Composites Ultrasonic Welding:

CF-PEI Processing Window

Design and Production of Composite Structures

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Chapter 1: Introduction

1.1 Composite materials

Composite materials are formed by joining of two materials to achieve the combination of properties that cannot be obtained in the original materials. These compounds can be selected to achieve unusual combinations of stiffness, strength, weight, high temperature resistance, corrosion resistance, hardness and conductivity.

Composite materials have the following characteristics:

- They consist of 2 or more physically distinct and separable components mechanically.
- They have several chemically distinct phases, completely insoluble with each other and separated by an interface.
- Their mechanical properties are superior to the sum of the properties of their components (synergy).

These materials arise from the need of obtaining materials that combine the properties of ceramics, plastics and metals. For example, in the transport industry composite materials are applied to make lightweight, rigid, impact resistance and corrosion resistance products, properties that appear rarely together.

In spite of obtaining materials with exceptional properties, their applications are reduced by some factors (e.g. hard manufacturability or incompatible materials) that greatly increase their cost.

Although there are a variety of composite materials, the following parts can be distinguished in all of them:

- Reinforcing agent: it is a phase of discrete nature and its geometry is crucial for defining the mechanical properties of the material.

- Matrix: it has a continuous basis and it is the responsible for the physical and chemical properties. It transmits efforts to the reinforcing agent. It also protects it and gives cohesion to the material.

1.2 Thermoplastic Composites

Thermoplastic and thermoset composite materials have a wide range of applications in land transportation, aerospace, and marine structures. They present many advantages compared with metals in the same applications, this is the reason because the use of polymeric composites is increasing.

Thermoset is a material that undergoes an irreversible chemical change and cannot be reformed with the reintroduction of the heat and pressure, therefore, thermosets cannot be welded. A thermoplastic material, after being formed can, with the reintroduction of heat and pressure, be remelted and reformed, undergoing only a change of state. This characteristic makes thermoplastic suitable for ultrasonic assembly [1].

Thermoplastic composites have high damage tolerance, excellent corrosion and solvent resistance, high fracture toughness, high impact resistance, good fatigue resistance, low storage cost, and infinite shelf life. Thermoplastic composite materials are reprocessable, repairable, and reformable, which together provide ease of fabrication and cost-effectiveness.

Joining of thermoplastic composites is an important step in the manufacturing of aerospace thermoplastic composite structures. In general, joining of thermoplastic composites can be categorized into mechanical fastening, adhesive bonding, solvent bonding, and fusion bonding or welding. Fusion bonding or welding has great potential for the joining, assembly, and repair thermoplastic composite components and also offers many advantages over other joining techniques.

They are various welding techniques but ultrasonic welding is considered as one of the most promising welding techniques for continuous fiber-reinforced thermoplastic composites [2].

1.3 Ultrasonic Welding

Ultrasonic welding is a process that uses a high frequency mechanical vibration to weld parts. The parts to be welded are held together under pressure and then subjected to a high frequency oscillation to transmit vibrations through the material.

An ultrasonic welding machine consists of four main components: a power supply, a converter, an amplitude modifying device (commonly called a Booster) and an acoustic tool known as the horn (or sonotrode). The power supply changes main electricity at a frequency of 50-60Hz, into a high frequency electrical supply operating at 20, 30 or 40 kHz. This electrical energy is supplied to the converter. Within the converter, discs of piezoelectric material are sandwiched between two metal sections. The converter changes the electrical energy into mechanical vibratory energy at ultrasonic frequencies.

The vibratory energy is then transmitted through the booster, which increases the amplitude of the sound wave. The sound waves are then transmitted to the horn. The horn is an acoustic tool that transfers and amplifies the vibratory energy directly to the parts being assembled, and it also applies a welding pressure. The vibrations are transmitted through the work piece to the joint area. Here the vibratory energy is converted to heat through surface and intermolecular friction, this then softens or melts the thermoplastic, and joins the parts together [3].

A schematic of the ultrasonic welding machine is shown in the figure 1:

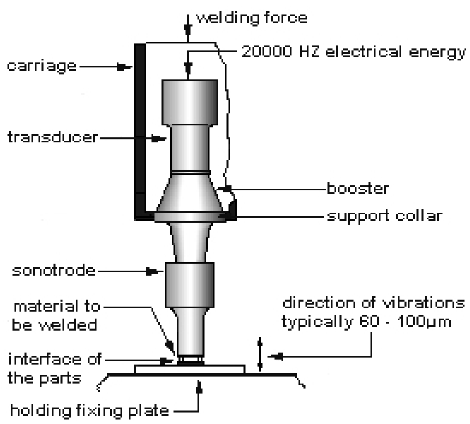

Figure 1. Schematic of the ultrasonic welding machine

To concentrate ultrasonic heating at the welding interface, energy directors are required on the surface in order to be welded. The energy director is one of important type of joint design. The energy director is typically a raised triangular bead of material molded on one of the joint surfaces. The primary function of the energy director is to concentrate the energy to rapidly initiate the softening and melting of the joining surface. The energy director permits rapid welding while achieving maximum strength; material within the director generally flows throughout the joint area.
The morphology, size and configuration of the energy directors have an important responsibility in the quality of the resulting welds [4].

The main advantages offered by ultrasonic welding are short welding times and excellent quality. As well, ultrasonic welding does not require the use of any foreign material in the joint. Another benefit of the process includes high productivity with low cost and ease of automated assembly line production.

Ultrasonic plastic welding is one of the most widely used processes for joining thermoplastics. This technique is typically used on parts that are too complex to be molded as one piece. Fast weld cycle times make the process ideal for production. This process is one of the most versatile as the same equipment can weld different parts and thermoplastic materials. Modern ultrasonic equipment provides sophisticated control and monitoring features making the process easy to automate and control. It is fast, simple and clean process [5].

Chapter 2: Objectives

The aim of this project is to find out the processing window for CF-PEI composite. That is, finding out under which combinations of the parameters involved in the process, the results of the weld are acceptable.

To do so, welding test and mechanical test will be executed to obtain results such as maximum power, melting time, energy, and lap shear strength (LSS). Likewise, fracture surface of the samples can be studied to make a better understanding of welding process by applying the outputs of welding process and mechanical tests.

Different parameters are involved in the ultrasonic welding process. The input parameters to control the welding process are the trigger force, the amplitude of the vibration applied to generate the heat to melt the energy director, the travel, the solidification force and the solidification time. The travel is the maximum displacement of the sonotrode against the samples during the process, measured as a percentage of the thickness of the energy directors. In this study, combinations of these parameters that lead to satisfactory mechanical properties of the joint will be researched.
Hence five parameters will be analysed to define the processing window of CF-PEI.

The figure 2 shows the ultrasonic welding process. According with this figure, the welding process starts by the trigger force. When this force is reached, the sonotrode gives the vibration and the joint starts to heat up. In that point the travel starts being measured. The vibration is stopped when the travel is reached. Finally, the solidification force is applied during the solidification time.
The output parameters in the process are: melting time, maximum power and energy.

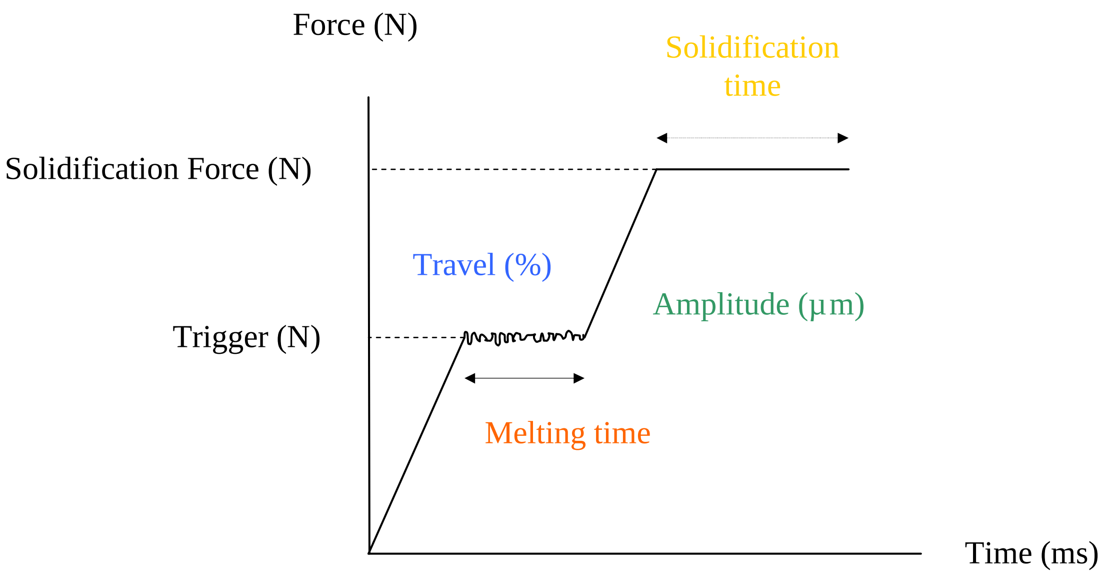

Figure 2. Process diagram of the ultrasonic welding process using an energy director. Input parameters: trigger, amplitude, travel, solidification force and solidification time

It is important to find out how wide the processing window is because the combinations inside that area are the acceptable ones. Outside this area, the quality of the joints will be not acceptable and not interesting to work with these conditions.

As an example, figure 3 shows a schematic of a processing window for CF-PEI composite:

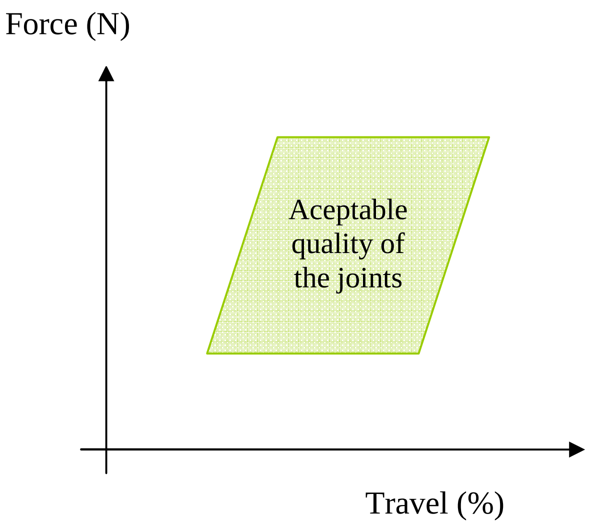

Figure 3. Schematic of a Processing Window CF-PEI

Chapter 3: Experimental settings

3.1 Working material

The material used is polyetherimide reinforced with fabric carbon fiber (carbon-PEI). PEI is an amorphous polyetherimide thermoplastic composite offering outstanding toughness and high heat resistance. This material is typically used in aerospace and industrial applications.

Table 1. Chemical Characterization, PEI thermoplastic resin reinforced with continuous carbon fiber [6]

Ingredient Name	% w/w
Main polymer: polyetherimide	39-45
Continuous carbon fiber	55-61
Partially cured epoxy resin	<1

In the fabrics, there are two types of yarns. The warp is the set of lengthwise yarns that are held in tension on a frame or loom. The yarn that is inserted over-and-under the warp threads is called the weft. As an example, the next figure shows the yarns in a fabric:

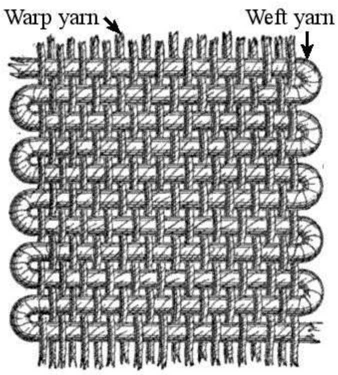

Figure 4.Schematic warp and weft in plain weaving

The type of fabric used is sateen 5. In this kind of fabric, each yarn of weft skips over four yarn of warp before passing under the next. This description is shown in the next figure:

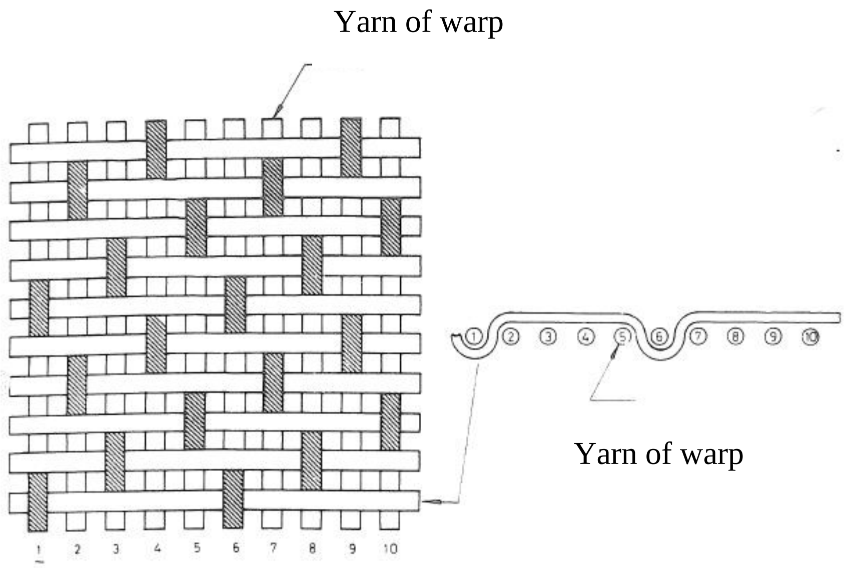

Figure 5. Schematic of type of fabric sateen 5

3.2 Experimental Procedure

The material was supplied by TenCate Advanced Composites, The Netherlands. Seven laminates for C-PEI were made in the Delft Aerospace Structures and Materials Laboratory (DASML). Each laminate has six layers of C-PEI and the final thickness of each laminate is around 1,92-1,94 mm.

The stacking sequence of these six layers of CF-PEI per laminate is shown in the next figure:

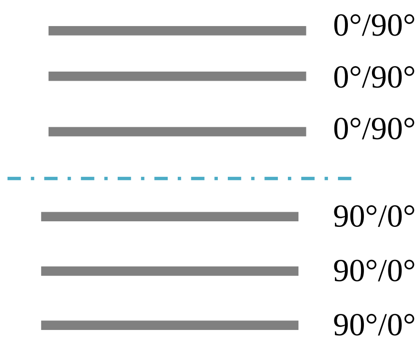

Figure 6. Schematic of stacking sequence of CF-PEI 6 layers

Direction 0° is the wrap direction and goes always on the external face of the laminate and direction 90° is the weft direction in the laminate. In order to be symmetric, it is necessary to flip over three layers to keep the direction 0° in the external face. The wrap direction will be the load direction in LSS test.

The first step was to cut six layers of CF-PEI prepreg and to put them in an oven at 270°C for 1 hour to remove as much as possible the NMP (N-methylpyrrolidone, chemical compound present in the resin). Each of the plies of prepreg was separated with Teflon plies. The layers could not touch each other or the grills of the oven. After 30 minutes, it was necessary to open the oven door to recycle the air inside. After 30 minutes more, the plies were taken out and they were put on a steel plate to cool down (5 minutes is enough). When it was cold (not before), it could be possible to take away the Teflon to use it again or to store it.

When the NMP was removed for the plies, the next step was to pile them up. After the plies were stacked together (figure 6), they were pressed in the press to obtain the laminates.

In the next table the processing cycle is shown:

Table 2. Conditions in the processing cycle to obtain the laminate

Processing cycle		**Laminate information**
Heating rate (°C/min):	7	**Laminate size:** 50x51 (cm^2)
$P_{heating}$(bar):	1	**Number of layers:** 6
$T_{consolidation}$(°C):	320	**Sketch:**
$P_{consolidation}$(bar):	20	**Steel glass kapton steel**
$t_{consolidation}$(min):	20	**Al**
$P_{cooling}$(bar):	10	**Laminate**
Cooling rate (°C/min):	15	**Al** **Steel glass kapton steel**

In the figures 7 and 8, the evolution of the pressure and the temperature in the press consolidation process are shown:

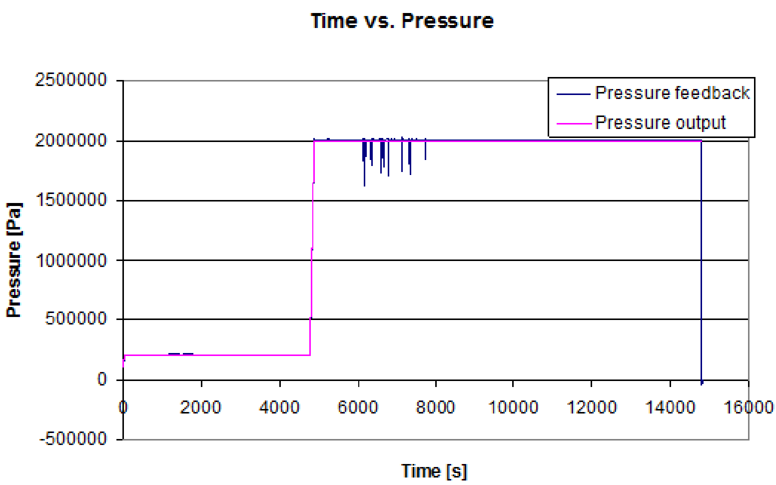

Figure 7. Evolution pressure in the pressed process. Consolidation at: 320°C, 10 bares and 20 minutes

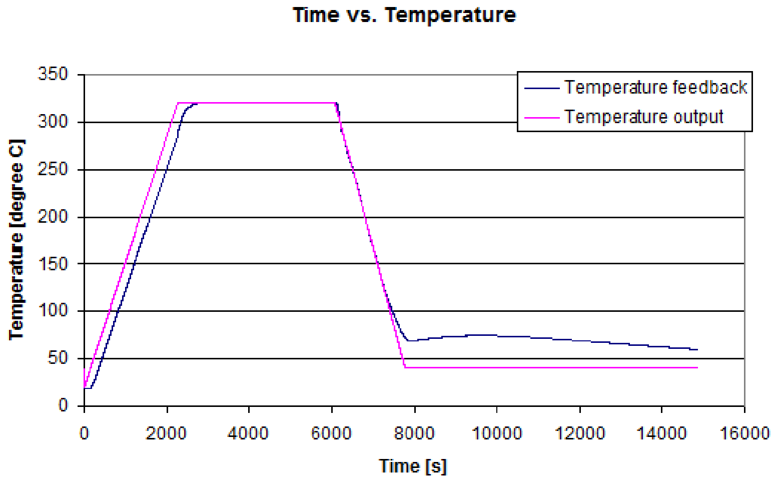

Figure 8. Evolution temperature in the pressed process.
Consolidation at: 320°C, 10 bares and 20 minutes

Once the laminates were made, their quality was inspected through ultrasonic C-scan and the results were checked with ALIS software. After inspection, each laminate was cut in small samples with these dimensions: 101.6 millimeters long and 25.4 millimeters wide. Whenever the samples were out of tolerances they were sanded to the final dimensions.

The next step was to clean the samples with a special solvent, PFQD fluid (quick drying industrial solvent for residue free surface cleaning and degreasing),and then they had to be dried in the oven during 6 hours (one hour per layer) at 135°C in order to remove moisture. Then the samples were placed in a dissecator in order to keep them dry until they were welded.

The energy director's material that was used for doing the welds was PEI. The material was also provided by TenCate Advanced Composites. One foil for PEI was made in one of the laboratories of the faculty. The energy director consisted of six plies of PEI. The first step was to cut six sheets of PEI and then to pile them up. After the plies were stacked together, they were pressed in the press to obtain the foil. The conditions of the consolidation are at 260°C, 10 bars and 20 minutes. The final thickness of these thick plies is around 0,27-0,29 mm.

Once the foil was made, it was cut in small pieces with these dimensions: 27x27 millimeters. The next step was to clean the pieces of the energy director with PFQD and then they had to be dried in the oven during 1 hour at 135°C. Finally they were placed in a dissecator.

At this moment, the samples are prepared to be welded and to be tested in the tensile machine to know the lap shear strength (LSS) of the specimens. The process window will be defined according to the values obtained through LSS tests.

3.3 Machines technology

Several machines were used to carry out the different tasks to find out the processing window of the CF-PEI material and they are described in this section.

The pre-impregnated material was supplied in rolls and to prepare the laminates it was necessary to cut six layers of the CF-PEI material per laminate (figure 9 and figure 10).
In order to dry the layers of CF-PEI, a Votsch VTL 100/150 oven was used (figure11). This oven has the following volume: 1000x1500x1000 mm (width x height x depth) and his maxim temperature is 300°C. The purpose of this oven is: curing, post-curing and heat treatments.
Finally to make the laminates, the plies of CF-PEI were stacked together and they were pressed in the Joos Press (figure 12). The maximum temperature of this hot platen press is 450°C and the maximum available force is 1000 kN. The purpose of this type of press is pressing of thermoplastic composite panels with a press area 600x600mm. One of the panels made, is shown in the figure 13.

When the laminates were made, each laminate was cut in small samples with a Unitom cutting machine. Unitom is the family of Struers materialographic cutt-off machines sharing a platform with a 350 mm cut-off wheel and a powerful 4.7 kW cutting motor.
The type of cutting machine is Unitom-5, qualified for high volume automated cutting and it is shown in the figure 14.

To dry the samples, a Heraus T6030 oven was used (figure 15). This oven has the following volume: 35x23x37 cm (width x height x depth) and the maximum temperature is 300°C. The purpose of this oven is: curing, post-curing and heat treatments.

The process followed to make the samples and the different machines used are shown in the following figures:
The same machines were used to make the energy directors of PEI except for the way to cut the pieces of energy directors; this task was done with a normal cutter.

Figure 9. CF-PEI supplied in roll

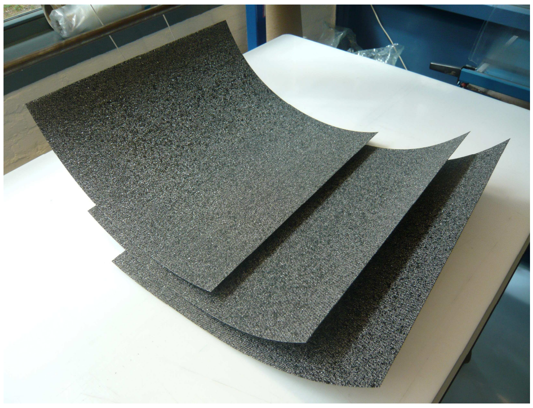

Figure 10. Cut layers of CF-PEI

Figure 11. Oven to dry the layers of CF-PEI

Figure 12. Press to make the laminates

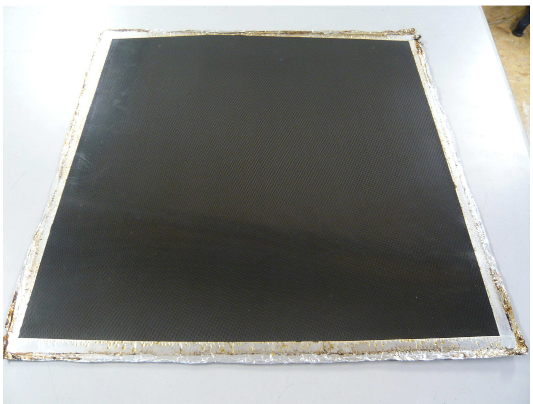

Figure 13. Laminate of CF-PEI

Figure 14. Cutting machine

Figure 15. Oven to remove the moisture of the samples

At this moment, the samples are prepared to be welded and to be tested to know the lap shear strength (LSS) of the specimens. The machines used in these steps were: ultrasonic welding machine and tensile machine. These machines play important roles in the present project.

3.3.1 Ultrasonic welding machine

The ultrasonic welding machine allows the use of high-frequency mechanical vibration to soften or melt the thermoplastic resin at the welding interface and the application of pressure to form a joint.

