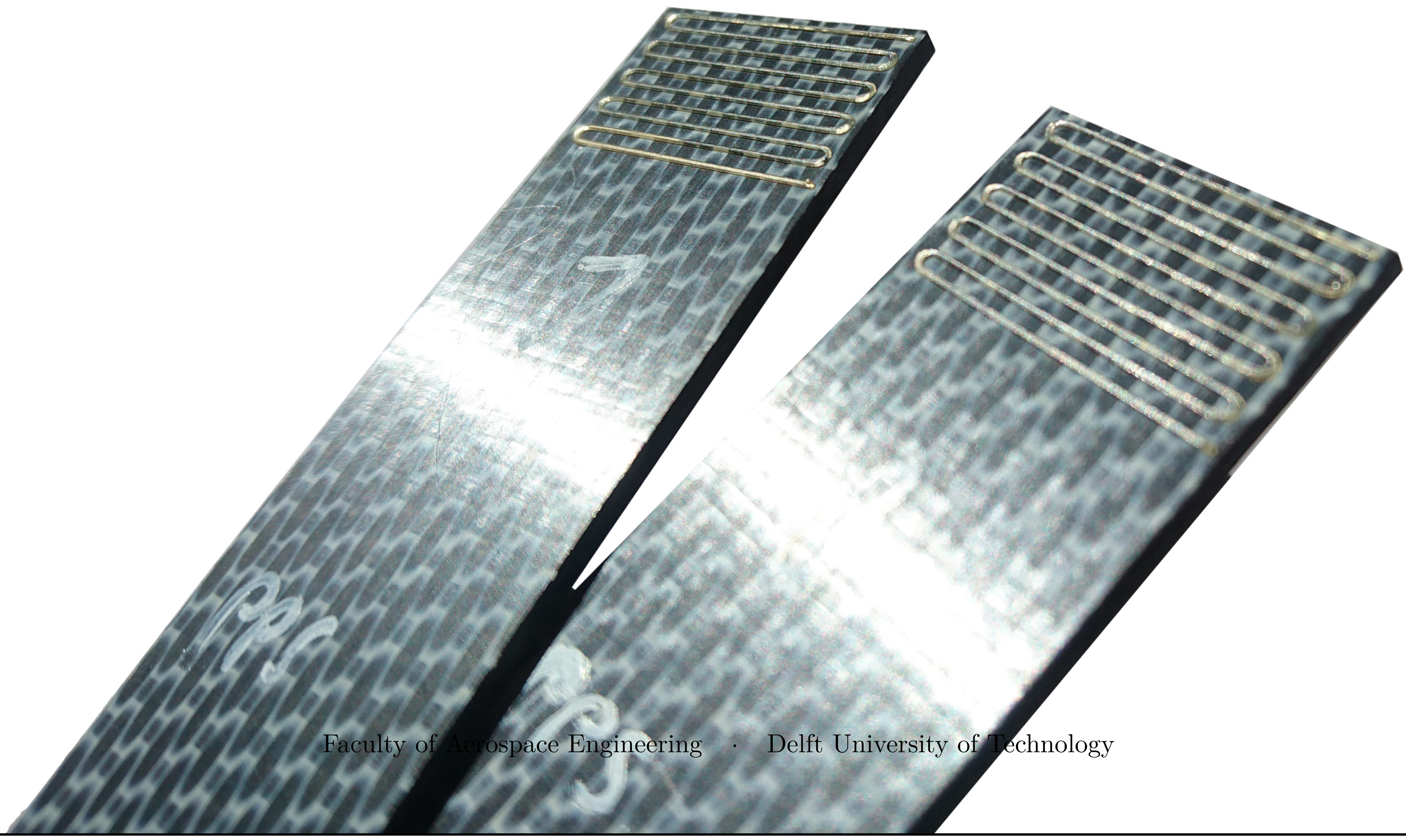
Master of Science Thesis

Investigating the use of Fused Deposition Modeling as Energy Director application method for Ultrasonic Welding of Thermoplastic Composites

M.A.P. Kerssemakers



Faculty of Aerospace Engineering · Delft University of Technology

Investigating the use of Fused Deposition Modeling as Energy Director application method for Ultrasonic Welding of Thermoplastic Composites

by

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The undersigned hereby certify that they have read and recommended to the Faculty of Aerospace Engineering for acceptence a thesis entitled "**Investigating the use of Fused Deposition Modeling as Energy Director application method for Ultrasonic Welding of Thermoplastic Composites**" by **M.A.P. Kerssemakers** in partial fulfillment of the requirements for the degree of Master of Science.

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Abstract

The joining of high performance Thermoplastic Composite (TPC) structures by Ultrasonic Welding (USW) is considered a promising alternative for mechanical joining or adhesive bonding methods. The process is fast, clean, and highly automated. In the USW process, an intermediate, unreinforced polymer layer is required at the weld interface to concentrate the heat generation at this weld interface and is called the Energy Director (ED). This research investigates a new method to manufacture and apply this ED at the weld interface, being Fused Deposition Modeling (FDM).

With FDM, complex products can be manufactured directly from a Computer Aided Design (CAD) model, without additional mould or special tooling required. The goal is to simultaneously manufacture and adhere a dedicated ED geometry on a consolidated TPC substrate with FDM, such that no additional fixation step of the ED is required before welding. The new technique is successfully applied with a PEEK (Polyether ether Ketone) ED and a consolidated CF/PPS (Carbon fibre/Polyphenylene Sulfide) substrate. The deposited ED has sufficient bonding with the substrate that it remained fixated during handling prior to and during the weld process. This resulted in a successful weld, having similar strength and quality as found with welds having a loose, flat film as ED.

A challenge encountered in using FDM as manufacturing method of the EDs, is a non-uniform thickness distribution occurring in the ED. Additional research on the influence of a variation in thickness is done, where it is found to reduce the overall single Lap Shear Strength (LSS), and divide the fracture surface of a single weld in two areas welded to different weld stages.

Acknowledgments

Before you lies the final report of my master's thesis project. A project that started almost a year ago as a literature study and grew to the complete work presented here. Although I am very proud of the performed research and obtained results, I know this work would never have been completed without the help, encouragement, and guidance of a lot of people.

I want to start by thanking dr. ir. Genevieve Palardy and dr. ir. Irene Fernandez-Villegas for their supervision, expert knowledge, and guidance throughout my thesis. Along with the other members of the welding group, they were always willing to share their knowledge or give new insights to my work, which is greatly appreciated.

Furthermore, I want to give special thanks to my family for their support and encouragement, not only during this final work, but throughout my entire career as student at the TU Delft. My final words of thanks are for all of my friends, whom not only made my entire study that much more enjoyable, were also always ready to lend a helping hand.

Ties Kerssemakers
Delft, January 2018

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ACU	Advanced Control Unit
AM	Additive Manufacturing
CAD	Computer Aided Design
CF	Carbon Fibre
CUW	Continuous Ultrasonic Welding
DASML	Delft Aerospace Structures and Materials Laboratory
ED	Energy Director
FB	Fusion Bonding
FDM	Fused Deposition Modeling
FS	Fracture Surface
LSS	Lap Shear Strength
OM	Optical Microscopes
PEEK	Polyether Ether Ketone
PPS	Polyphenylene Sulfide
STL	Stereolithography
$\mathbf{T}_g$	Glass Transition Temperature
$\mathbf{T}_m$	Melting Temperature
TC	Thermocouple
TP	Thermoplastic
TPC	Thermoplastic Composite
TS	Thermoset

TSC Thermoset Composite

USW Ultrasonic Welding

Chapter 1

Introduction

To meet ever more strict emission regulations the aerospace, maritime, and automotive industries are looking to make their structures more lightweight to save fuel. This is in part done by replacing metallic structures with high performance composite structures. Fibre reinforced polymers offer better strength- and stiffness-to-weight ratios, and have better fatigue life than their metallic counterparts [1]. Different fibres used are for example Carbon Fibre (CF), Glass Fibres, and Aramid fibres. The polymers can be divided into Thermosets (TSs) like Epoxy, and Thermoplastics (TPs) like Polyether Ether Ketone (PEEK). Currently, most (primary) structures in the aerospace industry are manufactured from Thermoset Composites (TSCs). However, an increase in the use of Thermoplastic Composites (TPCs) is seen, which is attributed to their relative high toughness, easy storage, and cost-effective manufacturing process [2]. Another advantage of using TPCs is the ability to join them using Fusion Bonding (FB), or welding, instead of traditional joining methods like mechanical fastening or adhesive bonding [3, 4].

Ultrasonic Welding (USW) is a FB method that is used to join unreinforced thermoplastics for decades and proven to be fast, clean, and highly automated [5, 6]. With the increasing use of TPCs in structural applications, research on implementing USW as joining mechanism is increasingly being done [7–9]. Bonds formed with USW are of comparable quality and strength as autoclave consolidated or compression molded parts [10]. A comparison between ultrasonic spot welds and riveted joints revealed that similar in-plane load carrying capabilities can be achieved, but the out-of-plane load carrying capabilities of the spot-welded joints proved inferior to the riveted joints [4].

Within the USW process for TPCs an unreinforced polymer layer is required at the weld interface, the so called Energy Director (ED). The ED concentrates heat generation at this interface and has a big influence on the welding process. Numerous shapes and application methods for the ED have been investigated, for example a co-moulded triangular protrusion [11], a loose, flat film of resin [12], or co-consolidated flat strips [13]. This report adds another application method for the ED, being Fused Deposition Modeling (FDM) or more commonly, but wrongly, called 3D-printing. It is a form of Additive Manufacturing (AM) where products are manufactured in a layer-by-layer fashion without the need for a mould [14, 15].

During FDM molten material is extruded from a heated nozzle which moves according to a predetermined path to create the product. The material is selectively deposited to form the required product. Almost all TP polymers can be used in this process if the machine can withstand the sometimes high required temperatures. With FDM complex shapes can be manufactured fast and highly automated, without the need for additional moulds or tooling [16]. Previous research by Plaisier [17] showed that it is possible to simultaneously manufacture and join an extruded product on an already consolidated TPC substrate. It is therefore believed that using FDM to apply the ED on a TPC substrate could lead to an even higher level of automation of the USW process. Since both fully integrated EDs and loose EDs have proven to result in successful welds the amount of bonding between the ED and substrate is believed to be sufficient if the combination can withstand handling forces arising due to moving of the part and be welded without additional fixation.

This research is split into two parts. Part 1 focuses on simultaneously manufacturing and adhering the ED on a consolidated substrate with the FDM process. This was successfully achieved with a PEEK ED being extruded on consolidated CF/Polyphenylene Sulfide (PPS) substrates. The formed bond between the ED and substrate is sufficient to withstand handling forces and the weld process without an additional fixation step. The achieved weld has similar strength as welds performed with the more conventional PEEK ED films and CF/PPS substrates. Besides this success, two challenge were encountered in this research, the first being that more still more bonding between the substrates and ED is required as some of the ED shifted at the start of the weld. Also, no bonding was achieved between CF/PEEK substrates and the PEEK ED. The second challenge is an irregular thickness in the extruded EDs, which can lead to uneven melting and flow of the ED [13].

The second part of this research has a focus on the influence of a thickness variation in the ED by welding substrates with an ED having a deliberate thickness step. The ED is divided into two equal areas with different thickness values, called the Split ED. Six configurations are used, where the reference case has a 0.25 mm thick layer on both sides. The remaining configurations have a 0.25 mm film on one side and a thinner film on the other side (0.20 mm, 0.15 mm, 0.10 mm, 0.05 mm, and 0.00 mm). With an increasing difference in thickness the single lap shear strength (LSS) decreases and the dispersion in measured LSS increases. The Fracture Surfaces (FS) show different failure mechanisms and weld stages within one weld.

