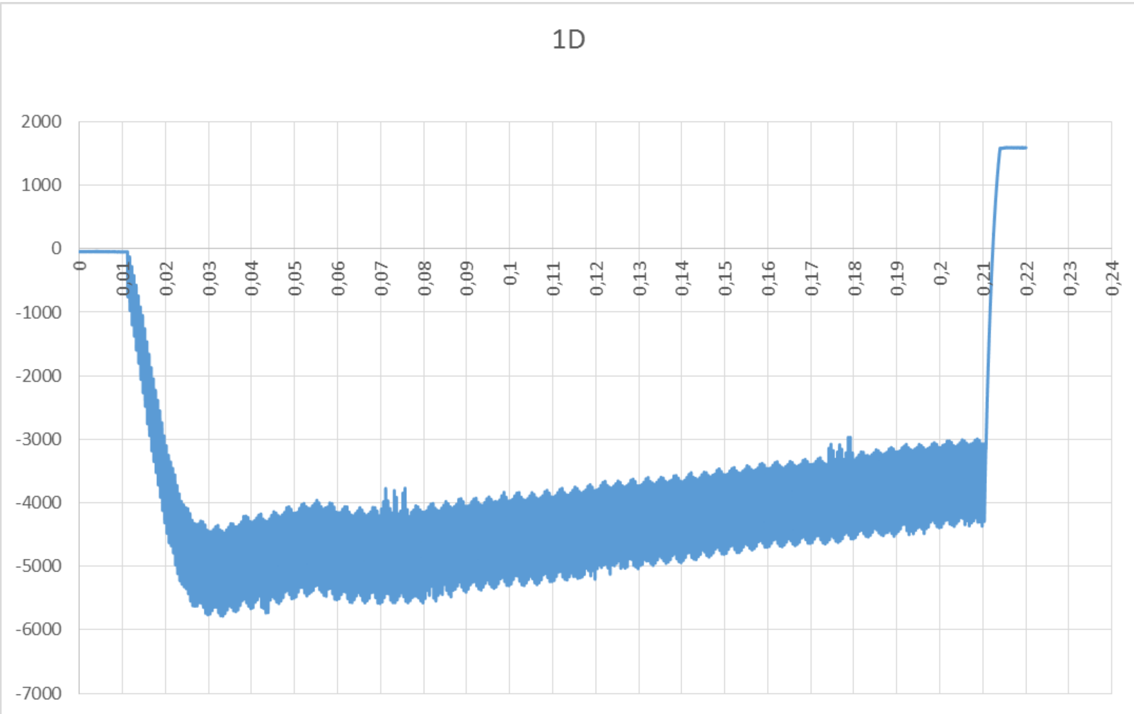
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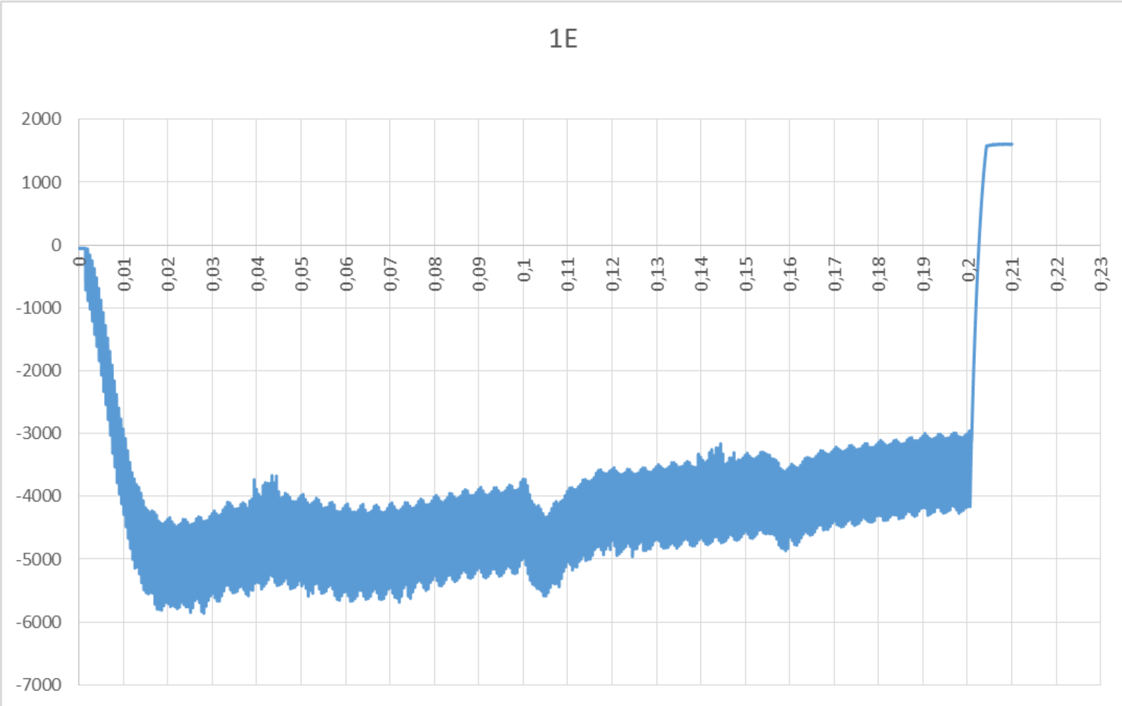
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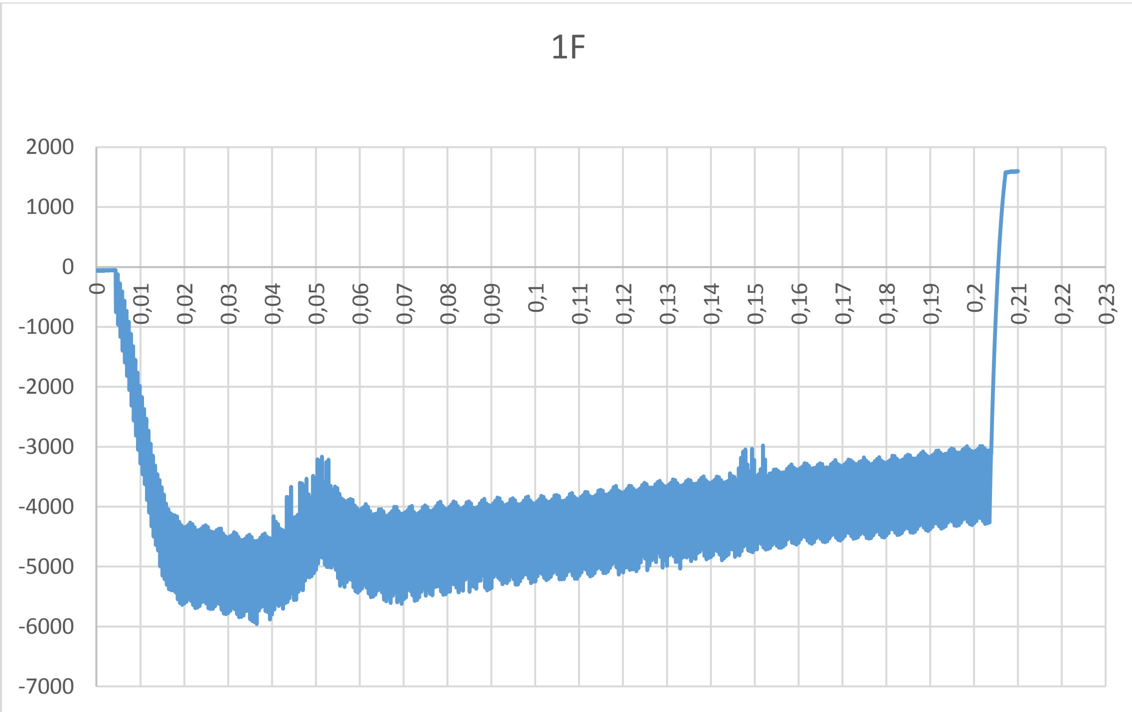
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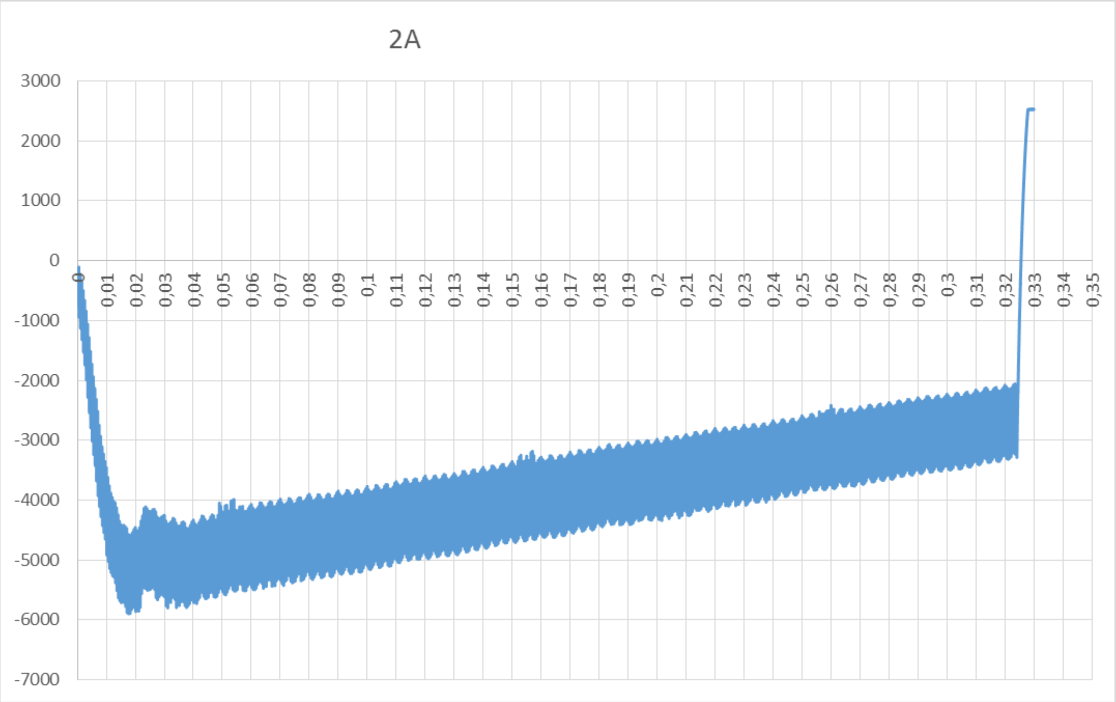
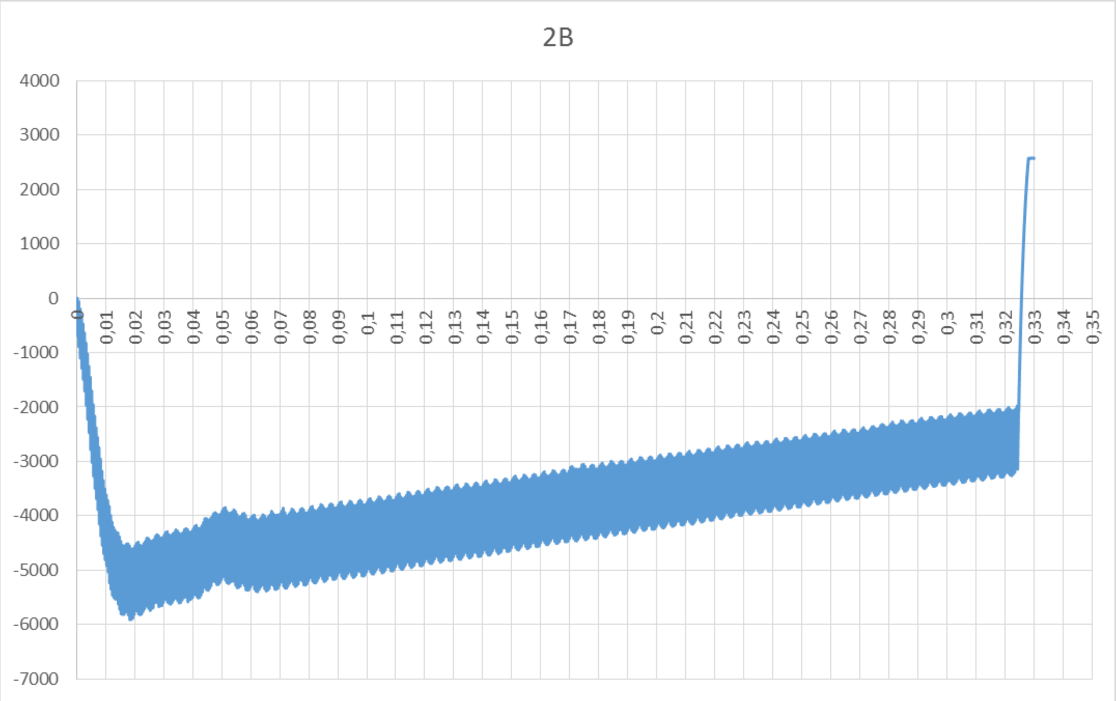
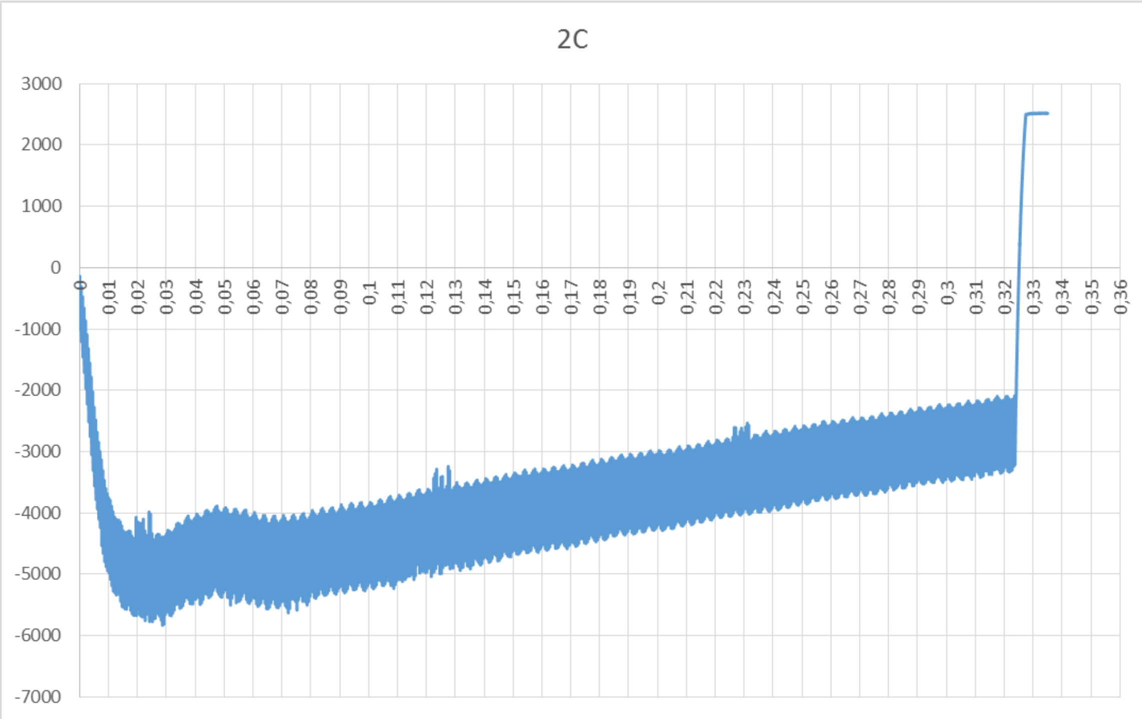
Second configuration

Input values for this configuration:

- Current (KA): 6
- Force (KN): 3
- Welding time (ms): 325



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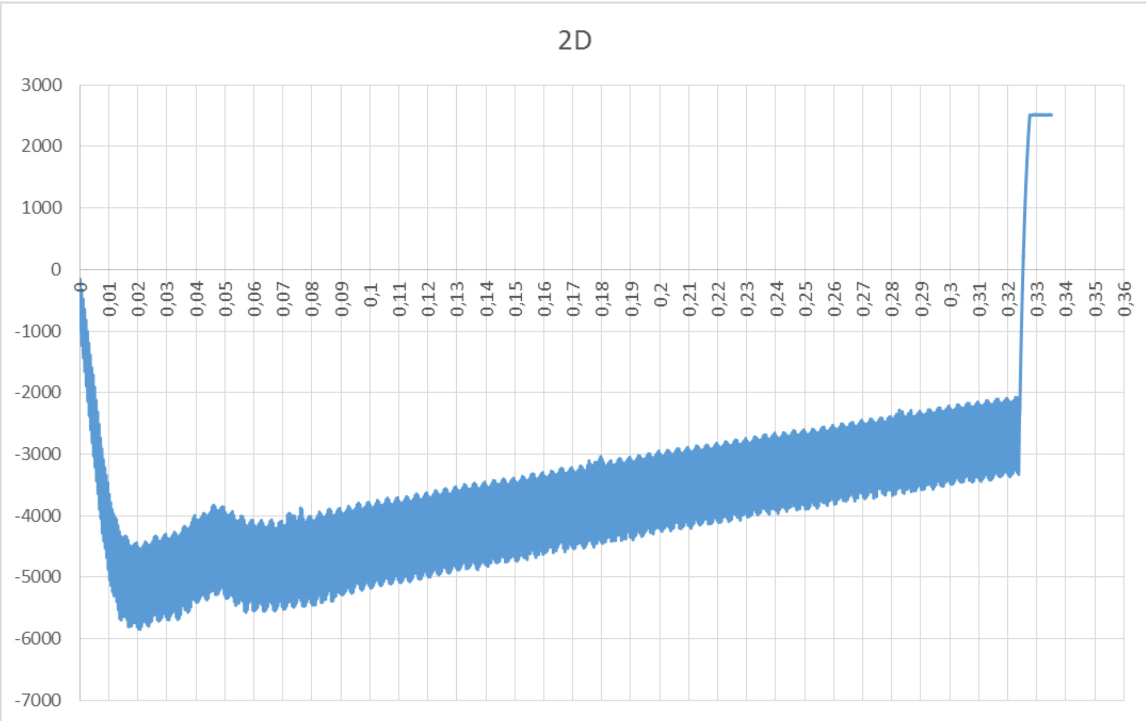
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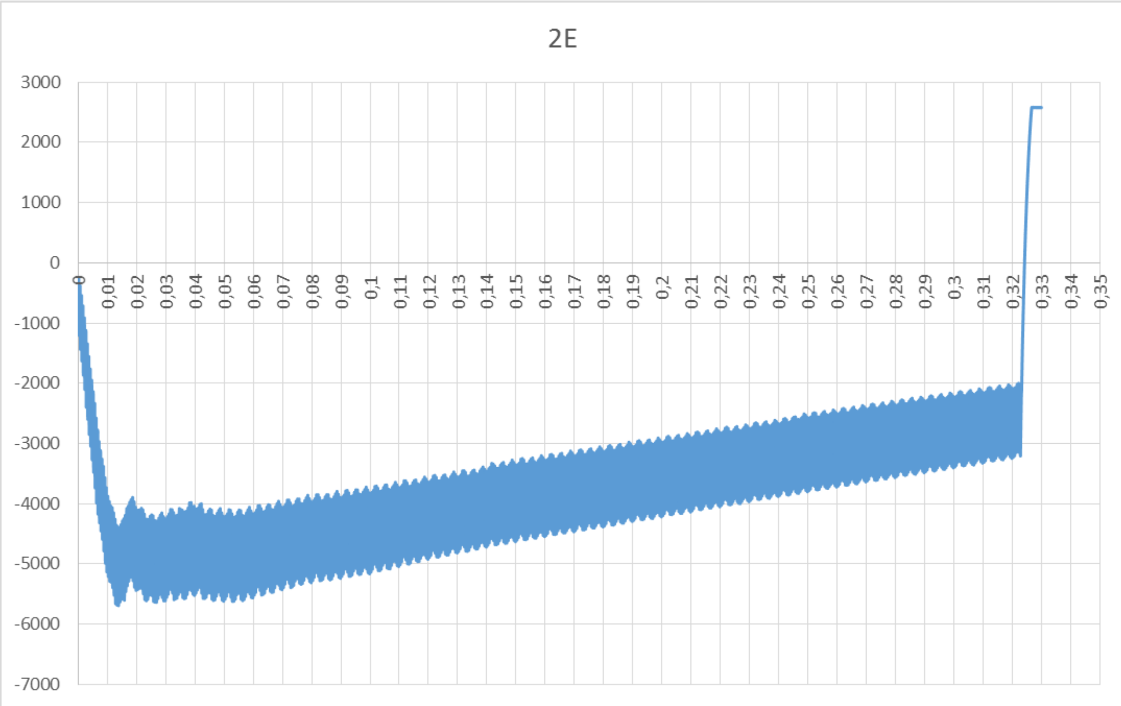
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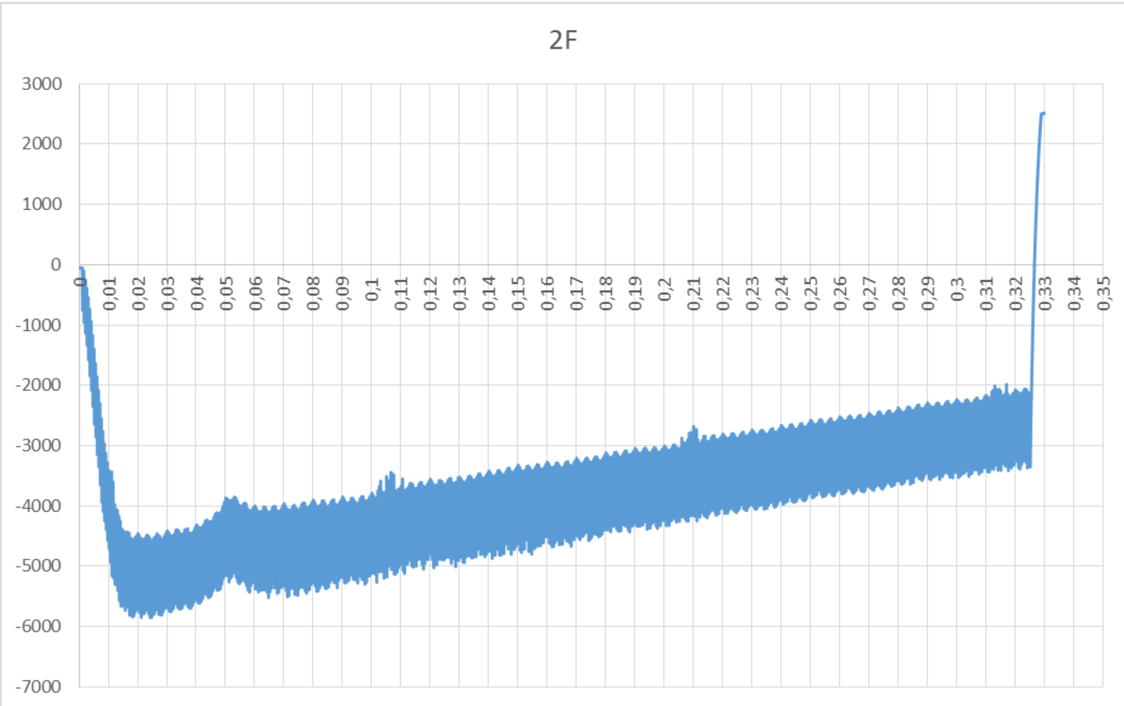
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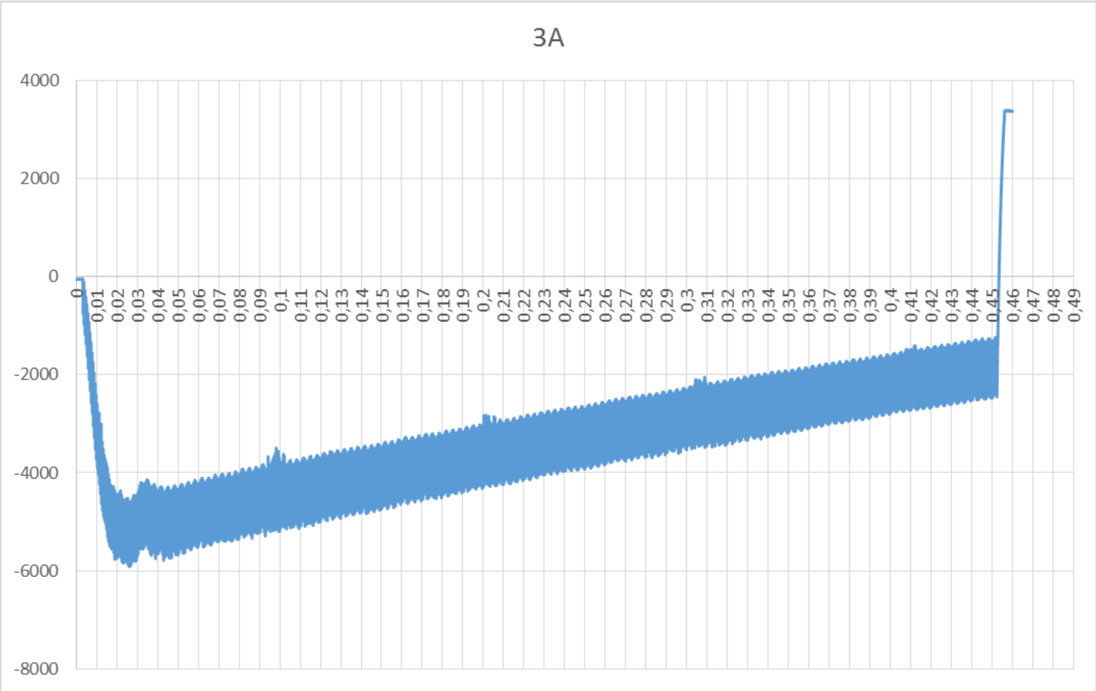
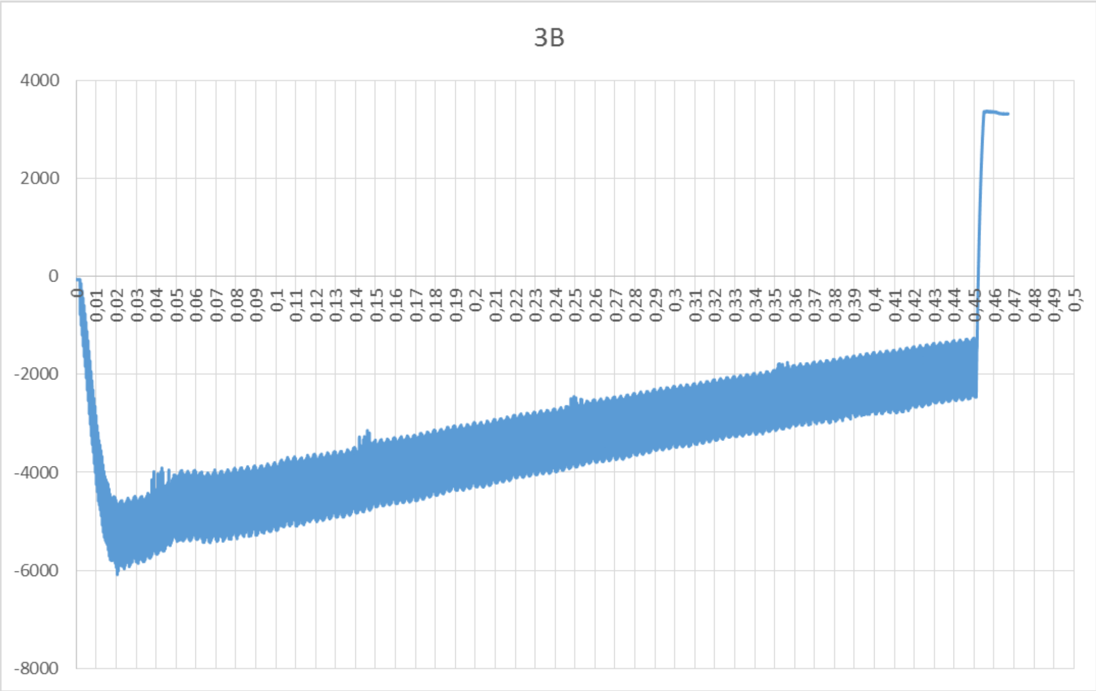
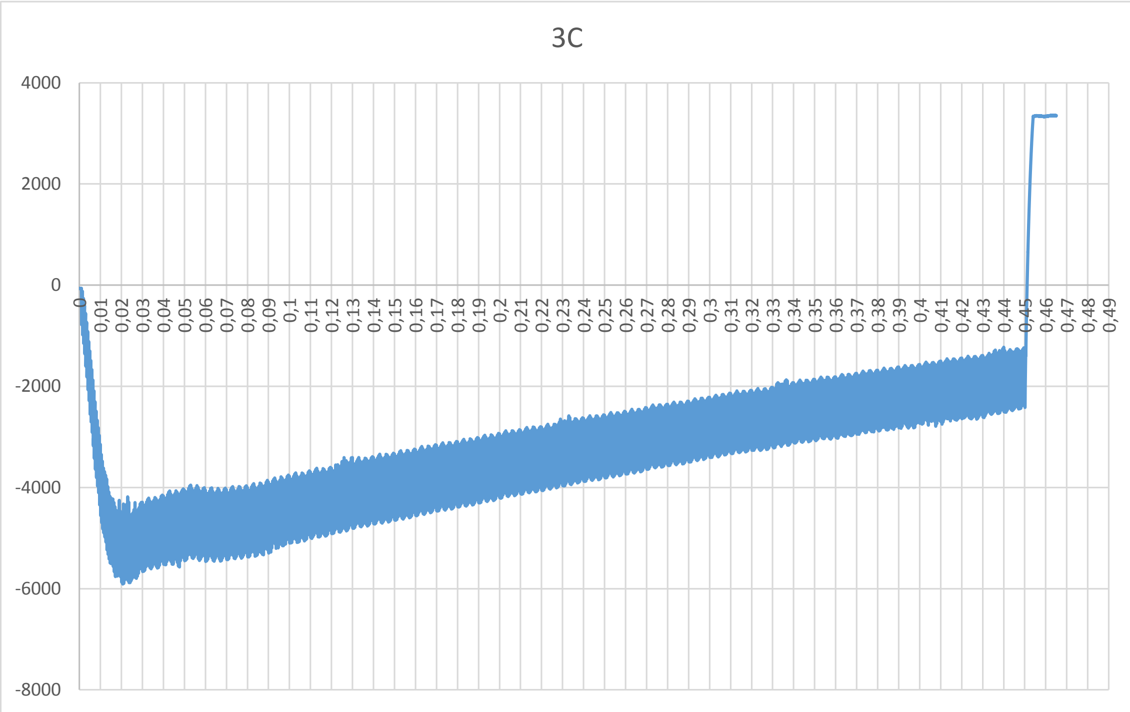
Third configuration

Input values for this configuration:

- Current (KA): 6
- Force (KN): 4
- Welding time (ms): 450



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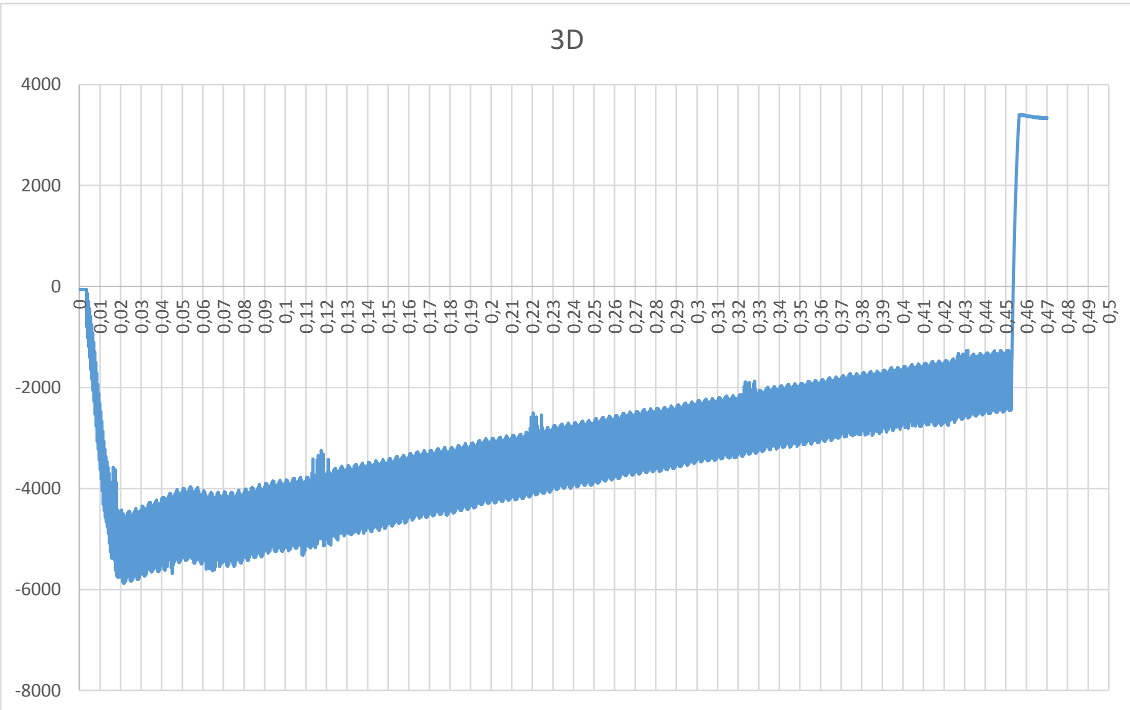
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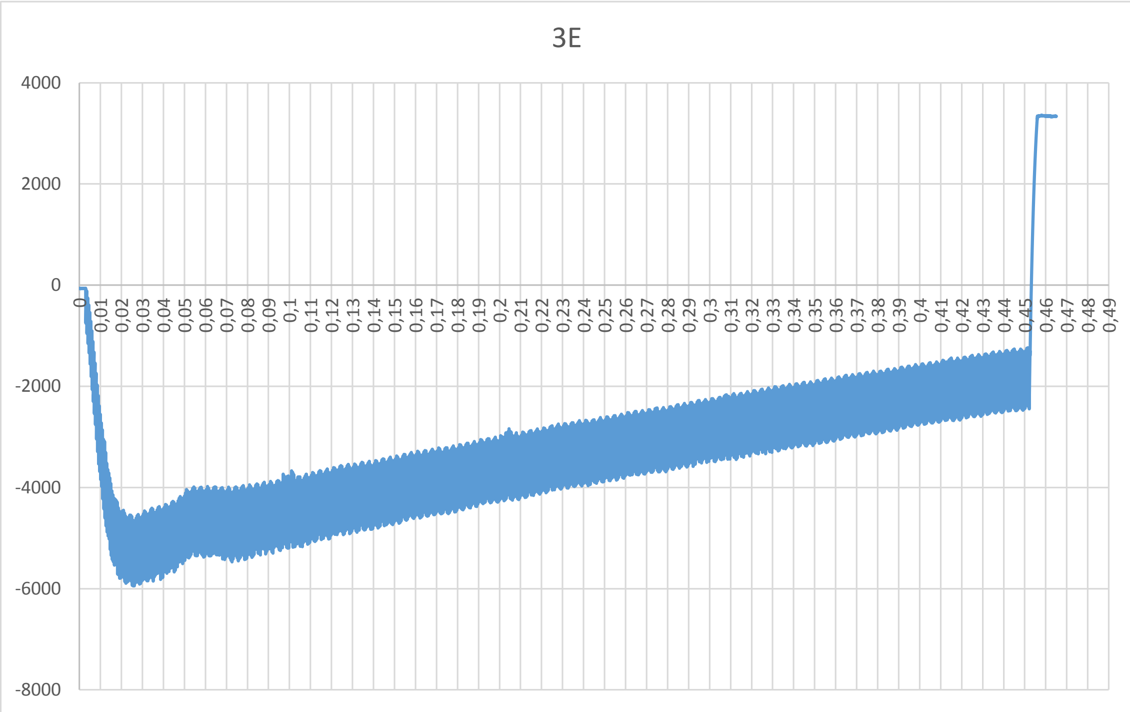
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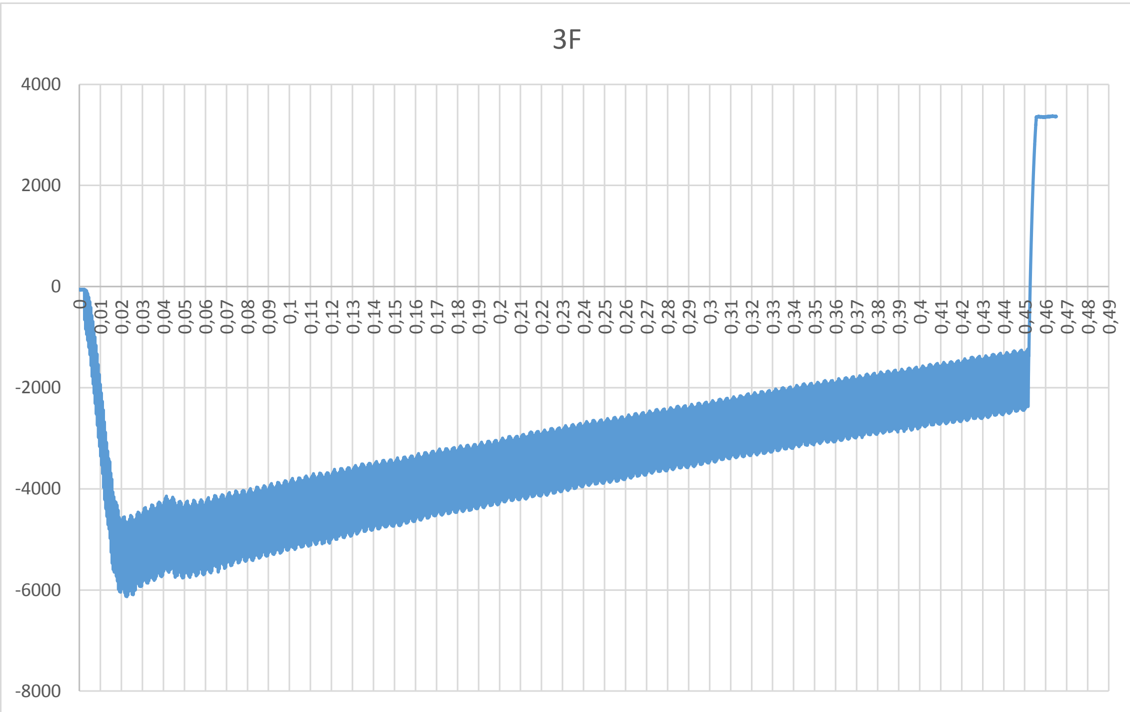
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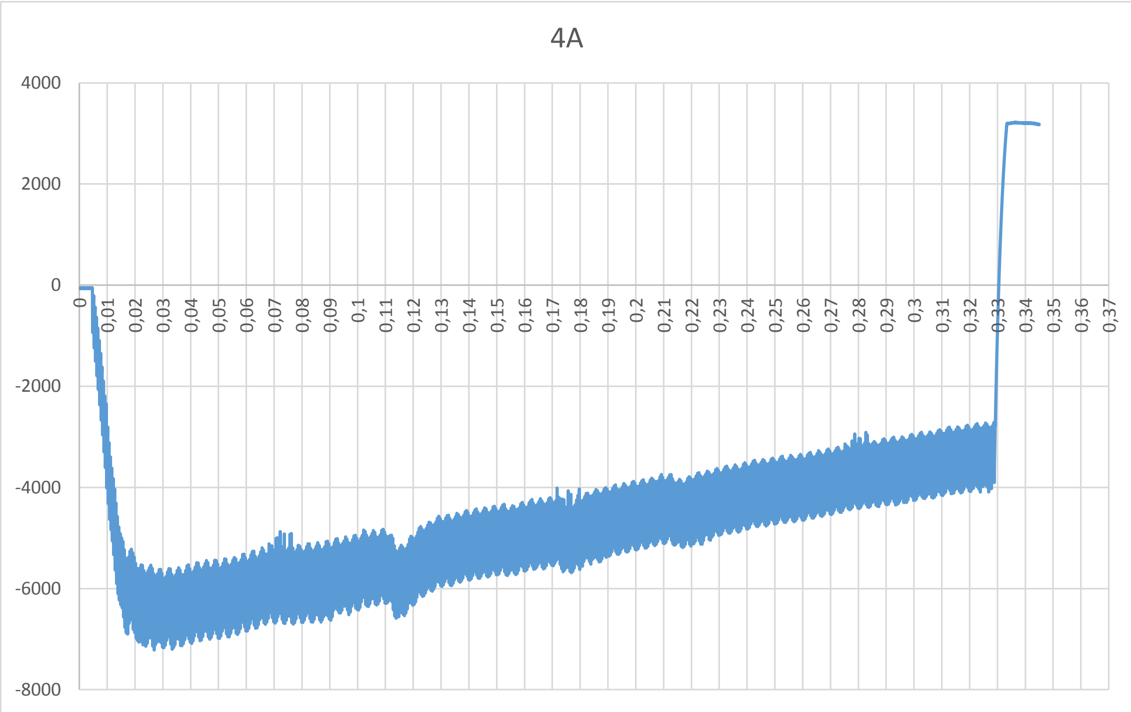
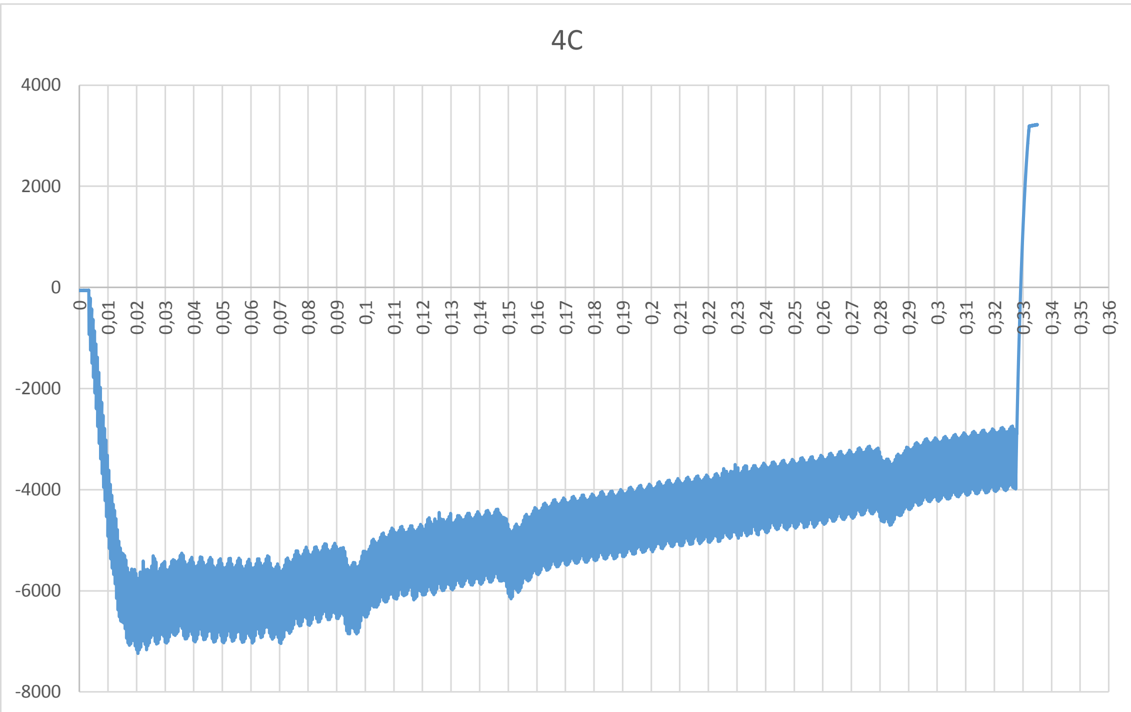
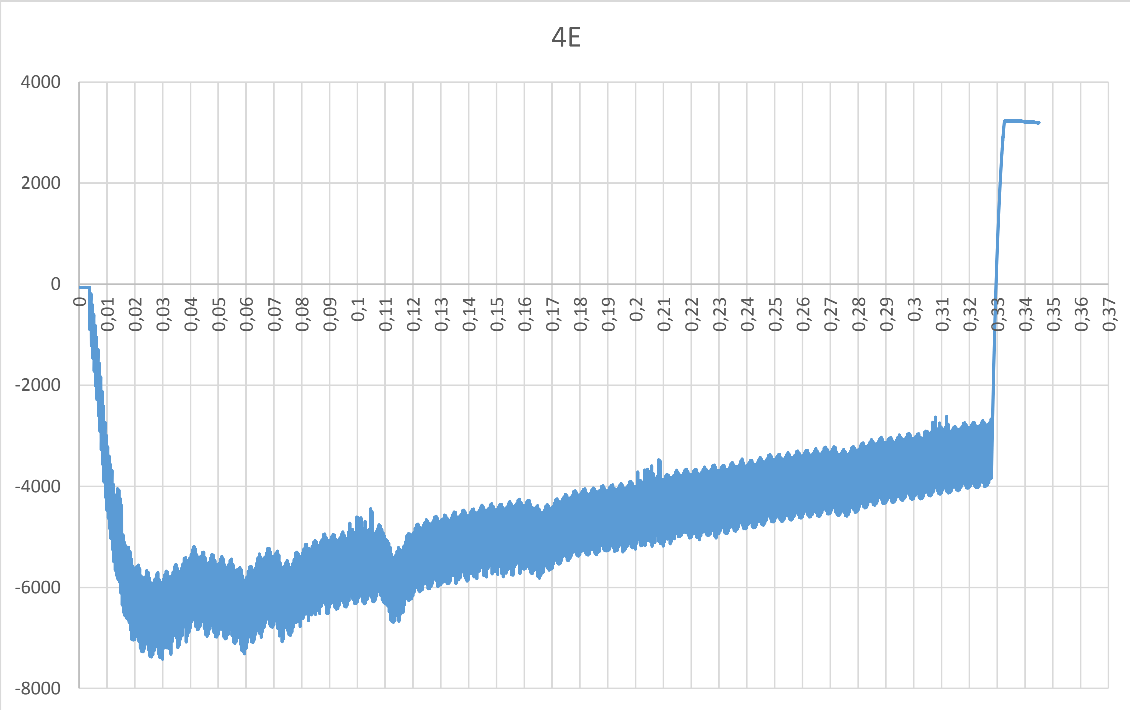
Furth configuration