The basic construction for an ultrasonic welding machine is shown in the figure 16:

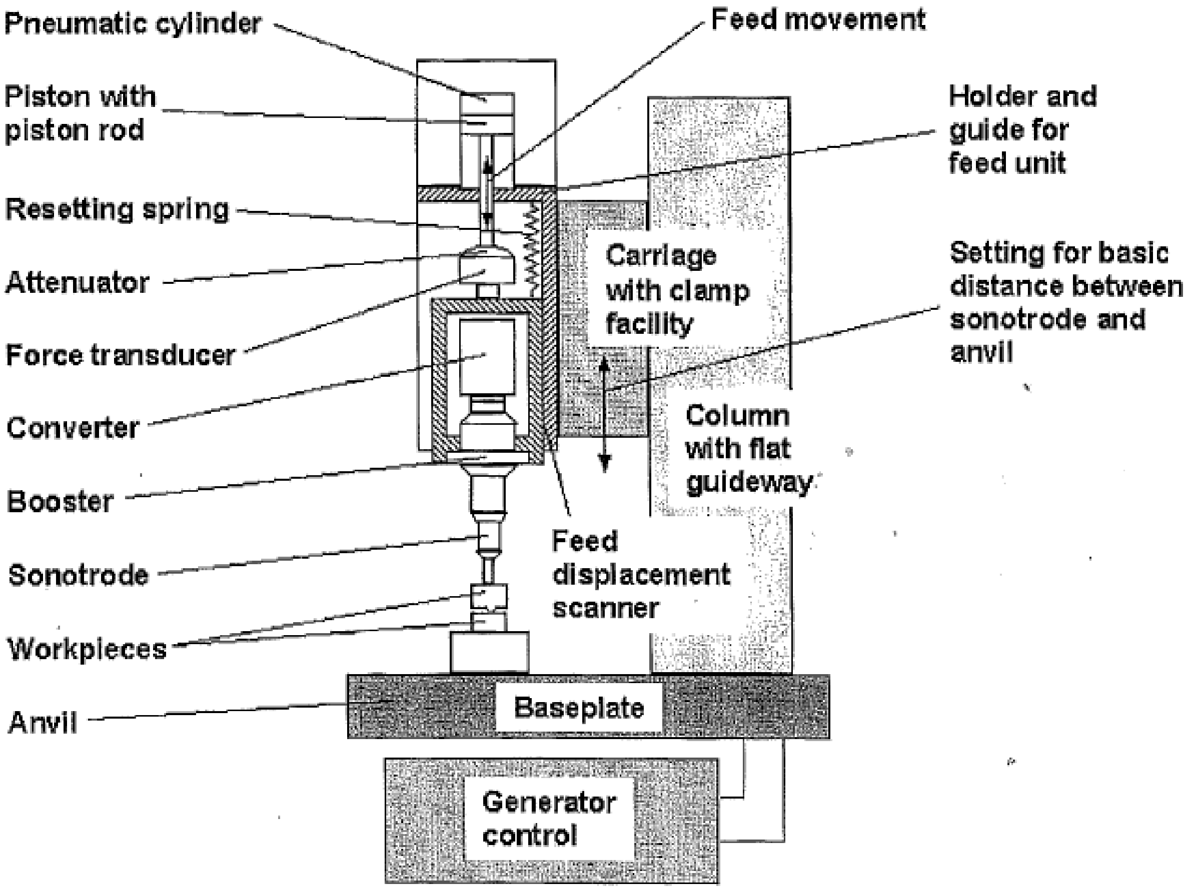

Figure 16. Basic construction of a pneumatic ultrasonic welding machine

For welding the samples, an ACU Dynamic 3000 welding machine, from Rinco Ultrasonic AG Company, was used. The ultrasonic welding machine Dynamic 3000 Series is suitable for technically demanding welding operations of thermoplastic parts from medium to large size [7].

The ultrasonic welding machine used in the experiments is shown in the next figure:

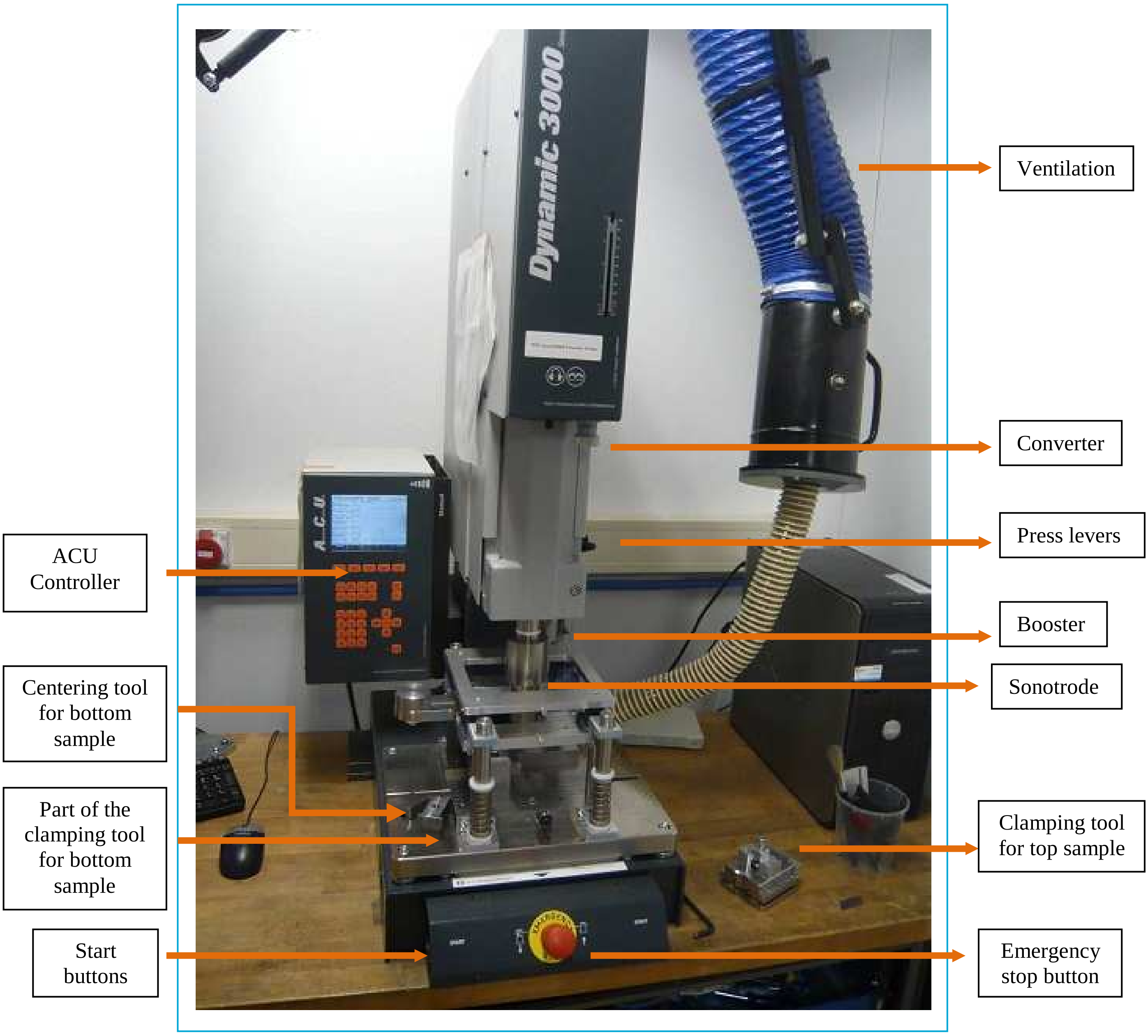

Figure 17. Ultrasonic Welding Machine, ACU Dynamic 3000 (Rinco Ultrasonic AG)

It is very important that before starting the welding, the sonotrode has to be cleaned (possible resin residues), the press levers have to be tight and the ventilation of enclosed area has to be switched on. Another important thing, it is that to manipulate the samples it is necessary to use gloves not to get them dirty.

The clamping of the two substrates to be welded is an important step in the welding process. If this step does not execute with careful, the samples can be displaced during the welding process. This is the reason because it is necessary to fix properly both samples to obtain a correct welding. It is also important to execute the clamping of the two substrates in a correct way to make sure that all the samples welded have the same overlap length (12.7mm).

Also, the energy director has to be positioned between the two samples in a correct way to do an acceptable test. It will be fixed on the lower sample with adhesive tape.

For clamping the bottom sample, there are two workpieces that don't allow the movement for this sample. One of the pieces is used to fix the vertical position of the sample with a screw that put pressure on it. The purpose of the other piece is to center the sample and make sure it is in the correct position. There is also a pin to avoid the horizontal movement of the sample.
The top sample is fixed with aid of the upper clamping tool which has a screw to avoid the movement of this sample during the weld. There is another piece used to fix the overlap distance.

When both samples are fixed, it is possible to do the weld. The welding process starts when the trigger force is reached. Once the weld and the dwell time have elapsed, the sonotrode returns to its original position.

The process for welding the samples and the set up for clamping the test specimen are shown in the following pictures:

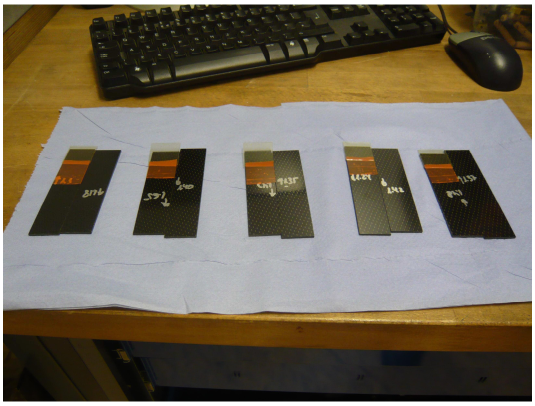

Figure 18.Test specimens with energy director

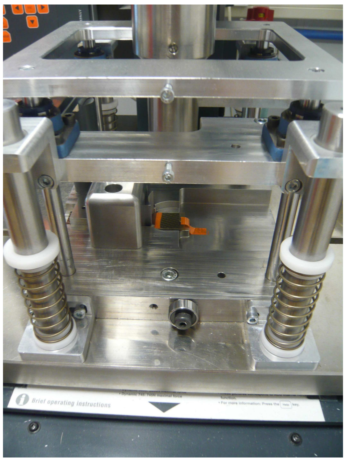

Figure 19. Clamping for the bottom sample

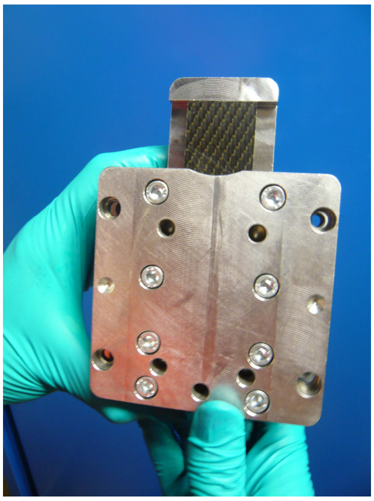

Figure 20. Clamping for the top sample

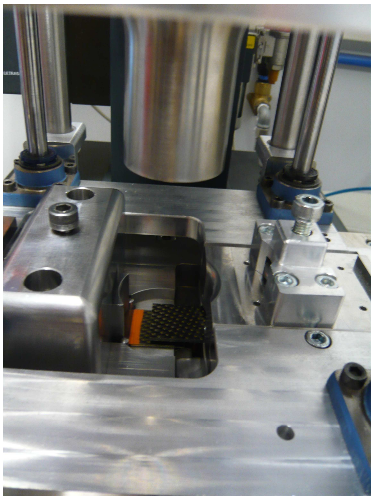

Figure 21. Samples ready to be welded

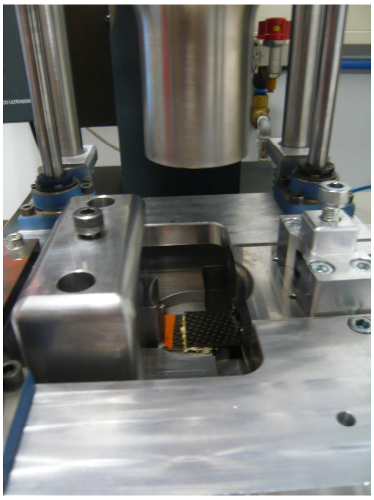

Figure 22. Samples welded

Figure 23. Samples after welding

The machine used to carry out the static tests was a Zwick 250 kN Tensile Machine (maximum load of 250 kN), shown in Figure 24. The materials testing machine can be used for tensile and compression test.

The static test is based on the ASTM D-5868-01 (Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding).This test method describes a procedure for the testing of lap shear bond strength, using composite materials not recommended in Test Method D 3136 such as FRP.

Figure 24. Static tensile machine Zwick 250 kN

Each sample welded, having a constant rectangular cross section, is mounted in the grips of the Zwick 250 kN and loaded in tension, while recording force versus crosshead displacement. Tabs are not required during the test because this kind of testing machine offers the advantage of allowing the offset of the grips.

In the figures 25 and 26, the starting position for testing and the samples after testing are shown:

Figure 25. Starting position for testing

Figure 26. Samples after testing

One of the values that can be obtained out of the test is the Lap Shear Strength (LSS). This data are really important to define the processing window of the CF-PEI.

Chapter 4: Results and Discussion of the results

Several tests were performed using different parameters combinations. The parameters under study were travel distance, trigger force and amplitude. The values of the trigger force were 300, 500, 1000 and 1500 N. For each value two different amplitudes were used: 19,8 (amplitude 1) and 33 µm (amplitude 9).

Solidification force and solidification time are parameters also involved in the process. The value of the solidification force was 1000 N and the value of the solidification time was in the beginning 1200 ms. These values were chosen based on previous research within Design and Production of Composites Structures, in the Delft University of Technology. During the research carried out in this Master Thesis project the fracture surfaces of the samples were found to have numerous bubble-like voids. To solve this problem the value of the solidification time was increased from 1200 ms to 3000 ms. The results will be analyzed in this chapter.

Every combination of trigger force and amplitude was combined with several travel values. The welded samples were mechanically tested to define limit values of the travel, and consequently the processing window.

The process window was defined according to the values obtained through LSS tests. It was necessary to define a criterion to study which values of LSS are acceptable with low scatter. The highest value obtained during the experiments was 40 MPa. The criterion used in order to define the processing window was considering only the values higher than 80% of the highest value (40 MPa). So values above 32 MPa (0.8x40MPa = 32MPa) are considered inside the processing window.

Also using the value of the coefficient of variation, (COV defined as the ratio of the standard deviation to the mean) it is possible to define if the combinations of parameters are inside the processing window. Distributions with COV > 6 are considered to have an excessive scatter and hence they are ruled out of the processing window.

For a better understanding of the welding process and the influence of the different parameters used in the test, the results of the welding process will be analyzed together with the fracture surfaces of the samples.

All the results obtained in this master thesis are shown in Appendix I collected in tables with their corresponding representation of the curves Power-Time and Travel-Time.

In the next figure is shown an example of curves Power-Time and Travel-Time obtained in the welding process:

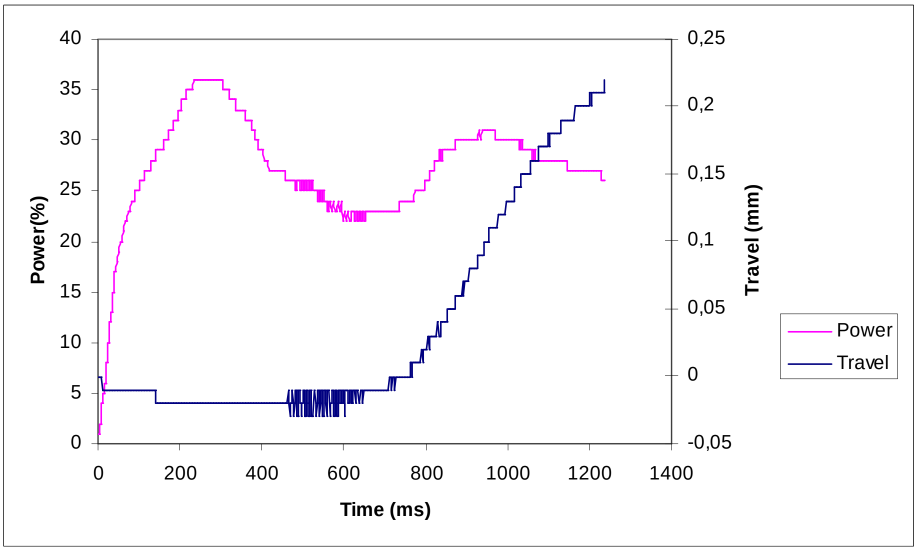

Figure 27. Example of curves Power-Time and Travel-Time

According to the figure 27, in the curve power-time the power is applied until the first peak is reached. In that point the ED starts to make soft and the power starts to decrease until a minimum is reached. In that moment more power is needed because the sonotrode is touching the samples. A maximum is reached and in that point the ED is melted and there is interdiffusion between the ED and the composites.
In the curve travel-time, when the amplitude is applied, the ED starts to expand. Because of this, the sonotrode goes up (that corresponds with the minimum area). Then the sonotrode starts to go down and the ED starts to melt.

These curves have been used in order to choose the values of the travel. The first value tested for each trigger was 80% or 90% with the purpose to pass the second peak in the power curve. The second value of the travel chosen for each trigger is the corresponding to the second peak. Finally, the next value of the travel is chosen below the second peak in order to obtain the inferior limit of the travel.

Discussion of the results for Amplitude 1

All the welded samples were compared following different criteria, such as, the influence of increasing the trigger and the solidification time or the consequences of using a low or high travel during the process.

Trigger 300N and amplitude 1

The results obtained for trigger 300N are collected in the following table:

Table 3. Summary results: Trigger 300 N and Amplitude 1

Trigger 300 N Amplitude 1 (19.8μm)					
Solidification time: 1200 ms			**Solidification time: 3000 ms**		
Travel (%)	**LSS (MPa)**	**COV (%)**	**Travel (%)**	**LSS (MPa)**	**COV (%)**
			30	31.26	7.657
38	31.774	12.24	38	35.27	3.309
50	32.28	6.96	50	35.01	5.205
80	29.29	16	80	39.83	5.65

Concerning to solidification time 1200 ms, the values of the lap shear strength (LSS) are not acceptable. For travel 38% and 80%, LSS is lower than 32MPa and for travel 50%, the value is really close to 32MPa. Also the coefficients of variation (COV) for all the travel values are high, especially for travel 38% and 80%. The consequence of these results is the appearance of voids in the weld line that increases the scatter and reduces the strength of the welds. For travel 38% and 50%, it is possible to observe remainders of resin in the fracture surfaces because these travel values are not enough to get the whole ED to flow out of the welding interface and if the process executes with a higher travel (80%) no resin remainders can be observed on the fracture surfaces. In that case, there is notable displacement of the fibres, showing a fracture surface with high deformation.

It is not interesting to work with solidification time 1200 ms. It is possible that the solidification time is so low that the material can not reach its T_g and this causes a certain “deconsolidation” of the resin and the appearance of voids at the interface, obtaining not successful results for the LSS and COV.

Concerning the solidification time 3000 ms, it is possible to obtain less voids that in the case for solidification time 1200 ms but the voids are still in the fracture surfaces.
The quantity of the voids is decreasing as the travel is increasing. Likewise, it is possible to observe many voids for travel 30%, less for travel 38% and also for travel 50% and for travel 80% an amount of them not considerable.

Travel 30% is not considered inside the processing window because the result of the LSS is less than 32 MPa, also with a COV higher than 6. Likewise, remainders of resin can be observed in the fracture surfaces. For travel 38% and 50% the results of LSS are quite similar but in the case of travel 38% the COV is around 2% less. If the travel is increased until 80%, the value of LSS is really near 40MPa. In this case, there is much displacement of the fibres. They start to open and deform. The value of COV is increasing when the travel is increased.

Checking the Power-Time curves for the different travel values (shown in Appendix I, figure 64), it is possible to observe that better results are obtained if the second peak in the power curve is passed. At that point there seems to be a better interdiffusion between the composites and the ED.

As an example, the most representative samples for each combination are shown in figure 28 and it is possible to see the evolution of increasing the travel:

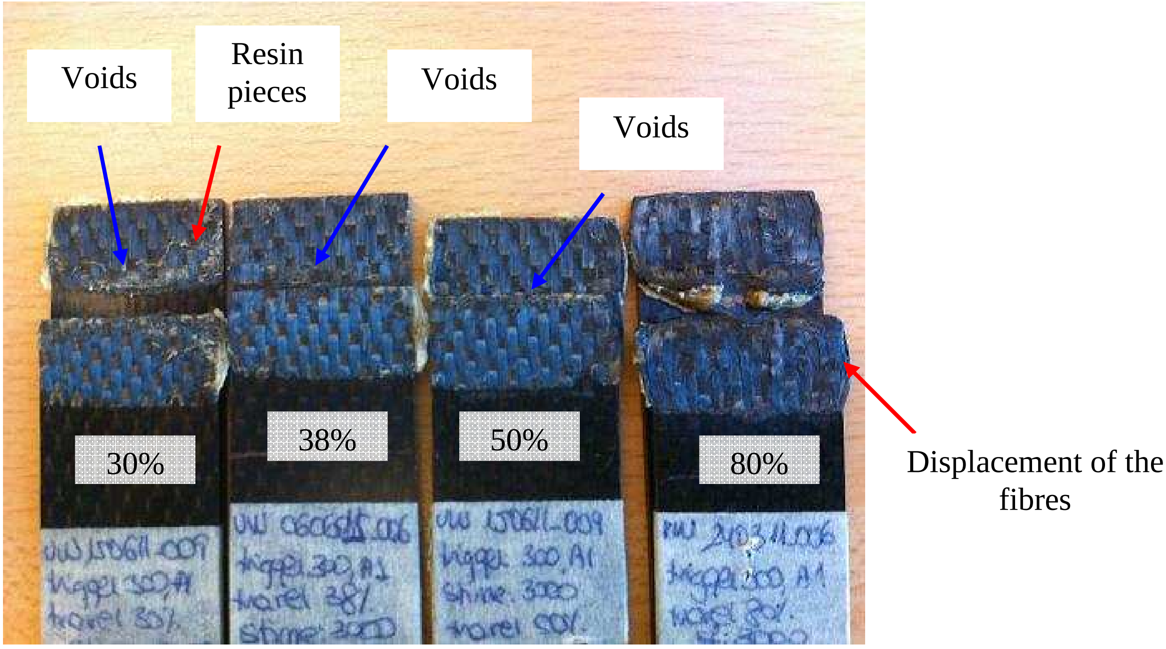

Figure 28. Fracture surfaces: evolution of the travel for trigger 300N, A1 and solidification time 3000ms

Figure 29 shows the difference between solidification time 1200ms and 3000ms for travel 80%:

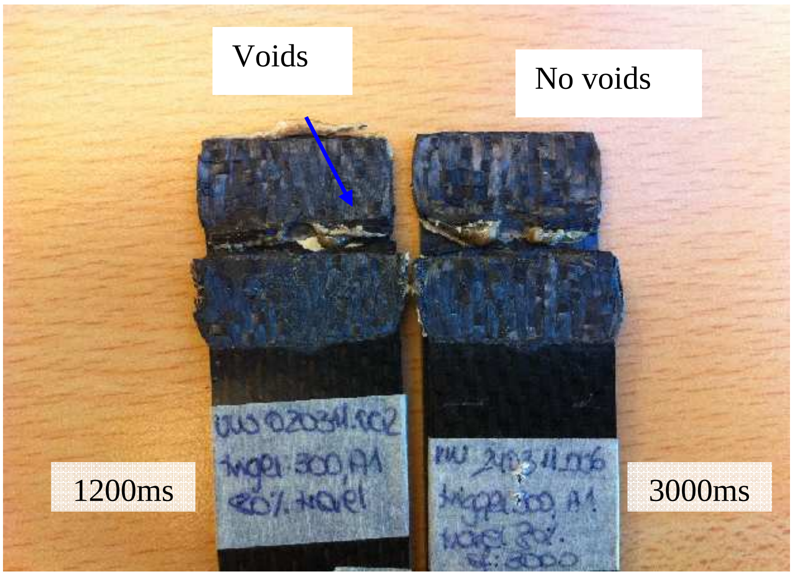

Figure 29.Difference between solidification time 1200ms and 3000ms

To summarize, the processing window for trigger 300N, amplitude 1, solid force 1000N and solidification time 3000 is defined between 38% and 80% of the travel.