1.1 Literature review on Ultrasonic Welding

Ultrasonic welding (USW) is a sub-category of the fusion bonding (FB) techniques [1]. Many methods to achieve a FB exist and an overview is given in figure 1.1. Each method heats up the weld interface to above the Melting Temperature (T_m) where the material is more viscous and able to flow. When the melted interfaces are pressed together the polymer chains from the different parts diffuse and entangle over the interface, forming a bond upon cooling [10]. A schematic overview of this process is given in figure 1.2.

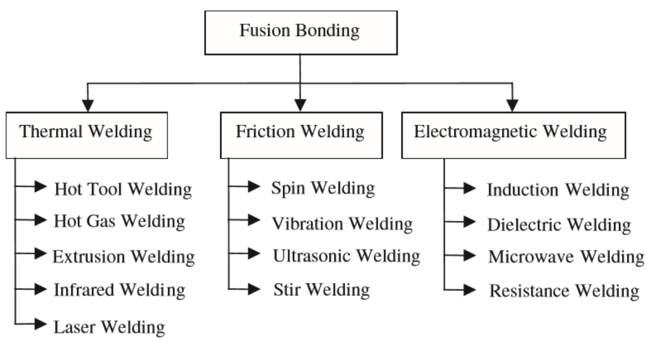


Figure 1.1: *Several fusion bonding techniques categorized by heat generation method, taken from [1]*

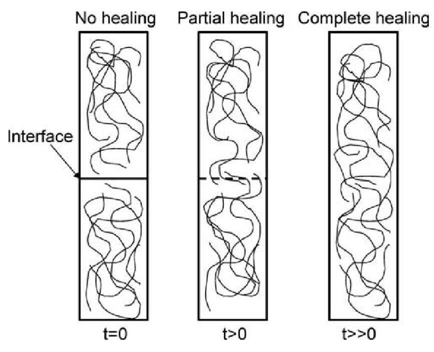


Figure 1.2: *Diffusion of polymer chains at the welding interface, taken from [10]*

This section continuous with a general description of the USW process and the ultrasonic welding machine in section 1.1.1. A detailed description of the melting process of the ED with the different weld stages is given in section 1.1.2. The influence of process parameters like welding force, amplitude, and of the ED shape and size on the weld process is explained in section 1.1.3. Different methods to apply the ED on the substrates are mentioned in section 1.1.4, followed by a brief description on the continuous ultrasonic weld process.

1.1.1 General ultrasonic welding process

Within the USW process heat is generated at the weld interface by introducing a high frequency (20-70 kHz), low amplitude (1-250 μm) vibration in the substrates, causing frictional and viscoelastic heating, whilst simultaneously applying a pressure [10]. A neat resin layer or protrusion present between the substrates concentrates this heat generation at the weld interface and is called the energy director, or ED for short. The USW process is fast, achieving a bond with vibration times around 1 second. This leads to a high power demand limiting the area that can be welded. To join larger structures with USW, Continuous Ultrasonic Welding (CUW)) or sequential welding can be used, on which more information is given in section 1.1.5. The ultrasonic welder and three phases of the weld process are described in more detail below.

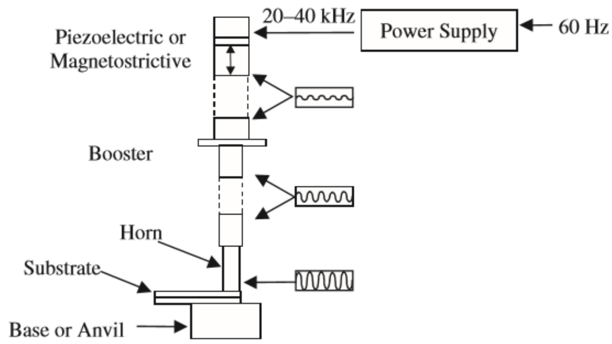


Figure 1.3: *Schematic overview of an ultrasonic welder, taken from [1]*

A schematic overview of an USW machine is given in figure 1.3. The vibration is induced in a piezoelectric via an alternating current. The amplitude of the vibration is amplified by a booster. The horn, or sonotrode, is connected to this booster and has an additional amplification to the amplitude. The substrates are fixed on a base and pressed together between this base and the sonotrode. Modern machines can stop the vibration phase after a set time, energy input, or sonotrode displacement.

Three distinct phases are present in the ultrasonic weld process, being the Force ramp-up phase, Vibration phase, and Consolidation phase. A description of these phases is given below:

Force ramp-up The sonotrode moves downward and starts to increase the force on the substrates and ED with a certain rate until the set weld force is reached. The welding force set, along with the area of the ED result in a certain amount of compressive stress on the ED, which influences the weld process as is described later in section 1.1.3.

Vibration phase The vibration phase is where the ED and substrate melt and fuse together. During this phase the machine applies the vibration with set amplitude, frequency, and force. These are kept constant by changing the power input and displacement of the sonotrode. In some occasions the force is set to rise with a certain rate during a single weld. The vibration phase ends when a predetermined time, energy, or displacement of the sonotrode is reached. The melt process itself can be further divided in five stages which are described in section 1.1.2.

Consolidation phase During consolidation the vibration is stopped but the force remains present for a set amount of time. This force is the consolidation force and can be different than the welding force.

1.1.2 Melting process of Energy Director

Research on the melting process of the ED and surrounding substrate material is already been performed in 1989 by Benatar [7] using co-moulded trianngular EDs. It was found that the USW process consisted of five highly coupled subprocesses, being 1) vibration of the parts, 2) viscoelastic heating of the ED, 3) heat transfer to the substrate material, 4) flow of ED and wetting of the substrate, and 5) intermolecular diffusion. In a numerical study by Zhang et al. [18], where a rectangular ED was used, it was found that the temperature increase until the Glass Transition Temperature (T_g) was mainly driven by friction dissipation and after the T_g by viscoelastic heating.

This can be explained by looking at equation (1.1) which shows the viscoelastic heating rate $\dot{Q}_v$ as function of the loss modulus of the resin (E”), amplitude (ϵ_0) and frequency (ω) of the vibration [19]. The loss modulus increases around the T_g which in turn increases the viscoelastic heating rate.

$$\dot{Q}_v = \frac{\omega \cdot \epsilon_0^2 \cdot E”}{2} \tag{1.1}$$

Another numerical study by Levy et al. [20] was able to predict the required power for a weld with a flat ED quite accurately. This study also confirmed that the heating rate before the T_g is dominated by friction dissipation and after by viscoelastic heating. The friction dissipation beyond the T_g is reduced due to adhesion arising between the ED and substrate, limiting the friction. Both the study from Zhang and Levy predict the fastest temperature rise and highest temperature at the edge of the ED. This is due to higher slippage between the ED and substrate on the edge than in the center of the ED.

An experimental study by Villegas [19] used flat, loose films of ED to investigate if the use of power and displacement data obtained during a weld could give a better understanding in the melt process. An example of such power and displacement curves is given in figure 1.4, where 5 stages are indicated. The five stages represent different stages in the melt and weld process as described below. These curves can help determine optimal processing parameters and this technique is called in situ monitoring.

Stage 1 In the first stage the ED starts to heat up without noticeable changes to the ED surfaces.

Stage 2 The ED starts to melt locally and hot spots of molten ED appear, where viscoelastic heating takes over. The sonotrode remains at the same displacement as still solid areas in the ED prevent this displacement. At the end of stage 2 the entire ED is molten.

Stage 3 With the entire ED molten the sonotrode starts to displace downward, squeezing the ED between the substrates. An increase in power and displacement characterize this stage.

Stage 4 The displacement continues to increase, indicating further squeeze flow of the ED. In this stage the surrounding matrix material starts to melt in the first layer. The melting of the substrate decreases the required power resulting in a Power plateau or peak.

Stage 5 The final stage is dominated by melting of the matrix material in the substrates, leading to a decrease in power as was also the case with the melting of the ED. In this stage the substrate is heated beyond the first layers as well.

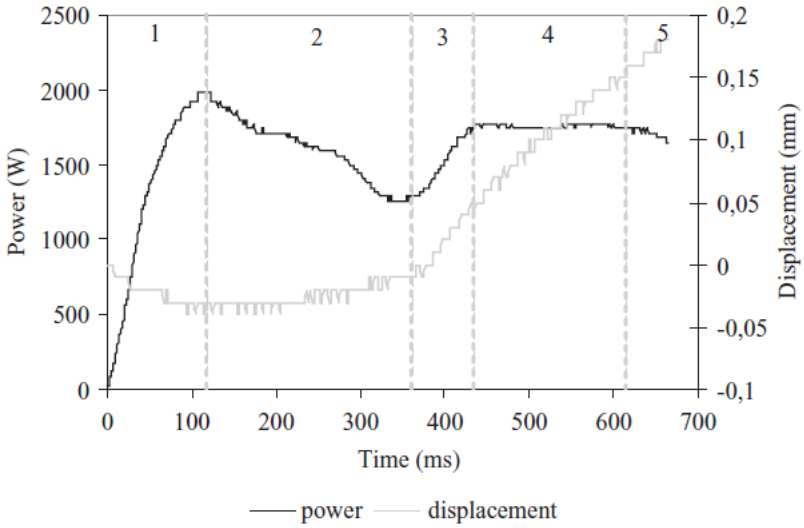


Figure 1.4: *Example power and displacement curve with five different stages indicated. Positive displacement represents a downward movement of the sonotrode, compressing the ED. The substrate material is CF/PEI (Polyetherimide) with a loose, flat film of PEI as ED. The welding force is 500 N and the amplitude is 86.2 µm. Taken from [19]*

1.1.3 Effect of process parameters, energy director shape and thickness on weld process and optimum parameters

Obtaining a strong and consistent weld is important, but difficult to achieve. Numerous parameters affect the welding process (weld force, amplitude, ED) and changing circumstances alter the required settings or controlling parameter. The strength of a weld can be determined from the single Lap Shear Strength (LSS). The Fracture Surface (FS) can reveal if a weld was performed at the optimal conditions, as the failure mode can be determined from it. Four failure modes can be observed and these are described below [1]:

Weld interfacial failure The weld fails within the neat resin layer between the substrates. No signs of fibre breakage are present, resulting in the weakest bond.

First ply failure Failure occurres in the first layer of the substrate with broken fibres visible. This failure mode displays the highest achieved strengths.

Interfacial + first ply failure This combination of the above mentioned failure modes result in welds with intermediate strength and both fibre breakage and failure in the neat resin layer visible.

Substrate failure It could occur that the surrounding fibres in the substrate are heavily damaged by the weld process. This results in failure of the substrate instead of the weld, which should be prevented.

Determining the correct optimum weld parameter, be it time, energy, or displacement, must be done for each individual set of welding settings and ED configuration. With changing weld force, amplitude, and/or ED this optimum changes as well [21]. The previously mentioned method of in situ monitoring (section 1.1.2) can be used to determine this optimal parameter easily and fast as investigated by Villegas [22]. It was determined that the optimum weld is achieved in stage 4 of the weld process, just after the second power peak.

The effect of weld force and amplitude on the weld process are easily visualized with in situ monitoring as shown in figure 1.5. With different force or amplitude the required power and weld time change. The optimum parameter is always located just after the second power peak as indicated in figure 1.5 [23].