Input values for this configuration:

- Current (KA): 7.5
- Force (KN): 2
- Welding time (ms): 325



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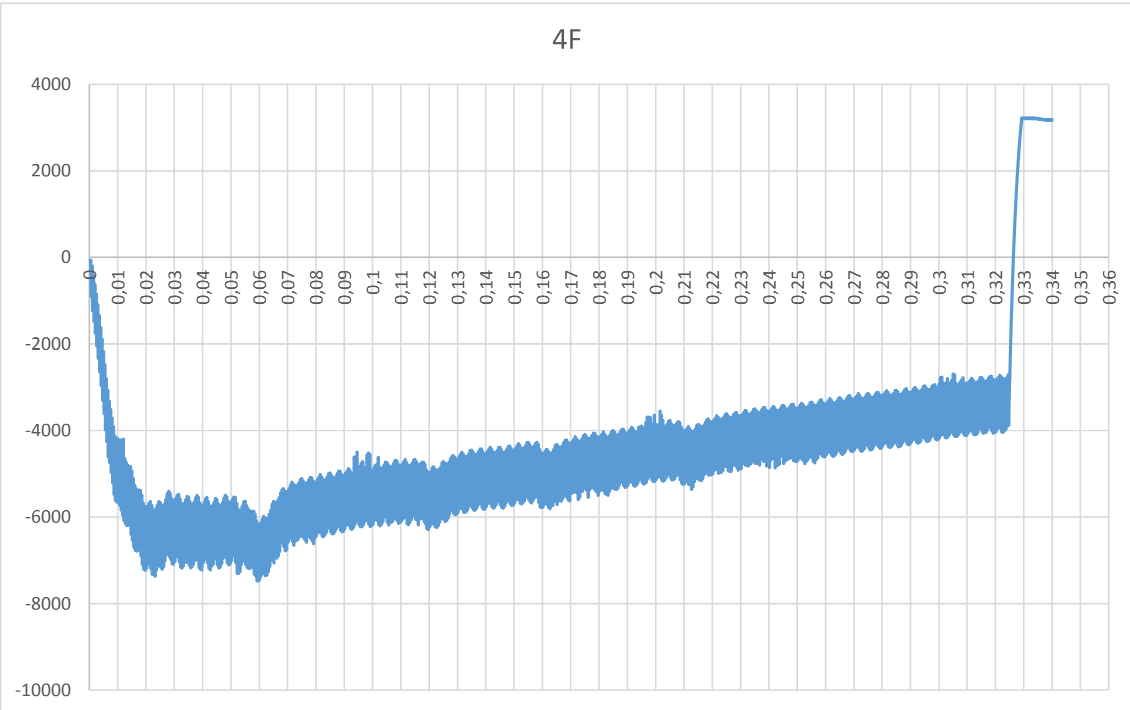
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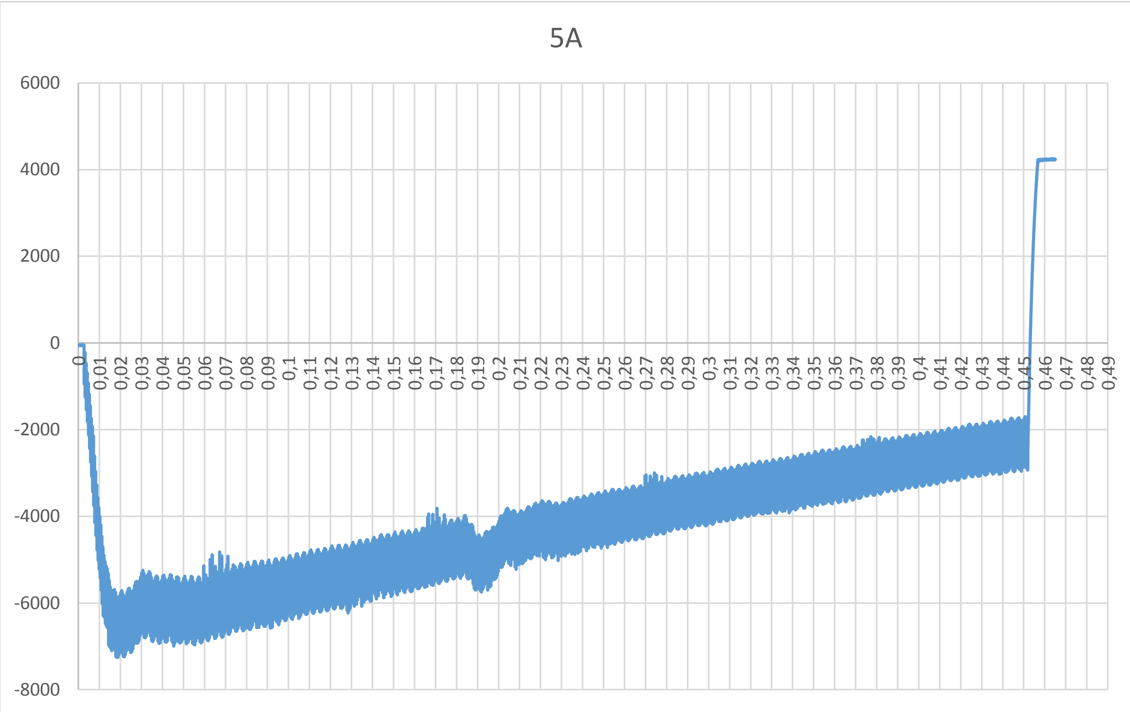
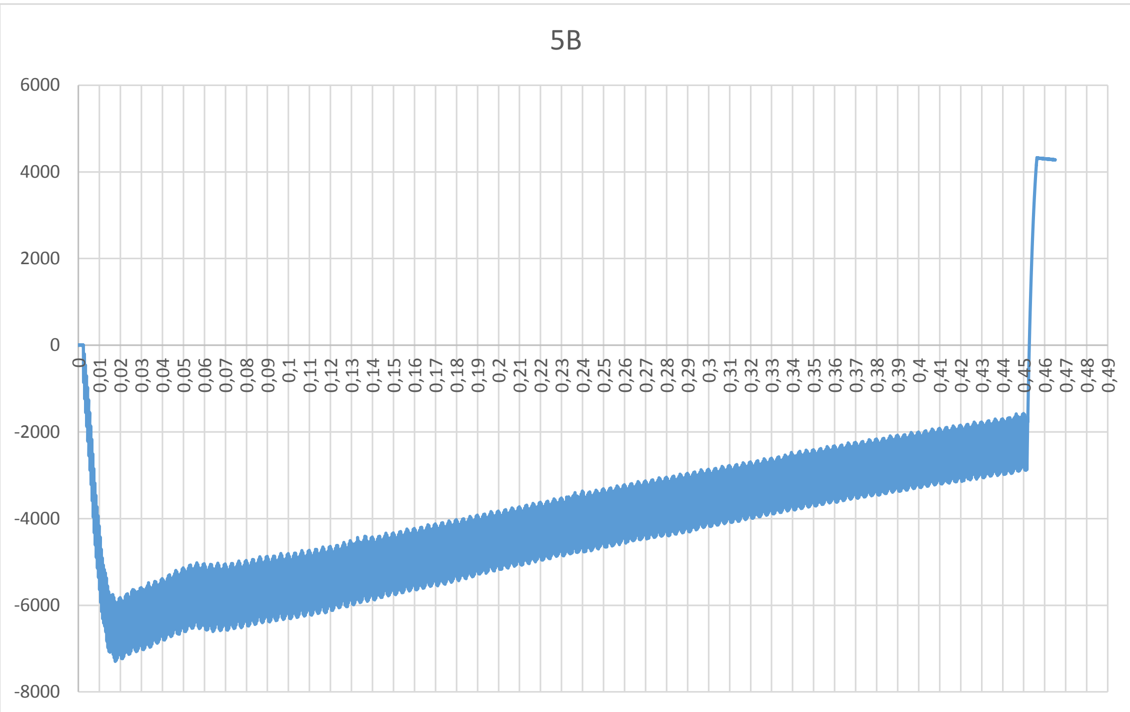
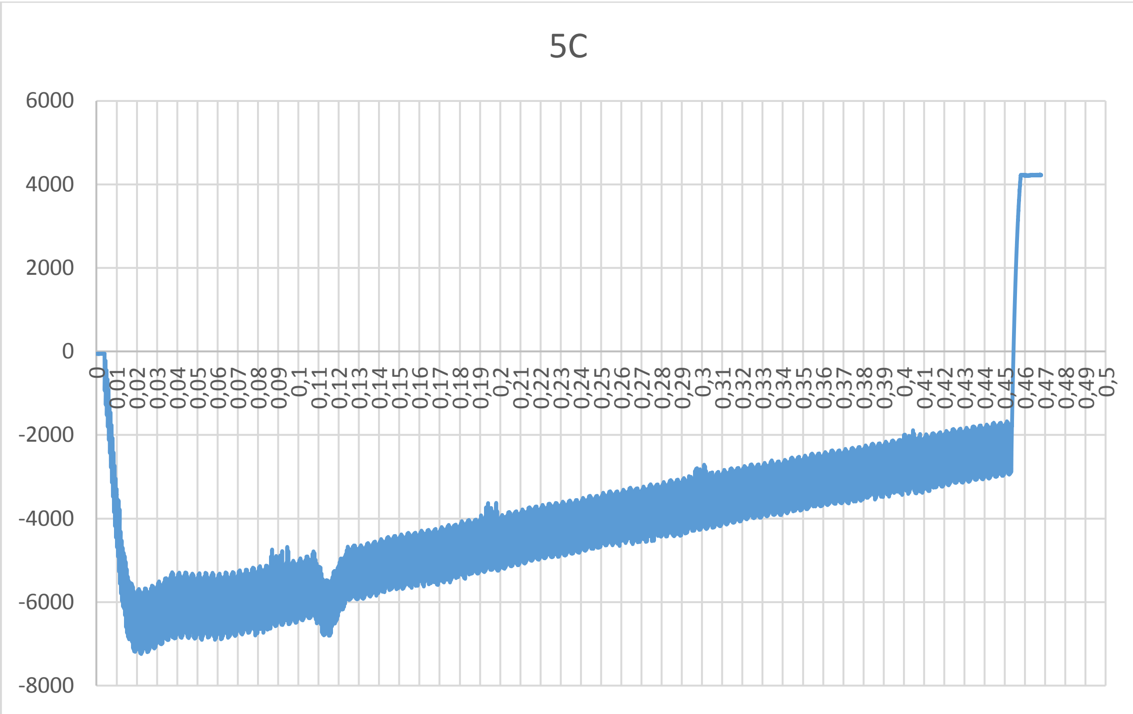
Fifth configuration

Input values for this configuration:

- Current (KA): 7.5
- Force (KN): 3
- Welding time (ms): 450



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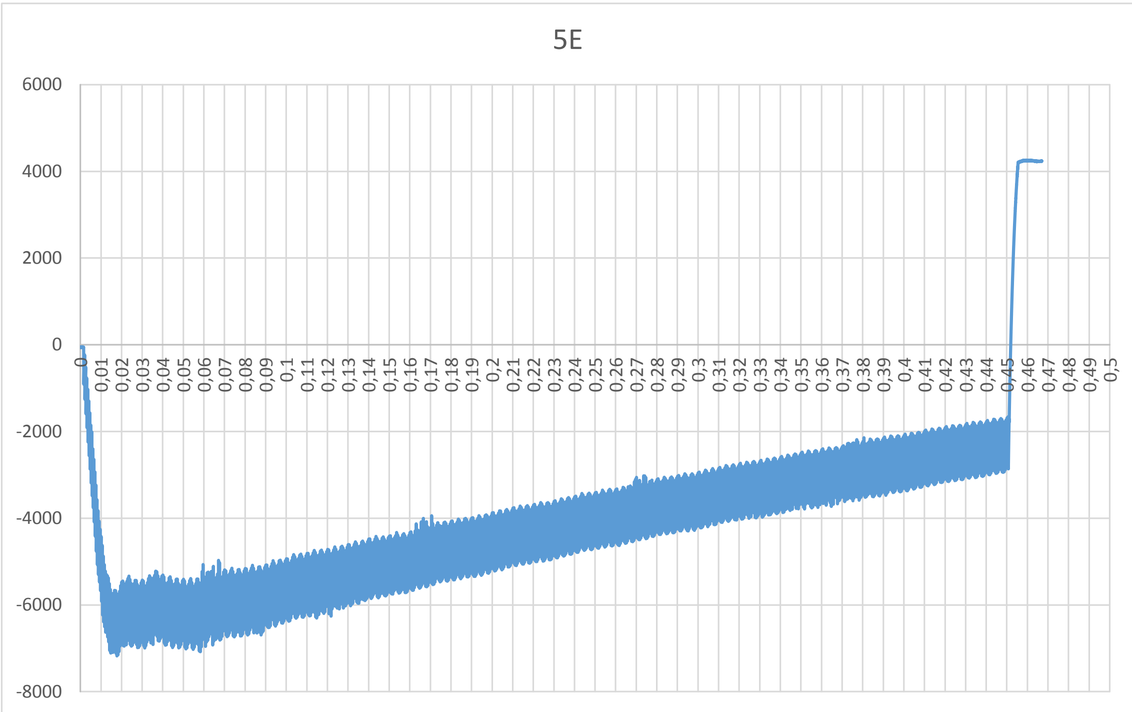
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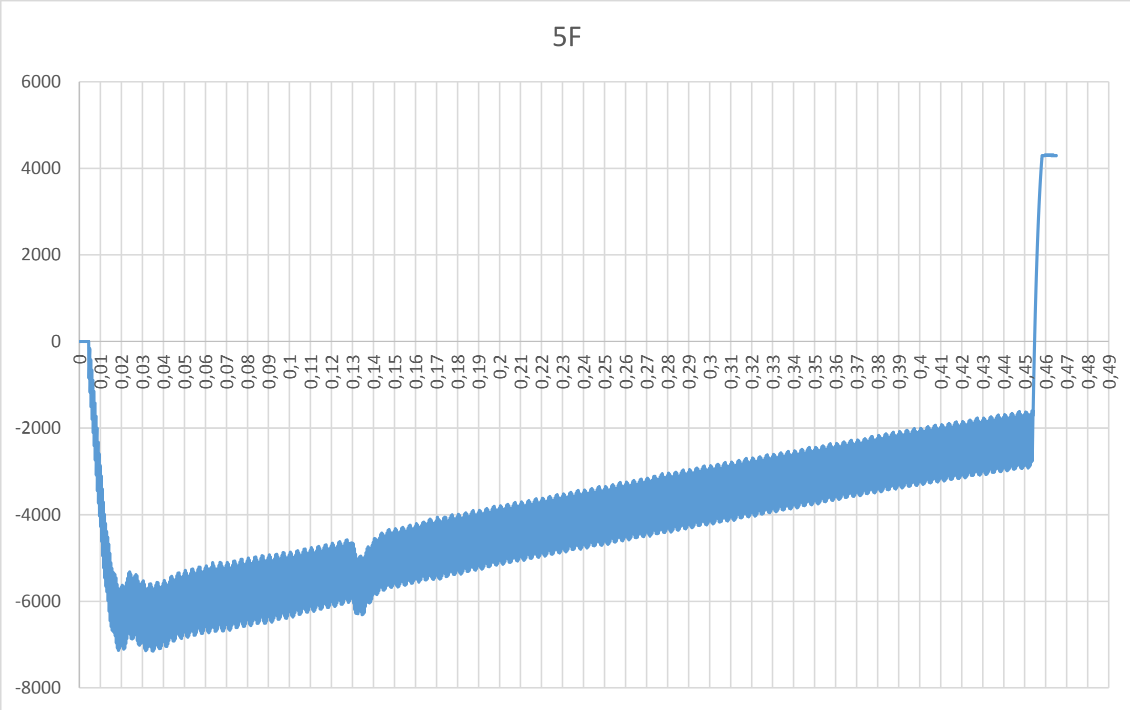
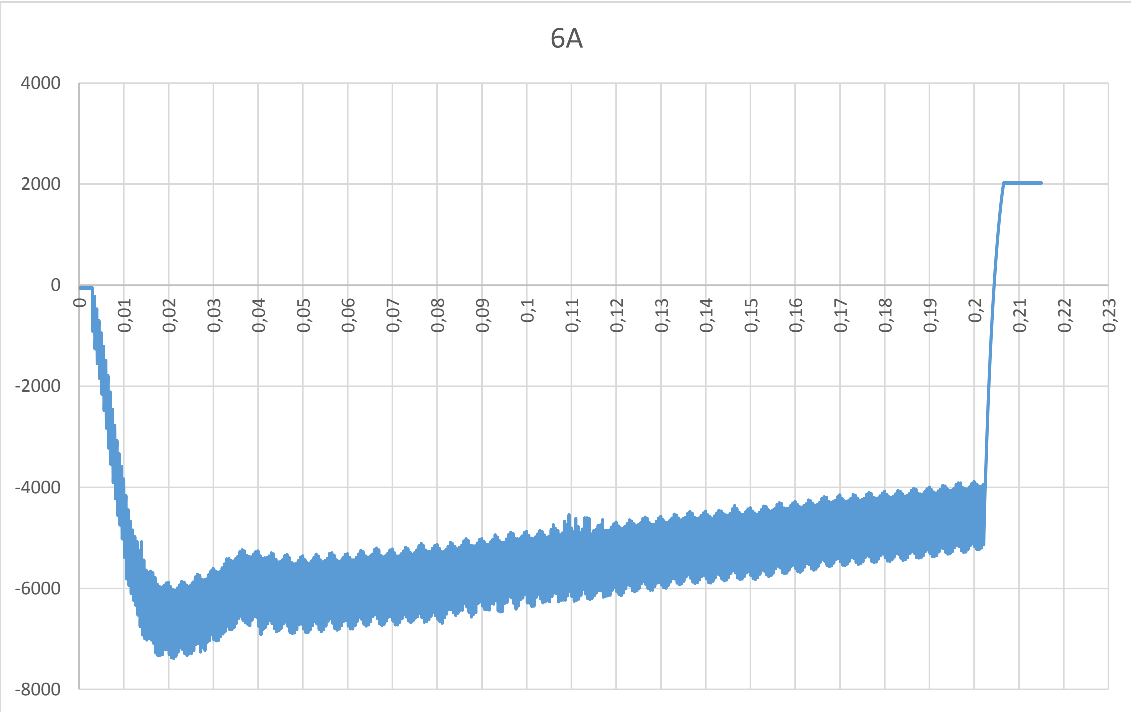
-6000
-8000