<u>Trigger 500N and amplitude 1</u>

The results obtained for trigger 500N are collected in the following table:

Table 4. Summary results: Trigger 500 N and Amplitude 1

Trigger 500 N Amplitude 1 (19.8μm)					
Solidification time: 1200 ms			**Solidification time: 3000 ms**		
Travel (%)	**LSS (MPa)**	**COV (%)**	**Travel (%)**	**LSS (MPa)**	**COV (%)**
55	33.56	4.51	30	31.856	6.41
68	36.974	5.77	68	36.65	4.485
80	30.708	6.54	80	37.732	3.78
90	32.552	7.32			

Concerning solidification time 1200 ms, for travel 80% and 90% their COV are higher than 6%. In the case of travel 80% the LSS is less than 32MPa and for travel 90% the value is really close to the lower limit. The LSS for the rest of the travel are acceptable, especially for the case of 68% (close to 37MPa) but the scatter is really close to 6%. It is not possible to obtain good results because there are avoids in the fracture surfaces and it is necessary to increase the solidification time.

For solidification time 3000ms, the LSS of travel 30% is lower than 32MPa and its COV is higher than 6 and these are the reason to dismiss this value of the travel for the processing window. This travel is not enough to do a successful welding, there are too many resin residuals on the fracture surfaces. Also, it is possible to check voids on them.

Checking the fracture surfaces for travel 80%, the quality of the joints is good. The value of LSS is quite good and the COV is not so high. There are not voids on them.
For travel 68%, it is possible to observe voids in the fracture surfaces. This might be the reason because its LSS is lower than LSS of the travel 80% and its scatter is 1% higher.

As compared to 300N, for travel 80% there is not deformation of the fibers (compare figures 28 y 30).

Comparing the results for travel 80% with solidification time 1200ms and 3000ms, for solidification time 3000ms the samples increases the LSS from 30.71MPa to 37.73MPa. As well, the COV is reduced by 50%.

Better results are obtained if the second peak in the curve power-time is passed (check figure 60 in Appendix I). The energy director spreads more between the fibers.

The most representative samples for each combination are shown in Figure 30 and it is possible to see the evolution of increasing the travel:

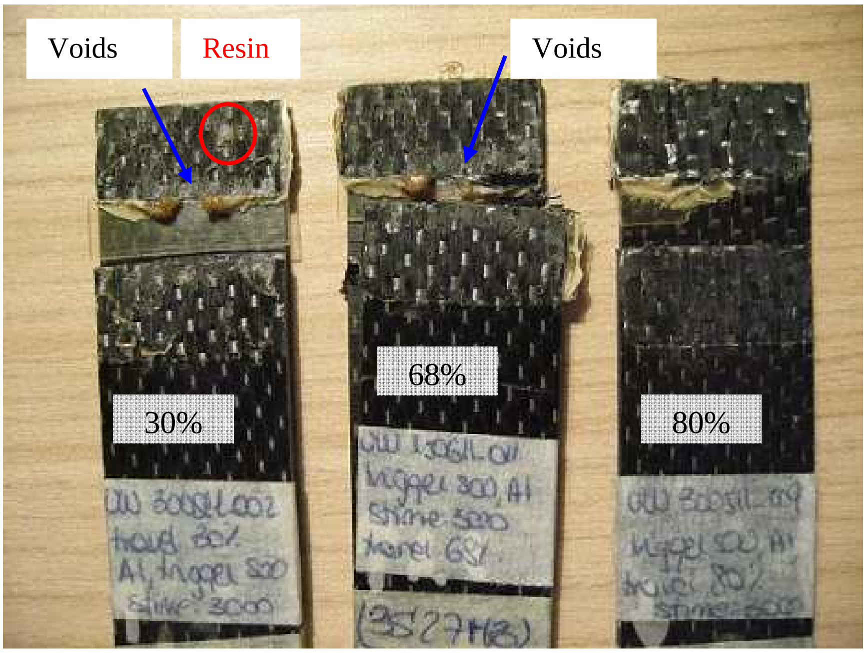

Figure 30. Fracture surfaces: evolution of the travel for trigger 500N, A1 and solidification time 3000ms

With these experiments, the processing window for trigger 500N, amplitude 1, solid force 1000N and solidification time 3000 is defined between 68% and 80% of the travel. According with the results obtained, it would be interesting to decrease the travel less than 68% (no lower than 30%) to check when the values of LSS are lower than 32MPa.

Trigger 1000N and amplitude 1

The results obtained for trigger 1000N are collected in the following table:

Table 5. Summary results: Trigger 1000 N and Amplitude 1

Trigger 1000 N Amplitude 1 (19.8μm)					
Solidification time: 1200 ms			**Solidification time: 3000 ms**		
Travel (%)	**LSS (MPa)**	**COV (%)**	**Travel (%)**	**LSS (MPa)**	**COV (%)**
60	32.67	18.56	30	27.50	6.569
70	37.15	5.15	70	33.97	1.657
80	40.33	9.388	80	36.64	3.66

Concerning to solidification time 1200 ms, the scatter for travel 60% is too high (18.5%) and also for travel 80% (~9.5%). For travel 70%, LSS is good and the scatter is inside the limits but it is possible to see voids and resin residuals on the fracture surfaces.

Concerning the solidification time 3000 ms, in the fracture surfaces for travel 30% there is too many resin because there was not a complete diffusion and also it is possible to observe voids. This value is dismissed of the processing window, its LSS is lower than 32MPa and its COV is higher than 6.

For travel 70%, the LSS value is close to the lower end of the processing window. The reasons could be the presence of resin (but it is lower quantity than for travel 30%) and also the presence of voids (less than for travel 30%).

The value of LSS for travel 80% is the highest in this case and the scatter is not too high. There is more interdiffusion between the ED and the composites and also there is more squeezing out of the ED. It is possible to observe broken fibers in one of the side of the welded area [8]. This fact is shown in the next figure:

Figure 31. Broken fibers in one of the side of the welded area

Welding conditions: trigger 1000N, A1, solidification time 3000ms and travel 80%

Also the evolution of the bubbles and the resin for the different travels are shown in the following figure:

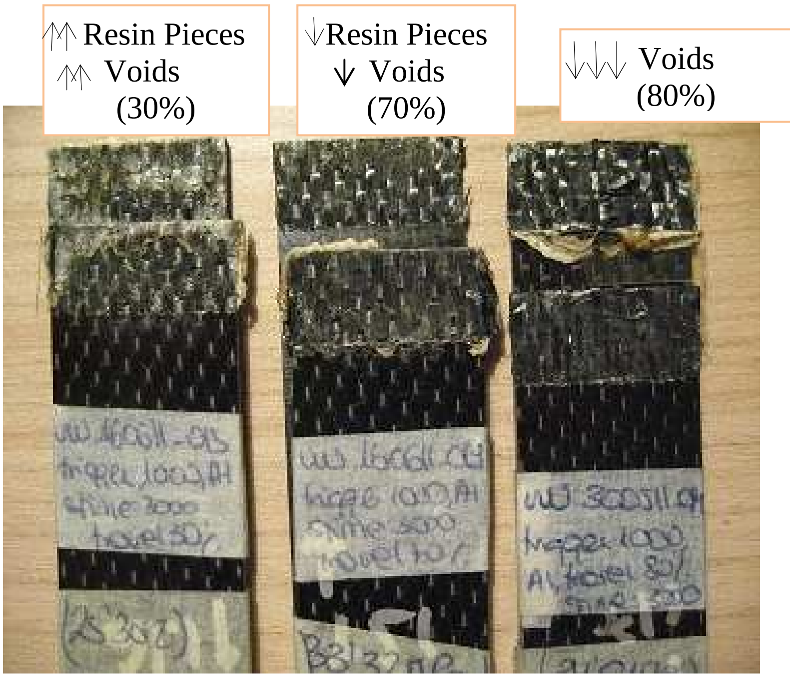

Figure 32. Fracture surfaces: evolution of the travel for trigger 1000N, A1, solidification force 1000N and solidification time 3000ms

Checking the Power-Time curves for the different travels (shown in Appendix I, figure 62), again it is better to pass the second pick in the curve in order to obtain better results.

With these experiments, the processing window for trigger 1000N, amplitude 1, solidification force 1000N and solidification time 3000 ms is defined between 70%-80% of the travel. Checking the results, it would be appealing to increase the travel more than 80% to observe what will happen with the values of LSS and also with the scatter.

Trigger 1500N and amplitude 1

The results obtained for trigger 1500N are collected in the following table:

Table 6. Summary results: Trigger 1500 N and Amplitude 1

Trigger 1500 N Amplitude 1 (19.8μm) Solidification time: 3000 ms		
Travel (%)	**LSS (MPa)**	**COV (%)**
30	25.484	4.373
60	33.49	3.373
90	36.578	5.094

For the last value of the trigger for the amplitude 1, the samples were welded only with solidification time 3000 ms.

For travel 30%, the values of the LSS are lower than 32MPa and this travel is not considered inside the processing window. It is possible to observe that there exists resin on the fracture surfaces of the samples. This means that the value of the travel is not enough to achieve a successful welding and it is necessary to choose a higher travel.
For travel 60%, it is also possible to see resin residuals on the fracture surfaces but the quantity of the resin is lower than the case of travel 30%.
For travel 90%, there are no resin residuals. The value of the LSS is higher than travel 60% but the COV is higher. Checking the fracture surfaces it is possible to observe the

movement of the fibers. They begin to open and deform. As compared to 300N, it is possible to observe that the fibers for 300N are more deformed than for 1500N. Checking the average values of the melting time (table 7), for trigger 300N the melting time is higher (2116.79ms) than for trigger 1500N (971.4ms). For trigger 300N, the fibers have more time to heat up and in consequence they become more deformed.

Checking the figure 63 in Appendix I, superior results are obtained if the second peak in the curve power-time is passed.

The most representative samples for each combination are shown in the next figure and it is possible to see the evolution of increasing the travel:

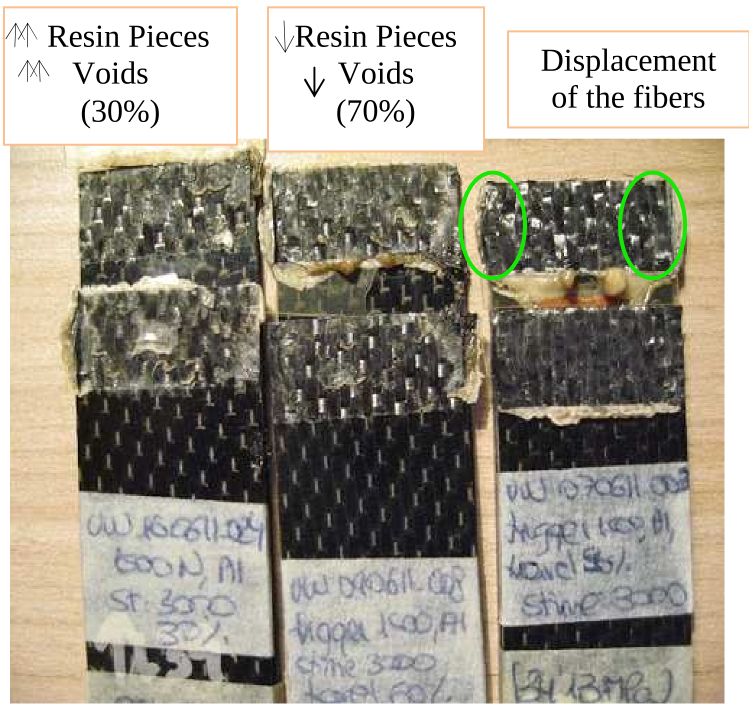

Figure 33. Fracture surfaces: evolution of the travel for trigger 1500N and A1

With these experiments, the processing window for trigger 1500N, amplitude 1, solidification force 1000N and solidification time 3000 ms is defined between 60%-90% of the travel. One recommendation for the future would be to increase the travel until 95% or 100% to check the influence of the values of LSS and also the values of COV.

The evolution of the melting time, energy, power, LSS and COV for each value of the trigger for amplitude 1 are explained in detail below (for the cases that the samples were welded with solidification time 3000ms).

<u>Evolution of the melting time</u>

The table 7 collects the average values obtained for the melting time for each value of the trigger and they are depicted in the figure 34:

Table 7. Average values for the melting time for each value of the trigger

Trigger 300N		Trigger 500N		Trigger 1000N		Trigger 1500N	
Travel (%)	**Melting time (ms)**	**Travel (%)**	**Melting time (ms)**	**Travel (%)**	**Melting time (ms)**	**Travel (%)**	**Melting time (ms)**
30	1431.4	30	903	30	642.2	30	621.4
38	1620.4	68	1231.4	70	920.4	60	832.2
50	1646.8	80	1297.6	80	1094.6	90	971.4
80	2116.79						

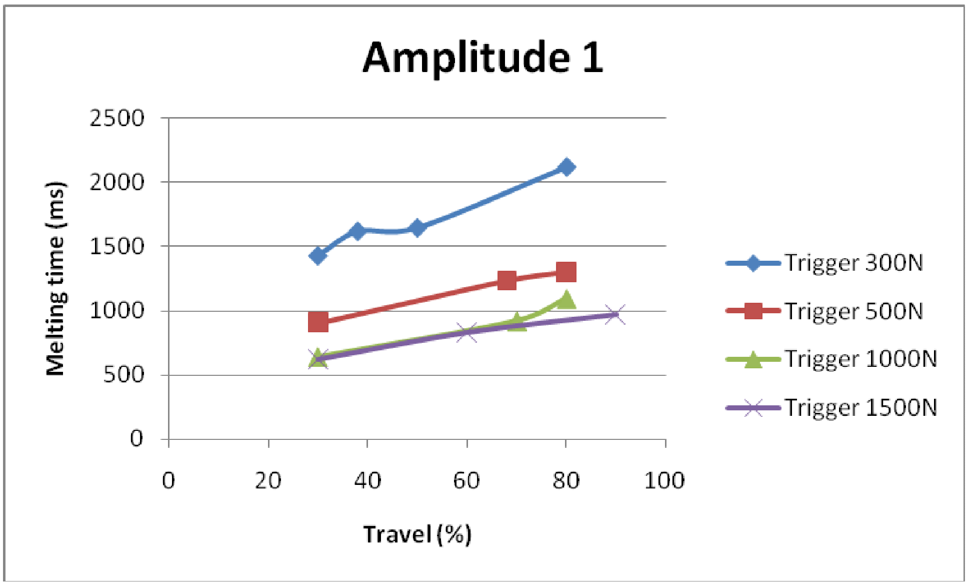

Figure 34. Evolution of the melting time for the different values of the trigger for amplitude 1

According to the figure 34, for each value of the trigger, it is obvious that the melting time is increasing as the travel is increasing. As it is needed more time for a longer displacement of the sonotrode.

The melting time decreases when the trigger is increasing. According to the table 7, as an example, for travel 30% of the energy director thickness, increasing the trigger from 300N to 1500N, decreases the melting time from 1431.4ms to 621.4ms (810 ms less).

When the trigger force applied is low, the heat generation in the interface is less effective and this is the reason because the melting time increases when the trigger is low.

Evolution of the energy

The table 8 collects the average values obtained for the energy for each value of the trigger and they are depicted in the figure 35:

Table 8. Average values for the energy for each value of the trigger

Trigger 300N		Trigger 500N		Trigger 1000N		Trigger 1500N	
Travel (%)	**Energy (Ws)**	**Travel (%)**	**Energy (Ws)**	**Travel (%)**	**Energy (Ws)**	**Travel (%)**	**Energy (Ws)**
30	1007.978	30	736.966	30	610.312	30	676.958
38	1081.122	68	984.482	70	914.728	60	824.88
50	1113.96	80	1054.458	80	1028.846	90	1063.13
80	1494.778						

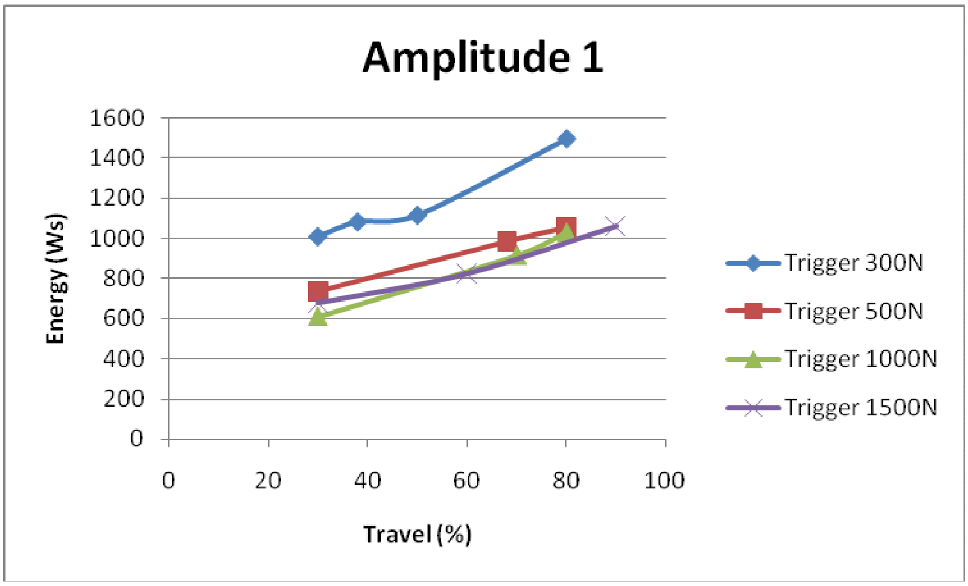

Figure 35. Evolution of the energy for the different values of the trigger for amplitude 1

The welding energy shows the same behavior as the melting time. The process consumes more energy as the travel is increasing because it is needed more time to reach the travel.

The energy of the process decreases when the trigger is increasing. It is possible to heat the interface faster with a high trigger than a low trigger. This is the reason because the process consumes less energy if a high travel is used in the welding process [9].

As an example, according to the table 8, for travel 30% increasing the trigger from 300N to 1500N, decreases the energy from 1007.978 Ws to 621.4 Ws (38.36% less).

Evolution of the maximum power

The table 9 collects the values obtained for the maximum power for each value of the trigger:

Table 9. Average values for the power for each value of the trigger

Trigger 300N		Trigger 500N		Trigger 1000N		Trigger 1500N	
Travel (%)	**Maximum Power (%)**	**Travel (%)**	**Maximum Power (%)**	**Travel (%)**	**Maximum Power (%)**	**Travel (%)**	**Maximum Power (%)**
30	34.6	30	37.8	30	42	30	48.6
38	34.2	68	36.4	70	42.8	60	44.6
50	34.8	80	37.2	80	39.8	90	49.8
80	36						

The next figure depicts the influence of the trigger in the maximum power:

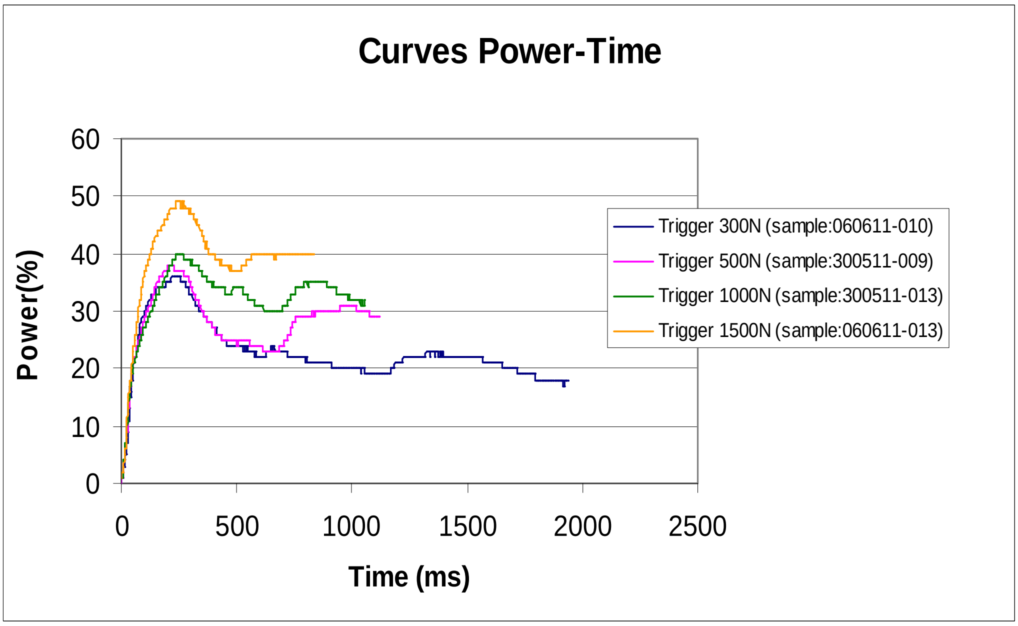

Figure 36. Curves Power-Time for trigger 300N (travel80%), 500N (travel80%), 1000N (travel 80%) and 1500N (travel 90%).

For each trigger, the maximum value of the travel was chosen to be represented in the curve power-time (each curve is an average because there were 5 tests with the same conditions).

According to the figure 36, it is possible to observe that the maximum power is increasing with the trigger force. For trigger 300N the maximum power was 36% and for trigger 1500N was 49.8% (around 27,72 % more).

The curve power-time is longer when the trigger force is decreasing. For trigger 300N the melting time was 2116.79ms and for trigger 1500N was 971.4ms (around 54% less using high trigger).

Evolution of the LSS and COV

The table 10 collects the values obtained for the LSS and for the COV for each value of the trigger and they are depicted in the figures 37 and 38:

Table 10. Results for the LSS and COV for each value of the trigger

Trigger 300N		**Trigger 500N**		**Trigger 1000N**		**Trigger 1500N**	
Travel (%)	**LSS (MPa) [COV,%]**	**Travel (%)**	**LSS (MPa) [COV,%]**	**Travel (%)**	**LSS (MPa) [COV,%]**	**Travel (%)**	**LSS (MPa) [COV,%]**
30	31.26 [7.657]	30	31.856 [6.41]	30	27.50 [6.569]	30	25.484 [4.373]
38	35.27 [3.309]	68	36.65 [4.485]	70	33.97 [1.657]	60	33.49 [3.373]
50	35.01 [5.205]	80	37.732 [3.78]	80	36.64 [3.66]	90	36.578 [5.094]
80	39.83 [5.65]						

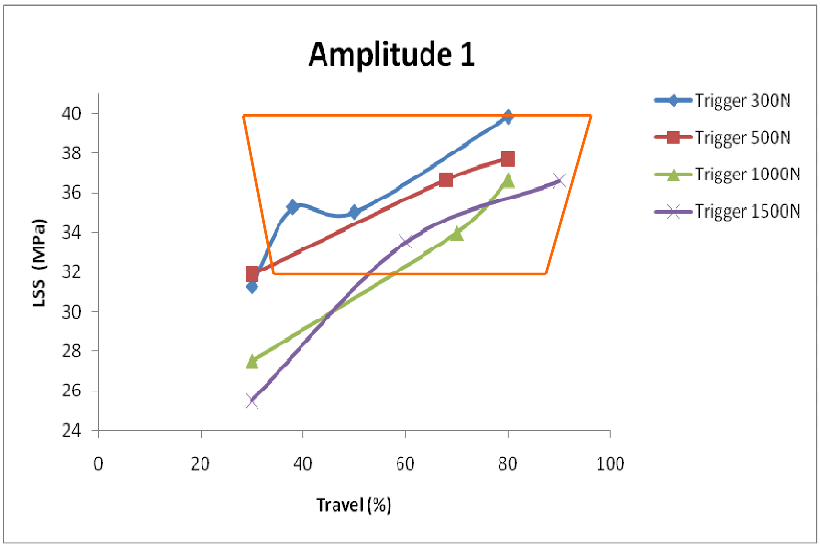

Figure 37. Evolution of the LSS for the different values of the trigger for amplitude 1. Line orange: threshold for the processing window

According with the figure 37, for the same value of the trigger, increasing the travel the value of LSS is higher. Analyzing the fracture surfaces of the samples, it is possible to observe that the voids and the resin residuals are lower if the process is executed with a high travel. As well, if the value of the trigger is low, the results of LSS for the same travel are higher and it is more interesting to execute the welding process with low trigger than with high trigger.