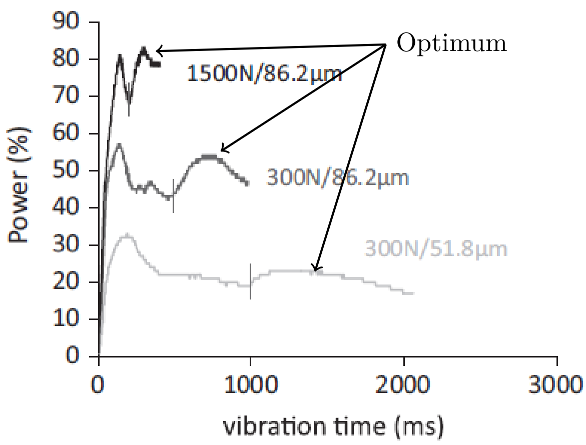
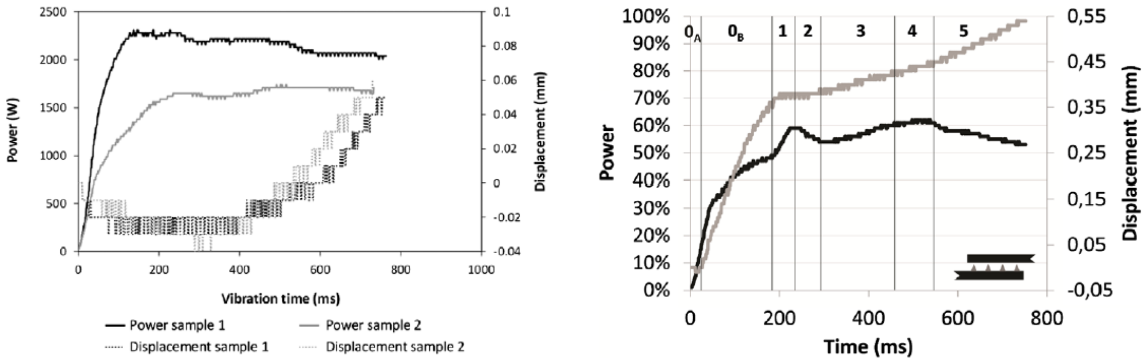


Figure 1.5: *Three power curves of welds between CF/PEI (Polyetherimide) substrates and PEI ED films, with different force (1500 N and 300N) and/or amplitude (86.2 µm or 51.8 µm, adapted from [23]*

A study on the influence of the ED thickness of a flat ED by Palardy and Villegas [24] showed that for thin ED the weld curves were different compared to thicker EDs. The power curve changed to have a consistent plateau after the initial ramp up as shown in figure 1.6a. The optimum was found at the onset of sonotrode displacement around 500 ms and 0 mm displacement. As the optimum is not located at a unique displacement value, displacement controlled welds are no longer possible and energy controlled welds should be used. The absence of displacement is an important step towards the development of continuous USW, as further discussed in section 1.1.5. The plateau in power indicates that the resin in the substrate and the ED occur simultaneously.

The weld process for welds with triangular shaped EDs have been investigated by Villegas and Palardy [11] via the same in situ monitoring. The weld curves for such a weld are given in figure 1.6b, where besides the earlier mentioned five weld stages two additional stages occur. The increase in displacement at the start of the weld represents melting and collapsing of the triangular shaped EDs. From stage 1 at the displacement plateau, the curves resemble the five stages found when welding flat EDs as seen in figure 1.4.



(a) *Example weld curves of two welds with thin 0.06 mm ED, 500 N force, and amplitude of 86.2 μm, from [24]*

(b) *Example welding curves with triangular ED, 500 N force, and amplitude of 86.2 μm, from [24]*

Figure 1.6: *Example weld curves for different ED thickness (left) or shape (right)*

1.1.4 Energy director application methods

Several methods exist to position the ED at the weld interface for USW of TPC. Villegas et al. [12] found that for TPCs a loose resin film covering the entire weld interface works perfectly well for the USW process. The positioning by hand is no problem in a laboratory environment, but is not suitable for use on an industrial scale. A study by Broek [13] integrated flat ED strips in the substrate during consolidation. The design of the ED was driven by the demoulding process and not the welding process which can negatively influence the weld. Another problem was the irregular thickness of the ED, where the resin did not entirely fill the grooves in the mould. This irregular thickness resulted in uneven welds. Renooij [25] moulded triangular EDs on the substrates, but the fibres in the substrate displaced due to this application as shown in figure 1.7.

1.1.5 Continuous ultrasonic welding

The area which can be joined by USW of TPCs is limited in size due to the high power demand. This can be solved by using Continuous USW (CUW), where the sonotrode moves along the weld line with respect to the substrate during the vibration phase. Such a method is already in use for unreinforced TPs, where the anvil rotates, guiding the substrates passed the

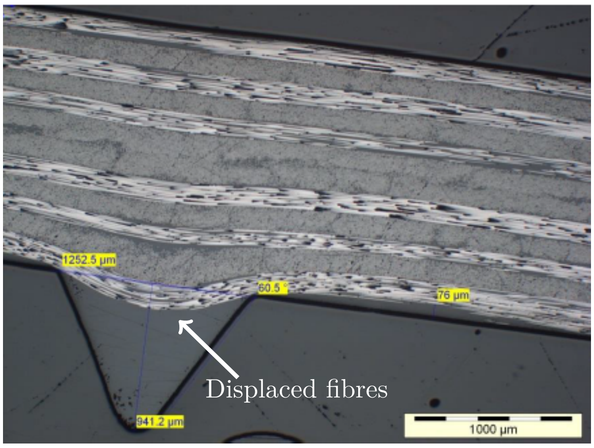
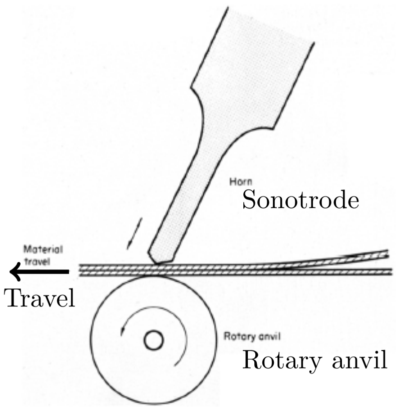
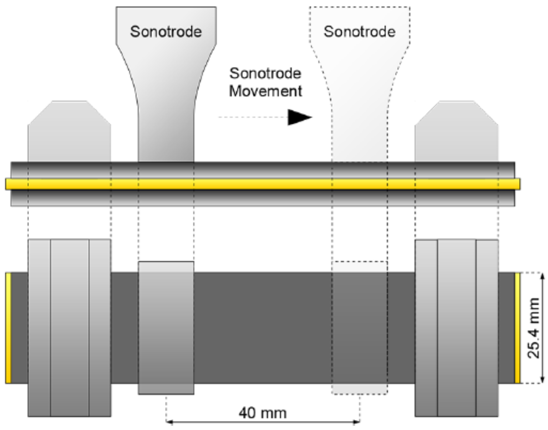


Figure 1.7: *Integrated triangular ED with displaced surface fibres, adapted from [25]*

sonotrode as schematically shown in figure 1.8a [5]. Due to the high stiffness of TPC substrate materials, this process is more difficult to achieve. A study by Senders et al. [26] developed a technique called zero-flow CUW, where a thin ED was applied at the weld interface, for which no flow of the ED is required to achieve the optimal weld. An schematic overview of such a process is given in figure 1.8b. The process resulted in successful continuously welded joints.



(a) *Schematic overview of a continuous weld process for unreinforced TPs materials, adapted from [5]*



(b) *Schematic overview of a continuous ultrasonic weld process for thermoplastic composites, taken from [27]*

Figure 1.8: *Continuous ultrasonic welding process for unreinforced and fibre reinforced thermoplastics*

1.2 Literature review on Fused Deposition Modeling

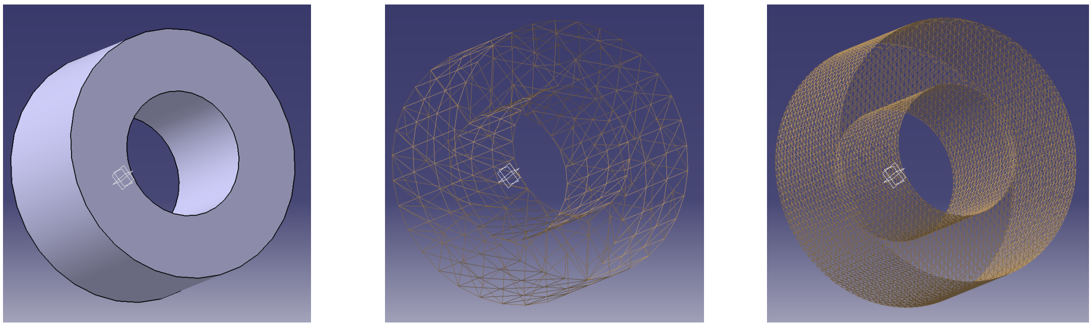
Additive manufacturing (AM) is developed in the 1980's as a means to rapidly manufacture prototypes. It was referred to as Rapid Prototyping and created physical prototypes directly from a Computer Aided Design (CAD) model in a fast and cheap manner [14, 28, 29]. With increasing amount of different methods and applications, the term 'additive manufacturing' was introduced by ASTM to standardize terminology [30]. Nowadays 3D printing is a widely used synonym for AM, but is in fact a process on its own [14, 28].

Within the AM a distinction is made between seven sub categories, being Vat photopolymerization, powder bed fusion, sheet lamination, binder jetting, material jetting, direct energy deposition, and material extrusion. A brief introduction on each category is given, followed by a more elaborate description on fused deposition modeling (FDM). Because all AM methods start as a CAD model and .stl file these are discussed first.

1.2.1 The CAD model and .stl file

CAD models can be created in various 3D drawing programs like AutoCAD, CATIA and SolidWorks. They are strong tools in the design of (engineering) products to not only visualize the final product, but also predict weight distribution, part placement, movement possibilities and more. This is done by adding for example material properties and movement constraints in the design. An example of simple 3D CAD model is given in figure 1.9a. In AM almost all this information is obsolete and only the surface is of interest and this is exactly what the .stl file is for.

Introduced in 1987 for use in the Stereolithography (STL) process (one of the first AM methods), it now is the basis for all other AM methods. The surface of a CAD model is approximated with triangles and all other information is left out. This triangulation has led to several interesting backronyms like 'Standard tesselation language' or 'Surface tesselation language'. The size of the triangles influences the precision of the .stl file and final product. If the triangles are too big, small details can be lost, but small triangles result in bigger data files and longer processing times. An example of a a low resolution file with large triangles is given in figure 1.9b and a high resolution with small triangles in figure 1.9c [14, 31].



(a) *CAD model, 3D representation* (b) *Tesselated model with large triangles* (c) *Tesselated model with small triangles*

Figure 1.9: *CAD model with triangulated surfaces for STL file*

1.2.2 Summary AM methods

A brief description of the different AM methods is given below. The FDM process is part of material extrusion and discussed more elaborately later. This method is chosen due to the high level of automation, absence of additional liquid or powder, and previous research showing the potential to extrude on consolidated TPCs.

Vat photopolymerization

In this process a build platform is located in a bath containing a liquid resin. The platform start one layer thickness below the surface of the resin. A laser or other light source is concentrated at the surfaces outlining the cross-sectional area. This activates the polymerization process creating a solid layer. The build platform moves downward and the process is repeated creating a complete product. This process is one of the first AM process available as stereolithography developed by 3D Systems Inc. in the 1980's. Multiple materials can be used by changing the materials during production. An uneven thickness distribution can occur due to the viscousity of the liquid. A schematic overview of the process is given in figure 1.10.