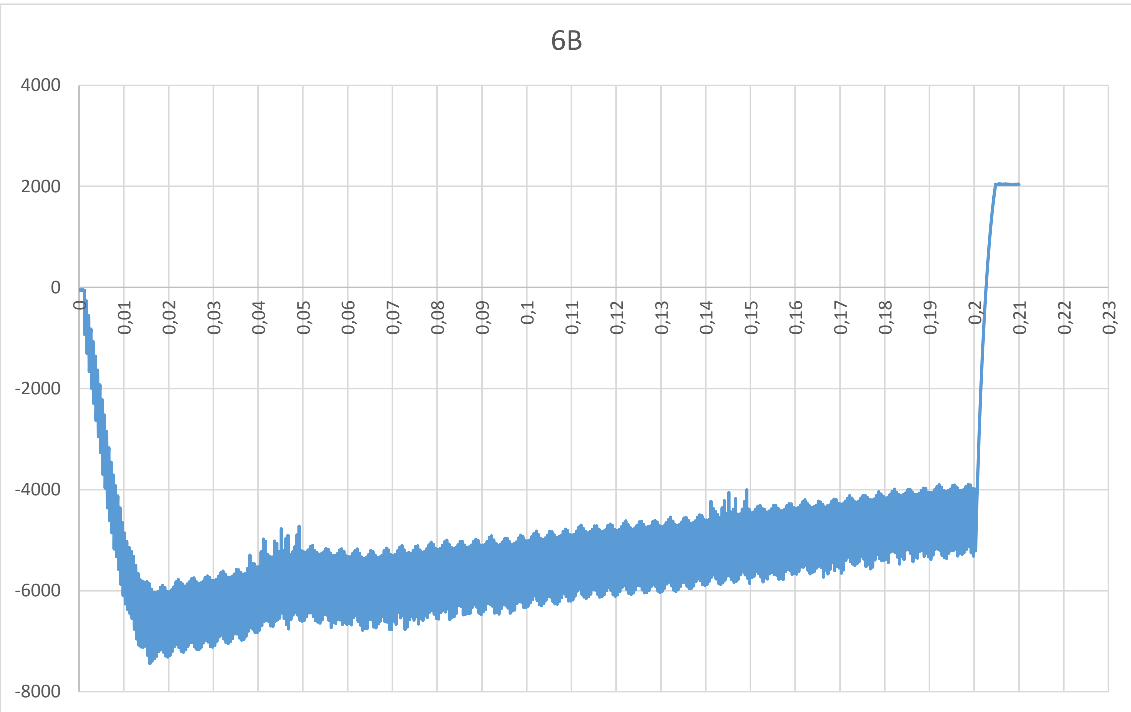

5F
6000
4000
2000
0
-2000
-4000
-6000
-8000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23
0,24
0,25
0,26
0,27
0,28
0,29
0,3
0,31
0,32
0,33
0,34
0,35
0,36
0,37
0,38
0,39
0,4
0,41
0,42
0,43
0,44
0,45
0,46
0,47
0,48
0,49

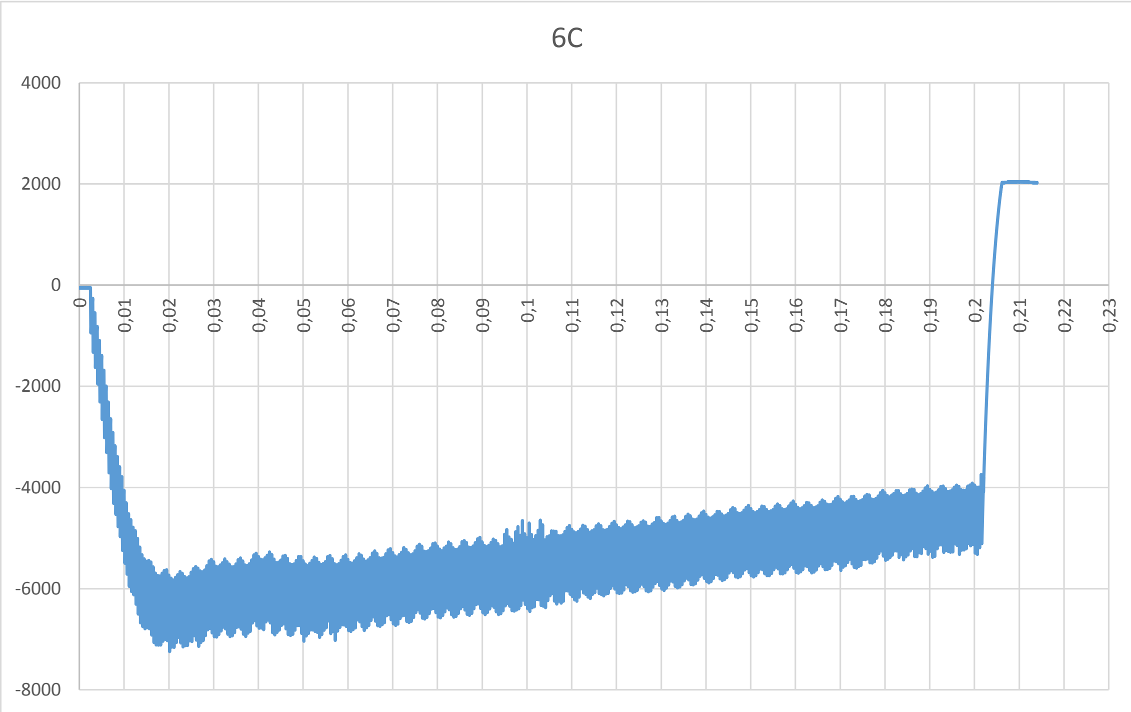
Sixth configuration

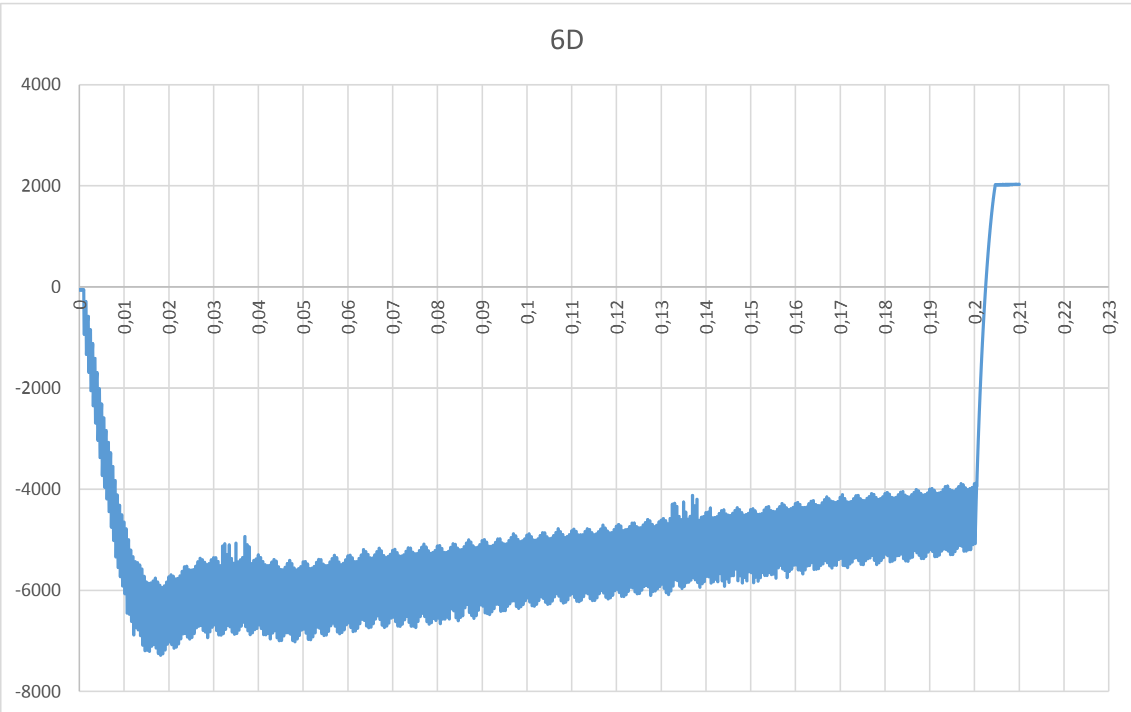
Input values for this configuration:

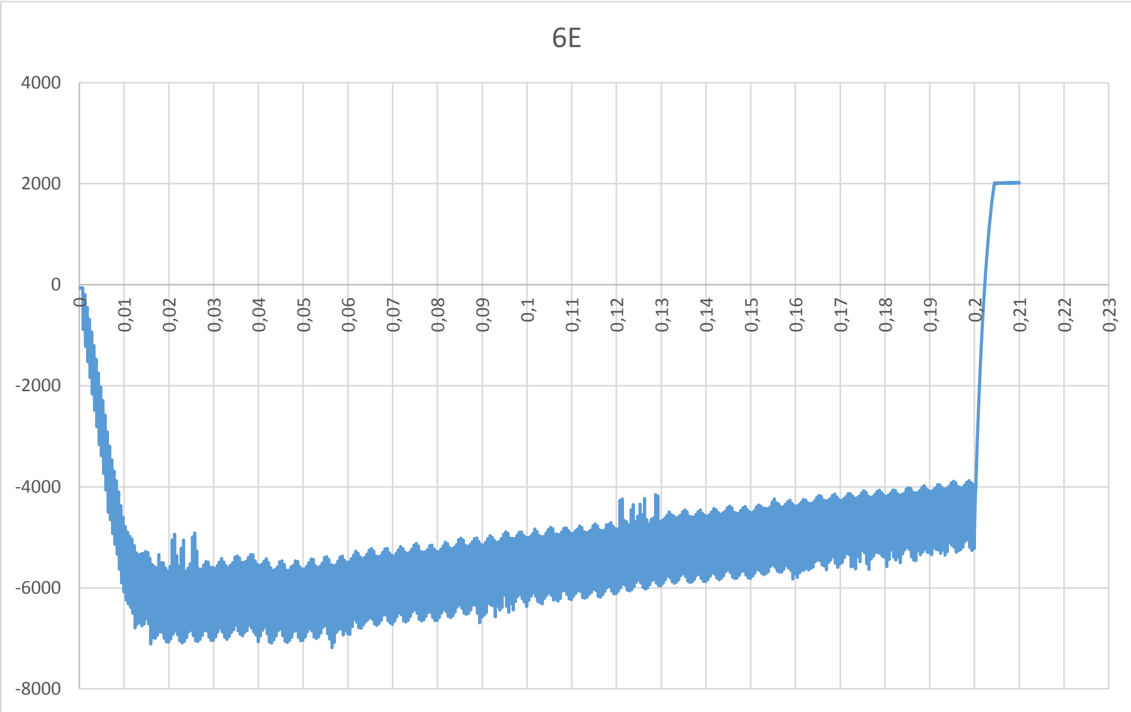
- Current (KA): 7.5
- Force (KN): 4
- Welding time (ms): 200



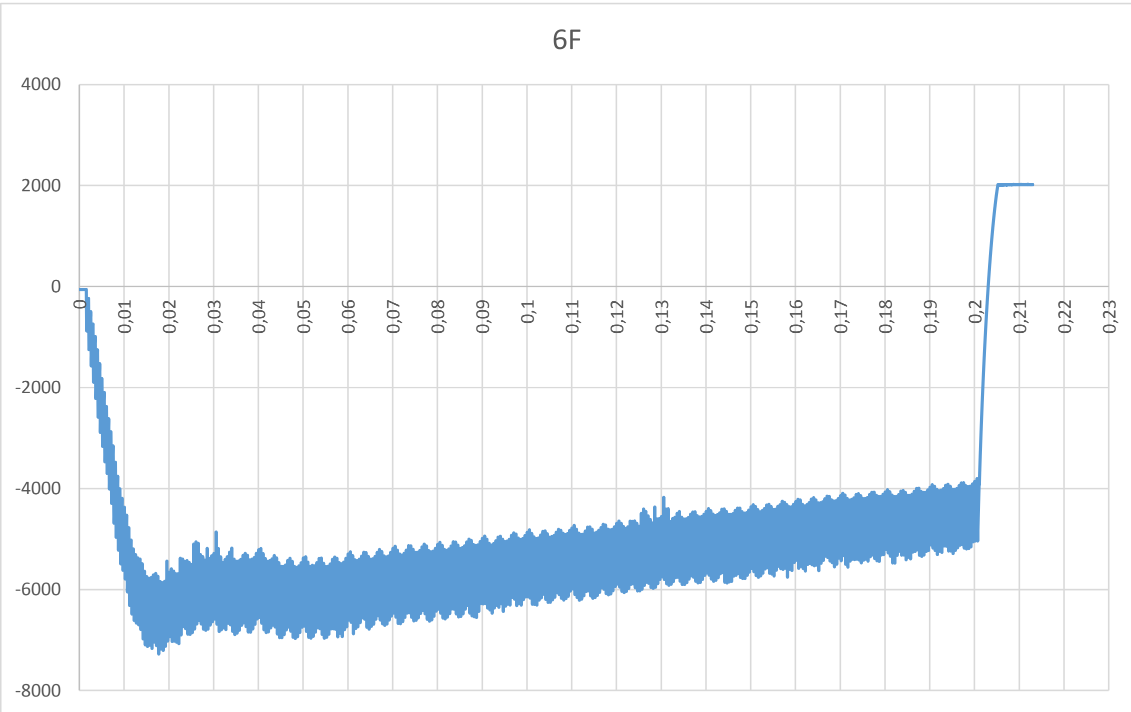



6C
4000
2000
0
-2000
-4000
-6000
-8000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23


6D
4000
2000
0
-2000
-4000
-6000
-8000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23



6E
4000
2000
0
-2000
-4000
-6000
-8000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23

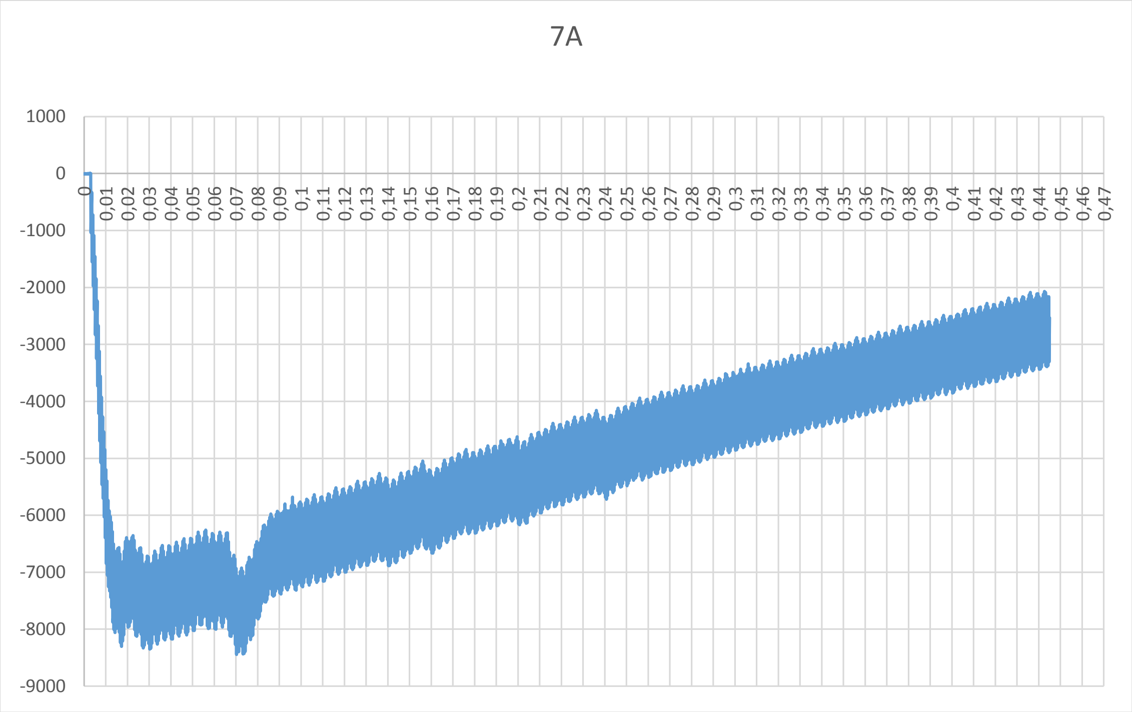


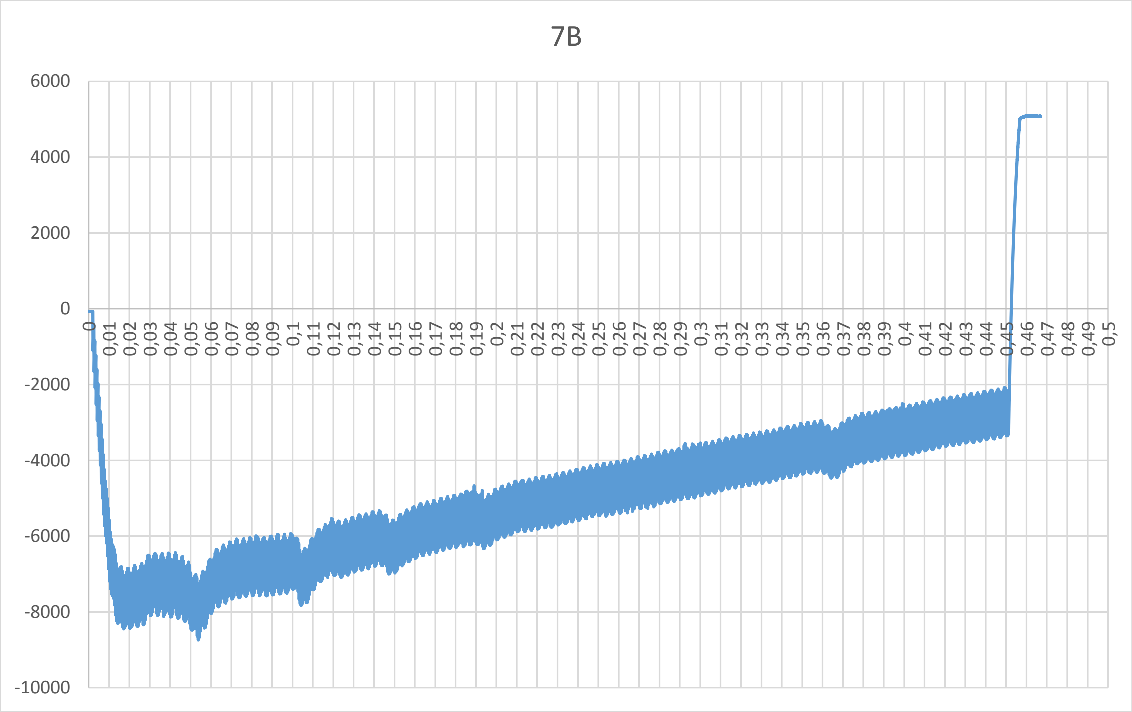
6F
4000
2000
0
-2000
-4000
-6000
-8000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23