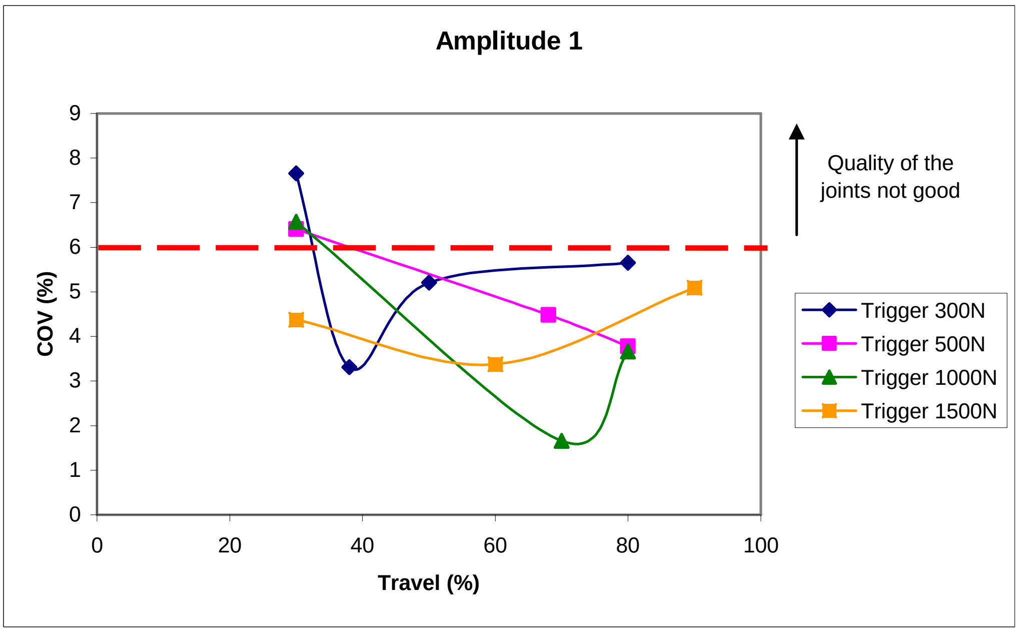

Figure 38. Evolution of the COV for the different values of the travel for amplitude 1

Observing the figure 38, all the values of COV above 6% are dismissed for the definition of the processing window because the quality of the joints are not enough good.

For trigger 1500N, the points in the figure 38 are lower than 6% but for the rest of the triggers (300N,500N and 1000N), there is always one point above 6% and this point corresponds to travel 30%.

Figure 39 depicts, as a summary, the values of LSS for each combination of the trigger with the different values of the travel:

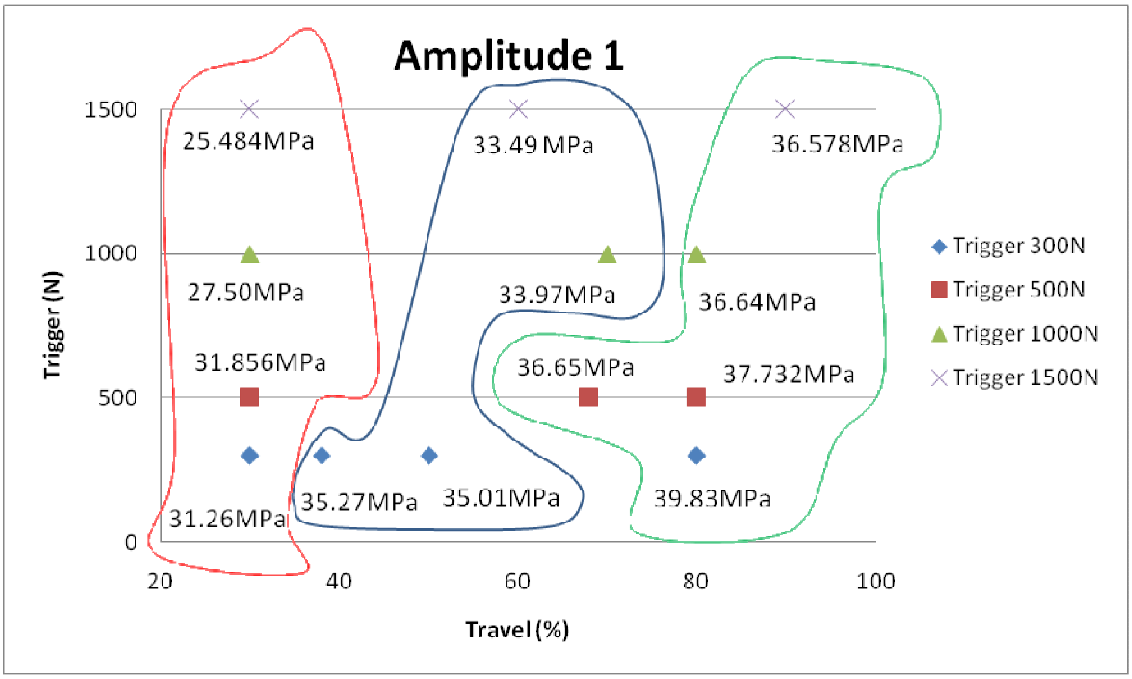

Figure 39 Summary: Trigger vs travel and theirs values of LSS

For a better understanding of the process, three possible areas can be observed in the figure 39. The first one (red) corresponds to the values of LSS less than 32MPa and it is not interesting to work with these conditions because the quality of the joints is not good enough. This area corresponds with the combination of the triggers with a low travel. The low value of LSS is because in most of the samples welded with that travel, there was either resin or bubbles in their fracture surfaces.

In the second area (blue), the values of the LSS ranged between 33MPa and 35MPa. It is better to execute the process with higher travel values because it is possible to observe better results in the third area (green).
In this area, LSS ranged between 36MPa and 40MPa. These values are quite good and also the fracture surfaces present less voids and no resin residuals on them. Checking the tables 7 and 8, this area consumes more energy and also the melting time requested in the process is higher.

Checking the different values of the trigger for the same value of the travel, better results were found using low trigger. As an example, for travel 80% for trigger 300 N the value of its LSS was 39.83MPA but for trigger 1500N decreases until 36.58MPa.
Using high trigger, the processing window is narrower than if the process is executed with low trigger.

Discussion of the results for Amplitude 9

The results obtained from the amplitude 9 for each value of the trigger are shown in the tables 11,12,13 and 14.
Only for trigger 300N the tests were executed with solidification time 3000ms, the rest were carried out with 1200ms.

Table 11. Summary results: Trigger 300 N and Amplitude 9

Trigger 300 N Amplitude 9 (33µm) Solidification time: 3000 ms		
Travel (%)	**LSS (MPa)**	**COV (%)**
90	34.25	7.78

In that case, it was only possible to do test with travel 90%. The result of LSS is more than 32MPa but the value of COV is high.
The melting time for this trigger is 1431.42ms. This value is long and there is much displacement of the fibres, showing a fracture surface with high deformation.
It is not possible to observe bubbles in the fracture surfaces.

Table 12. Summary results: Trigger 500 N and Amplitude 9

Trigger 500 N **Amplitude 9 (33μm)** **Solidification time: 1200 ms**		
Travel (%)	**LSS (MPa)**	**COV (%)**
25	29.06	14.62
37	33.55	5.31
60	34.51	4.89
80	34.2	1.82
100	29.74	13.26

For trigger 500N, travel 25% and 100% are not considered inside the processing window because the scatter of the LSS is too high to be acceptable and it is not interesting to work with these conditions.
The values obtained of their LSS are lower than 32 MPa and their COV are too high.
For travel 25%, there is many resin residuals because there was not a completely diffusion. For the rest of the travel values, there is no presence of that resin. Finally for travel 100%, it is possible to observe the movement of the fibers. They begin to open and deform.

For all the travel values, it is possible to observe bubbles in the fracture surfaces of the samples. This problem can be solved increasing the value of the solidification time and, according to previous experiments, higher LSS values are expected. For these combinations the highest LSS is 34.51MPa and that value is not too high.

The processing window for trigger 500N, amplitude 9, solidification force 1000N and solidification time 1200 ms is defined between 37%-80% of the travel.

It would be really interesting to research between travel 25% and 37% to know where exactly the quality of the joints start to be good. Also, to repeat the same combinations with solidification time 3000ms to compare the results obtained with solidification time 1200ms.

Table 13. Summary results: Trigger 1000 N and Amplitude 9

Trigger 1000 N Amplitude 9 (33µm) Solidification time: 1200 ms		
Travel (%)	**LSS (MPa)**	**COV (%)**
57	33.05	8.66
68	32.33	4.62
80	35.08	5.38

For travel 57%, the resin was not completed diffused and it is possible to observe in the fracture surfaces resin pieces, also bubbles in the edge of the surfaces. Its COV is more than 6% and the value of LSS is not much higher than 32MPa. For travel 68%, the LSS is really close to 32MPa. It is also possible to see bubbles on them and resin pieces. For the last travel, 80%, LSS is near 35MPa but the scatter is close to 5.5%. The fracture surfaces present bubbles and resin but the amount of them is lower than for the other travel values.

Table 14. Summary results: Trigger 1500 N and Amplitude 9

Trigger 1500 N Amplitude 9 (33µm) Solidification time: 1200 ms		
Travel (%)	**LSS (MPa)**	**COV (%)**
80	39.8	2.407

In that case, it was only possible to do test with travel 80%. The result of LSS is really high and also the COV is low.

It would be really interesting to increase the value of the travel to check if it is possible to obtain a higher value of the LSS. Also to increase the value of the solidification time until 3000ms to avoid the bubbles that it is possible to observe in the surfaces.

Chapter 5: Conclusions and Recommendations

This research, developed in the period between October 2010 and June 2011, was focused on the study and the analysis of the combinations of the parameters involved in the ultrasonic welding process, which give acceptable welds to find out the processing window of CF-PEI.

The results were analyzed in the previous chapter and the conclusions are shown in this chapter.

Many samples were tested using solidification time 1200ms. In their fracture surfaces were found numerous voids. It is possible that the solidification time is so low that the material can not reach its T_g and this causes a certain "deconsolidation" of the resin and the appearance of voids at the interface.
Increasing the solidification time until 3000ms, it is possible to observe that the quantity of the voids was lower, especially when the travel is increasing. Also, the results obtained for LSS and COV are more successful if the welding process is executed with solidification time 3000ms.

According to the output parameters, the melting time decreases when the trigger increases. When the trigger force applied is low, the heat generation in the interface is less effective and this is the reason because the melting time increases when the trigger is low. Concerning to the travel, the melting time increases as the travel increases because it is needed more time for a longer displacement of the sonotrode.
Relating to the energy of the process, this consumes more energy as the travel increases, because it is need more time to reach the travel. The energy decreases when the trigger increases. It is possible to heat the interface faster with a high trigger than a low trigger. This is the reason because the process consumes less energy if a high travel is used in the welding process.
Finally the maximum power increases with the trigger force. The curve power-time is longer when the trigger force is decreasing. For low trigger, it is needed more time in the process.

To summarize, when the trigger force increases the melting time and the energy of the process decreases and the maximum power increases.

For all the triggers used, it was possible to observe that better results were obtained if the second peak in the curve power-time is passes. At that point there seems to be a better interdiffusion between the composites and the ED. So it is better, inside the thresholds, higher values of the travel.

Another important conclusion is that, for the same value of the trigger, increasing the travel the value of LSS is higher. Analyzing the fracture surfaces of the samples, it was possible to observe that the voids and the resin residuals were lower if the process was executed with a high travel. As well, if the value of the trigger is low, the results of LSS for the same travel are higher and it is more interesting to execute the welding process with low trigger than with high trigger. But in that case, it consumes more energy and also the melting time requested in the process is higher.

To summarize, when the trigger force decreases, better results for LSS were obtained but the process needs more melting time and energy. It would be interesting to find equilibrium between the high values of LSS and low melting time and low energy of the process.

To end, *some recommendations* for future investigations are going to mention.

Because of the time of the project, it was not possible to find the processing window for amplitude 9 (only for trigger 500N but solidification time 1200ms). It would be really interesting to repeat all the experiments with the same conditions (same values of the travel, solidification time 3000ms and solidification force 1000N) with amplitude 9, to study and to analyze the influence of increasing the amplitude and the consequence of using a low or high amplitude during the process. This comparison will be analyzed contrasting the melting time, the energy, the maximum power, the values of LSS and COV.

The table 15 shows a summary of the thresholds found for each value of the trigger for amplitude 1:

Table 15. Summary of the thresholds found in that study

Welding conditions: Amplitude 1, solidification force 1000N and solidification time 3000ms				
Trigger (N)	300	500	1000	1500
Processing window (%travel)	38-80%	68-80%	70-80%	60-90%

According to the table, for trigger 500N it would be appealing to do more tests with travel less than 68% (no lower than 30%) to check when the values of LSS are lower than 32MPa. Also, it would be a good idea to increase the travel until 90% in order to know the values of the LSS and COV and if it is possible to do wider the processing window for 500N.

The case for trigger 1000N is really similar. A good suggestion would be increase the travel more than 80% to check the values of the LSS and COV. Maybe the processing window could be wider for the superior limit. Also the same for the trigger 1500N, it would be interesting to increase the travel more than 90% to observe what happen.

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I cannot finish without saying how grateful I am with my family. I wish to thank my parents, Berta and Juan Manuel, my sister, Laura and Lolo. They have always supported and encouraged me to do my best in all matters of life. To them I dedicate my Master Thesis.

Lastly, I offer my regards and blessings to all of those who supported me in any respect during the completion of my project.

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Appendix I:

Experimental Results

Table 16. Results: Trigger 500 N, Amplitude 9 and Travel 37%

Material: C-PEI			ED description: PEI flat			
WELDING CYCLE						
Force build-up		Trigger (N)		500		
Melting on		Rise of force (N/mm)		0		
		Amplitude (µm)		33		
		Travel (%)		37		
Solidification		Force (N)		1000		
		Holding time (ms)		1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 110211_ UW 150211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.25	68	510	741.57	10915.18	34.35
_002	0.26	69	532	827.34	9952.39	31.06
_003	0.25	69	448	640.59	11450.53	35.85
_005	0.24	66	447	688.87	10729.52	33.71
_001	0.24	56	507	700.45	10401.29	32.81

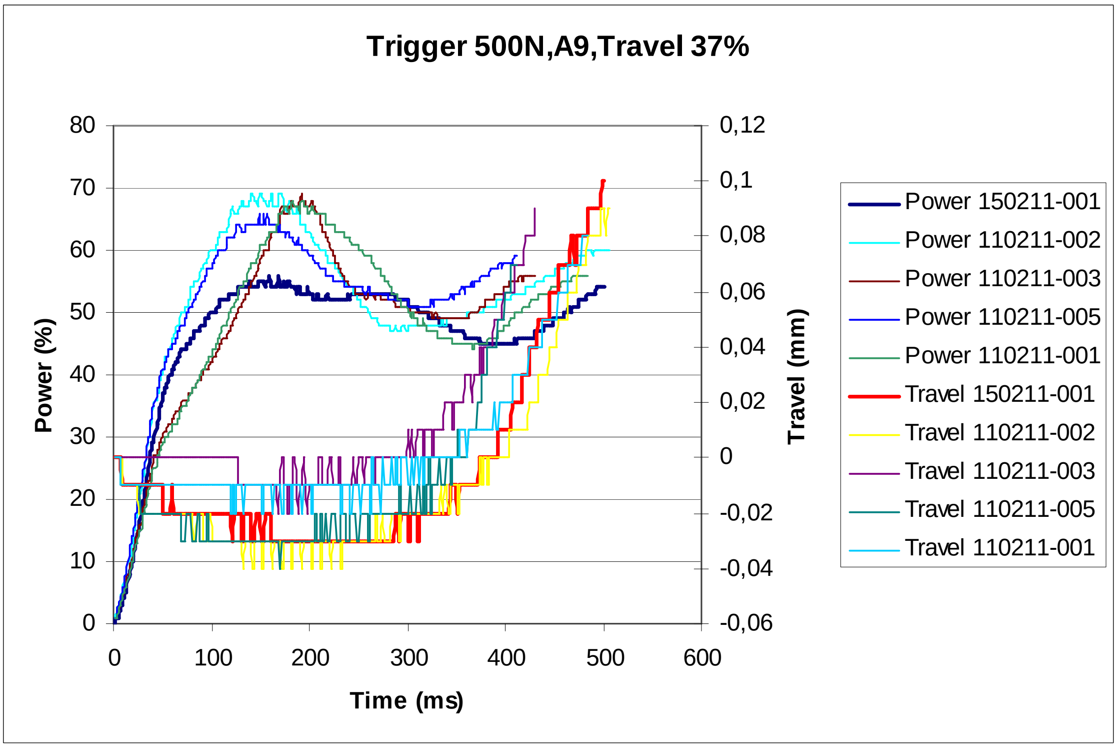

Figure 40. Trigger 500 N, Amplitude 9 and Travel 37%

Table 17. Results: Trigger 500 N, Amplitude 9 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		33			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 150211_ UW 160211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_003	0.35	67	614	966.97	11143.18	35.05
_004	0.36	64	680	1023.01	10706.23	33.5
_001	0.35	69	642	968.8	10745.90	33.8
_002	0.38	69	688	1094.8	10751.78	34.05
_003	0.39	66	780	1238.75	11118.34	34.6

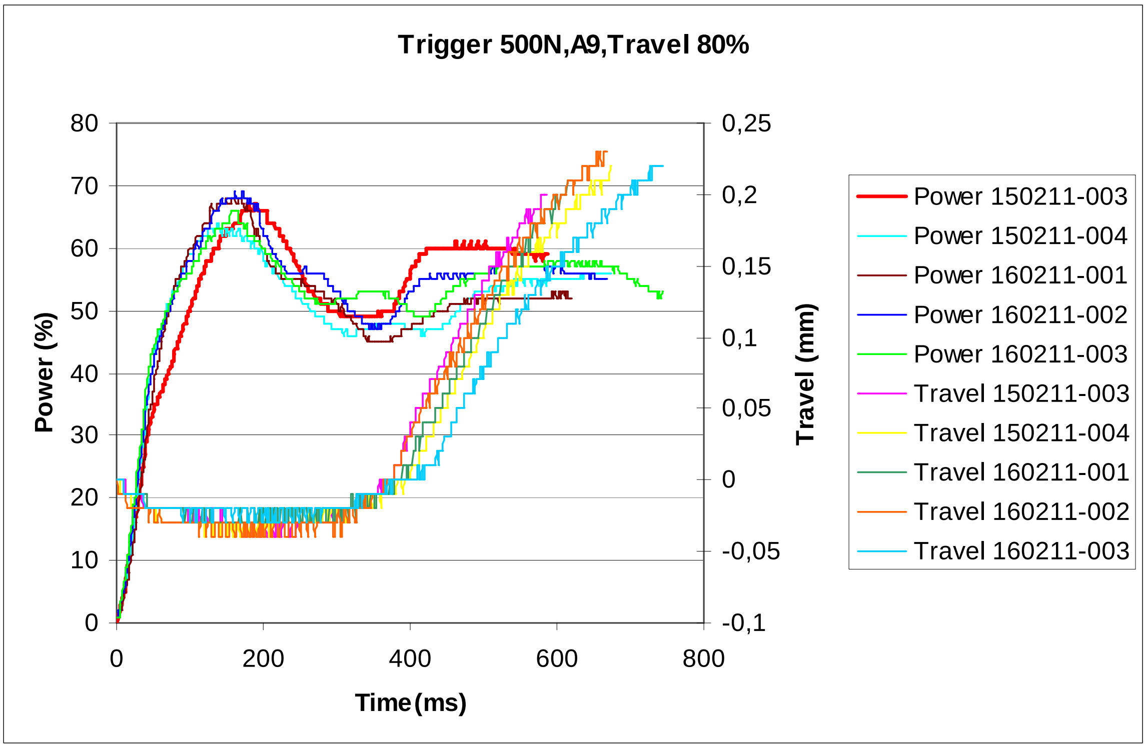

Figure 41. Trigger 500 N, Amplitude 9 and Travel 80%

Table 18. Results: Trigger 500 N, Amplitude 9 and Travel 60%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			500		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			33		
	Travel (%)			60		
Solidification	Force (N)			1000		
	Holding time (ms)			1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 170211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.31	71	731	1143.4	10289.32	32.5
_002	0.31	67	487	718.93	11239.17	35.23
_003	0.31	69	524	779.2	11473.29	35.98
_004	0.31	73	618	901.19	10365.46	32.89
_006	0.30	66	607	941.88	11501.87	35.98

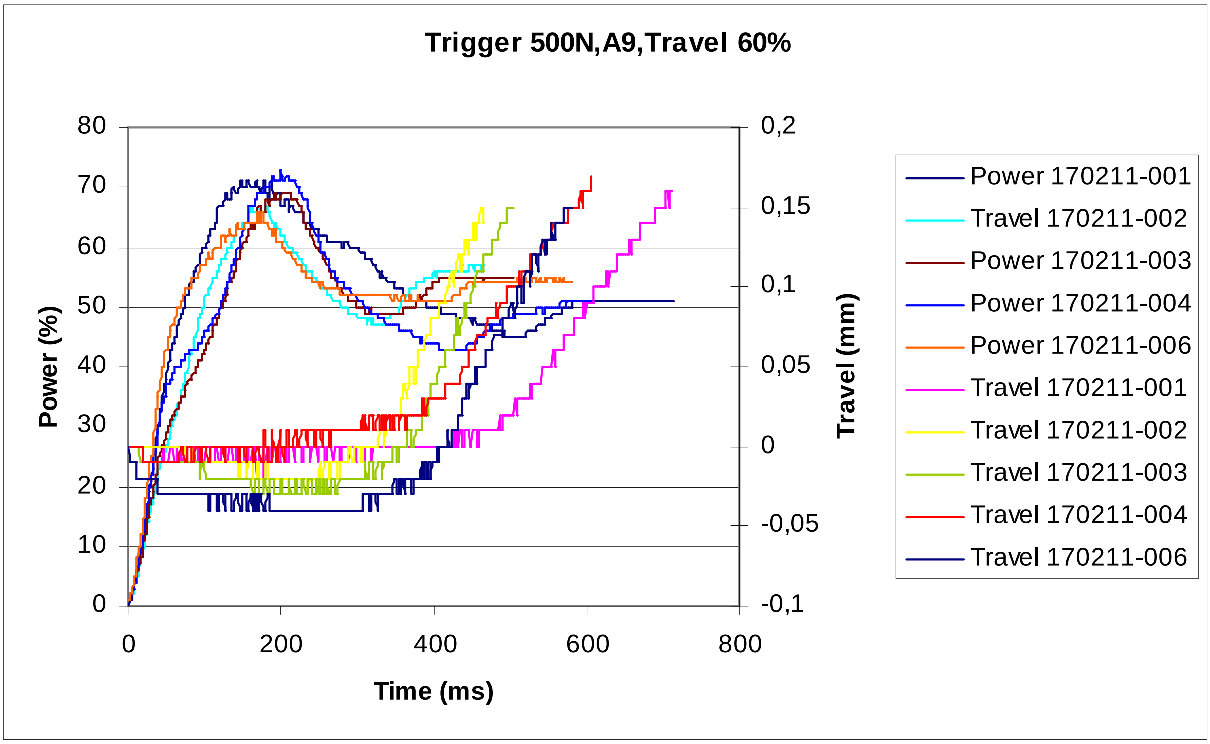

Figure 42. Trigger 500 N, Amplitude 9 and Travel 60%

Table 19. Results: Trigger 500 N, Amplitude 9 and Travel 100%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			500		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			33		
	Travel (%)			100		
Solidification	Force (N)			1000		
	Holding time (ms)			1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 170211_ UW 210211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_007	0.42	69	800	1211.78	10732.40	33.86
_001	0.42	61	965	1430.97	10495.58	32.71
_002	0.42	72	863	1355.4	7537.47	23.75
_003	0.44	60	776	1115.19	9299.83	29.34
_004	0.43	64	696	1051.35	9297.72	29.06