Powder bed fusion

Within the powder bed fusion one layer thickness of powder is applied on the build platform at a temperature of almost the T_m. As with previous process a laser scans the cross-section melting the powder together forming a solid layer. A new powder layer is added and the process repeats itself. The unmelted powder remains between the product the entire process eliminating the need for additional support structures to bridge empty spaces. Thermoplastics, metals and even some ceramics can be used in this process [28]. A schematic representation of the process is given in figure 1.11

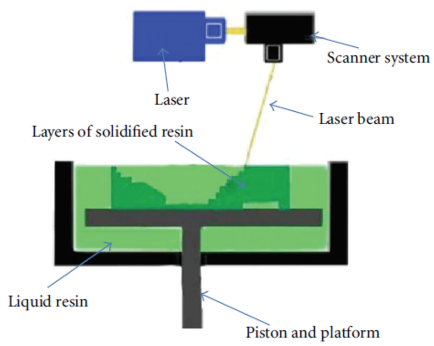


Figure 1.10: *Stereolithograpy machine, taken from [14]*

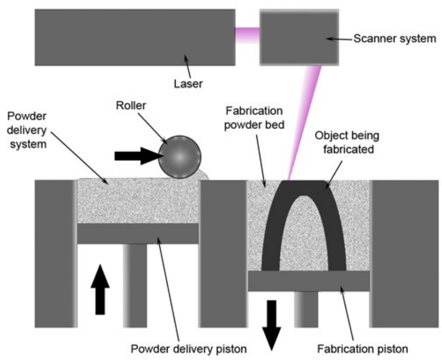


Figure 1.11: *Schematic overview of a powder bed fusion process, [32]*

Sheet lamination process

As the name suggests, sheets are cut as the required cross-section and bonded together to form the final product. If a material can be produced in sheets and be bonded together it can be used in this method, for example metals, polymers and even paper. The process has low costs and large products can be build, but the cutting of sheets create a large amount of waste material [14, 28, 33]. A schematic of the process can be found in figure 1.12.

Binder jetting

This process, developed by MIT, resembles the traditional 2D Inkjet printer, and is originally named 3D printing. A nozzle ejects droplets of binder material on a powder bed that solidifies upon contact. A new layer of powder is added and the process is repeated for each new layer. Multiple nozzles can be added to decrease printing time creating a relatively fast process. As with powder bed fusion, a wide variety of materials can be used and no support structure is required [28]. A schematic drawing of the process is shown in figure 1.13.

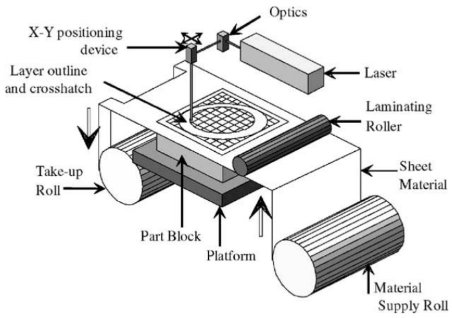


Figure 1.12: *Schematic of sheet lamination process, taken from [33]*

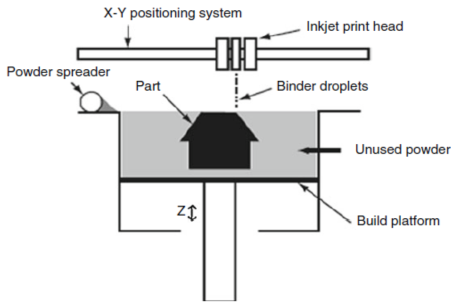


Figure 1.13: *Schematic view of binder jetting, taken from [28]*

Material jetting

Similar to the binder jetting process droplets of liquid material are ejected on a build platform. Different is that the actual build material is ejected and solidified at the build platform. Depending on the material and process the product is solidified by cooling, photopolymerization or other techniques [28]. The process is schematically shown in figure 1.14

Direct energy deposition

This process uses a heat source, for example a laser, to create a pool of melted material at the surface and add additional material in the melted pool in a continuous manner. This additional material can be a powder blown in the pool or a filament feed. As the heat source continues the material solidifies and forms the product. This method is often used with metals and is sometimes named 'metal deposition' [28]. A schematic drawing is given in figure 1.15.

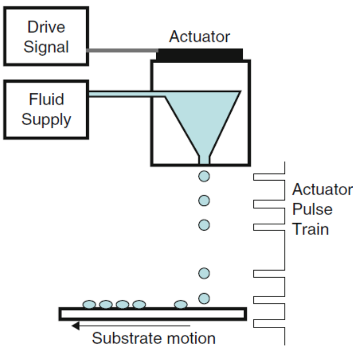


Figure 1.14: *Schematic of material jetting, taken from [28]*

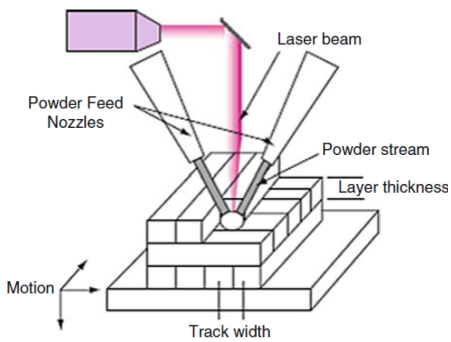


Figure 1.15: *Example of direct energy deposition, taken from [28]*

1.2.3 The fused deposition modeling process

Within the material extrusion category material is extruded from a nozzle in a continuous manner and deposited on a build platform. FDM is a widely used form of material extrusion where material is taken from a material feed and deposited on a build platform. The material feed can be a pool of melted material, small spheres of polymer or a continuous solid filament. A schematic overview a machine with a continuous filament is given in figure 1.16. This particular machine has two nozzles which allows the extrusion of two different materials, for example to extrude support material which can be dissolved after the build [16, 28, 34].

The nozzle often moves in the horizontal plane according to a predetermined path, extruding the material on selected positions. The cross-sectional shape that can be traced has almost no limits giving this process high freedom of form. Upon completion of one layer the build platform moves downward by one layer thickness and the next layer is deposited on the previous layer. The precision with which a model can be manufactured depends greatly on the thickness of one layer and the width of the deposited filament. Smaller dimensions result in higher precision but longer extrusion times [35].

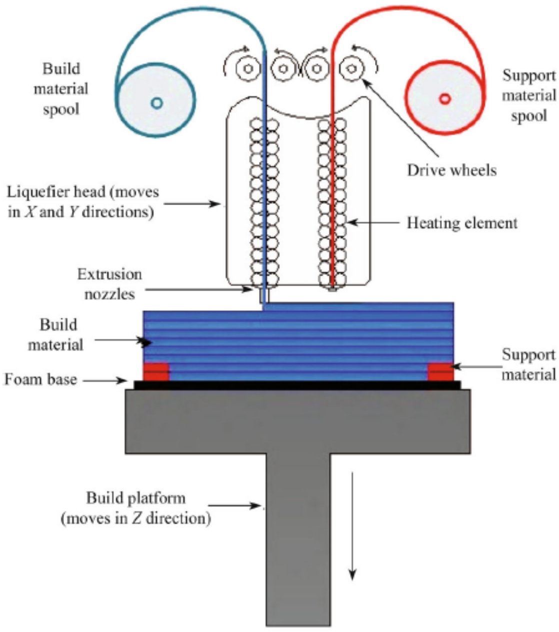


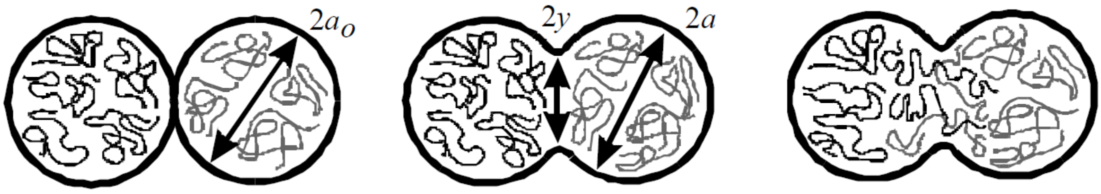
Figure 1.16: *Schematic drawing of an FDM machine having two nozzles to extrude different materials, from [16]*

As with the other AM techniques the process starts with a 3D CAD model from which the surface is approximated by triangles in the .stl file. Special software divides the product in separate layers according to input settings such as layer thickness, layer width, and required support structure. Information on extrusion path, locatio This .gcode is sent to the extruder, which executes the given steps to create the final product. This process is schematically shown in figure 1.17.

Adjacent layers and extrusion paths bond through the diffusion of polymer chains where the filaments touch. This diffusion process occurs at elevated temperatures, preferably above the

Figure 1.17: *Flow diagram from CAD to final product in the Fused Deposition Modeling process*

T_g [36]. The process is schematically shown in figure 1.18.



(a) *Two adjacent filaments with a contacting surface* **(b)** *Necking at the interface at elevated temperature* **(c)** *Diffusion of polymer chains at the interface*

Figure 1.18: *Bonding process of two adjacent filaments, from [36]*

Plaisier [17] investigated the possibility to extrude a product directly on a consolidated TPC substrate and simultaneously form a bond between them. A similar process as described above is believed to occur between the resin in the substrate and extruded polymer. The temperature of the substrate and surrounding environment had significant impact on the final bond strength. It was found that for optimal bond strength the temperature of the substrate and extruded material should be (just) above their T_g. The final bond had a LSS (LSS) of 2.1 MPa which is low for use in structural applications.

1.3 Combining of the USW process and FDM

Due to the high level of automation in the FDM process and the potential to extrude directly on consolidated TPCs, FDM is believed to be a suitable candidate to apply the ED for the USW process. Since the bond between the substrate and ED is only required to withstand some handling forces and be welded, the low LSS found by Plaisier [17] is believed to be sufficient for this purpose. With the high freedom of form in the process it is believed that the ED can be designed to specific needs for each weld.

1.4 Research objective and Research questions

The combination of FDM and USW process gives this research the following main objective:

"Increase the level of automation in the Ultrasonic Welding of Thermoplastic Composites by applying the Energy Director on Consolidated substrates with Fused Deposition Modeling and addressing occurring challenges."

The following sub-objectives are formulated to achieve the main objective:

- Use the FDM technique to extrude an ED on a consolidated TPC substrate with an acceptable bond between the ED and substrate.
- Successfully weld TPC substrates using USW and an ED that is extruded using FDM directly on the consolidated TPC substrate.
- Find the influence of a thickness difference within an ED by welding an ED having a deliberate thickness step.

The main research question that belongs to previous stated objectives is formulated as:

"Can the USW process be further automated by using FDM as a means to apply the ED on consolidated TPCs?"

Two sub-questions for this project are stated:

- What are the possibilities and challenges in using extruded Energy Directors in the Ultrasonic welding process?
- How does a variation in Energy Director thickness affect the weld process and final weld quality in the Ultrasonic weld process?

1.5 Methodology

To achieve the objective and answer the research questions an elaborate experimental study based on theoretical backgrounds is done. It is divided in two parts, each answering one of the sub-research questions. The first part investigates the effect of an extruded ED on the weld process. A replica of the now predominantly used flat films is extruded with the Indmatec HPP 155, referred to as the Extruded Film, and welded with CF/PEEK substrates. Next, a shape more suitable for the FDM process is used and extruded directly on the consolidated substrates. This ED is referred to as the Attached ED as it is expected to form a bond sufficiently strong to withstand handling forces and welding without additional fixation. CF/PPS substrates are used because insufficient bonding occurred between the Attached ED and the CF/PEEK substrates. Successful welds between the Attached PEEK ED and CF/PPS substrates are achieved but some challenges occurred, being obtaining sufficient bonding between the ED and consolidated substrate and the inaccuracy in thickness of the Attached ED.