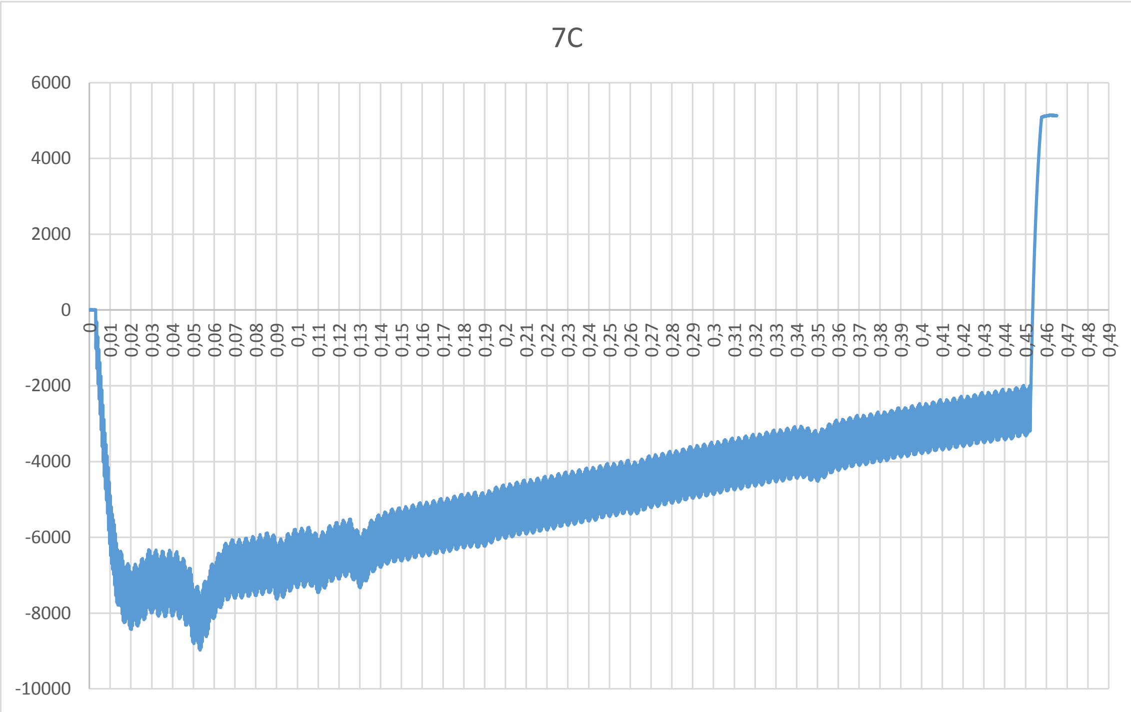
Seventh configuration

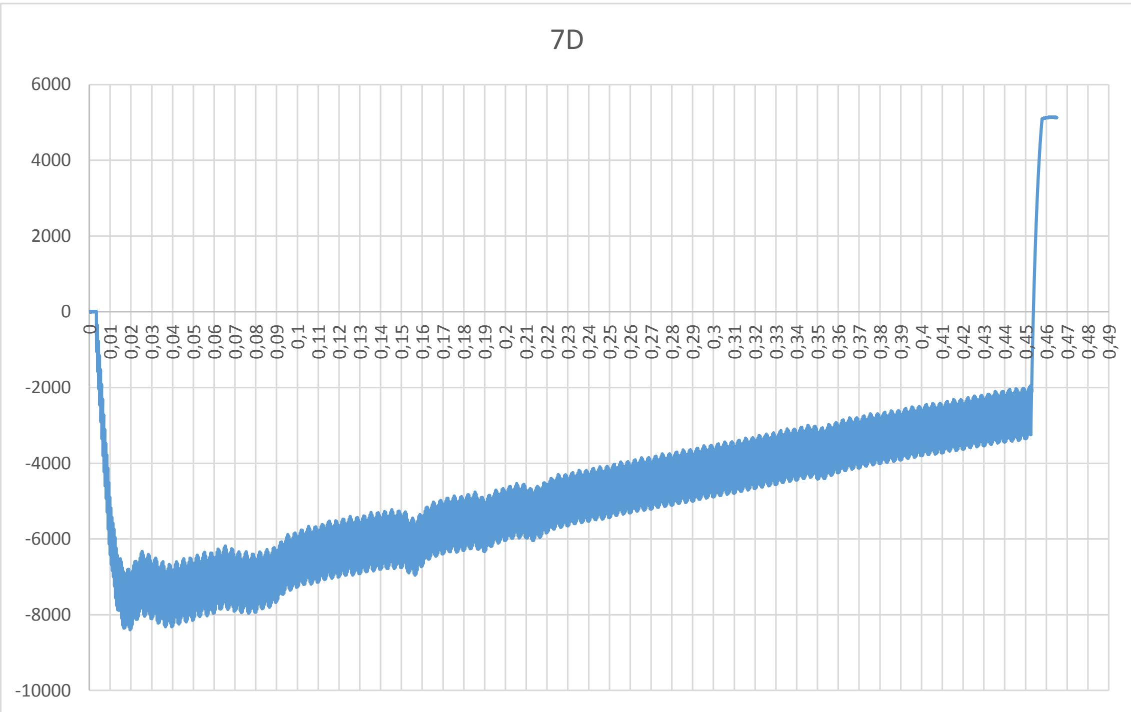
Input values for this configuration:

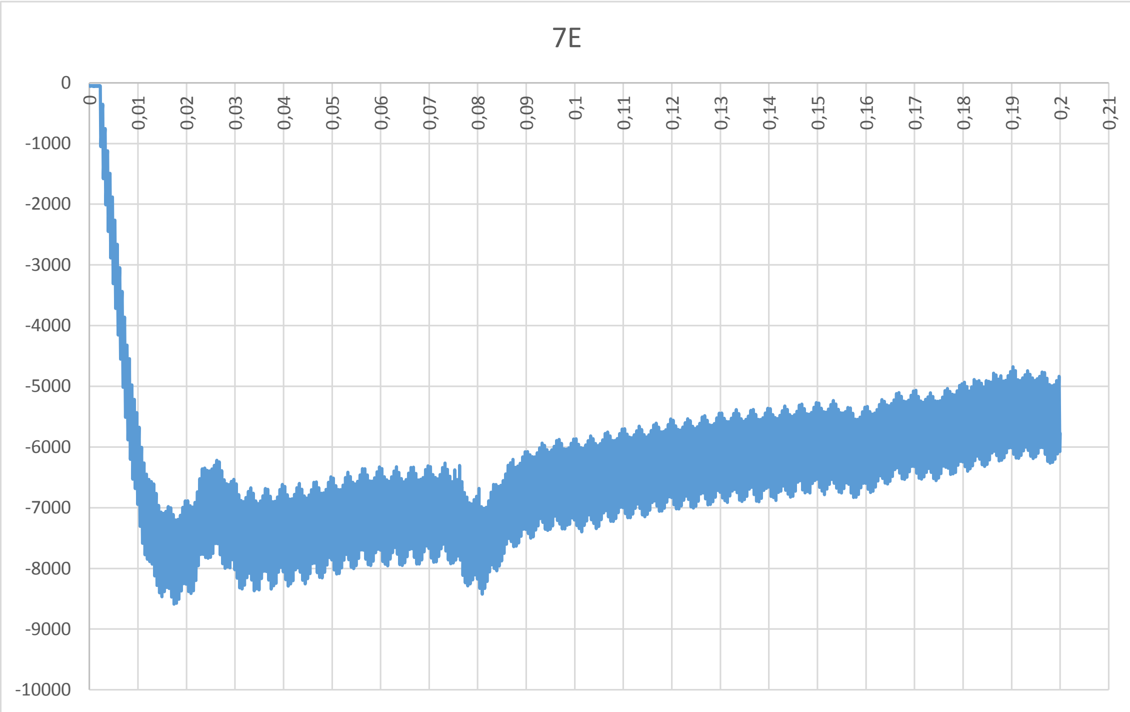
- Current (KA): 9
- Force (KN): 2
- Welding time (ms): 450

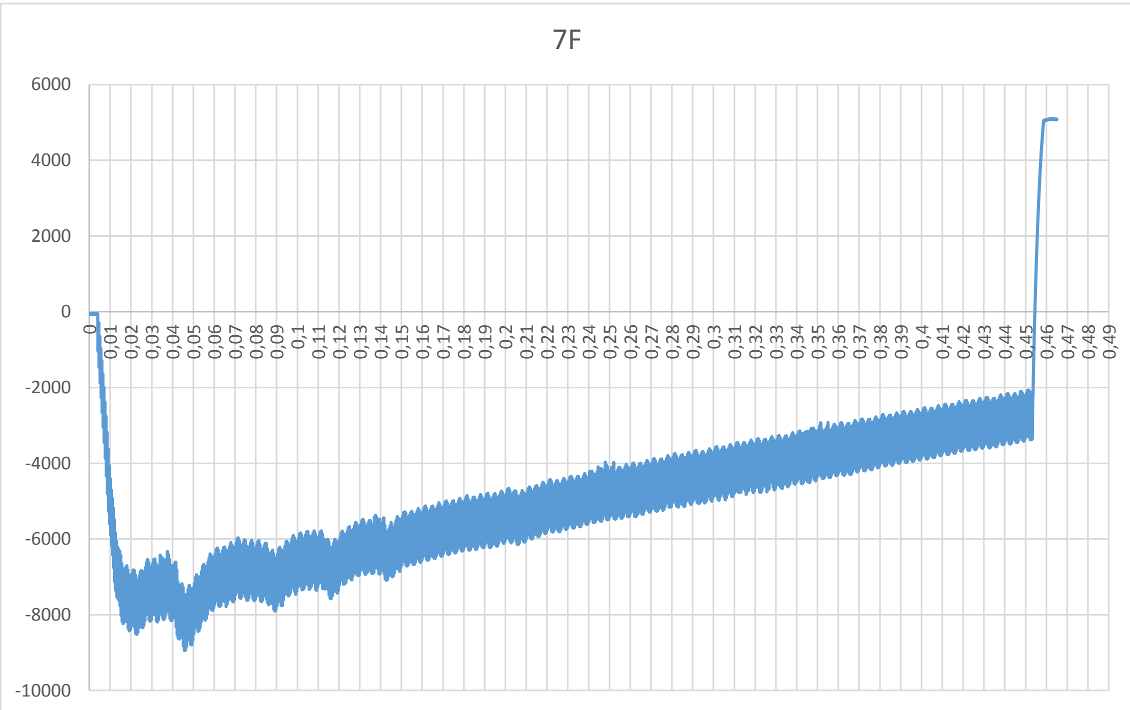





7C
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000


7D
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000

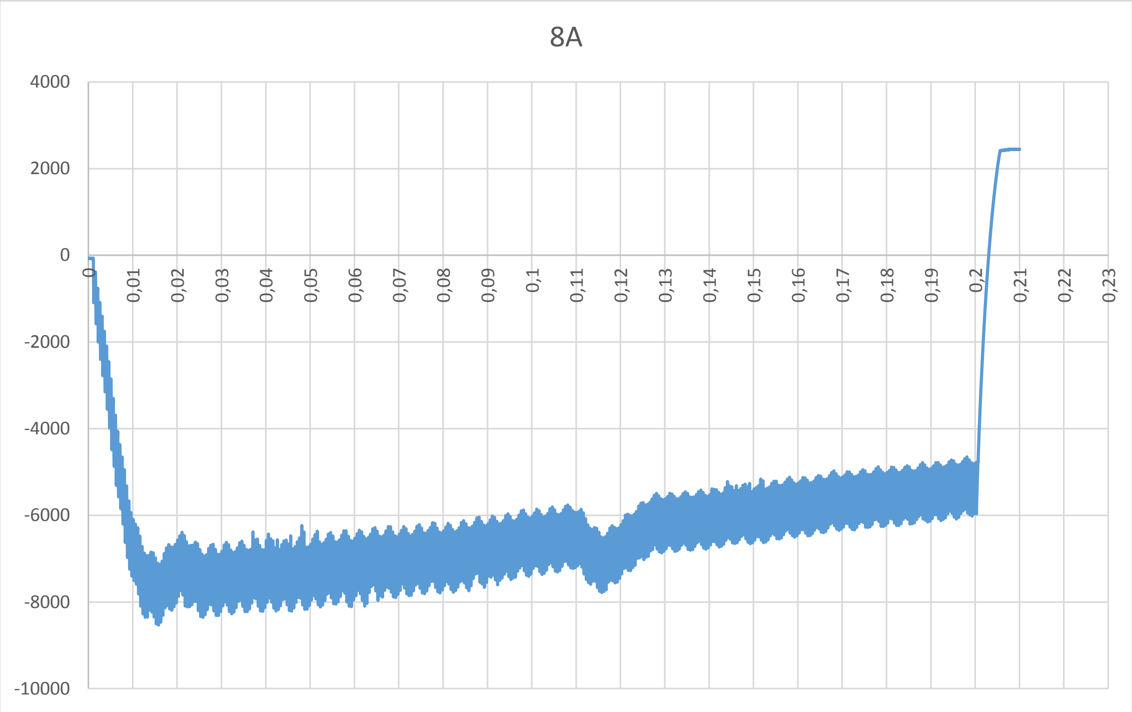

7E
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
-8000
-9000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21

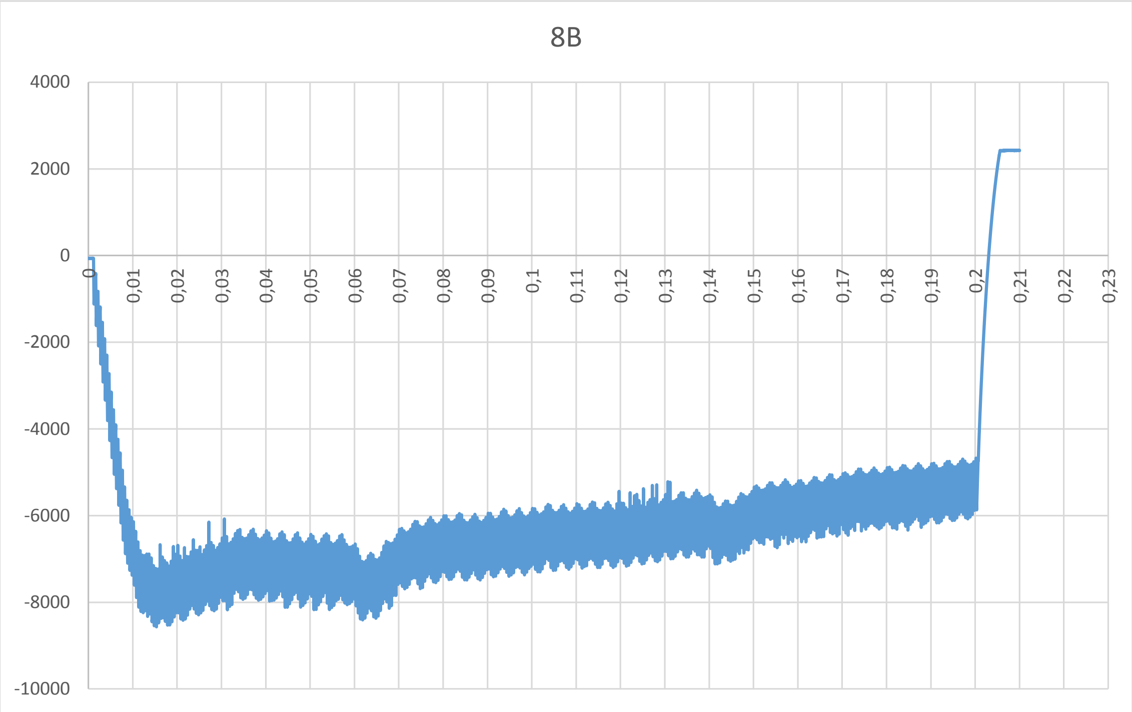

7F
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23
0,24
0,25
0,26
0,27
0,28
0,29
0,3
0,31
0,32
0,33
0,34
0,35
0,36
0,37
0,38
0,39
0,4
0,41
0,42
0,43
0,44
0,45
0,46
0,47
0,48
0,49

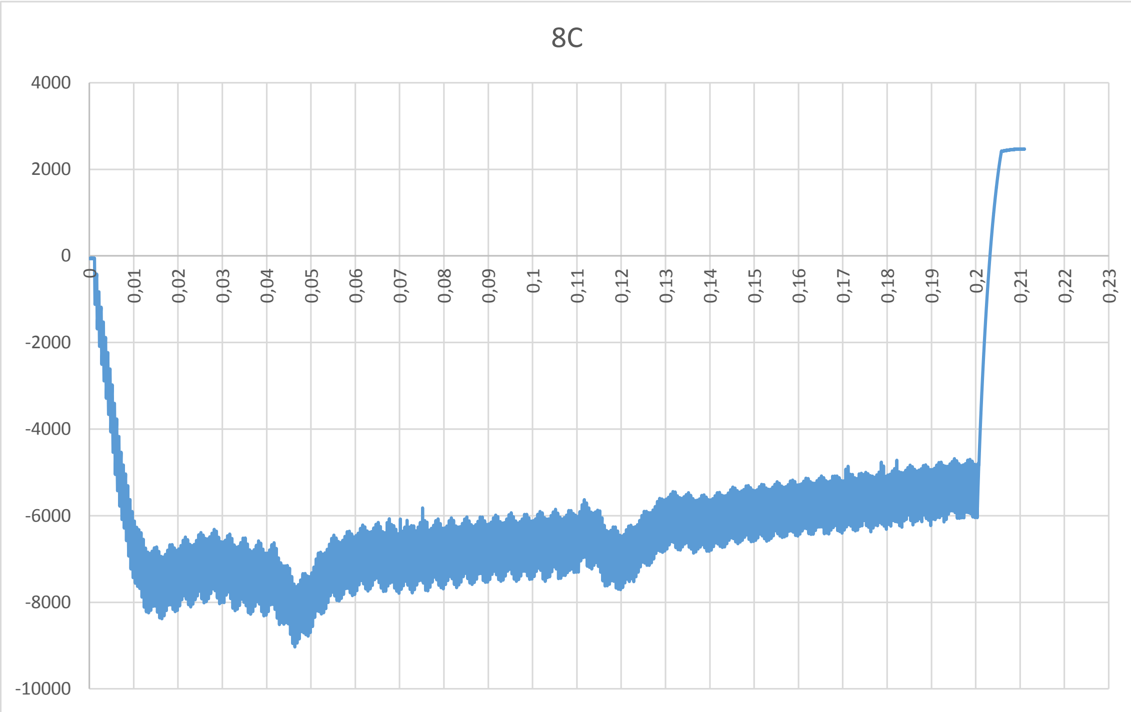
Eighth configuration

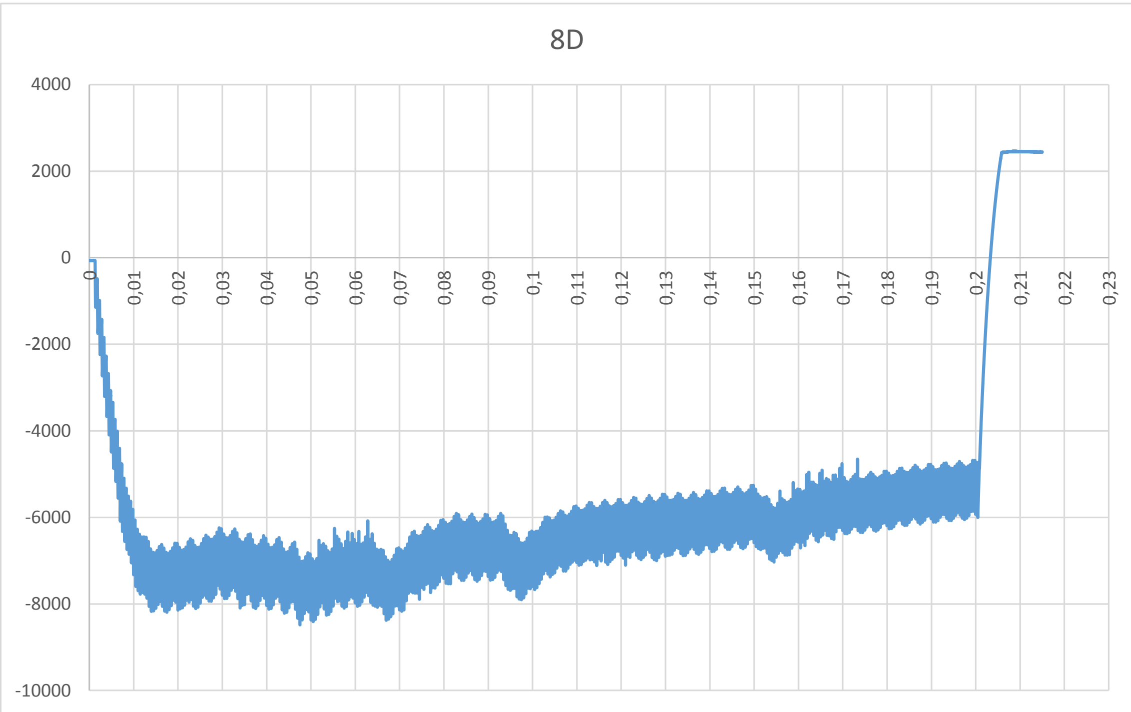
Input values for this configuration:

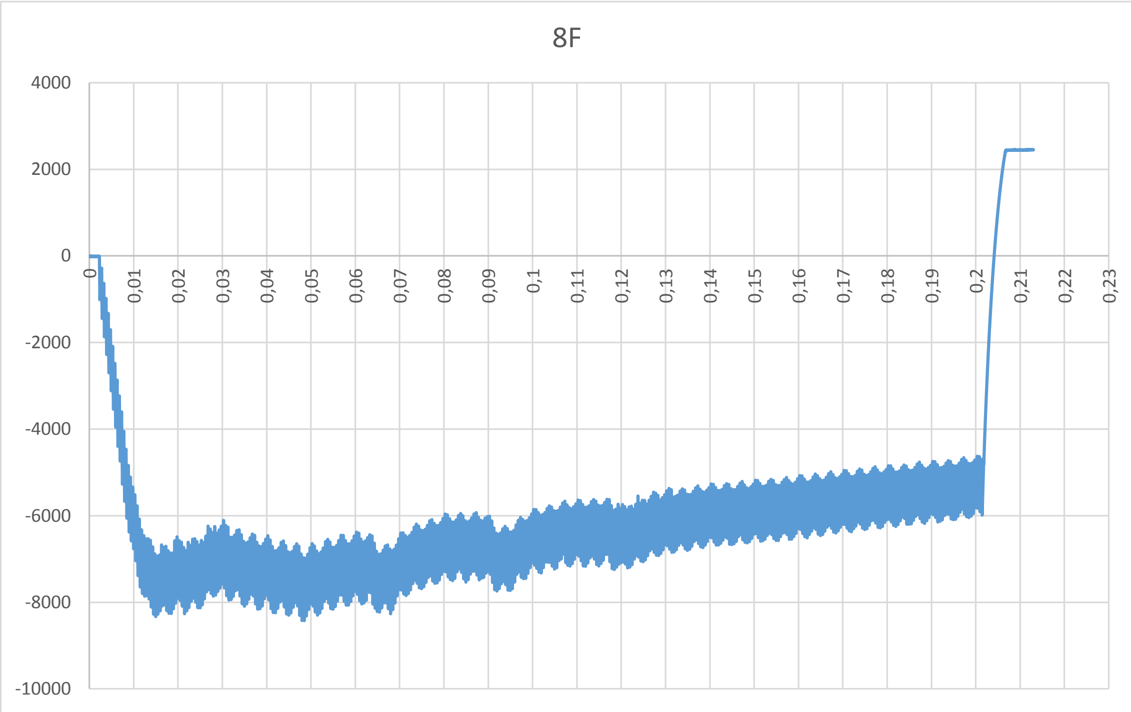
- Current (KA): 9
- Force (KN): 3
- Welding time (ms): 200

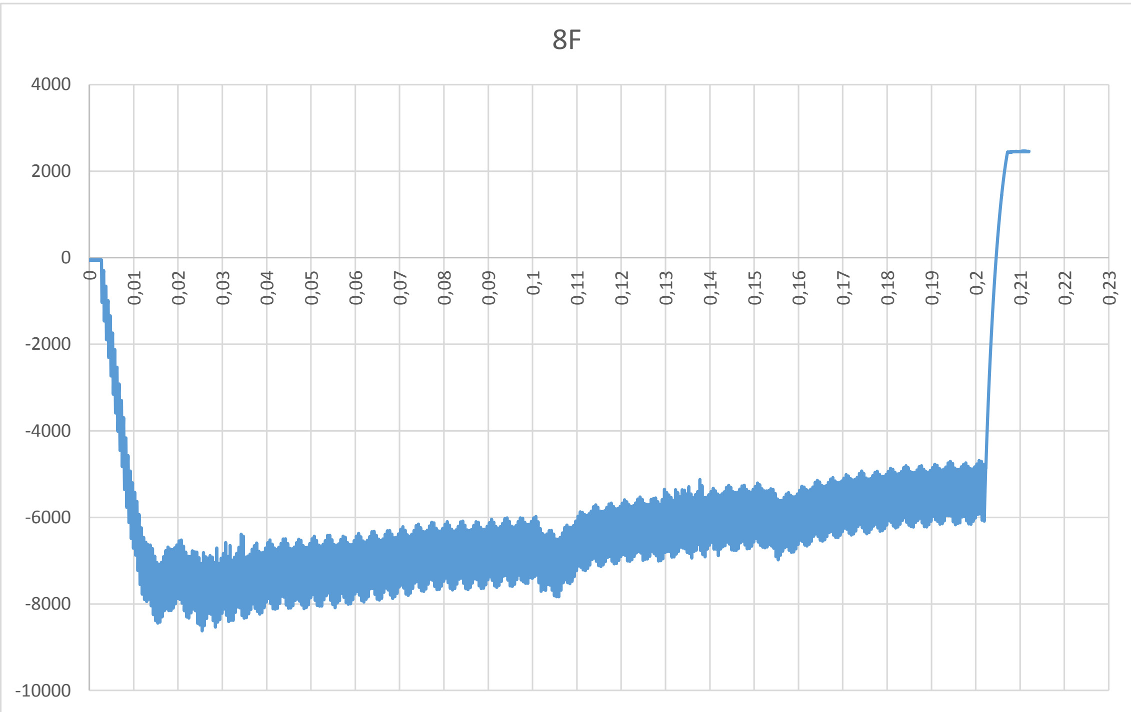





8C
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23


8D
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23

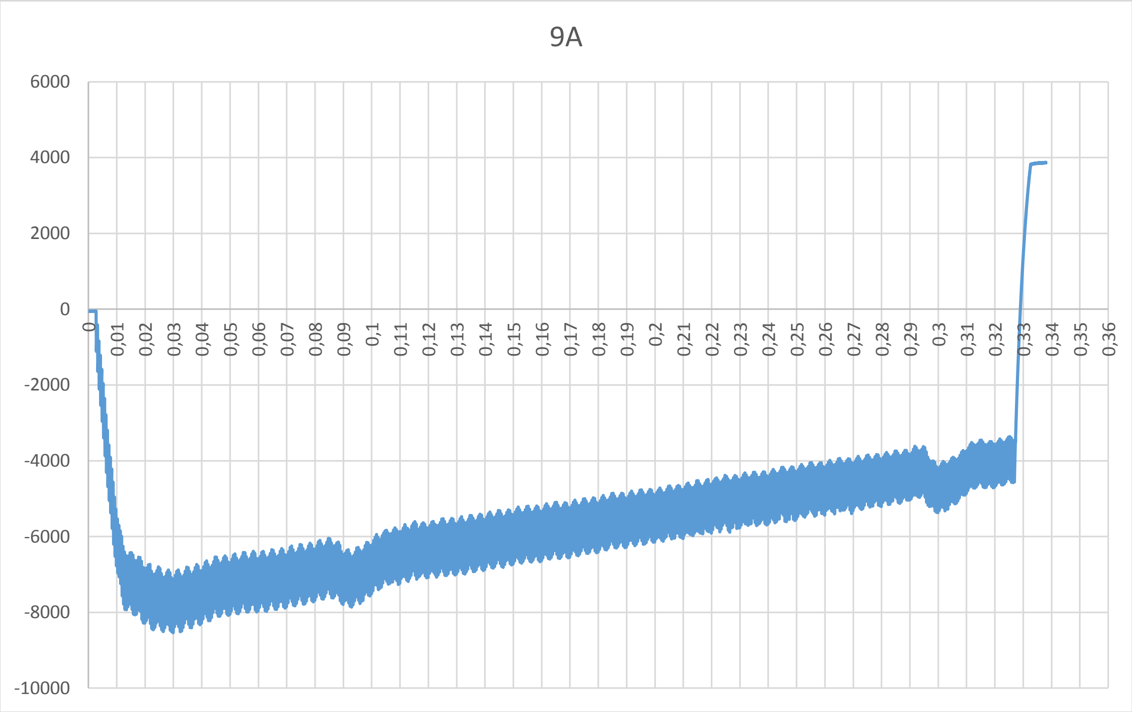

8F
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23

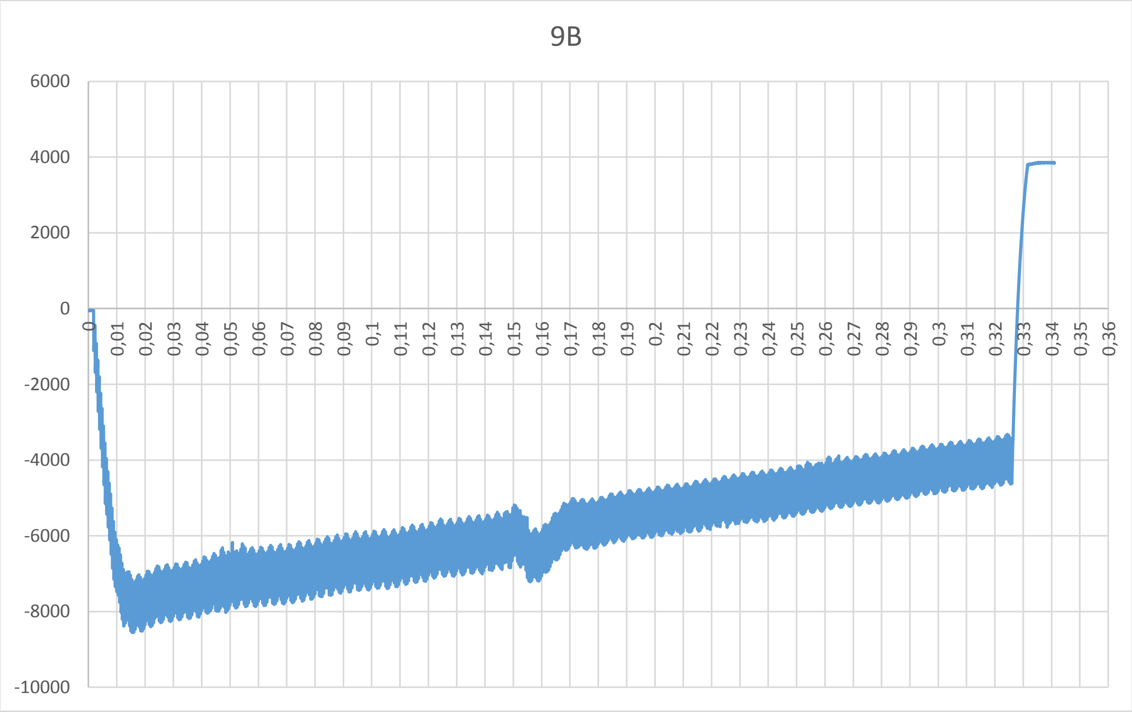

8F
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23

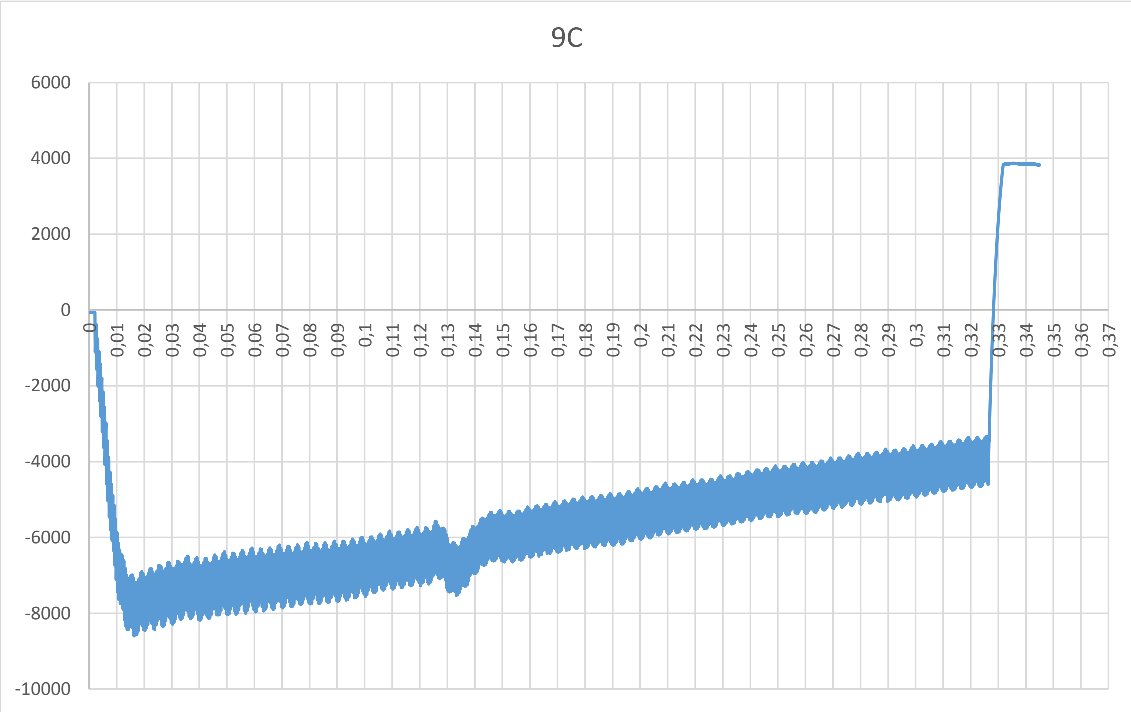
Ninth configuration

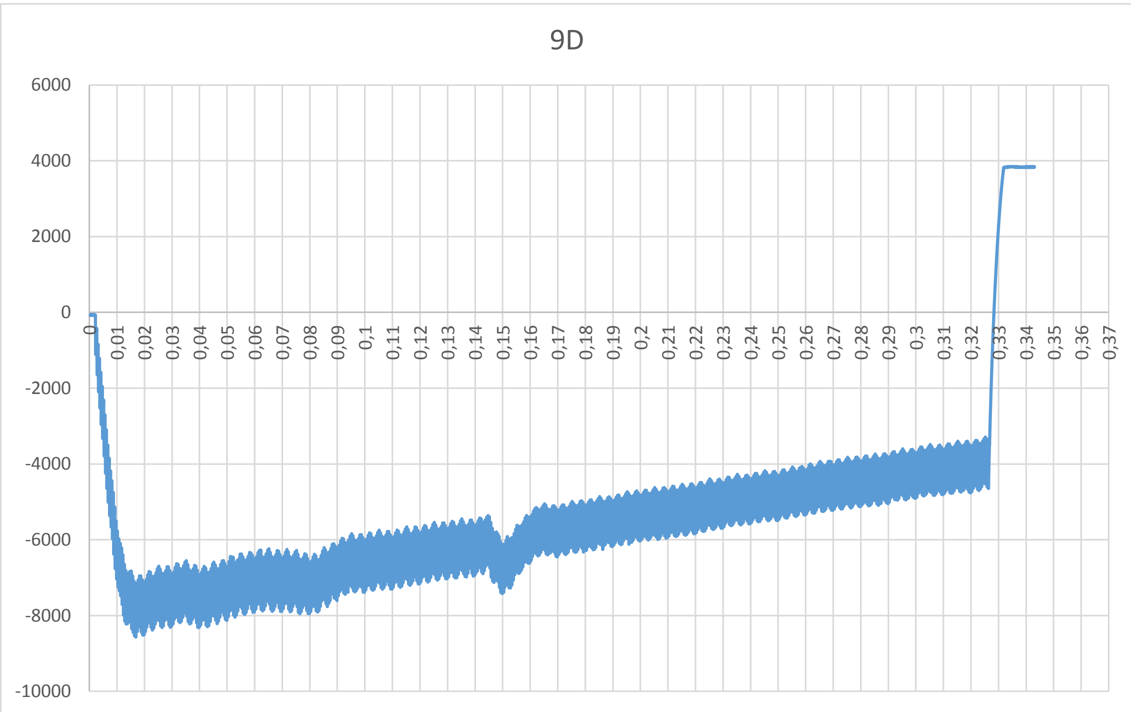
Input values for this configuration:

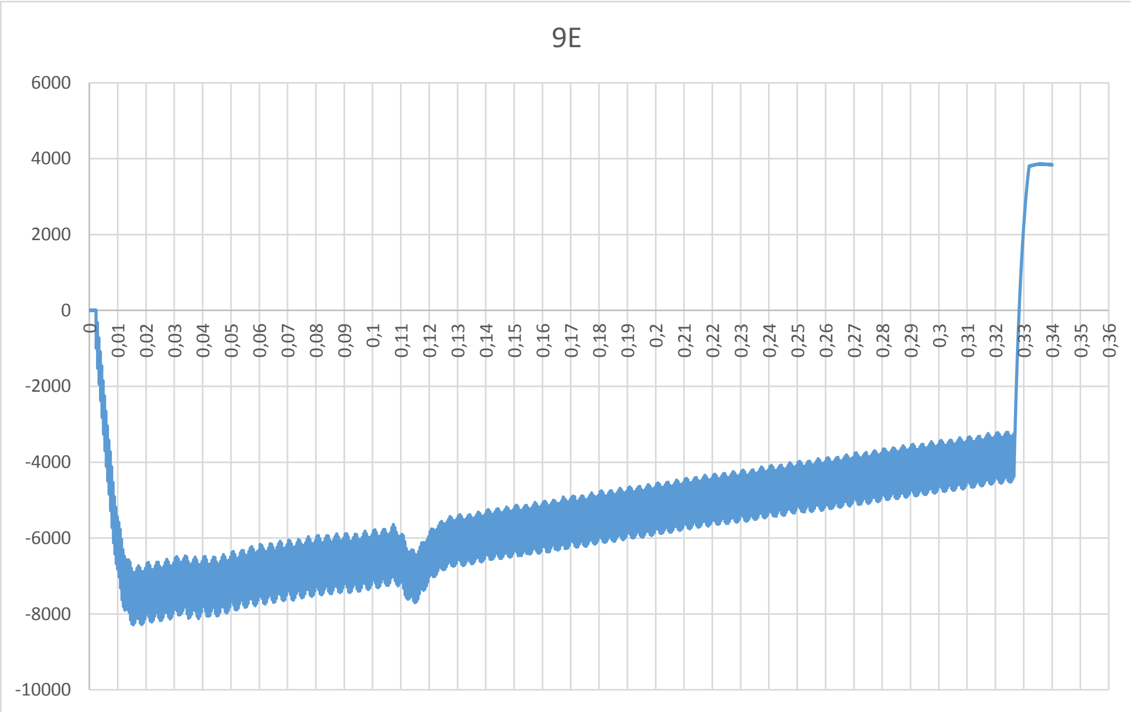
- Current (KA): 9
- Force (KN): 4
- Welding time (ms): 45000

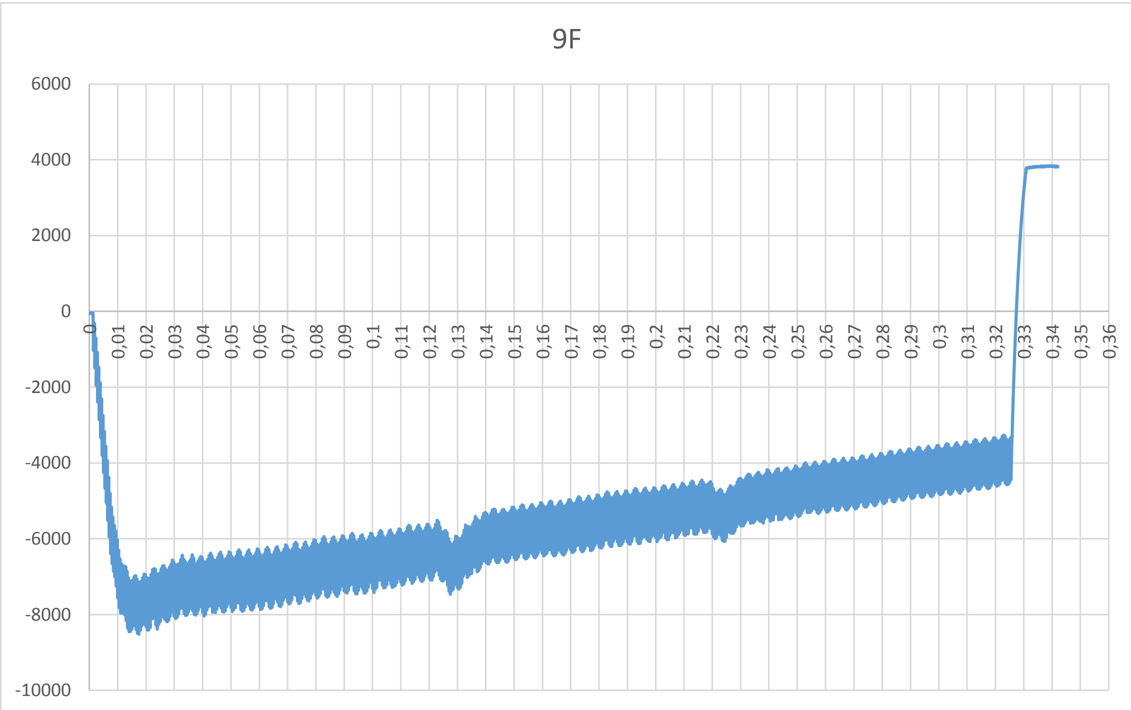





9C
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0 0,01 0,02 0,03 0,04 0,05 0,06 0,07 0,08 0,09 0,1 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18 0,19 0,2 0,21 0,22 0,23 0,24 0,25 0,26 0,27 0,28 0,29 0,3 0,31 0,32 0,33 0,34 0,35 0,36 0,37