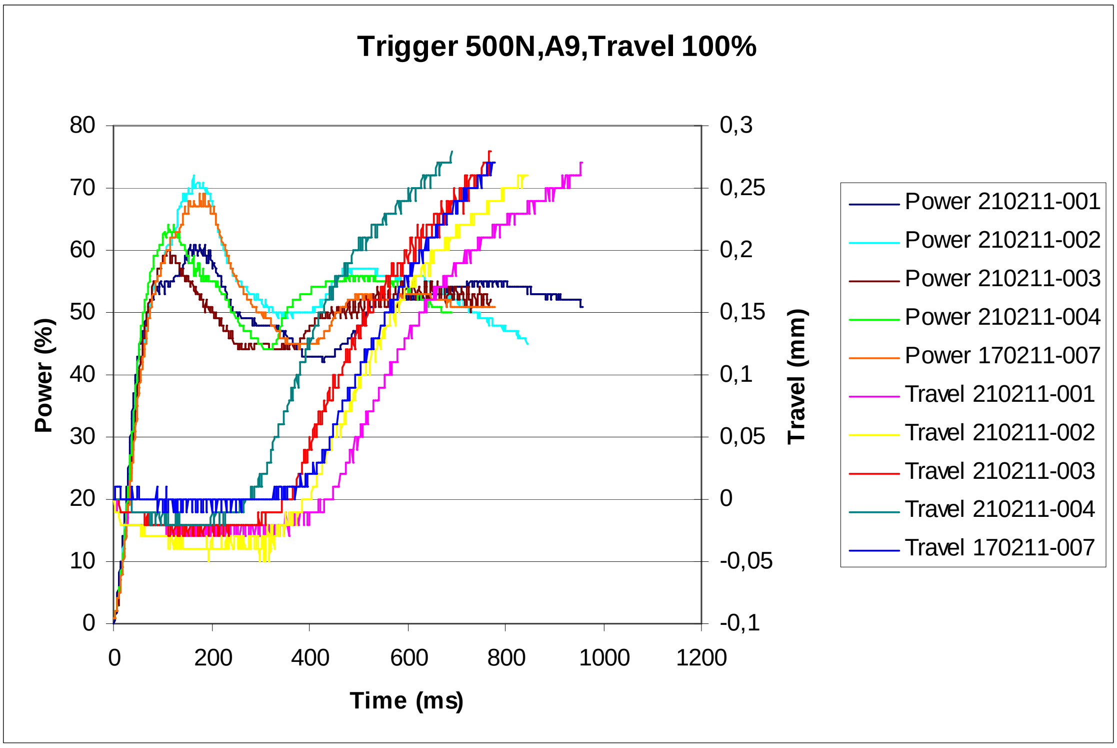

Figure 43. Trigger 500 N, Amplitude 9 and Travel 100%

Table 20. Results: Trigger 500 N, Amplitude 9 and Travel 25%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		33			
	Travel (%)		25			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 220211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_011	0.19	66	431	647.93	8619.17	27.05
_012	0.19	61	370	473.51	7183.63	22.5
_013	0.19	62	444	589.91	10111.07	31.68
_014	0.20	66	486	679.55	10080.90	31.53
_015	0.20	65	464	642.6	10464.04	32.56

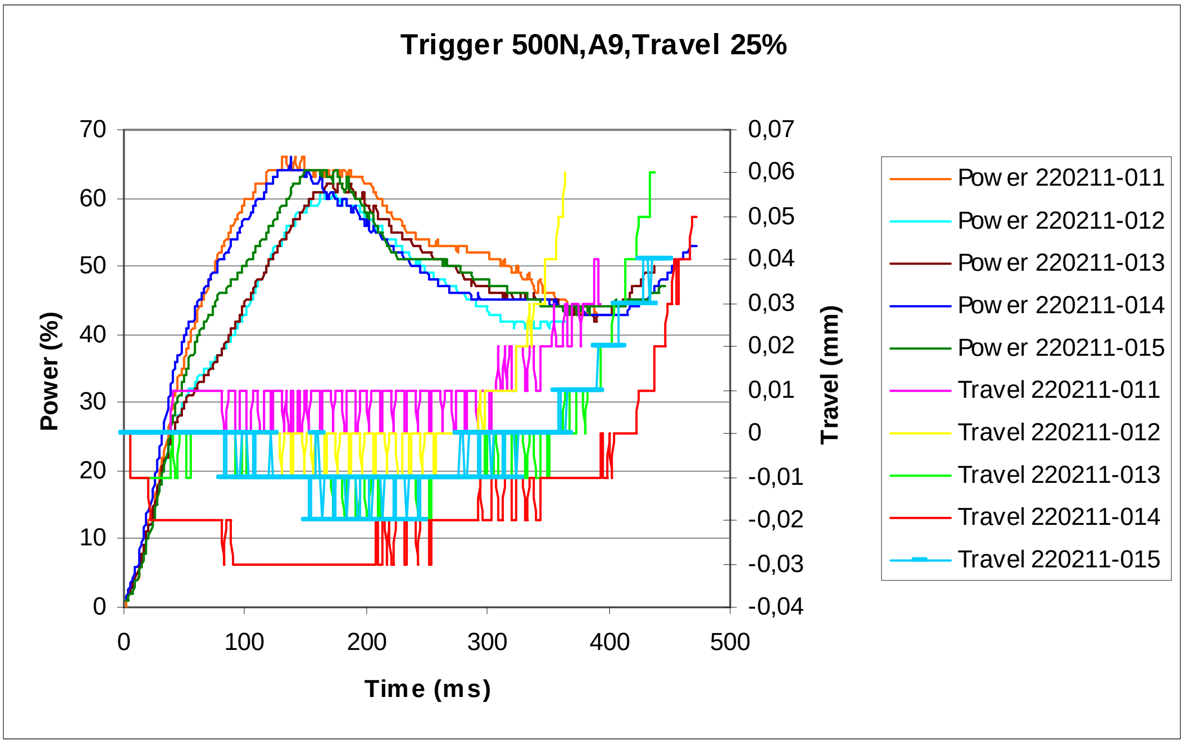

Figure 44. Trigger 500 N, Amplitude 9 and Travel 25%

Table 21. Results: Trigger 1500 N, Amplitude 9 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			1500		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			33		
	Travel (%)			80		
Solidification	Force (N)			1000		
	Holding time (ms)			1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 220211_ UW 230211_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_016	0.25	88	393	753.6	12673.33	39.61
_001	0.25	80	422	735.64	12384.91	39.16
_002	0.25	81	468	873.8	12556.56	39.37
_003	0.25	87	445	870.83	12657.43	39.38
_004	0.25	86	393	716.73	13199.58	41.49

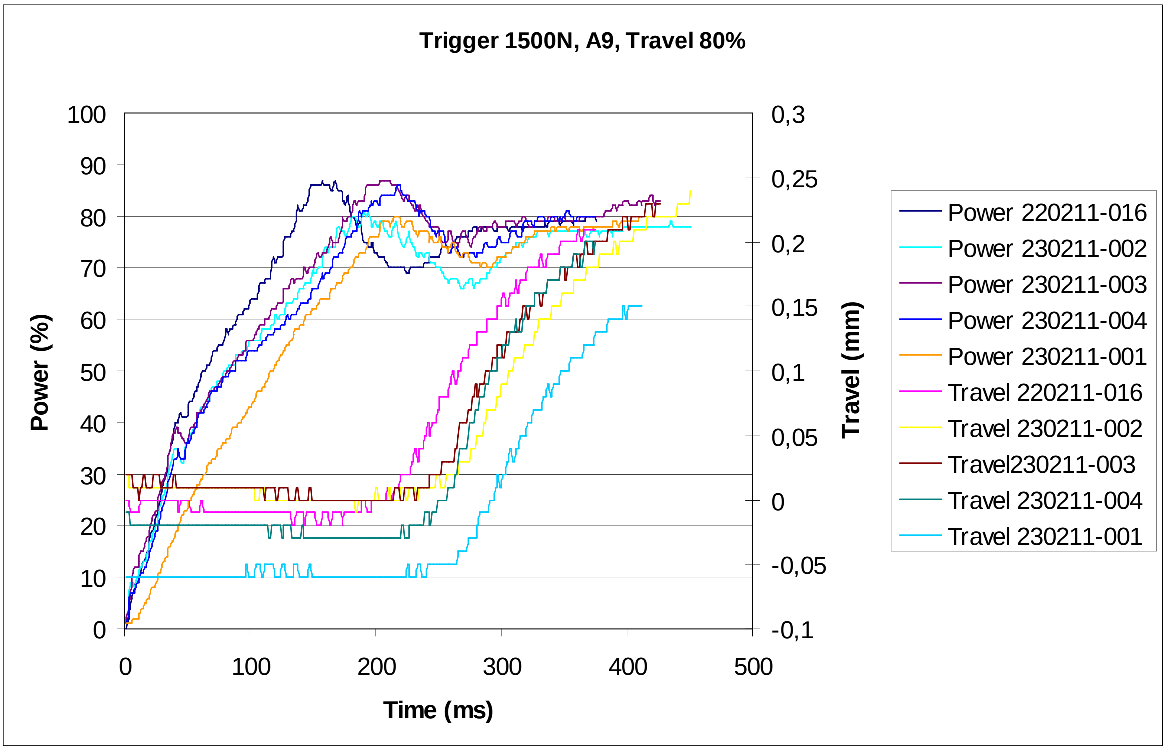

Figure 45. Trigger 1500 N, Amplitude 9 and Travel 80%

Table 22. Results: Trigger 1000 N, Amplitude 9 and Travel 80%

Material: C-PEI		ED description: PEI flat				
WELDING CYCLE						
Force build-up	Trigger (N)		1000			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		33			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 010311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.29	85	402	737.28	11268.58	35.34
_002	0.29	72	453	778.66	10475.01	33.02
_003	0.30	74	475	768.2	10833.01	34.15
_004	0.30	76	538	911.91	12171.94	38.08
_005	0.29	79	454	788.04	11094.53	34.8

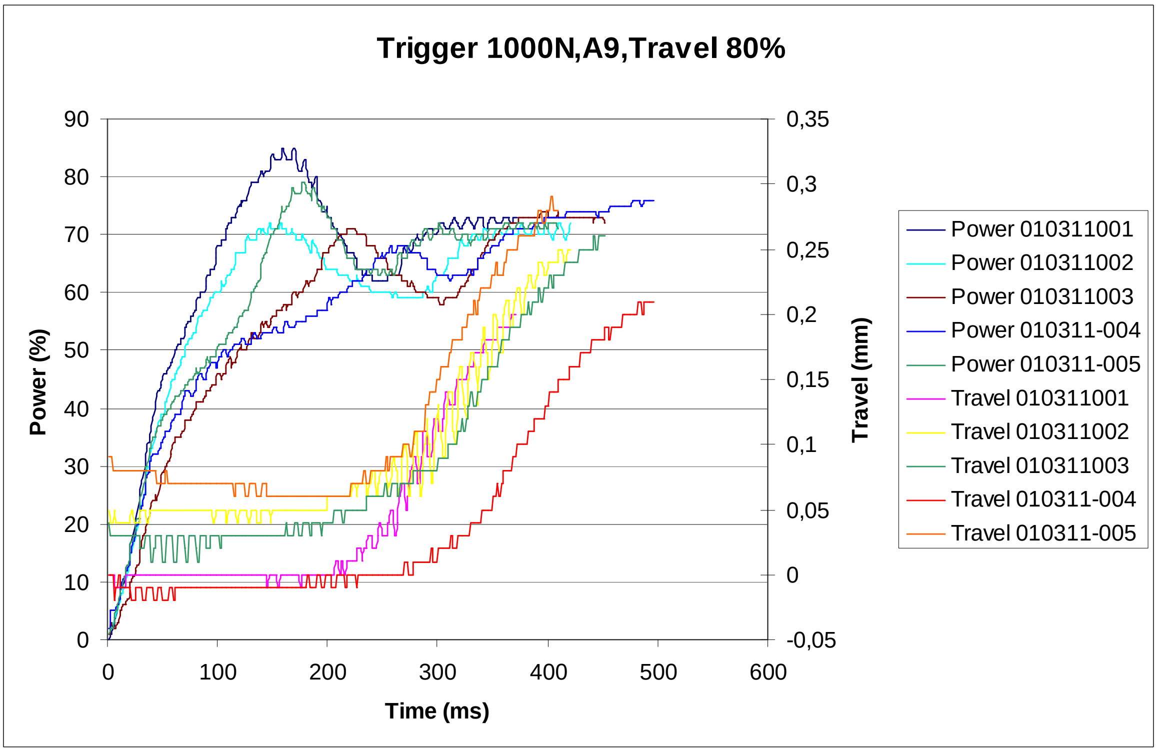

Figure 46. Trigger 1000 N, Amplitude 9 and Travel 80%

Table 23. Results: Trigger 300 N, Amplitude 1 and Travel 80%

Material: C-PEI		ED description: PEI flat				
WELDING CYCLE						
Force build-up	Trigger (N)		300			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 020311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	1.01	33	2206	1439.49	10913.30	34.4
_002	1.01	34	2873	1727.35	10195.43	31.82
_003	1.17	33	2582	1626.6	6861.25	21.55
_004	0.54	38	2295	1496.32	9274.40	28.96
_005	0.59	26	2013	1274.89	9549.08	29.72

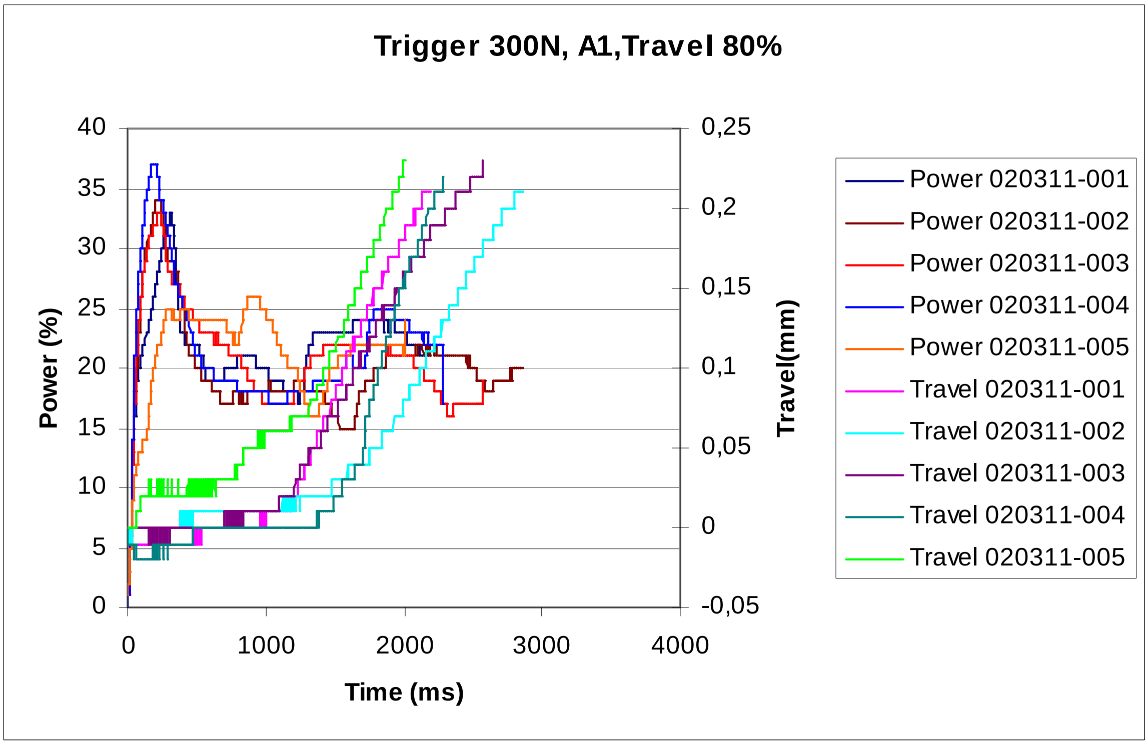

Figure 47. Trigger 300 N, Amplitude 1 and Travel 80%

Table 24. Results: Trigger 500 N, Amplitude 1 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 020311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_006	0.49	39	1208	917.26	9080.77	28.39
_007	0.47	38	1240	965.77	9734.07	30.48
_008	0.52	35	1262	917.68	10677.03	33.46
_009	0.51	40	1116	888.65	10204.95	31.86
_010	0.48	39	1472	1038.12	9349.53	29.35

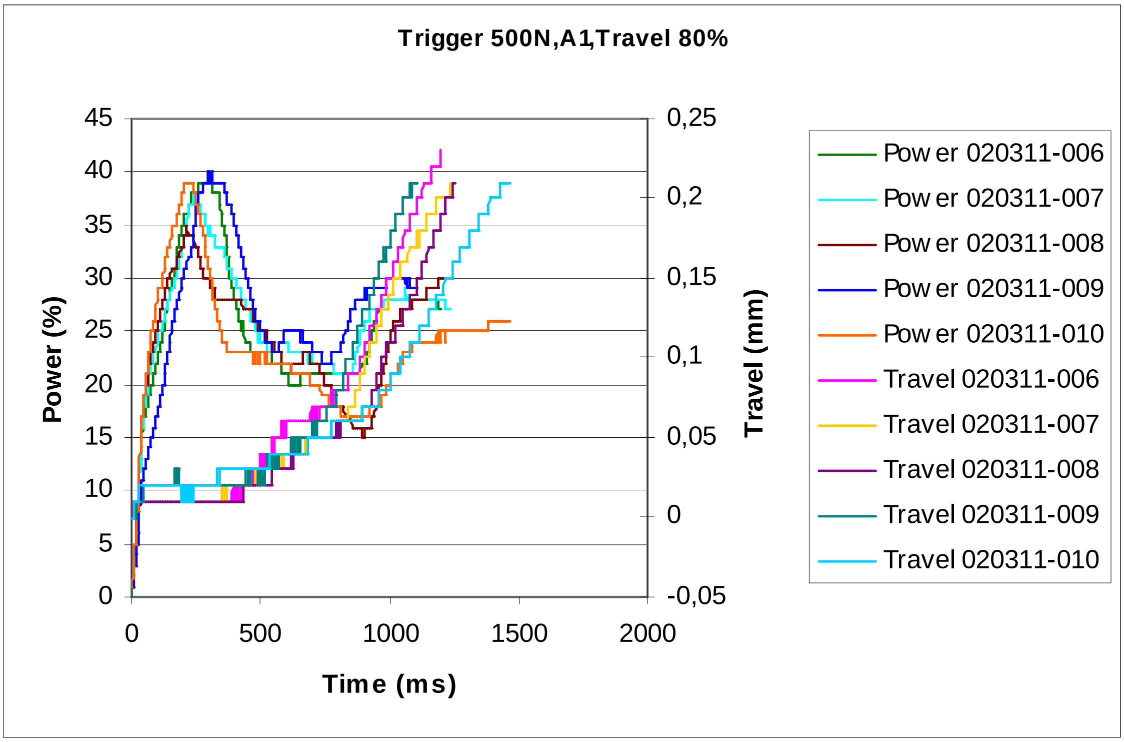

Figure 48. Trigger 500 N, Amplitude 1 and Travel 80%

Table 25. Results: Trigger 300 N, Amplitude 1 and Travel 50%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		300			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		50			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 080311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.99	33	1866	1132.45	9234.61	29.062
_002	0.75	34	1121	853.52	10696.62	33.55
_003	0.75	30	1445	945.98	9992.80	31.15
_004	0.77	36	1504	990.6	10506.37	32.81
_005	0.76	31	1969	1228.28	11089.77	34.87

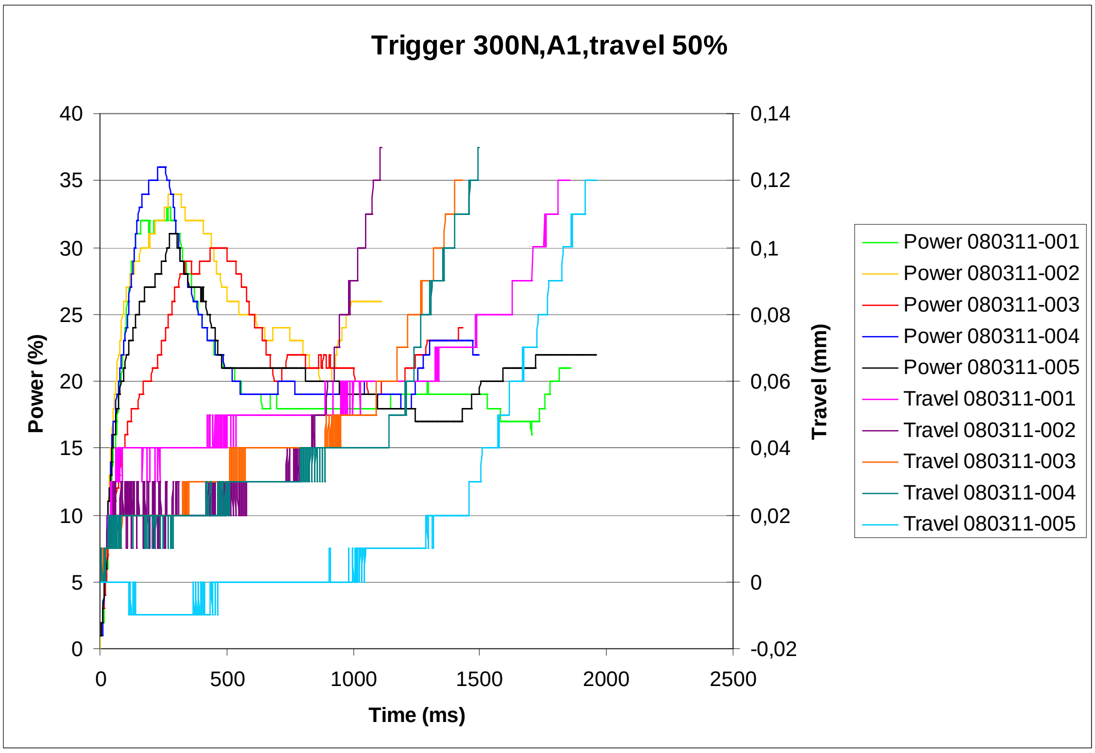

Figure 49. Trigger 300 N, Amplitude 1 and Travel 50%

Table 26. Results: Trigger 1000 N, Amplitude 1 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		1000			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 080311_ UW 240311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_007	0.27	41	902	883.39	12626.40	39.31
_008	0.27	40	784	758.94	13380.53	41.94
_009	0.27	40	798	781.04	13925.82	43.70
_010	0.29	39	852	791.55	13611.08	42.52
_008	0.27	43	978	915.76	13977.40	43.47