The latter challenge is the subject of the second part of this research. Flat, PEEK films with a different thickness are combined, resulting in an ED that is divided in two thickness sections, referred to as the Split ED. Six configurations are tested, with the following thickness distributions: 0.25/0.25 mm (reference configuration), 0.25/0.20 mm, 0.25/0.15 mm, 0.25/0.10 mm, 0.25/0.05 mm, and 0.25/0.00 mm. Of all these configurations the weld curves, fracture surfaces, cross sections, and LSS are compared and hypotheses on the influence of the thickness distributions are formulated. These hypotheses are investigated further by deliberately stopping the weld at several points to observe the melting process.

1.6 Report outline

The remaining of this report describes the performed research in detail, starting with an elaboration on the used material and machinery in chapter 2. The first research part on the extrusion of the ED is described in chapter 3, where a more elaborate research plan is given, along with the results and some preliminary conclusions. The same is done for the investigation on the influence of a thickness variation in chapter 4. At the end of the report the main conclusions are summarized and recommendations for future research are given in chapter 5.

Chapter 2

Experimental Set-up

This chapter gives a short overview of the materials and equipment used during this research. All materials and equipment are available at the Delft Aerospace Structures and Materials Laboratory (DASML) at the TU Delft.

2.1 Materials used and manufacturing methods

Two different substrate materials are used in this research being $[0/90]_{3s}$ 5 harness satin weave CF/PEEK, and $[0/90]_{3s}$ 5-harness satin weave CF/PPS both from TenCate Advanced Composites. The six layers are consolidated on a hot-platen press according to the scheme shown in table 2.1 and have a thickness of around 1.9 mm. The CF/PPS is consolidated at the DASML whereas the CF/PEEK was send to TPRC for consolidation. The consolidated panels are cut with a water cooled diamond saw to samples of 101.6 x 25.4 mm

The PEEK ED films are APTIV FILMS 1000 series from Victrex and available in 0.25 mm and 0.05 mm thickness. Intermediate thicknesses are obtained by pressing several layers 0.05 mm ED together according to the scheme given in table 2.1, resulting in films of 0.20 mm, 0.15 mm and 0.10 mm. The 0.24 mm PPS ED consists of four layers 0.06 mm PPS film combined as described in table 2.1. The PEEK used in the FDM machine is delivered by Apium Additive Technologies GmhB as a 1.75 mm diameter filament. This material is used for all extruded parts during this research.

Table 2.1: *Consolidation steps for substrates and pressed EDs*

		CF/PEEK	*CF/PPS*	*Pressed PEEK ED*	*Pressed PPS ED*
Temperature	[°C]	385	320	330	280
Consolidation Time	[min]	20	20	35	35
Pressure	[MPa]	2	1	2	2

2.2 Ultrasonic welder

The DASML is currently in possession of two USW machines, one for static welding and one for continuous welding. For this research the static welder, the Rinco Dynamics 3000 as shown in figure 2.1, will be used. The welder operates at a fixed frequency of 20 kHz and a 9-step variable amplitude setting. The final peak-to-peak amplitude depends on both the setting (1-9) and the combination of booster and sonotrode. This research utilizes a titanium, cylindrical sonotrode with a diameter of 40 mm (part 1 in figure 2.1), resulting in a maximum peak-to-peak amplitude of 86.2 μm. The welder has a maximum power output of 3000 W and can apply a welding force of 3000 N.

A specially designed fixture is used to weld samples for Single Lap Shear Strength (LSS) with an overlap area of 25.4 x 12.7 mm. This fixture completely clamps one of the substrates (part 4 in figure 2.1) while allowing the second substrate to freely move in vertical direction (part 2 and 3 in figure 2.1). This freedom of motions prevents bending in the substrate during welding when squeeze flow of the ED occurs.

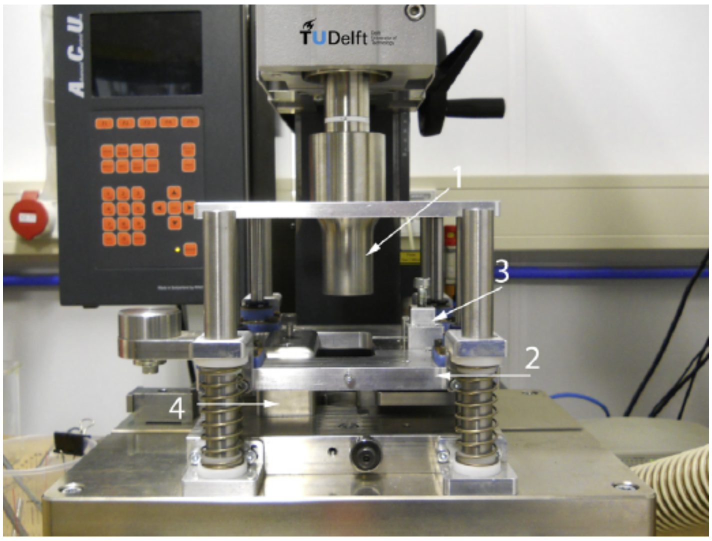


Figure 2.1: *The Rinco Dynamics 3000 with cylindrical sonotrode (1), movable part of fixture (2 and 3) and static fixture (4), taken from [23]*

2.3 Weld settings and optimum controlling parameter

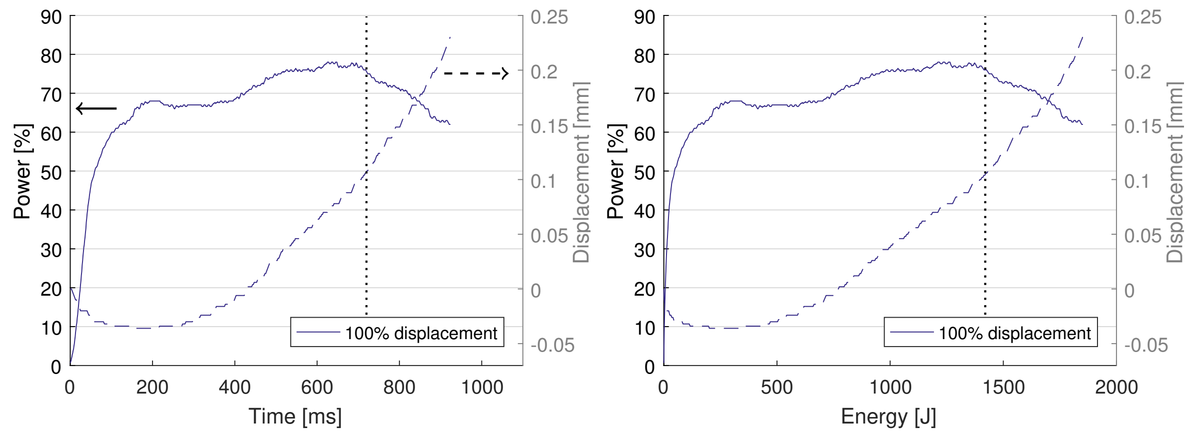
During a single weld the amplitude, force, and frequency are kept constant by adjusting the power input and vertical displacement of the sonotrode. An Advanced Control Unit (ACU) connected to the welder controls and monitors this process. Unless explicitly stated otherwise, all welds are performed with the settings shown in table 2.2, leaving the controlling parameter, substrate material, and ED the only variables in the process.

Table 2.2: *Standard settings for the USW process*

Parameter	*Setting*	
Frequency	20	[kHz]
Amplitude	86.2	[μm]
Weld Force	500	[N]
Solidification force	500	[N]
Solidification time	4000	[ms]

The controlling parameter is determined using in situ monitoring with data from the USW machine as explained in section 1.1.3. As stated before, the optimum weld is achieved in stage four of the weld, just after the second power peak. Determining this location is done by first welding a sample with a set displacement equal to the total ED thickness, referred to as 100% displacement weld. This results in the complete power and displacement curves which can be plotted over time and energy as shown in figures 2.2a and 2.2b respectively. The black dotted lines in these figures represent the location of the optimum weld. Depending on this location one can find the optimum displacement (Displacement controlled welds), optimum energy (Energy controlled welds) and/or optimum welding time (Time controlled welds). For the given example the optimum can be chosen as either a displacement of 0.11 mm, an energy of 1440 J, or a time of 725 ms. Although displacement controlled welds are known to give the most consistent results it is not always possible to use, for example with thin ED as described in section 1.1.3.

For clarity, the power and displacement data from the welder is smoothened in all graphs of this report. An elaboration on this process is given in appendix A. Note that the power is indicated as a percentage and not in Watt. A value of 100% corresponds to 3000 W, the maximum available power from the welder. A positive displacement indicates a downward motion of the sonotrode, pressing the substrates together and squeezing the ED.



(a) *Weld curve plotted over Time* **(b)** *Weld curve plotted over Energy*

Figure 2.2: *Weld curves for weld with CF/PEEK substrates and 0.25 mm PEEK ED film. Black dotted lines represent the optimum, weld settings as table 2.2*

2.4 Fused deposition modeling machine

The Indmatec HPP 155 machine (figure 2.3) is one of the few available FDM machines capable of extruding PEEK. It is designed by Apium Additive Technologies GmgH. in Germany. The PEEK is fed to the machine as a 1.75 mm diameter filament and pushed through the 400°C nozzle. The effective build volume of 140 x 135 x 148 mm (X/Y/Z) is sufficient for this research. The build platform can be given a z-offset which makes it easier to extrude on substrates but the maximum temperature of 100°C is believed to be too low to extrude the PEEK on CF/PEEK and form a bond between them.

As with the USW process the same settings are used for all extruded products in this research. These settings are shown in table 2.3. To make the welds as comparable as possible and reduce

Figure 2.3: *The Indmatec HPP 155 FDM machine*

extrusion time, the layer thickness is varied such that the ED always consist of one layer.

Table 2.3: *Standard printer settings*

Parameter	*Setting*	
Build material	PEEK	
Nozzle temperature	390	[°C]
Build platform temperature	100	[°C]
Extrusion width	0.4	[mm]
Nozzle speed during extrusion	6	[mm/s]
Extrusion multiplier	1.2	[-]

2.5 Test equipment

Summarized here is the apparatus used in testing and analyzing the obtained welds.

Temperature measurements

Temperature measurements during extrusion of the ED are done using the Picologger USB TC-08 with K-Type Thermocouples (TCs). Up to 10 TCs can be used simultaneously but the sampling rate decreases. With one connected TC the sampling rate is 10 Hz which is used in this research.

Tensile testing

The LSS of a sample is obtained using a 250 kN Zwick/Roel universal testing machine. Hydraulic grips which are given an offset to prevent bending of the substrates are applied. The test speed is 1.3 mm/min according to the ASTM D 1002 standard.

Optical microscopes

Two different Optical Microscopes (OM) are used to analyze the Fracture Surface (FS) and cross section of the welds. The FS is observed both with the naked eye and the Zeiss Discovery.V8 Stereomicroscope. The cross section of the welds are observed with the Keyence VHX-2000 Optical Microscope. This microscope is also used to measure the thickness of some of the EDs used in this research, for example to quantify thickness variations in an ED. An example of such a measurement is shown in figure 2.4.