9D
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0 0,01 0,02 0,03 0,04 0,05 0,06 0,07 0,08 0,09 0,1 0,11 0,12 0,13 0,14 0,15 0,16 0,17 0,18 0,19 0,2 0,21 0,22 0,23 0,24 0,25 0,26 0,27 0,28 0,29 0,3 0,31 0,32 0,33 0,34 0,35 0,36 0,37

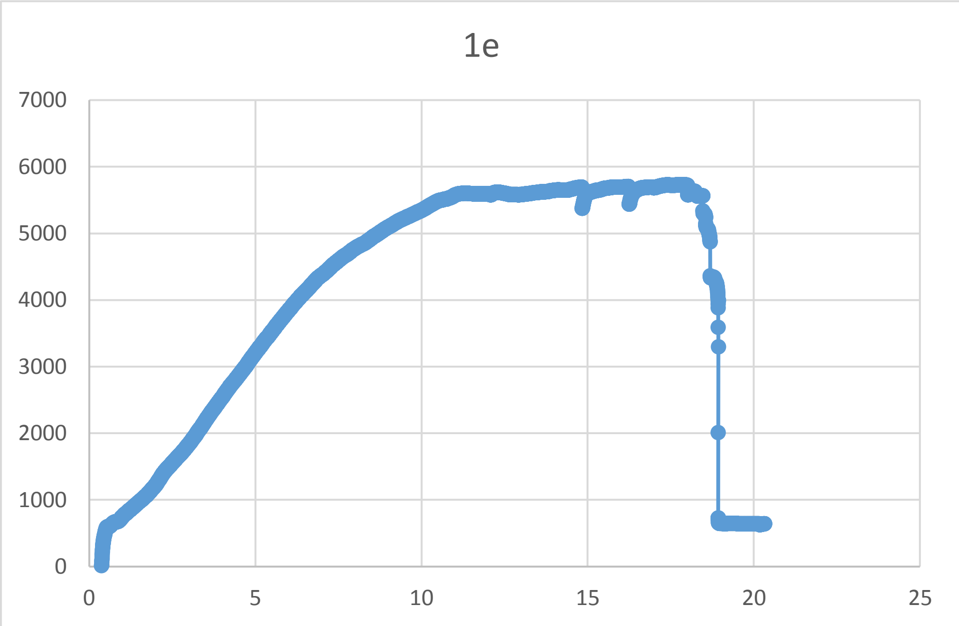

9E
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23
0,24
0,25
0,26
0,27
0,28
0,29
0,3
0,31
0,32
0,33
0,34
0,35
0,36

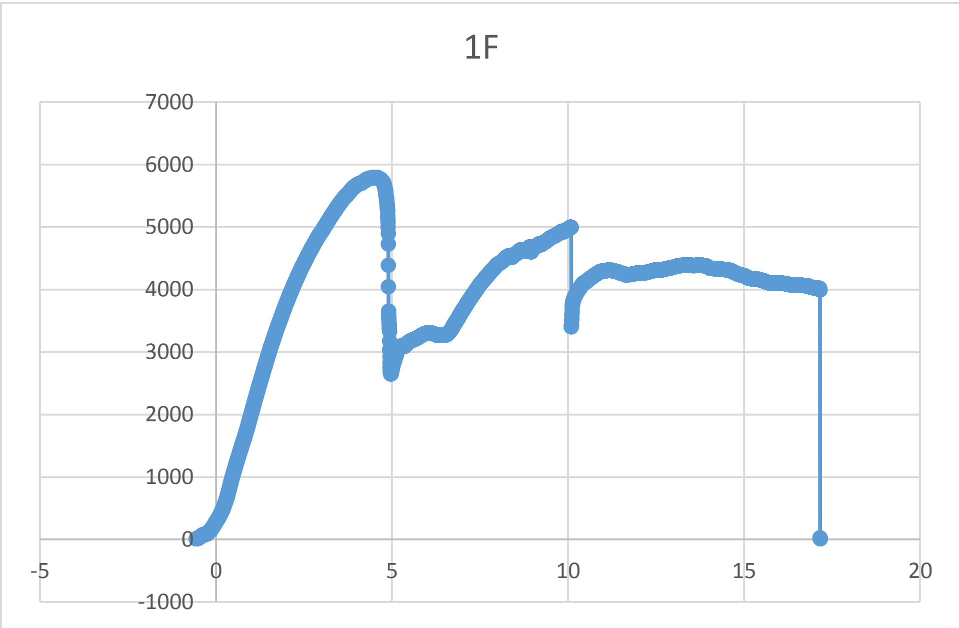

9F
6000
4000
2000
0
-2000
-4000
-6000
-8000
-10000
0
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,11
0,12
0,13
0,14
0,15
0,16
0,17
0,18
0,19
0,2
0,21
0,22
0,23
0,24
0,25
0,26
0,27
0,28
0,29
0,3
0,31
0,32
0,33
0,34
0,35
0,36