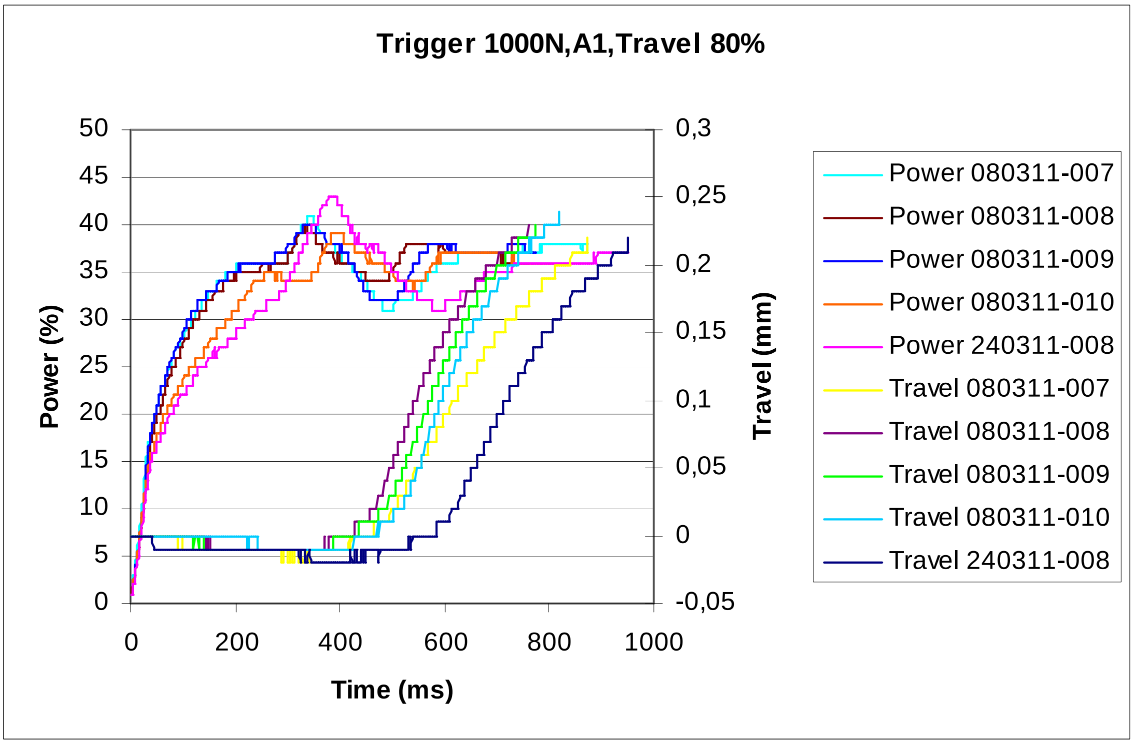

Figure 50. Trigger 1000 N, Amplitude 1 and Travel 80%

Table 27. Results: Trigger 500 N, Amplitude 1 and Travel 68%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		68			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 080311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_011	0.29	34	1289	948.64	11008.05	34.52
_012	0.29	38	1124	929.25	12329.24	38.71
_013	0.30	39	1172	893.73	11419.55	36.01
_014	0.31	36	1146	887.69	12484.77	39.67
_015	0.30	39	980	789.26	11294.53	35.96

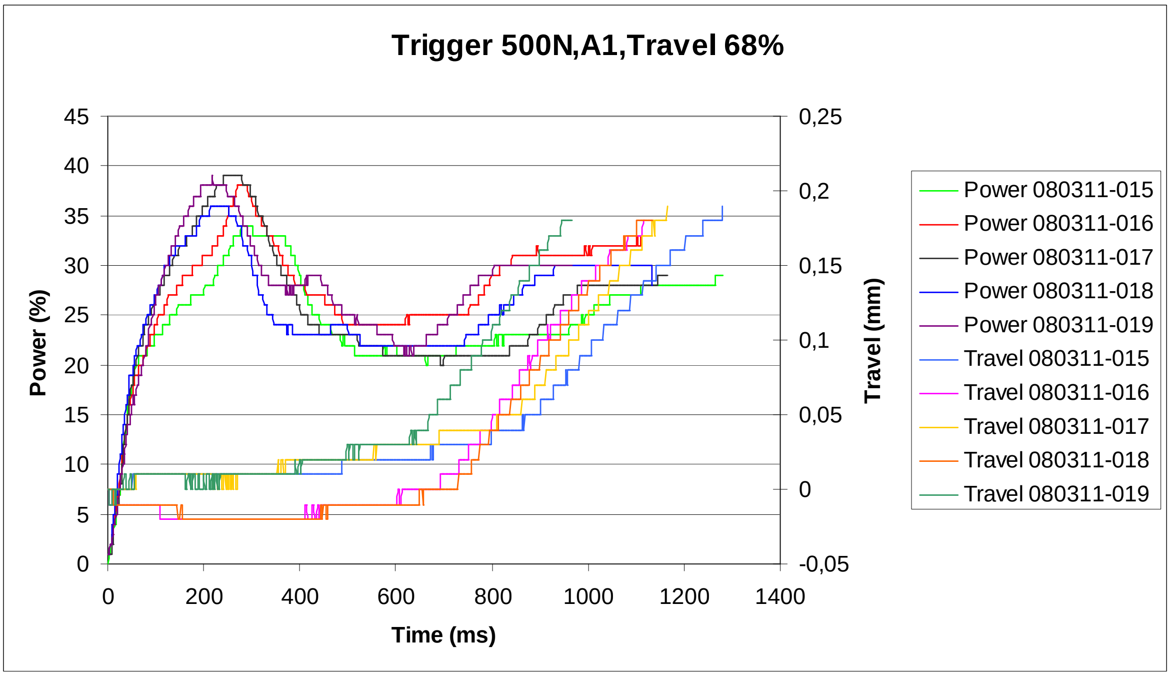

Figure 51. Trigger 500 N, Amplitude 1 and Travel 68%

Table 28. Results: Trigger 1000 N, Amplitude 9 and Travel 68%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			1000		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			33		
	Travel (%)			68		
Solidification	Force (N)			1000		
	Holding time (ms)			1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 080311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_016	0.26	79	413	784.15	10319.81	32.16
_017	0.27	80	402	754.92	9853.91	30.70
_018	0.26	80	422	786.03	10058.93	31.24
_019	0.27	84	403	759.81	10636.88	33.15
_020	0.26	73	376	645.49	10832.43	34.43

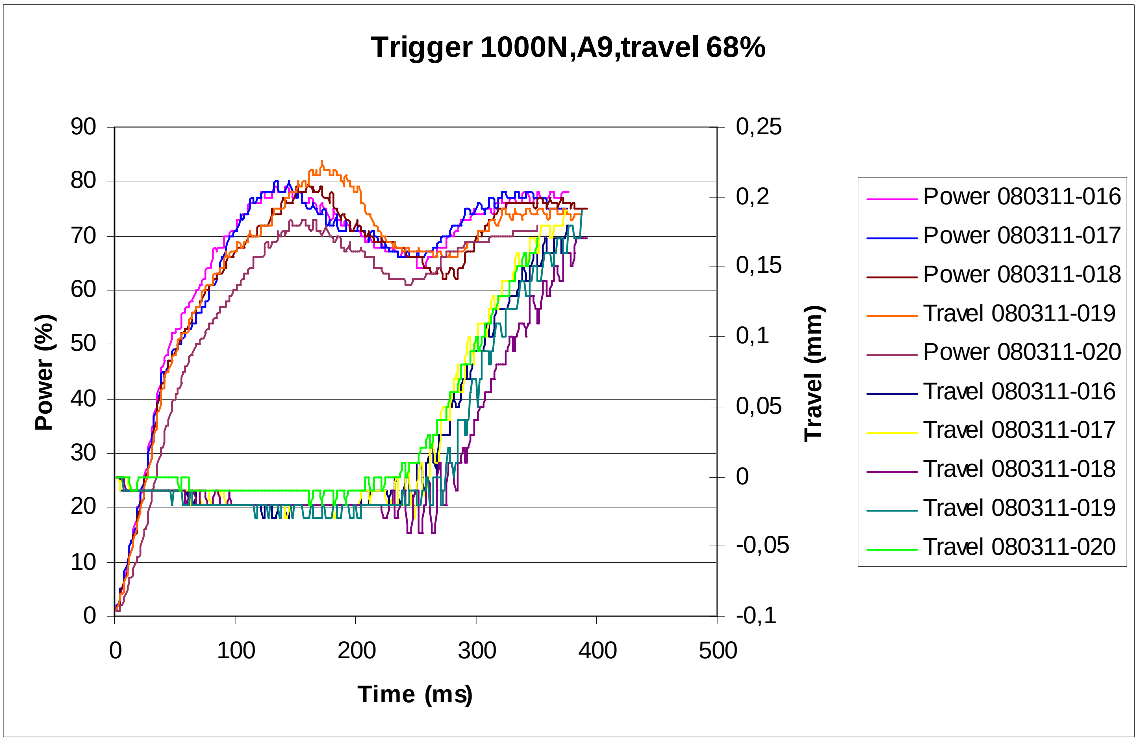

Figure 52. Trigger 1000 N, Amplitude 9 and Travel 68%

Table 29. Results: Trigger 300 N, Amplitude 1 and Travel 38%

Material: C-PEI			ED description: PEI flat			
WELDING CYCLE						
Force build-up		Trigger (N)		300		
Melting on		Rise of force (N/mm)		0		
		Amplitude (µm)		19.8		
		Travel (%)		38		
Solidification		Force (N)		1000		
		Holding time (ms)		1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.25	34	2353	1360.69	11814.26	37.02
_002	0.27	40	1551	1106.43	10228.32	32.06
_003	0.26	38	1880	1246.93	8806.30	27.43
_004	0.27	36	1716	1024.81	9173.70	28.55
_005	0.25	34	1845	1172.48	10770.18	33.67

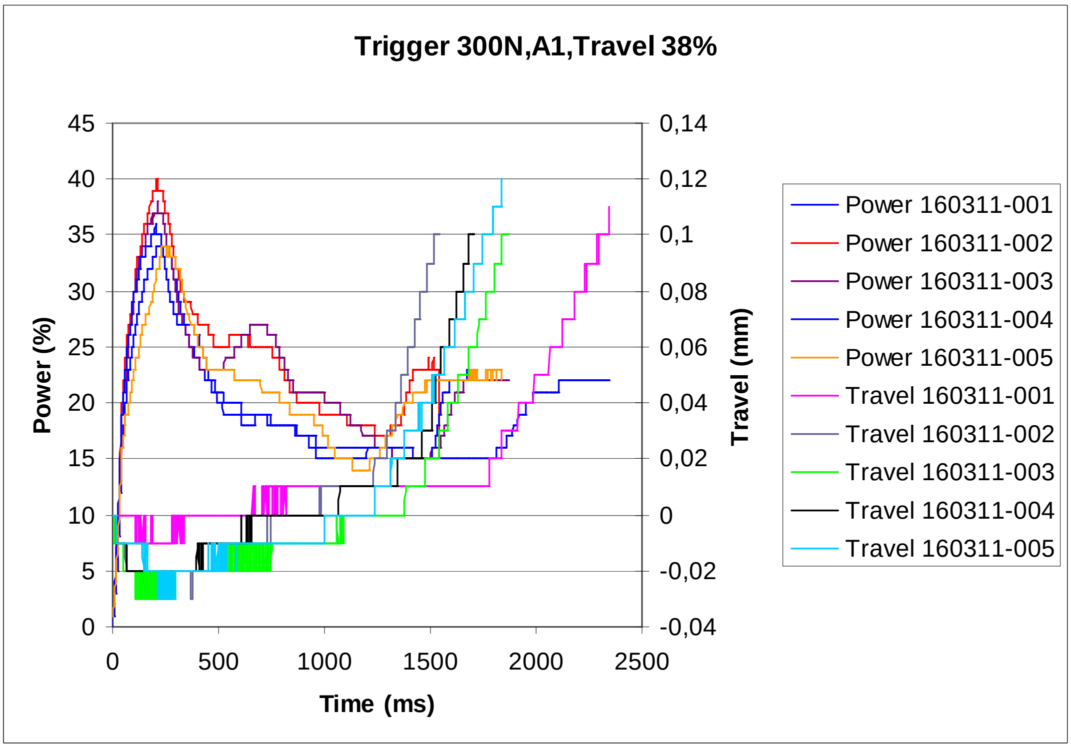

Figure 53. Trigger 300 N, Amplitude 1 and Travel 38%

Table 30. Results: Trigger 500 N, Amplitude 1 and Travel 55%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		55			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_006	0.27	39	1024	836.81	10064.28	31.35
_007	0.27	36	1092	835.42	11141.26	34.72
_008	0.28	39	975	779.68	10634.25	33.2
_009	0.27	37	1086	819.49	11321.36	35.22
_010	0.25	33	1442	1039.09	10687.24	33.31

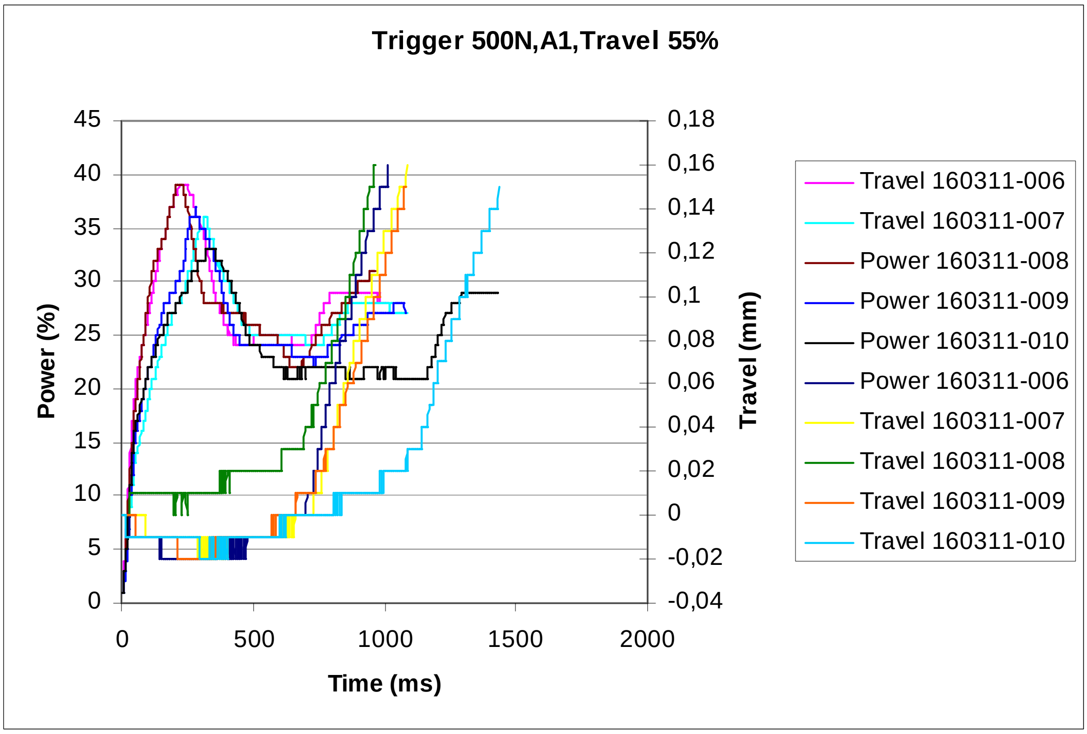

Figure 54. Trigger 500 N, Amplitude 1 and Travel 55%

Table 31. Results: Trigger 1000 N, Amplitude 1 and Travel 60%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			1000		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			19.8		
	Travel (%)			60		
Solidification	Force (N)			1000		
	Holding time (ms)			1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_011	0.23	40	939	818.9	11555.15	36.16
_012	0.22	44	853	832.28	8060.74	25.04
_013	0.23	43	667	640.19	8705.01	27.17
_014	0.22	41	726	679.8	12093.77	37.74
_015	0.23	41	756	707.3	12061.48	37.64

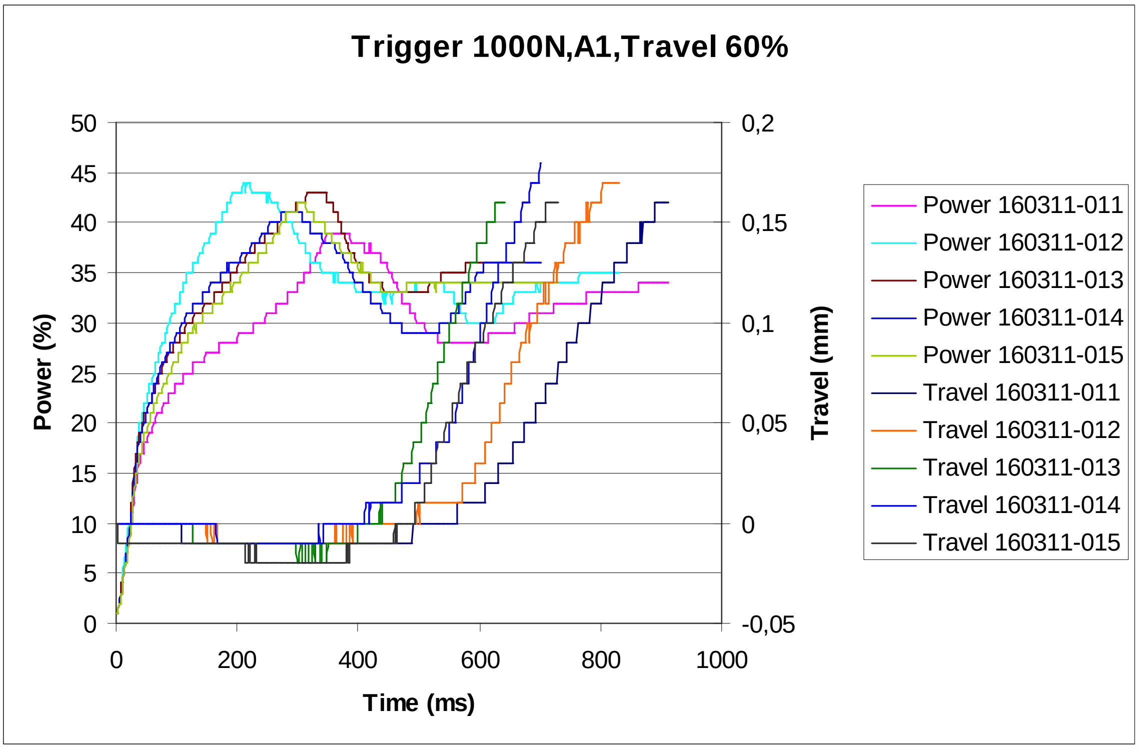

Figure 55. Trigger 1000 N, Amplitude 1 and Travel 60%

Table 32. Results: Trigger 1000 N, Amplitude 9 and Travel 57%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up		Trigger (N)		1000		
Melting on		Rise of force (N/mm)		0		
		Amplitude (µm)		33		
		Travel (%)		57		
Solidification		Force (N)		1000		
		Holding time (ms)		1200		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160311_ UW 180311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_016	0.23	75	356	618.81	11330.55	35.43
_001	0.24	82	405	741.54	9983.18	31.11
_002	0.26	80	356	645.04	9860.73	30.73
_003	0.25	80	389	699.29	9954.98	31.14
_004	0.23	76	390	669.29	11744.20	36.84

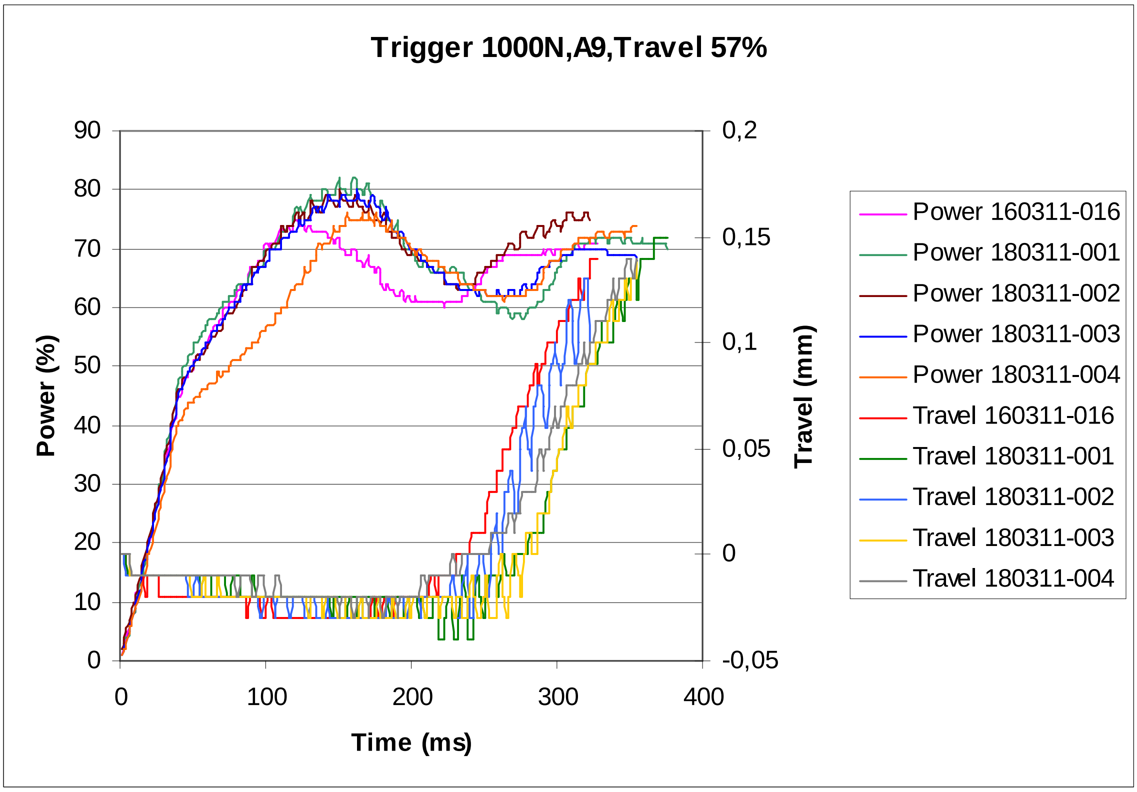

Figure 56. Trigger 1000 N, Amplitude 9 and Travel 57%

Table 33. Results: Trigger 500 N, Amplitude 1 and Travel 90%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		90			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 240311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.37	38	1856	1394.64	11175.40	35.24
_002	0.38	36	1380	1080.92	9628.79	30.13
_003	0.38	37	1671	1261.27	11252.57	35
_004	0.36	37	2352	1729.05	9998.11	31.18
_005	0.35	41	1496	1225.75	10026.85	31.21

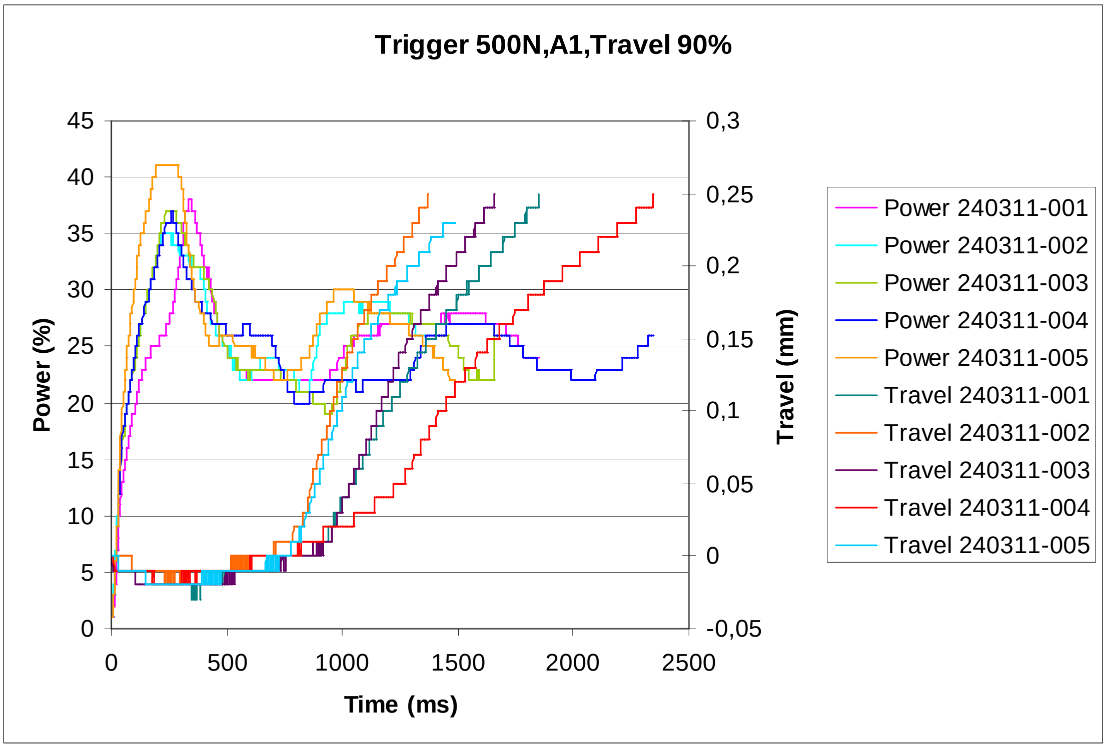

Figure 57. Trigger 500 N, Amplitude 1 and Travel 90%

Table 34. Results: Trigger 1000 N, Amplitude 1 and Travel 70%

Material: C-PEI		ED description: PEI flat				
WELDING CYCLE						
Force build-up	Trigger (N)		1000			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		70			
Solidification	Force (N)		1000			
	Holding time (ms)		1200			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 240311_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_010	0.25	41	930	828.39	11734.53	36.49
_011	0.24	41	856	775.02	11356.52	35.48
_013	0.25	41	807	723.41	11663.27	36.26
_014	0.24	41	847	748.18	12976.83	40.41
_015	0.25	41	680	657.69	11820.76	37.11