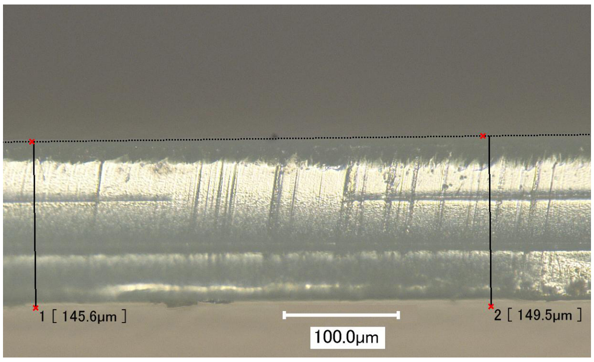


Figure 2.4: *Example thickness measurement of 0.15 mm ED film from the Keyence Optical Microscope*

Chapter 3

Research towards Welding with Extruded EDs

In this chapter research towards the effect of an extruded ED on the weld process is performed. A replica of the loose, flat films of ED, named the Extruded Film, is extruded and welded. An ED more suitable for the FDM process is extruded directly on consolidated substrates to increase the level of automation. The bond should be sufficiently strong to withstand handling forces and being welded without additional fixation. This ED is referred to as the Attached ED. The chapter starts with the research plan, followed by a discussion of the results, and at the end the possibilities and challenges of the process are stated.

3.1 Research plan

The sub-research question that applies to this part of the research is:

"What are the possibilities and challenges in using a with Fused Deposition Modeling manufactured Energy Director in the Ultrasonic Weld process?"

To answer the research question several different EDs are extruded in PEEK with the Indmatec HPP 155 machine as described in section 2.4. The nomenclature of the different EDs used is summarized in table 3.1. Three different configurations are used as reference cases, being a weld with CF/PEEK substrates with PEEK ED film, CF/PPS substrates with PPS ED film, and CF/PPS substrates with PEEK ED films. The films are manually positioned to cover the entire weld interface as shown in figure 3.1a. A more elaborate explanation for the use of CF/PPS in combination with a PEEK ED film is given in section 3.1.1.

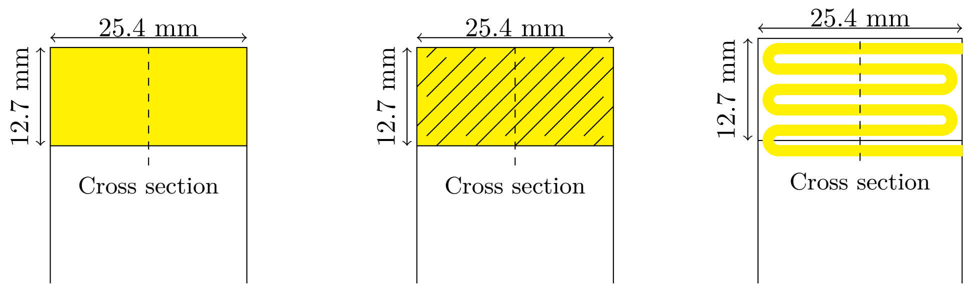
To investigate the effect an extruded ED has on the weld process, a replica of the PEEK ED films is extruded on the build platform as a flat sheet, large enough to cover the entire weld interface, named the Extruded film. The extrusion path and positioning at the weld interface can be seen in figure 3.1b, where the set FDM settings are a layer thickness of 0.25 mm and an extrusion width of 0.40 mm.

The next step is to extrude an ED which shape better suits the FDM process, consisting of less material resulting in a shorter extrusion time. A schematic overview of the resulting shape is given in figure 3.1c. It is extruded as a continuous path directly on consolidated substrates (CF/PEEK or CF/PPS). A bond between the ED and substrate should form such that the ED is secure enough for the combination to withstand handling forces and welding without additional fixation of the ED. This ED is referred to as the Attached ED. The dimensions of the Attached ED are an extrusion width of 0.40 mm, a thickness of 0.20 mm and a distance between the paths of 0.6 mm. These dimensions are chosen because previous research showed that strips with little distance between them result in better welds [13,37], and the amount of material equals that of a 0.08 mm ED film covering the entire surface, where previous research resulted in successful welds with even less material [26]. These dimensions are believed to be too narrow to be integrated on the substrates in the mould, as they will break upon demoulding [13]. Also the design can be altered to individual strings which will make manual application of this ED slow and imprecise.

The melt process of the Attached ED is investigated in more detail by stopping the weld at different stages of the weld.

Table 3.1: *Nomenclature and description of different energy director used*

Reference name	*Material*	*Description*
PEEK ED film	PEEK	0.25 mm thick flat film of PEEK positioned loose at the interface, see figure 3.1a
PPS ED film	PPS	0.24 mm thick flat film of PPS positioned loose at the interface, see figure 3.1a
Extruded film	PEEK	0.25 mm PEEK ED extruded on the build platform as a replica of the films, positioned loose at the interface, see figure 3.1b
Attached ED	PEEK	0.20 mm PEEK ED extruded directly on consolidated CF/PEEK and CF/PPS substrates. The shape is a continuous extrusion path of 1 path width wide (0.4 mm) as shown in figure 3.1c



(a) *PEEK or PPS ED film* **(b)** *Extrusion pattern for the Extruded film* **(c)** *Schematic shape for the Attached ED*

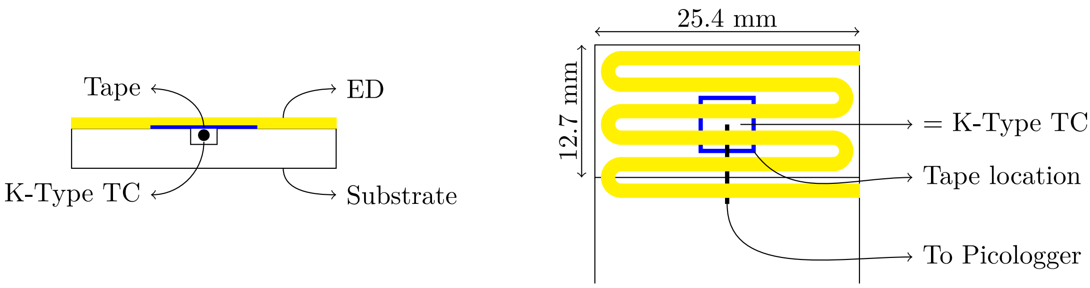
Figure 3.1: *Schematic drawing of the ED shapes used in this research (image not to scale). Dashed line indicates the line along which the cross sectional images are taken.*

The weld settings for all mentioned welds are summarized in table 2.2, except for the Extruded films. For these, the peak-to-peak amplitude was reduced to 77.6 μm to reduce the required power. In hindsight this might not have been necessary due to an error in earlier measurements. This reduction is believed to have little influence on the final weld and fracture surfaces, although small changes in the weld curve can occur, such as an elongated weld time and less power required. For the purpose of this research the resulting LSS and fracture surface are still valid.

3.1.1 Adhesion between Attached ED and CF/PEEK and CF/PPS substrate

The adhesion between substrate and ED for the Attached ED proved to be problematic when CF/PEEK was used as substrate material. The bond should be sufficient for the combination to withstand handling forces and being welded without additional fixation of the ED required. However, the Attached ED on CF/PEEK substrates detaches itself upon cooling, after which it can be freely moved over the surface. The reason for the limited adhesion is believed to be the relatively low temperature of the substrate during extrusion. The temperature during extrusion is measured with the Picologger at the location shown in figure 3.2. The result of such a measurement is shown in figure 3.3, which reveals that the temperature of the substrate is below the T_g of PEEK for almost the entire extrusion process. As already found by Plaisier [17] the strongest bond between an extruded part and a consolidated TPC substrate occurs when the substrate is just above the T_g, which is not the case. Since CF/PPS has a lower T_g (90°C compared to 145°C), the CF/PEEK is interchanged for CF/PPS substrates, for which the substrate temperature is consistently above the T_g.

Since USW are usually performed with ED having similar material as the resin, a reference weld with CF/PPS substrates and PEEK ED film is done to confirm the possibility of such a weld.



(a) *Side view* **(b)** *Top view*

Figure 3.2: *Approximate location of thermocouple during extrusion (image not to scale)*

3.1.2 Thickness measurements of Attached ED

Thickness measurement of the Attached ED are done for each sample at the four locations shown in figure 3.4. A micrometer with an accuracy of 0.01 mm is used to measure the thickness of the substrate before and after extrusion to determine the ED thickness. The set thickness is 0.20 mm but a large dispersion in values is measured, both within a single ED as between separate EDs.

As explained in section 1.1.4 a varying thickness in an ED can result in an uneven weld. The measured variation in thickness in the research by Broek [13] had thickness variations between 0.01 and 0.08 mm for the majority of the samples, with extreme cases up to 0.17 mm. The resulting welds show unevenly welded fracture surfaces. To decrease the influence of a thickness variations in the ED in this research it was decided to reject a sample if the

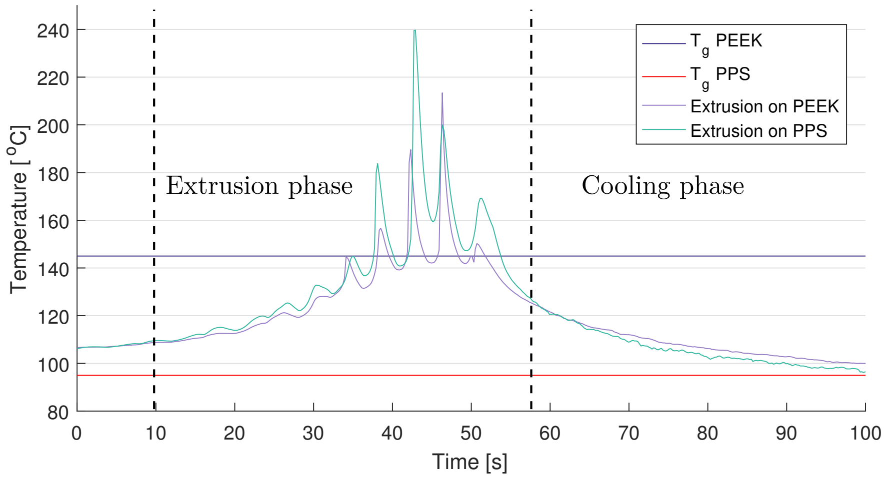


Figure 3.3: *Temperature curves in the substrate during extrusion of the Attached ED on CF/PEEK and CF/PPS, with the extrusion occurring between the dashed lines*

ED thickness varied more than 0.01 mm from the set value of 0.20 mm at any of the four locations. This resulted in the rejection of 67% of the Attached EDs (29 of 43), hinting that a more accurate application method might be required.