APPENDIX II

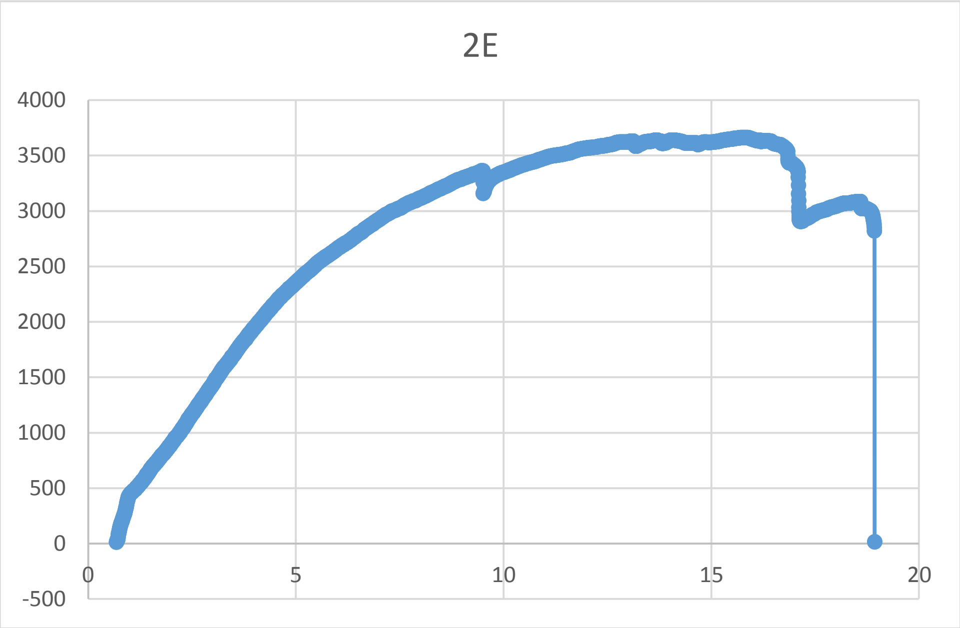
FIBEROPTIC SENSOR TEST DATA RESULTS

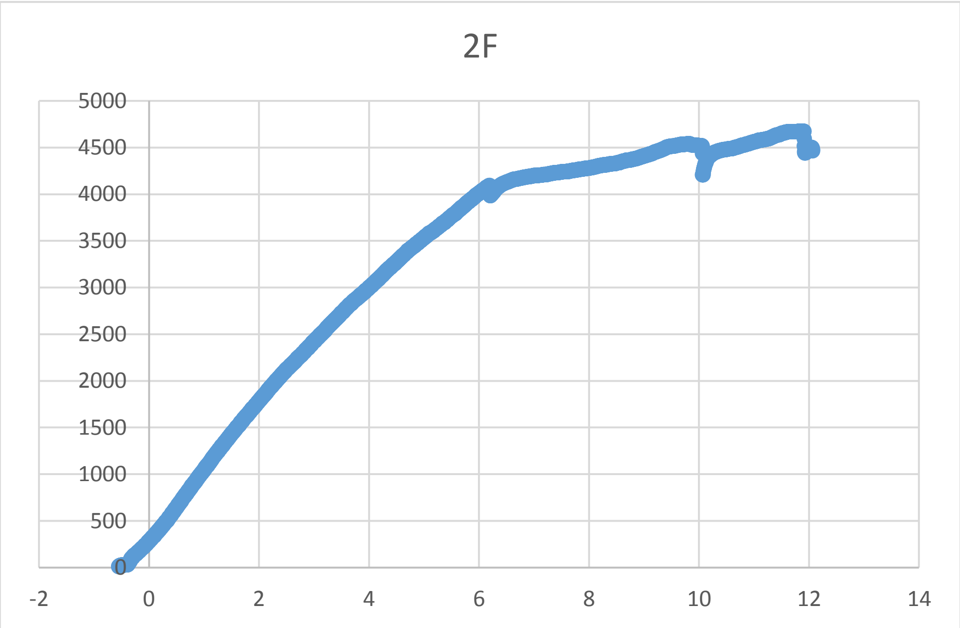
Test for first configuration



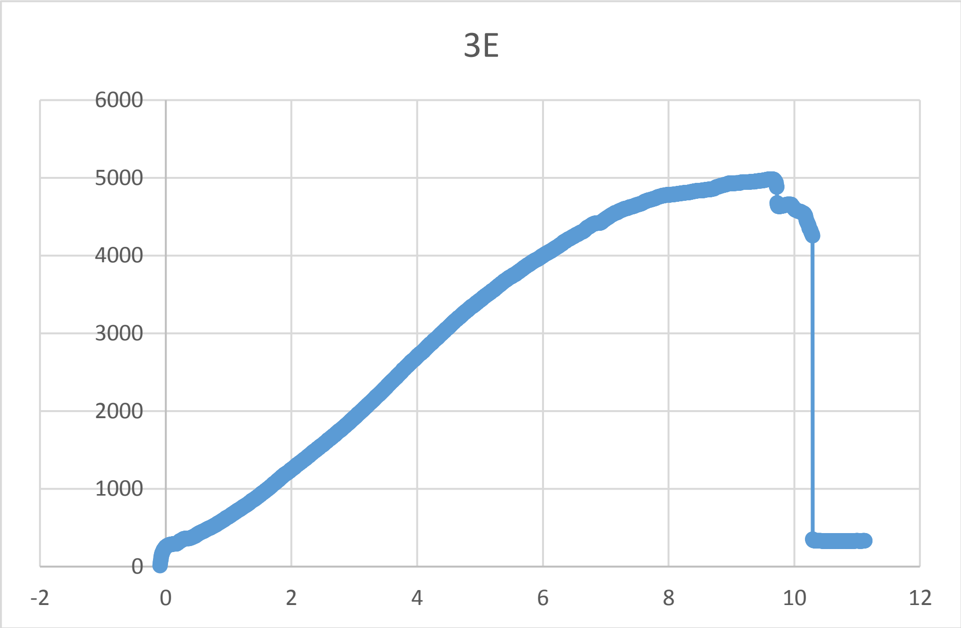


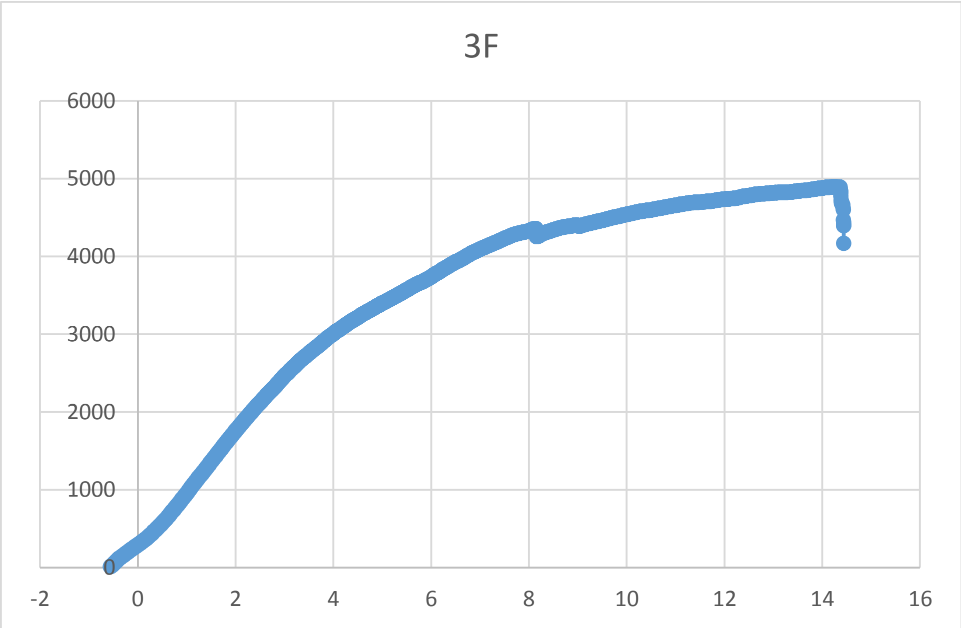
Test for second configuration



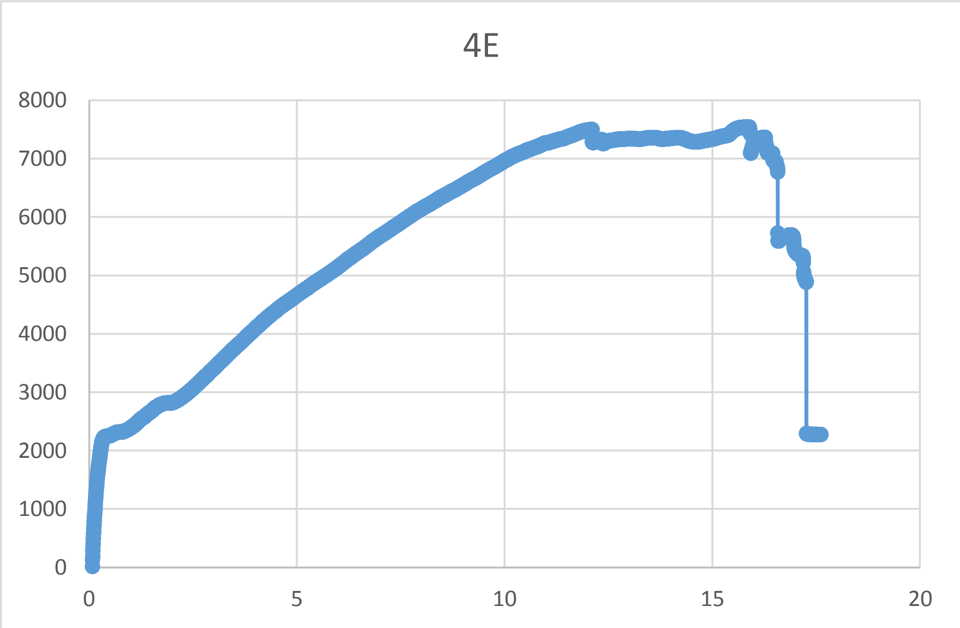


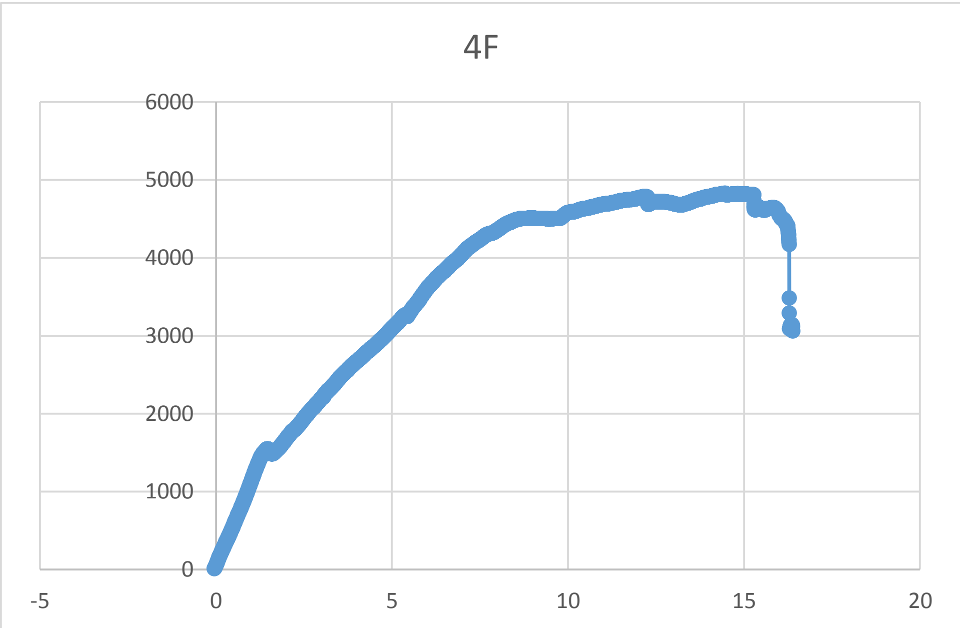
Test for third configuration



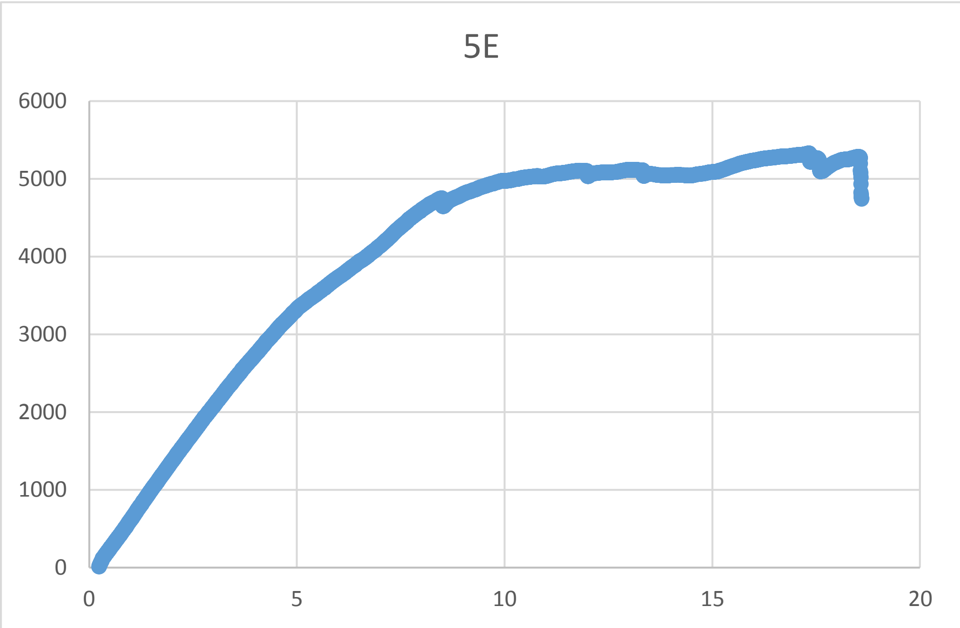


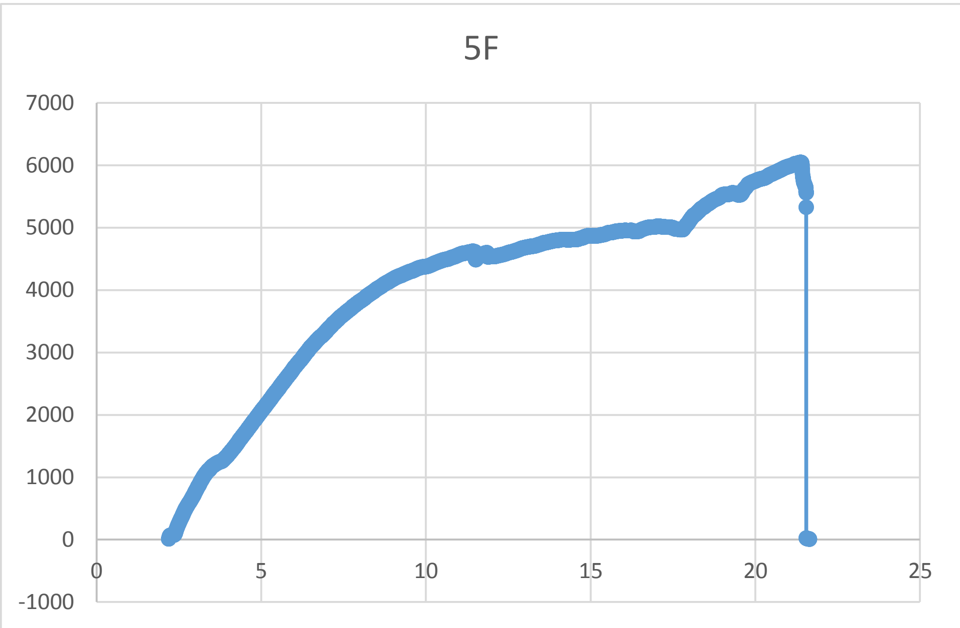
Test for fourth configuration





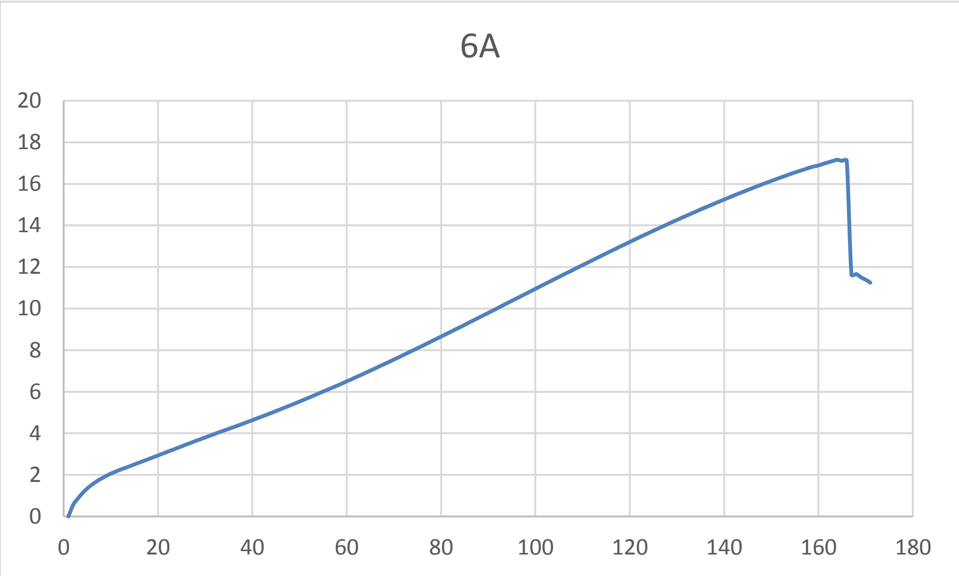
Test for fifth configuration

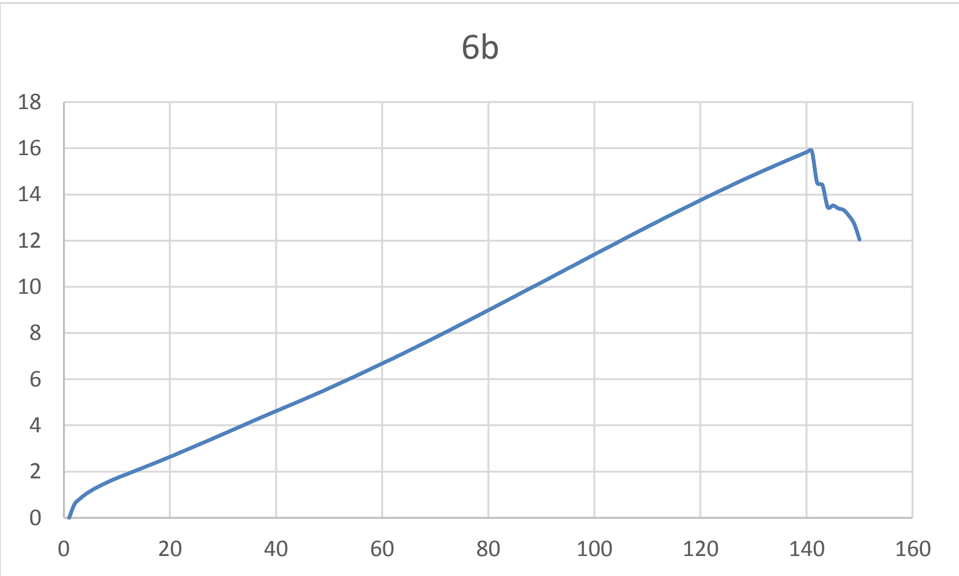


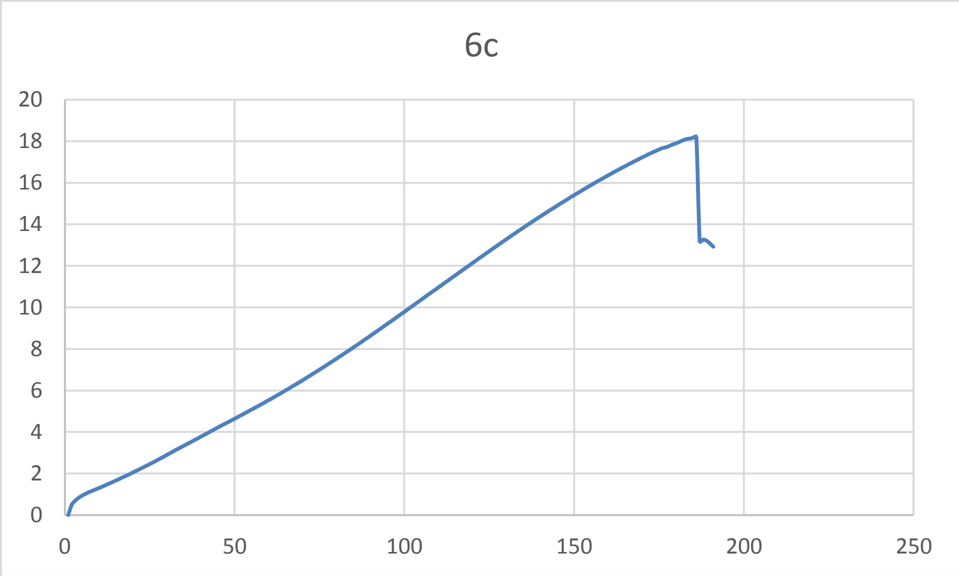


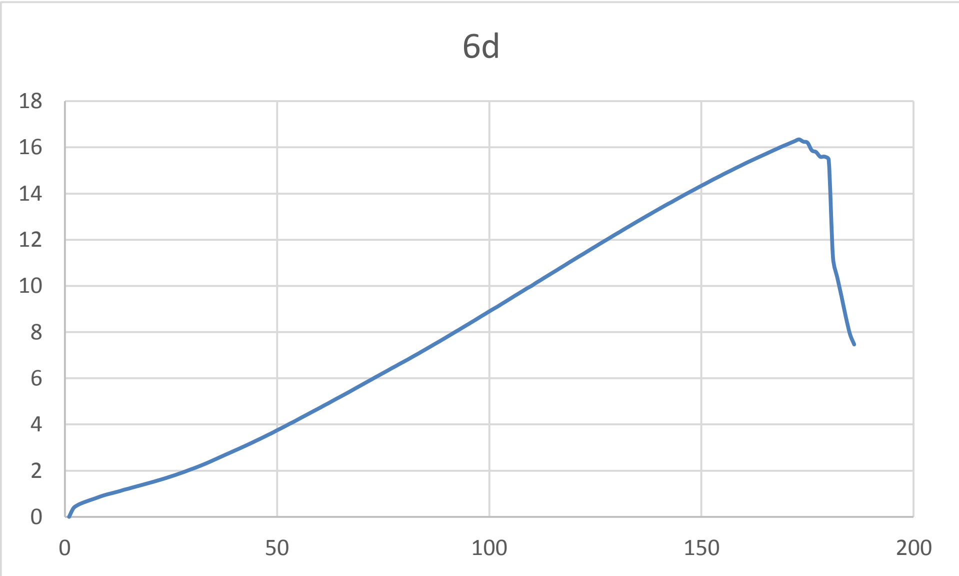
Test for sixth configuration

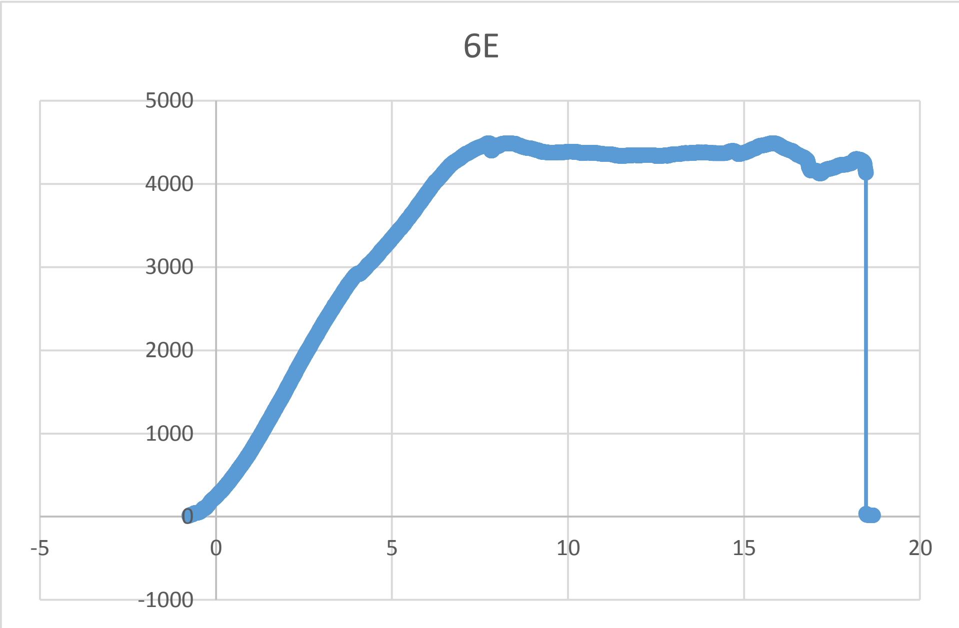
For this configuration, the results from shear test for coupons from A to D will be shown in addition to the Cross tension test, thanks to the support of an Associate Professor of University of Bolzano.

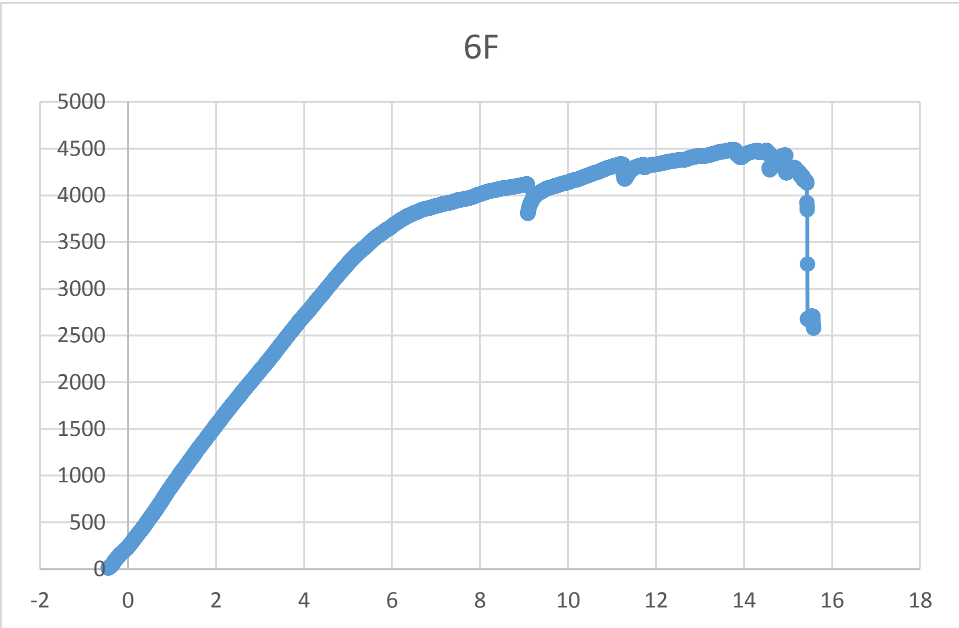




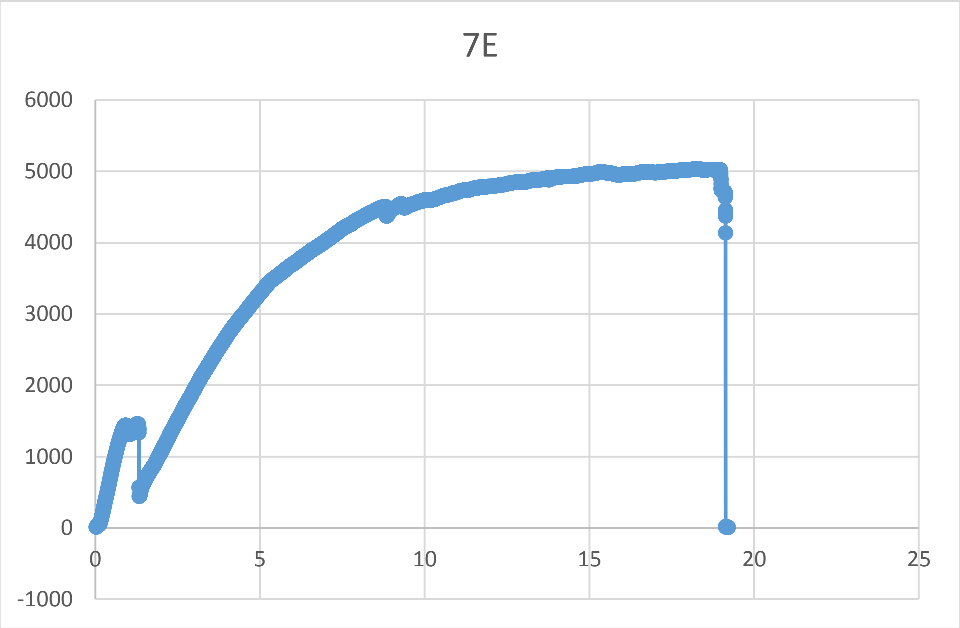

6c
20
18
16
14
12
10
8
6
4
2
0
0
50
100
150
200
250

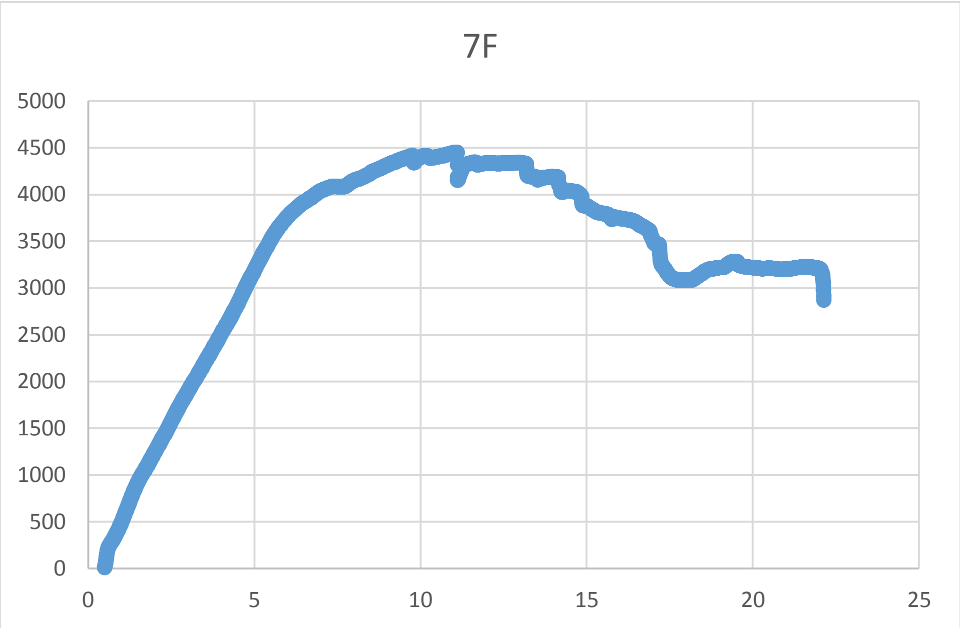

6d
18
16
14
12
10
8
6
4
2
0
0
50
100
150
200


6E
5000
4000
3000
2000
1000
0
-1000
-5
0
5
10
15
20

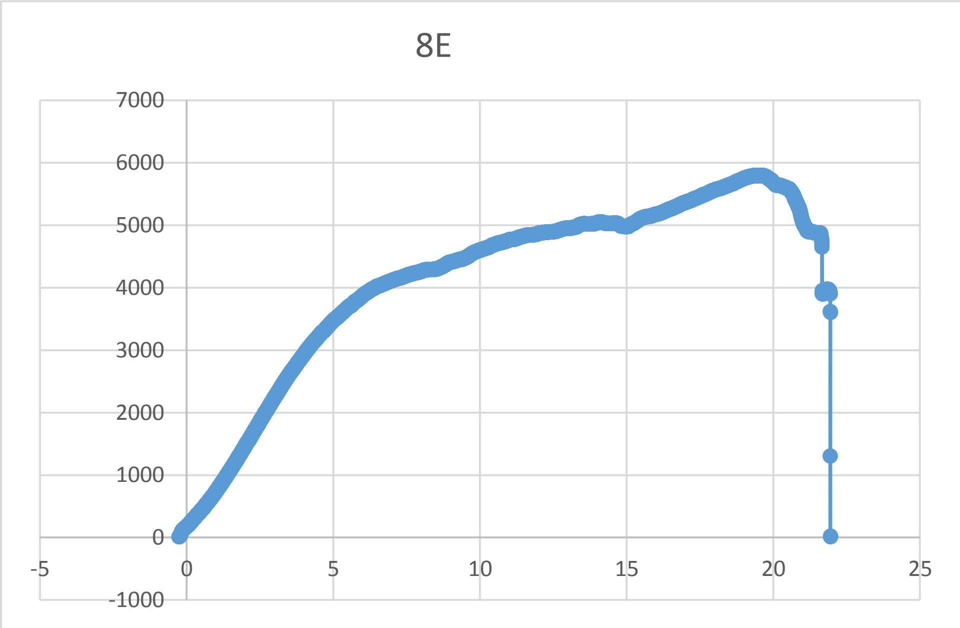

6F
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-2
0
2
4
6
8
10
12
14
16
18

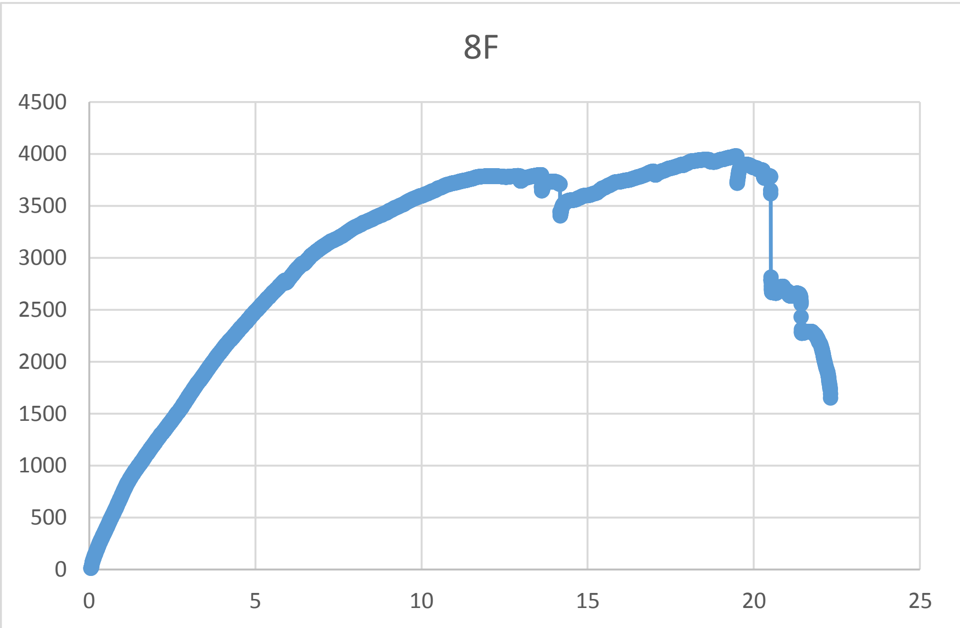
Test for seventh configuration



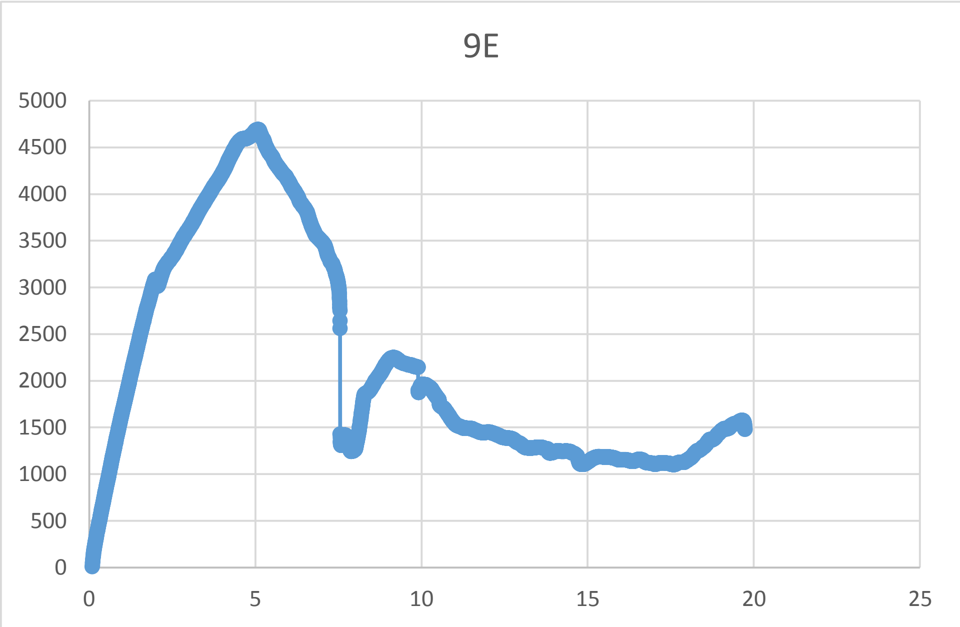


Test for eight configuration





Test for ninth configuration



Comparison of Max. Force-Displacement for each test