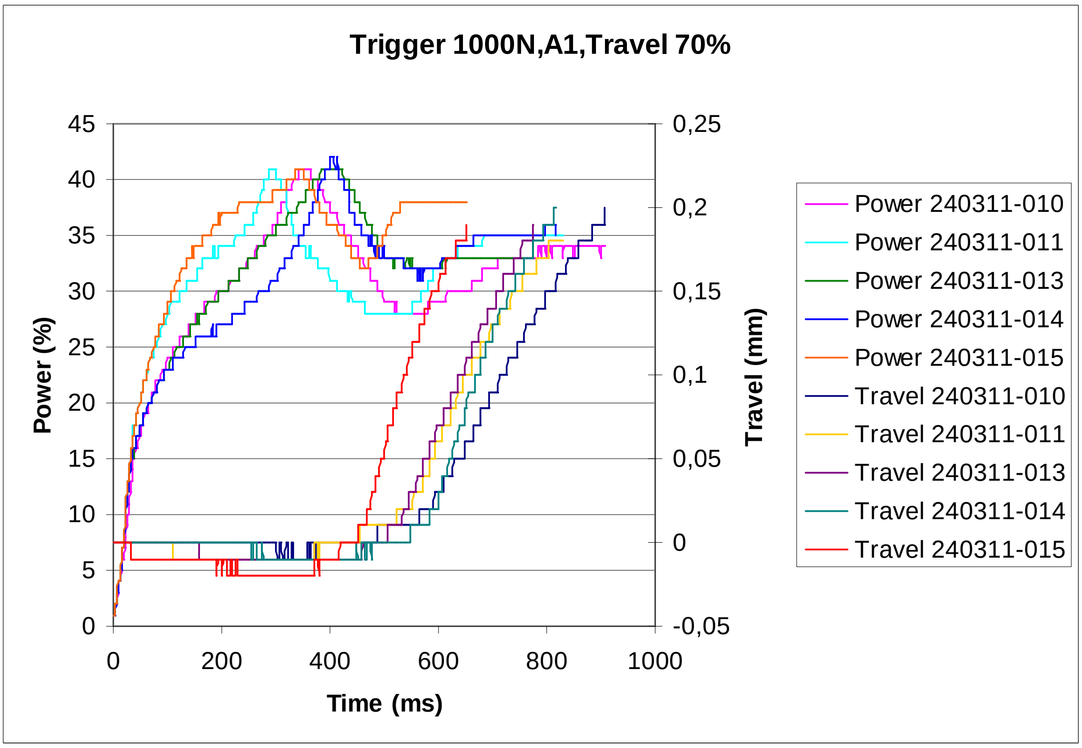

Figure 58. Trigger 1000 N, Amplitude 1 and Travel 70%

Table 35. Results: Trigger 500 N, Amplitude 1 and Travel 30%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			500		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			19.8		
	Travel (%)			30		
Solidification	Force (N)			1000		
	Holding time (ms)			3000		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 300511_ UW 070611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_002	0.19	39	1032	836.51	9826.26	30.76
_003	0.18	39	964	785.85	9724.06	30.43
_004	0.19	38	819	671.76	10501.72	32.61
_005	0.19	38	876	741.03	9646.84	30.36
_001	0.20	35	824	649.68	11188.76	35.12

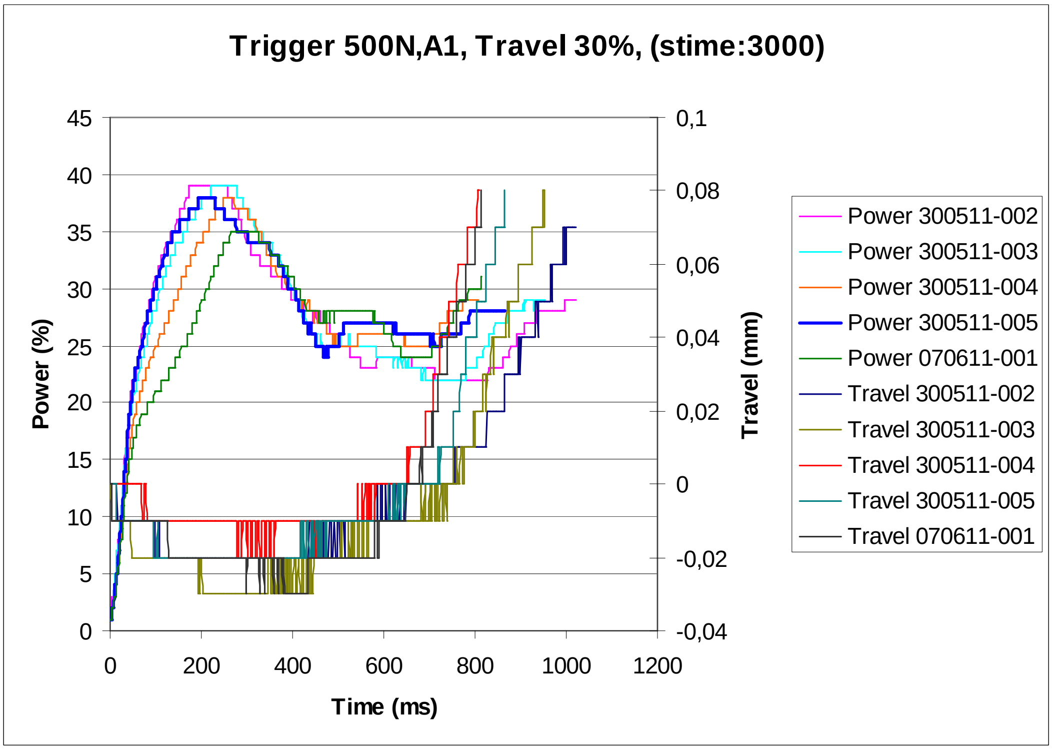

Figure 59. Trigger 500 N, Amplitude 1 and Travel 30%

Table 36. Results: Trigger 500 N, Amplitude 1 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 300511_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_007	0.35	36	1250	1011.26	12248.89	38.18
_008	0.36	38	1251	1042.64	12318.64	38.37
_009	0.35	38	1132	945.84	12163.84	37.98
_010	0.35	33	1661	1203.47	11172.66	35.25
_011	0.35	41	1194	1069.08	12487.39	38.88

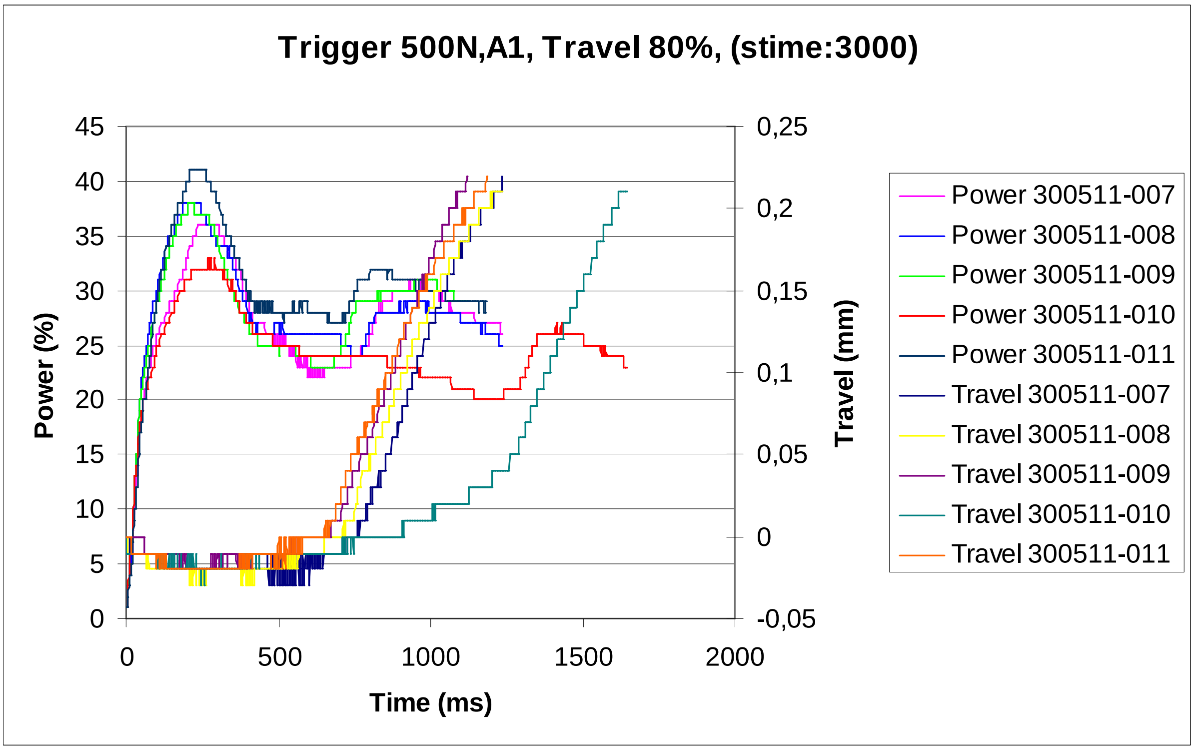

Figure 60. Trigger 500 N, Amplitude 1 and Travel 80%

Table 37. Results: Trigger 300 N, Amplitude 1 and Travel 38%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			300		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			19.8		
	Travel (%)			38		
Solidification	Force (N)			1000		
	Holding time (ms)			3000		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 060611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_004	0.26	29	1803	1128.37	11249.36	35.27
_005	0.26	35	1677	1187.54	11047.57	34.36
_006	0.27	35	1732	1102.51	11960.78	37.28
_007	0.28	35	1588	1046.44	11852.74	36.88
_008	0.27	37	1302	940.75	11504.44	35.77

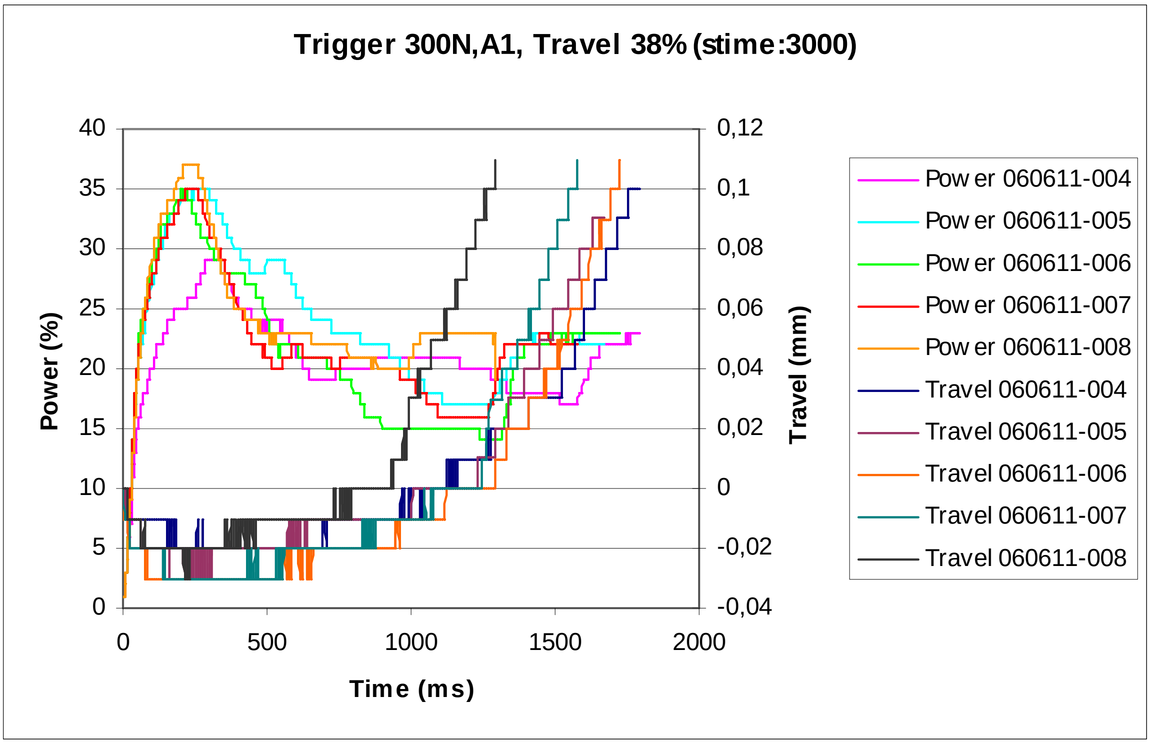

Figure 61. Trigger 300 N, Amplitude 1 and Travel 38%

Table 38. Results: Trigger 1000 N, Amplitude 1 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			1000		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			19.8		
	Travel (%)			80		
Solidification	Force (N)			1000		
	Holding time (ms)			3000		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 300511_ UW 060611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_012	0.28	37	1368	1213.29	11288.02	35.62
_013	0.27	40	1076	1021.27	12081.68	37.9
_014	0.28	41	1071	1025.5	11027.39	34.91
_001	0.27	39	992	921.97	12184.47	37.88
_002	0.27	42	966	962.2	11834.68	36.89

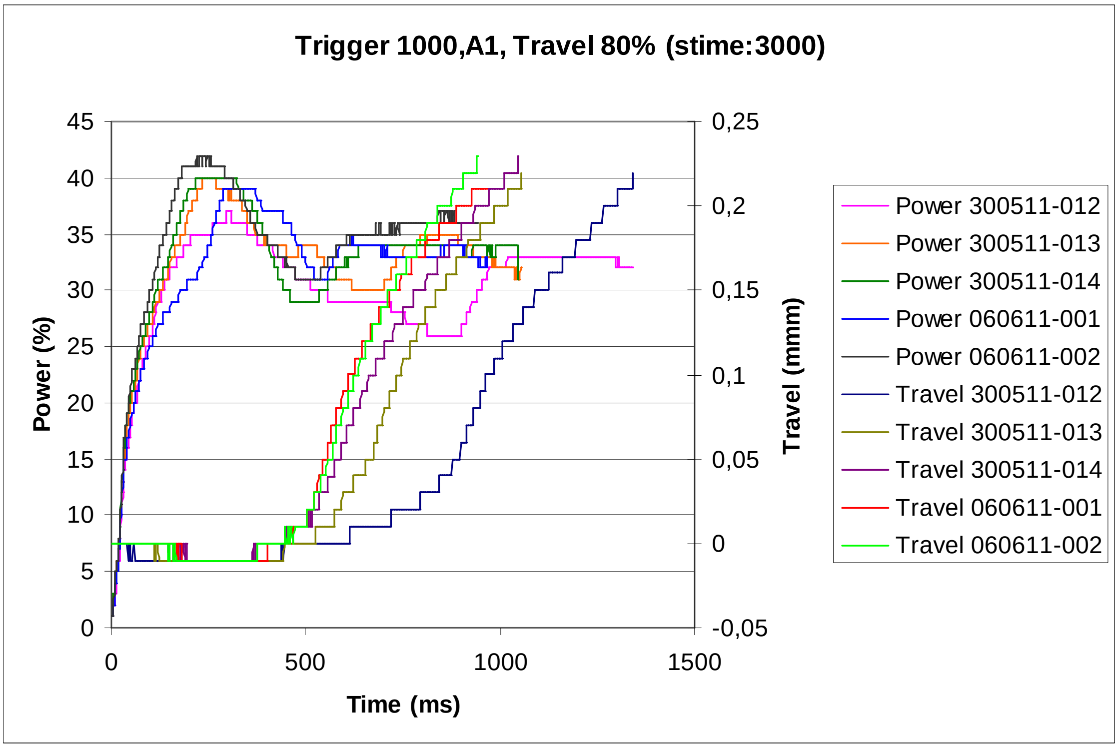

Figure 62. Trigger 1000 N, Amplitude 1 and Travel 80%

Table 39. Results: Trigger 1500 N, Amplitude 1 and Travel 90%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		1500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		90			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 060611_ UW 070611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_012	0.26	52	909	1054.66	12314.89	38.24
_013	0.26	49	862	974.66	12187.41	38.15
_014	0.27	41	1194	1131.49	11919.88	37.27
_002	0.27	53	982	1106.87	11233.29	35.10
_003	0.27	54	910	1047.97	10886.10	34.13

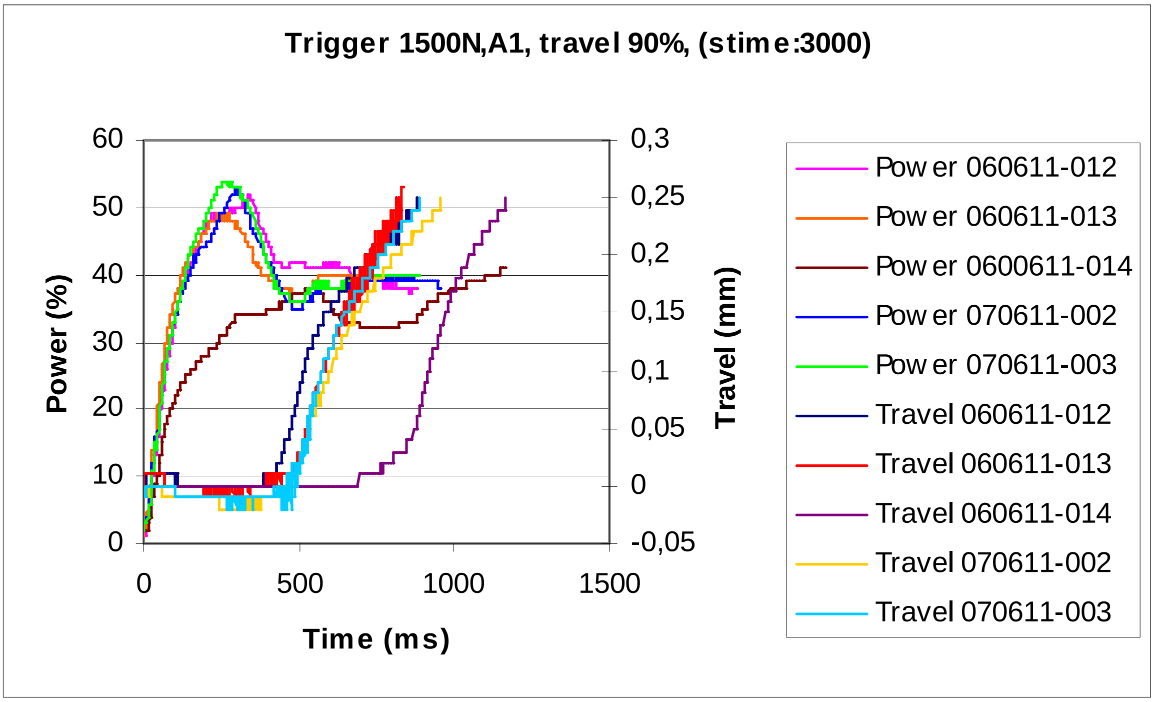

Figure 63. Trigger 1500 N, Amplitude 1 and Travel 90%

Table 40. Results: Trigger 300 N, Amplitude 1 and Travel 80%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		300			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		80			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 240311_ UW 060611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_006	0.44	35	2739	1732.88	12334.56	38.71
_007	0.42	37	2487	1587.95	11943.95	37.16
_009	0.41	37	2052	1403.76	13836.19	43.02
_010	0.40	36	1944	1321.74	13136.99	41.01
_011	0.41	35	2261	1427.56	12606.53	39.27

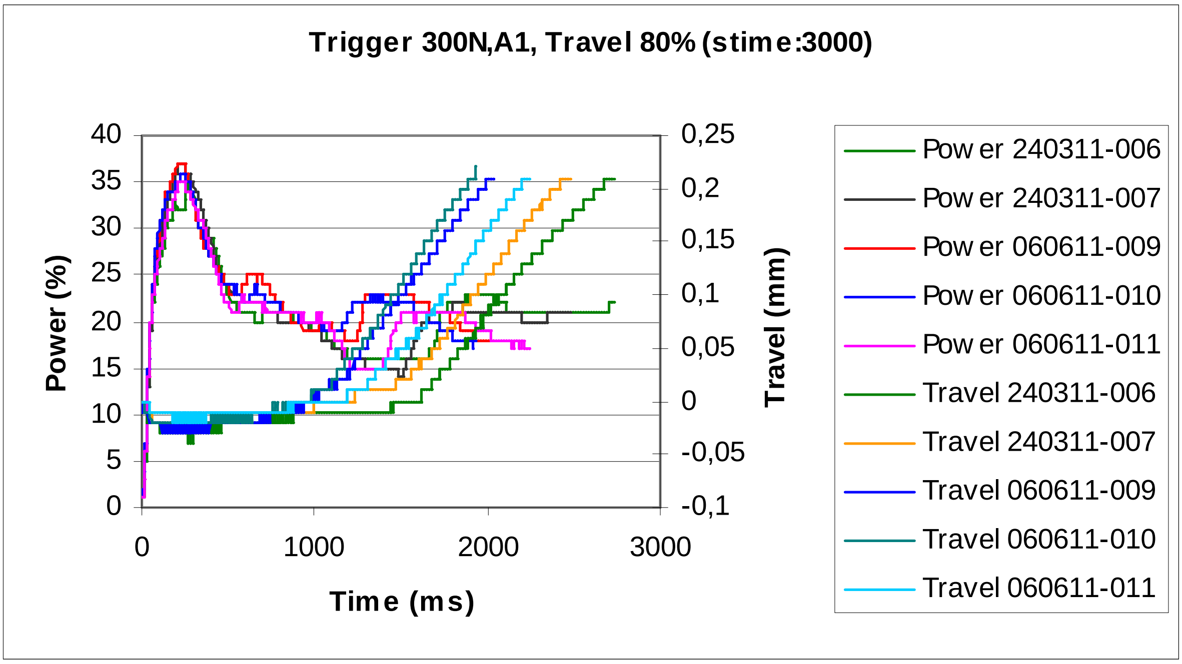

Figure 64. Trigger 300 N, Amplitude 1 and Travel 80%

Table 41. Results: Trigger 1500 N, Amplitude 1 and Travel 60%

Material: C-PEI	ED description: PEI flat					
WELDING CYCLE						
Force build-up	Trigger (N)		1500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		60			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 090611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_008	0.18	37	1078	934.51	10432.10	32.38
_009	0.18	48	663	728.41	10560.24	32.91
_010	0.18	48	740	800.18	11011.72	34.57
_011	0.18	44	878	841.67	10497.40	32.75
_012	0.19	46	802	819.63	11171.95	34.84