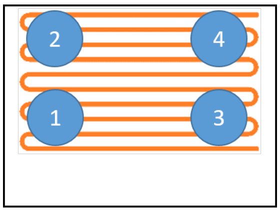


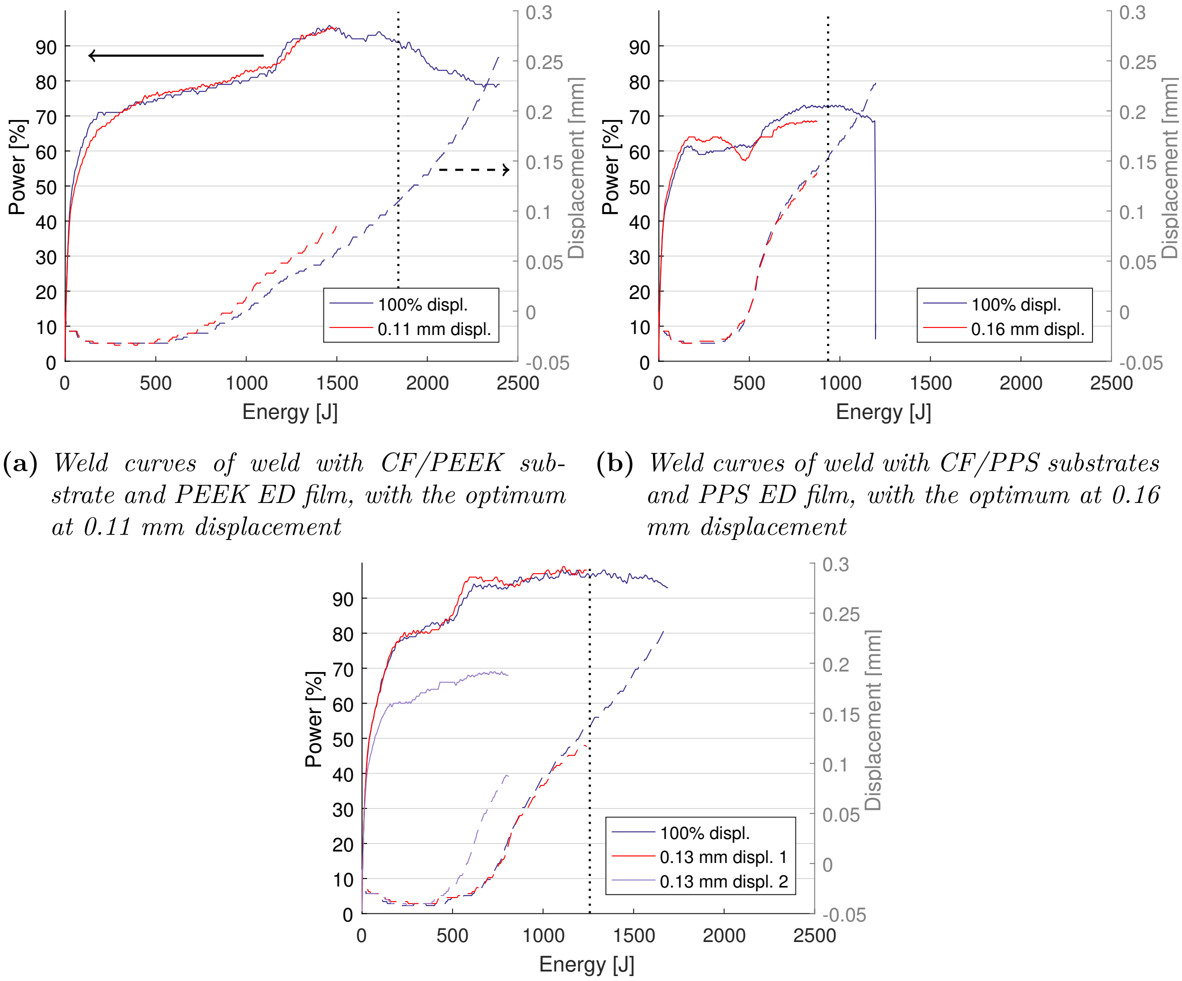
Figure 3.4: *Locations where the thickness of the Attached ED is measured (image not to scale)*

3.2 Results and discussion

This section contains the results and discussion of the welds with the various ED types described before, starting with the reference cases. After that the Extruded ED film is discussed, followed by the results of the Attached ED.

3.2.1 Reference cases

The three reference cases mentioned before are: 1) CF/PEEK substrate with PEEK ED film, 2) CF/PPS substrate with PPS ED film, and 3) CF/PPS substrate with PEEK ED film. Of each individual combination the optimum weld parameter is determined using the weld curves and in situ monitoring, as already described in section 2.3. The resulting weld curves are shown in figure 3.5, where the black dotted lines indicate the location of the optimum weld. All have their optimum at a distinct displacement such that optimum welds can be displacement controlled. From the reference welds at their optimum displacement the LSS is determined and the cross section of the weld line is observed.



(a) *Weld curves of weld with CF/PEEK substrate and PEEK ED film, with the optimum at 0.11 mm displacement*

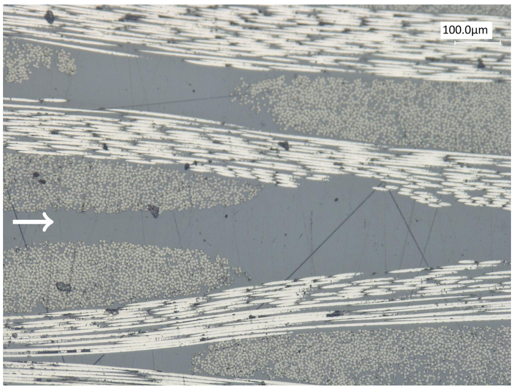
(b) *Weld curves of weld with CF/PPS substrates and PPS ED film, with the optimum at 0.16 mm displacement*

(c) *Weld curves of weld with CF/PPS substrate and PEEK ED film, with the optimum at 0.13 mm displacement*

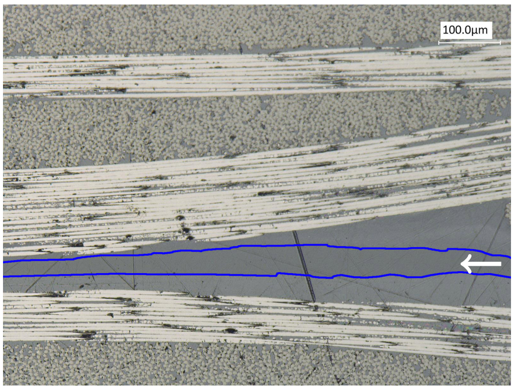
Figure 3.5: *Weld curves of reference welds. The 100% displacement refers to a weld displacement equal to the original ED thickness and the dotted lines represent the location of the optimum weld*

Note the high power and energy required in two of the reference cases, the CF/PEEK with PEEK ED film and sample 2 for the CF/PPS with PEEK ED film (figures 3.5a and 3.5c), compared to the third case. It was found that during welding of the first two the sonotrode was loosely fitted causing a high power loss. Due to this, both the power and energy introduced in the substrates appear higher than in reality is applied. Because the weld is displacement controlled this is believed to have little impact on the final LSS and cross section of the samples. An indication that the loosely fitted sonotrode caused this high power and energy can be seen from sample 2 in figure 3.5c, which is welded with a tightened sonotrode. The power and energy are in similar range as the CF/PPS with PPS ED film weld, which confirms the influence of the loose sonotrode.

An interesting difference between the CF/PEEK with PEEK ED film weld and CF/PPS with PEEK ED film weld appears when the cross section of both welds is observed along the weld line. The weld line of the first case, shown in figure 3.6a, is no longer visible as a separate layer between the substrates. In the weld with dissimilar materials between ED and resin, figure 3.6b a color difference at the weld line indicates that the PEEK ED does not mix with the PPS resin but forms a solid resin layer between the substrates. This layer is highlighted in figure 3.6b by the blue line.



(a) *Cross section of CF/PEEK with PEEK ED film welded at the optimum displacement of 0.11 mm.*



(b) *Cross section of CF/PPS with PEEK ED film welded at the optimum displacement of 0.13 mm. The blue line traces the PEEK layer between the CF/PPS substrates*

Figure 3.6: *Cross-section of reference welds between CF/PEEK with PEEK ED film and CF/PPS with PEEK ED film. The arrows indicate the weld line*

The average LSS for the reference cases is determined from three samples and shown in figure 3.7. The error bars represent the maximum and minimum measured LSS. It can be observed that the CF/PEEK with PEEK ED film resulted in the strongest weld. The CF/PPS with PPS ED film has a significantly lower LSS due to the difference in material. Noticeable is that the use of a PEEK ED film with CF/PPS substrates did not have a significant effect on the LSS compared to the case with the PPS ED film.

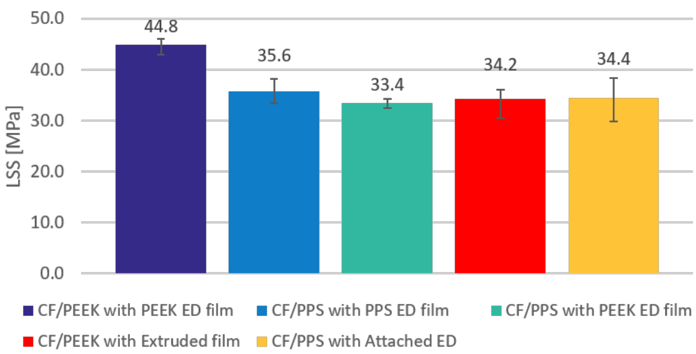


Figure 3.7: *Average LSS of the reference welds, welds with Extruded Film, and welds with the Attached ED. The error bars represent the maximum and minimum measured value*

3.2.2 Extruded film (PEEK) with CF/PEEK substrates

The Extruded film is manufactured on the build platform of the FDM machine and positioned in similar manner as the reference cases. The thickness was set at 0.25 mm but when measured with a caliper it varied between 0.25 mm and 0.30 mm. Furthermore, the top surface was not flat but contained ridges next to each extrusion path. An example of these ridges is given in the microscopic image in figure 3.8. The extrusion path for this ED is similar as for the Extruded film but the thickness was set at 0.15 mm.

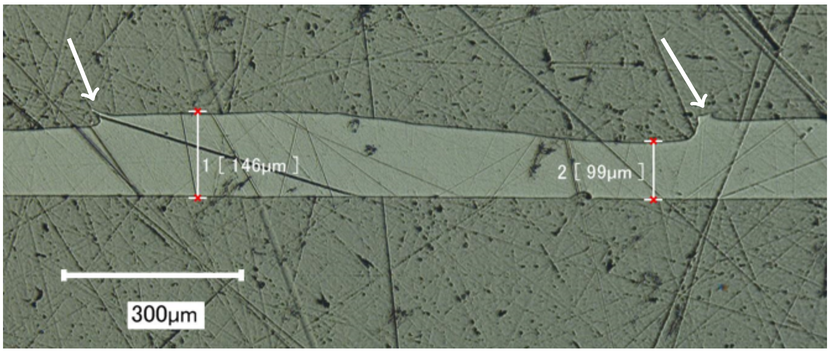


Figure 3.8: *Microscopic image of cross section of Extruded film ED with set thickness of 0.15 mm, with the arrows indicating the ridges*

When looking at the weld curves for these welds in figure 3.9 it can be seen that the displacement differs from the reference case. Furthermore, the power required is lower due to the reduction in amplitude from 86.2 μm to 77.6 μm. The displacement curve resembles the curve for a weld with triangular ED as described in section 1.1.3, with an immediate downward displacement of the sonotrode followed by a plateau in displacement. It is believed that the ridges act similar as the triangular EDs, being rapidly melted and squeezed until fully flattened. After this initial displacement, the weld continuous in similar fashion as the reference welds do from the beginning of the weld. The optimum is indicated with the dotted line at a displacement of 0.12 mm.