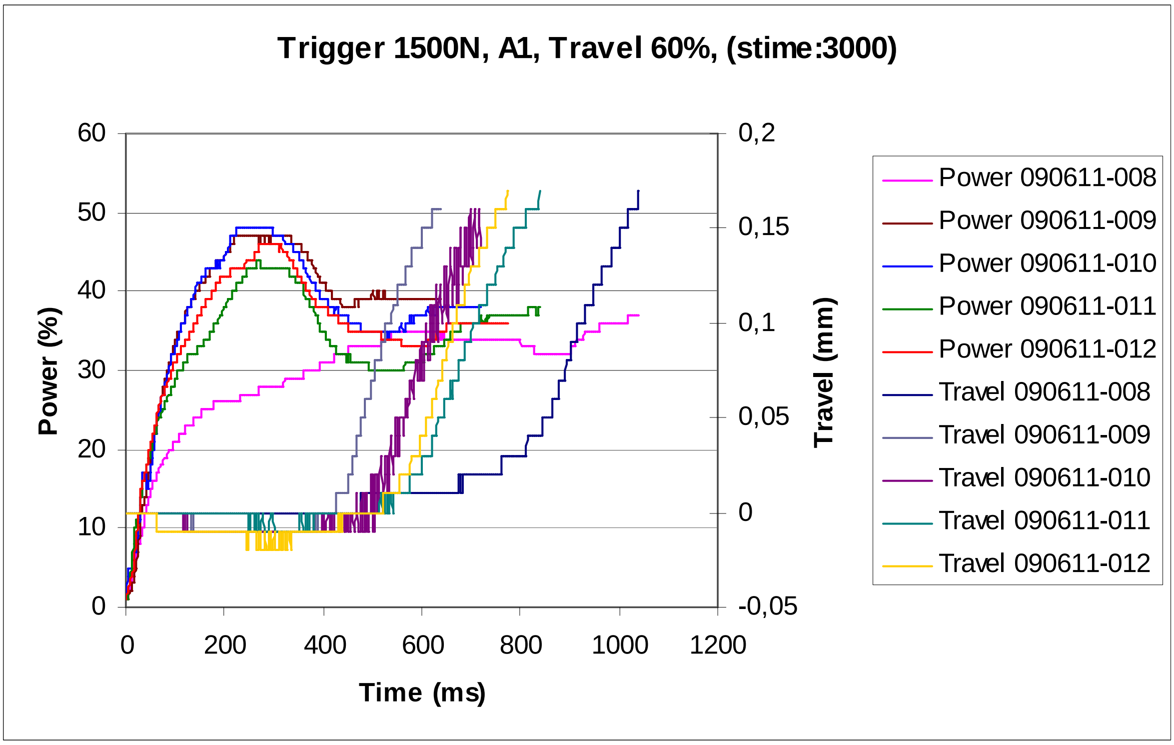

Figure 65. Trigger 1500 N, Amplitude 1 and Travel 60%

Table 42. Results: Trigger 300 N, Amplitude 9 and Travel 90%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		300			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		33			
	Travel (%)		90			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 090611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_013	0.49	55	1090	1429.78	11536.22	36.06
_014	0.48	61	1052	1377.68	10961.30	34.10
_015	0.49	63	1016	1416.86	11526.94	36.07
_016	0.49	59	1086	1426.28	11204.88	35.32
_17	0.55	62	1110	1506.51	9409.82	29.7

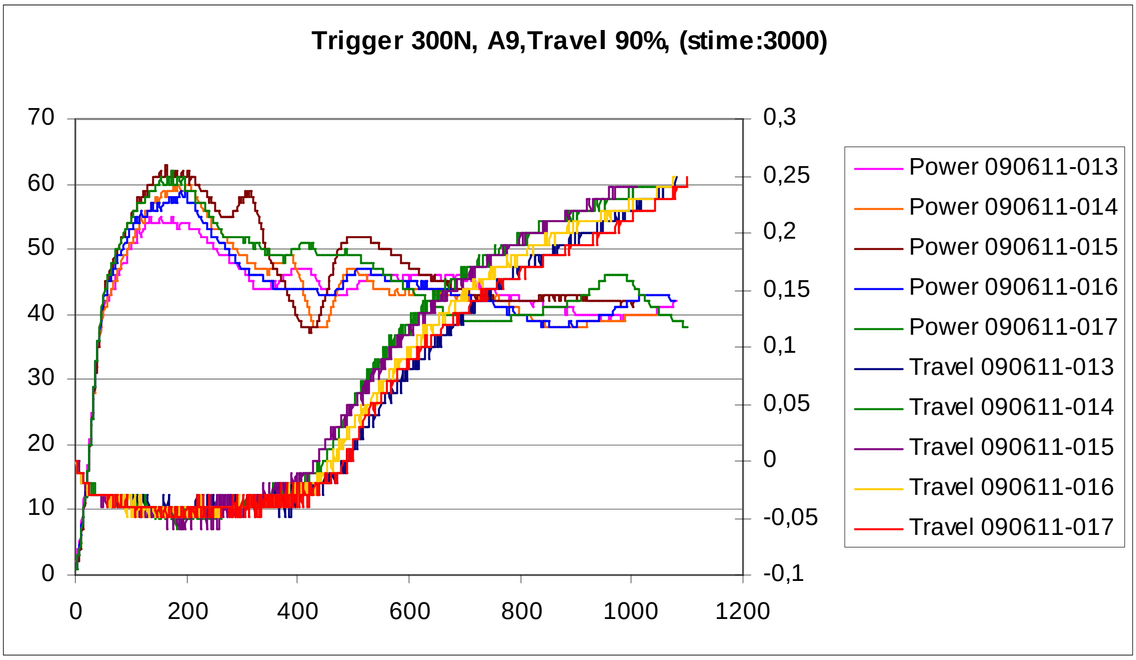

Figure 66. Trigger 300 N, Amplitude 9 and Travel 90%

Table 43. Results: Trigger 300 N, Amplitude 1 and Travel 50%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)			300		
Melting on	Rise of force (N/mm)			0		
	Amplitude (µm)			19.8		
	Travel (%)			50		
Solidification	Force (N)			1000		
	Holding time (ms)			3000		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 150611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_001	0.28	37	1476	1064.67	11064.76	34.57
_002	0.29	35	1781	1235.63	11897.08	37.04
_003	0.28	34	1779	1136.66	10507.52	32.69
_004	0.29	34	1558	1046.5	10977.31	34.08
_005	0.30	34	1640	1086.34	11743.19	36.66

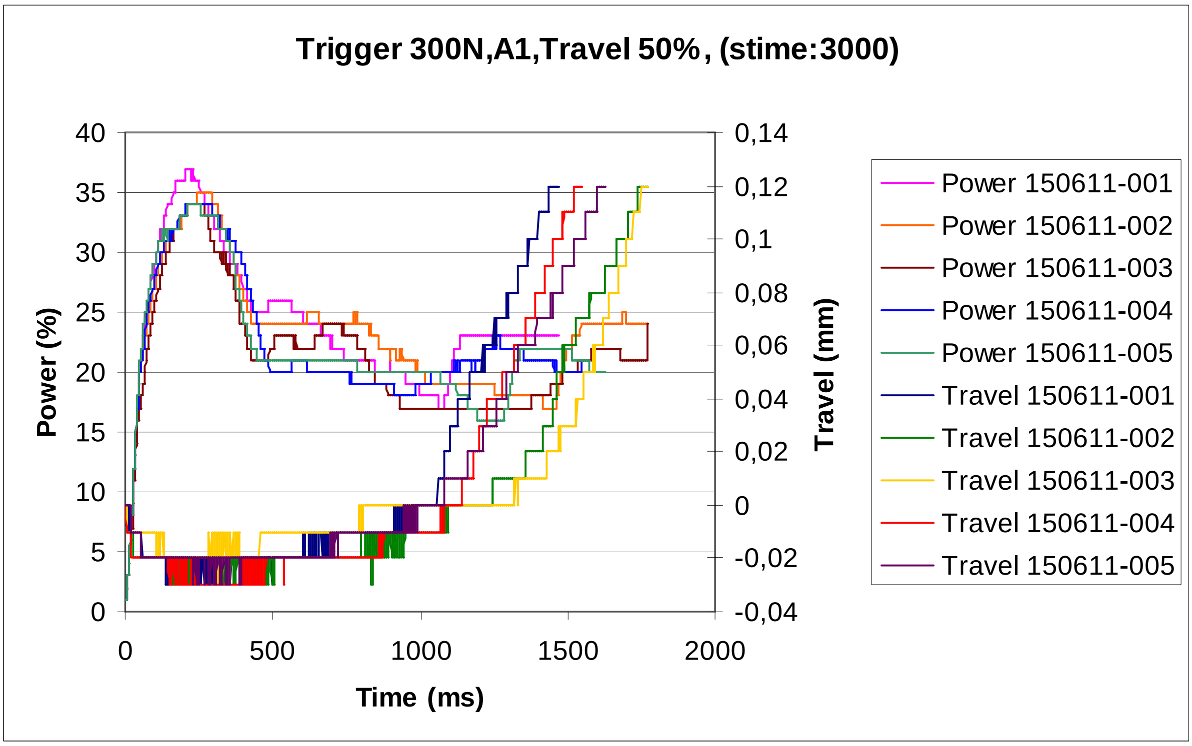

Figure 67. Trigger 300 N, Amplitude 1 and Travel 50%

Table 44. Results: Trigger 300 N, Amplitude 1 and Travel 30%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		300			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		30			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 150611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_006	0.20	32	1635	1150.58	8737.43	27.20
_007	0.22	38	1408	1007.9	10039.85	31.16
_008	0.23	36	1438	956.09	10403.31	32.41
_009	0.23	33	1253	922.82	10306.29	32.26
_010	0.24	34	1423	1002.5	10697.16	33.30

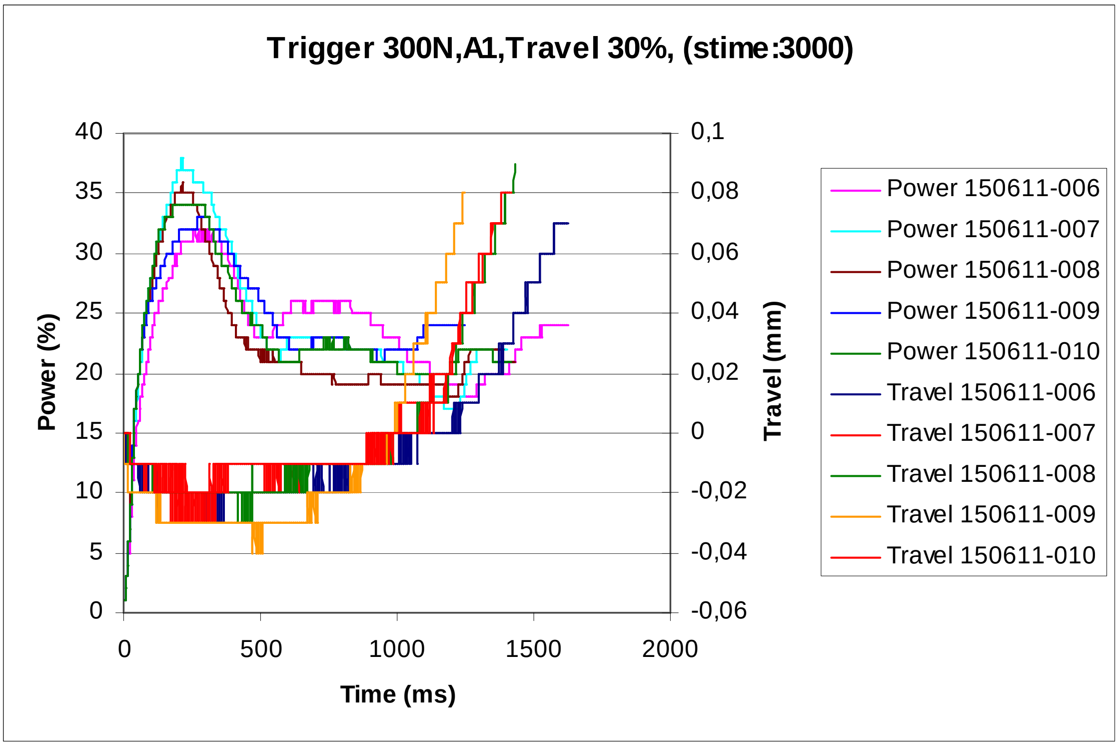

Figure 68. Trigger 300 N, Amplitude 1 and Travel 30%

Table 45. Results: Trigger 500 N, Amplitude 1 and Travel 68%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		500			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		68			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 150611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_011	0.31	37	1314	1085.38	11319.89	35.27
_012	0.31	37	1039	864.02	11628.24	36.22
_013	0.31	38	1104	928.84	12041.08	37.40
_014	0.32	31	1624	1143.92	11332.89	35.25
_015	0.31	39	1076	900.25	12529.01	39.14

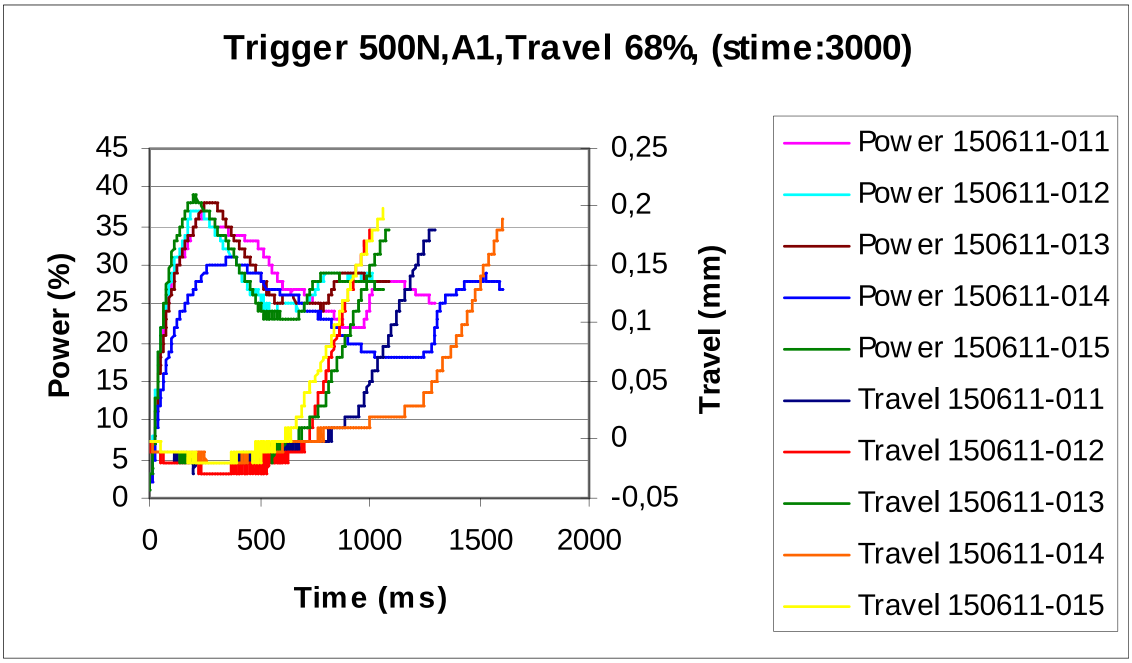

Figure 69. Trigger 500 N, Amplitude 1 and Travel 68%

Table 46. Results: Trigger 1000 N, Amplitude 1 and Travel 70%

Material: C-PEI ED description: PEI flat		
WELDING CYCLE		
Force build-up	Trigger (N)	1000
Melting on	Rise of force (N/mm)	0
	Amplitude (µm)	19.8
	Travel (%)	70
Solidification	Force (N)	1000
	Holding time (ms)	3000

OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_010	0.25	44	904	900	10827.68	33.71
_011	0.25	44	926	926.75	11220.29	34.84
_012	0.26	40	1032	1000.89	10896.59	33.90
_013	0.25	43	845	833.53	10956.74	34.10
_014	0.26	43	895	912.47	10679.66	33.32

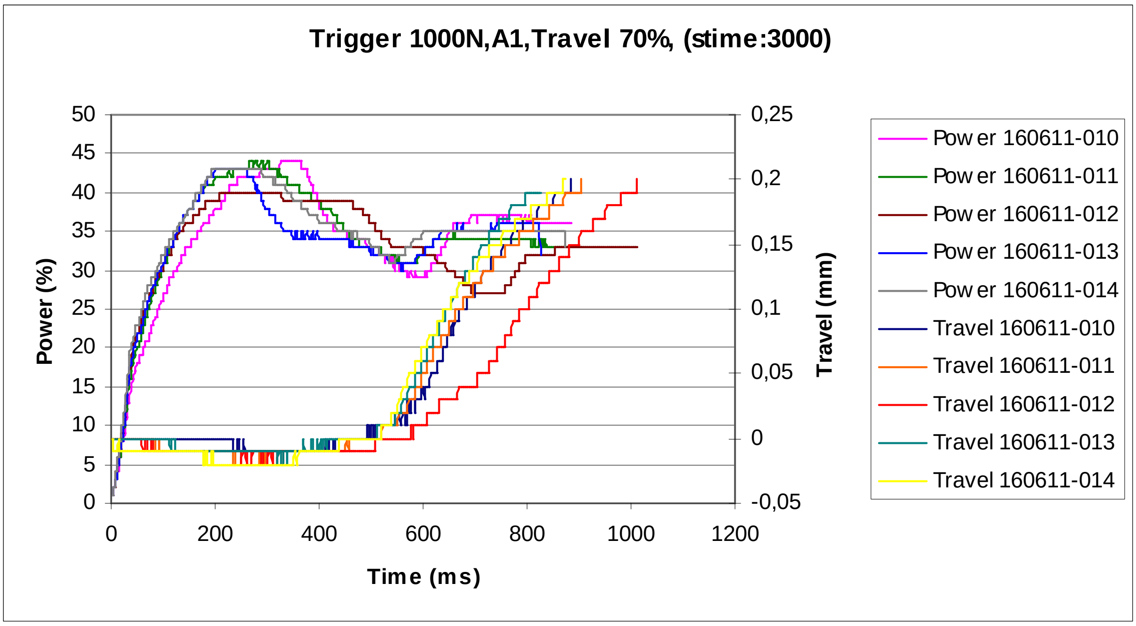

Figure 70. Trigger 1000 N, Amplitude 1 and Travel 70%

Table 47. Results: Trigger 1000 N, Amplitude 1 and Travel 30%

Material: C-PEI ED description: PEI flat						
WELDING CYCLE						
Force build-up	Trigger (N)		1000			
Melting on	Rise of force (N/mm)		0			
	Amplitude (µm)		19.8			
	Travel (%)		30			
Solidification	Force (N)		1000			
	Holding time (ms)		3000			
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_015	0.14	42	705	645.16	8141.07	25.302
_016	0.14	42	645	640.93	9421.11	29.38
_017	0.14	42	594	580.51	9374.37	29.31
_018	0.14	42	719	661.58	8468.78	26.36
_019	0.14	42	548	523.38	8662.04	27.16

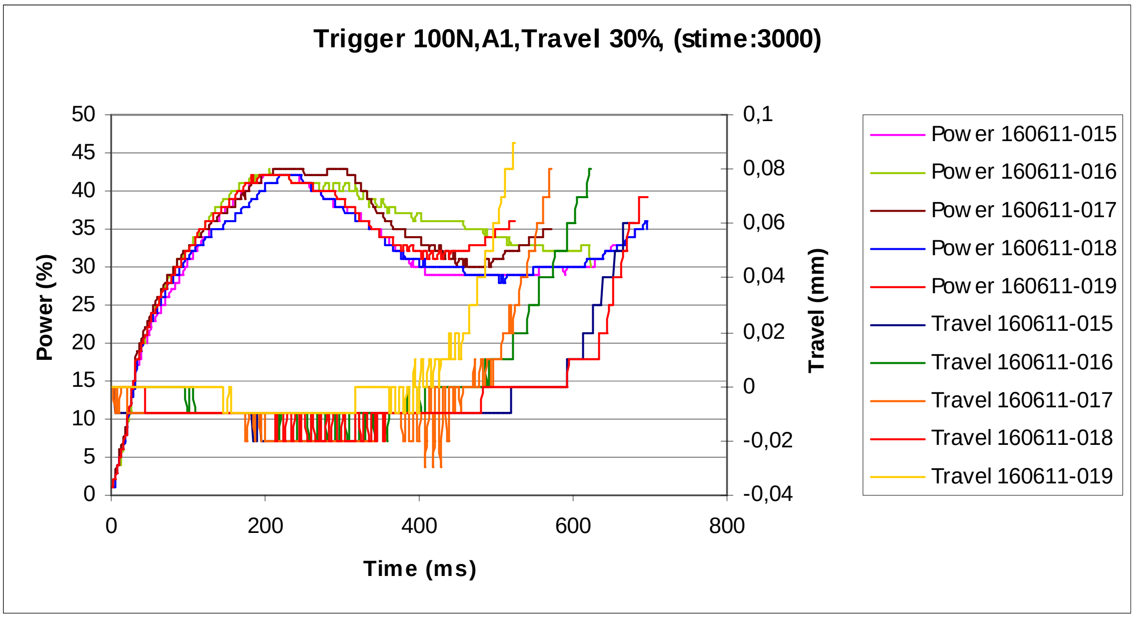

Figure 71. Trigger 1000 N, Amplitude 1 and Travel 30%

Table 48. Results: Trigger 1500 N, Amplitude 1 and Travel 30%

Material: C-PEI		ED description: PEI flat				
WELDING CYCLE						
Force build-up		Trigger (N)		1500		
Melting on		Rise of force (N/mm)		0		
		Amplitude (µm)		19.8		
		Travel (%)		30		
Solidification		Force (N)		1000		
		Holding time (ms)		3000		
OUTPUT					**MECHANICAL TESTING**	
Sample ref. UW 160611_	Weld distance (mm)	Max. Power (%)	Time (ms)	Energy (Ws)	Max. Load (N)	LSS (MPa)
_020	0.10	45	719	735.02	8267.79	25.87
_021	0.11	53	504	605.6	7794.26	24.57
_022	0.10	50	557	628.22	7747.59	24.42
_023	0.11	47	624	664.42	8608.88	27.17
_024	0.10	48	703	751.53	8123.88	25.39

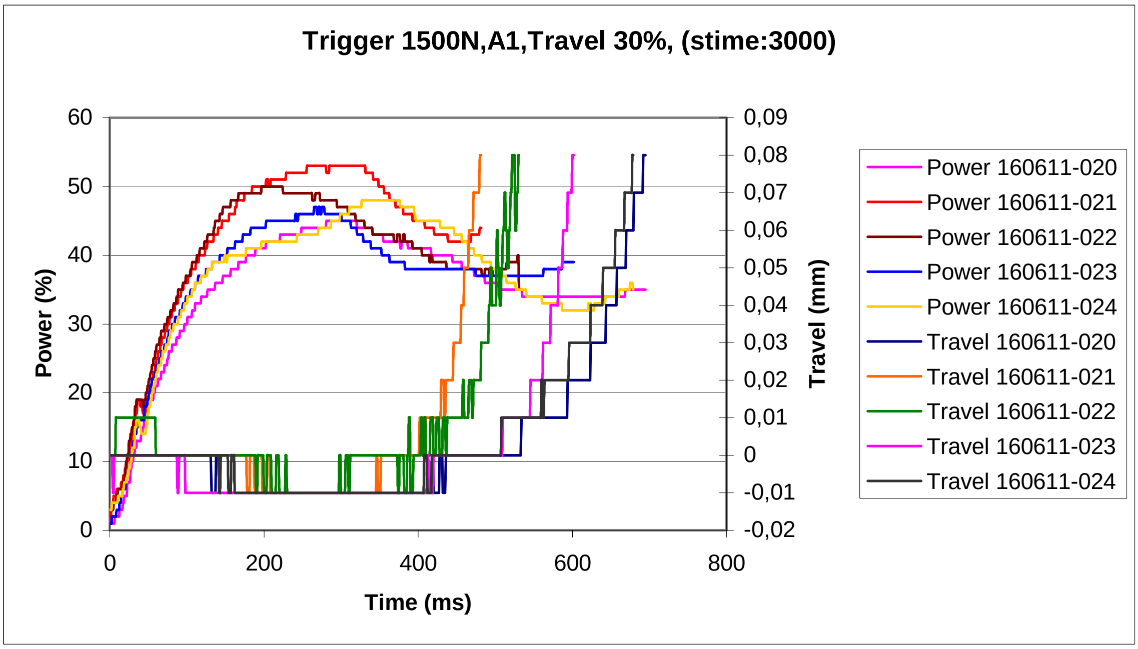

Figure 72. Trigger 1500 N, Amplitude 1 and Travel 30%

Appendix II:

Material Safety Data Sheet (MSDS)