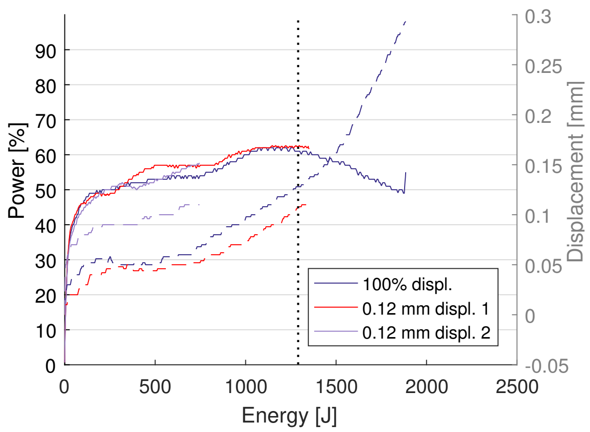
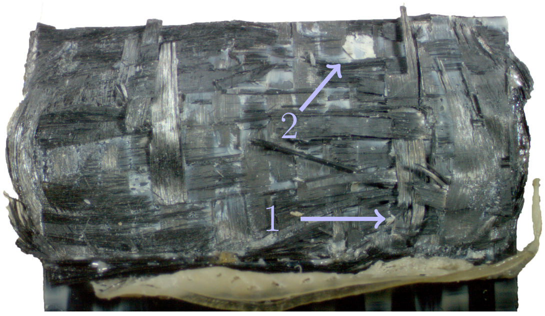


Figure 3.9: *Weld curves for CF/PEEK substrates with the Extruded Film as ED. The dotted line represent the optimum weld at a displacement of 0.12 mm*

Two weld curves of welds at the optimum displacement of 0.12 mm are shown in figure 3.9, and differ significantly from each other. Sample 1 has the displacement plateau around 0.05 mm, similar to the weld at 100% displacement. The plateau of sample 2 appears at a displacement of 0.09 mm. This causes the weld to reach the 0.12 mm set as controlling parameter at a much lower energy compared to sample 1 (750 J compared to 1300 J). The impact of this is visible in the fracture surface of the two samples. Sample 1, shown in figure 3.10a, has first ply failure, whereas sample 2, shown in figure 3.10b, has weld interfacial failure within the ED. Sample 2 only reached the end of stage 2 from the weld stages, where sample one is at the optimum in stage 4. It is believed that the ridges on the surface are higher for sample 2 which made the initial displacement larger.



(a) *Fracture surface of sample 1 from the Extruded film ED having first ply failure*

(b) *Fracture surface of sample 2 from the Extruded film ED having interfacial failure*

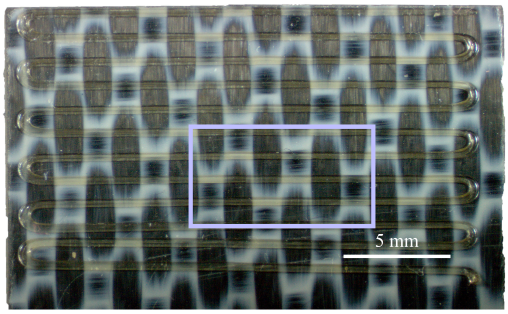
Figure 3.10: *Two fracture surfaces of welds with the Extruded film as ED at the optimum displacement of 0.13 mm*

The occurring irregular ridges appearing at the surface causes an irregular weld process and final weld quality. This irregularity in the weld, along with the long extrusion process of 127 seconds, this ED shape is believed not viable to manufacture using FDM.

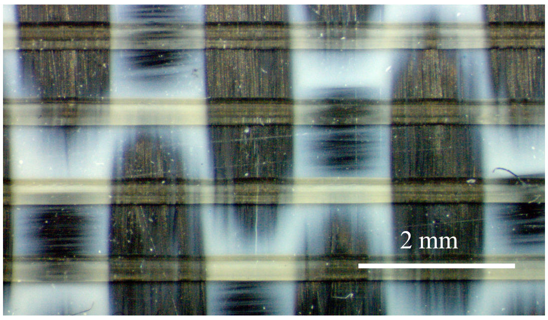
3.2.3 Results of Attached ED (PEEK) with CF/PPS substrates

As explained in section 3.1.1 insufficient bonding is found when the Attached ED was extruded on consolidated CF/PEEK substrates thus CF/PPS substrates are used instead. With this combination sufficient bonding was achieved for the combination to withstand handling forces and be welded without additional fixation of the ED. The resulting shape of the Attached ED on the substrate is shown in figure 3.11a with a close up in figure 3.11b. The thickness is set as 0.20 mm, extrusion width as 0.40 mm and distance between strands is 0.6 mm. The width is believed to be too narrow for this ED to be integrated on the substrates in the mould, as they will break.

The shape is chosen in this fashion to reduce extrusion time compared to the Extruded film from before. The direction of the strands is chosen such that they can be easily elongated if a longer weld surface is required, for example for continuous USW. The extrusion time for the Attached ED is 48 s, which is a reduction of 62% compared to the Extruded film which takes 127 s to extrude.



(a) *Attached ED on CF/PPS surface*



(b) *Close up of Attached ED on CF/PPS substrate*

Figure 3.11: *Attached ED on CF/PPS substrate*

Optimum weld for Attached ED (PEEK) on CF/PPS substrate

As before the optimum weld parameter is determined by welding a sample at 100% displacement and using the obtained weld curve with in situ monitoring. The resulting weld curves are shown in figure 3.12 with the black dotted line representing the optimum weld location. Due to the displacement plateau, the optimum weld has no distinct displacement value, eliminating the use of displacement as controlling parameter. Instead, the weld will be energy controlled with the optimum at 780 J.

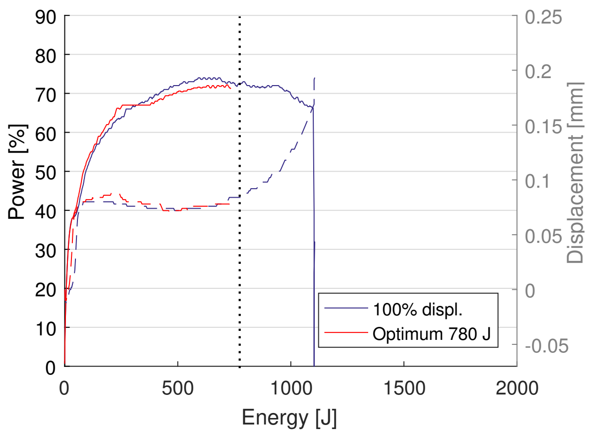
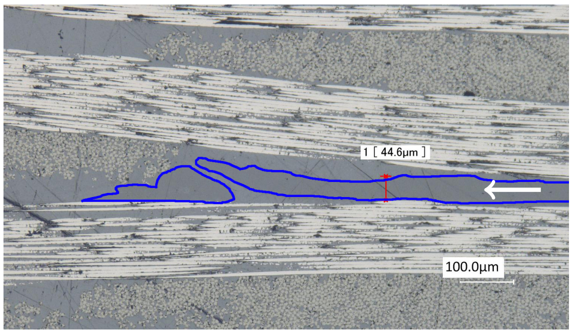


Figure 3.12: *Weld curves of 0.20 mm Attached ED. 100% displacement is set at 0.20 mm. The dotted line represents the optimum energy of 780 J*

The obtained weld curve, especially the displacement curve, is seen before when welding EDs that do not cover the entire weld interface. Examples are triangular EDs [11], integrated strips [13], and before in this research with the ridges on the Extruded film in section 3.2.2. To investigate if the melting process is similar as the triangular ED, the process is investigated further by stopping the weld at several intermediate weld points.

A fracture surface of a weld at the optimum of 780 J is given in figure 3.13a. No remnant ED is visible on the FS of which the failure mode is first-ply-failure. Some fibre bundels at the left edge have been displaced outward and the surface looks flattened, indicating the weld is a little overwelded. A microscopic image of the weld line is shown in figure 3.13b and as with the reference case (CF/PPS with PEEK ED film) a distinct layer of PEEK remains visible. Difference between these cross section is the irregular distribution of the PEEK for the Attached ED compared to the constant layer visible in figure 3.6b. It is believed that this irregularity is caused by the ED not covering the entire weld interface.

(a) *Fracture surface of weld with CF/PPS substrate and Attached ED welded at the optimum of 780 J*



(b) *Cross section with the blue line tracing the PEEK layer between the CF/PPS substrates and the arrow indicating the weld line*

Figure 3.13: *Fracture surface and cross section of weld with CF/PPS substrates and Attached PEEK ED at the optimum energy of 780 J*

The average LSS of 6 samples of the weld with the Attached ED is 34.4 MPa and also shown in figure 3.7. The strength is similar as the reference case with CF/PPS substrate and PEEK ED films. The dispersion in measured values is larger, ranging from 29.9 MPa to 38.4 MPa. This increase in dispersion is believed to be caused by using energy as controlling parameter instead of displacement.

Investigation on the melt process of the Attached ED

To investigate the melt process and flow of the Attached ED the weld process is stopped at three points of interest observed in the weld curves from figure 3.12. Different process parameters are used to stop at the required stages, being:

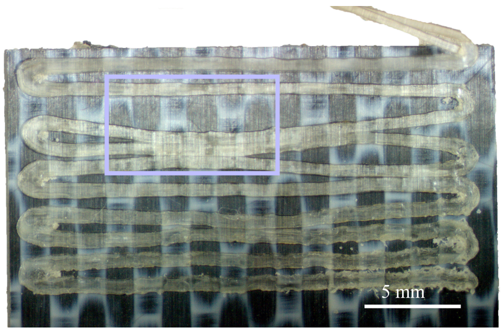
- 0.05 mm displacement: Stopped during initial displacement, before the displacement plateau is reached. To better see the state of the ED the consolidation phase is not applied in this case.
- 120 ms time: Stopped at the onset of the plateau. Time is used because the displacement at which the plateau occurs varies,making it unreliable to use as controlling parameter on this occasion.
- 500 J energy: At the center of the displacement plateau. 500 J was consistently found to be halfway in the plateau.

The optimum energy of 780 J is already covered in this section. Th process after the optimum is irrelevant for this part of the research as it will only show overheating of the weld.

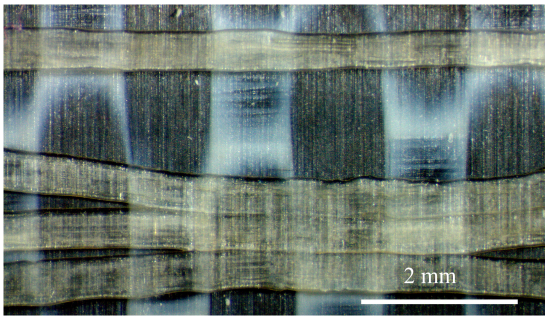
During initial displacement - 0.05 mm displacement

Before the displacement plateau is reached the bond between the two substrates is still non-existing. A look at the 'fracture surface' (figure 3.14a) reveals that the ED is a flattened compared to the original (figure 3.11). The substrate material where no ED is present, is not affected as can be seen from the close-up in figure 3.14b. Interesting is that the surface shown is not the substrate on which the Attached ED was extruded. Most likely the initial heating by friction is greater at the free surface, resulting in faster melting.

The flattening of the ED corresponds with the melting process of triangular EDs. As can be seen in the fracture surface, some individual strands shifted from their original position at an earlier stage of the weld process. As the distance between the strands affect the weld process [13, 37], this phenomena can result in variations in the weld process. Better adhesion between the ED and substrate is required to prevent the movement of the ED.



(a) *Fracture surface of Attached ED after weld of 0.05 mm displacement*



(b) *Close-up of Attached ED after 0.05 mm displacement weld*

Figure 3.14: *Fracture surface of the weld with Attached ED and CF/PPS substrate welded at a displacement of 0.05 mm, stopped before the displacement plateau was reached. The weld parameters are similar as in table 2.2, only the consolidation phase is not applied.*

Weld process at onset of plateau - 120 ms

At the onset of the plateau, at 120 ms, a cross section of the weld is shown in figure 3.15. At the onset of the displacement plateau, after 120 ms weld time, it is expected that the flow fronts of individual strands have met. The cross section shown in figure 3.15 reveals this is not the case. Gaps between different flow fronts are still visible as indicated by the arrow at number 1 and 2. The large stretch of ED at number 3 indicates that some of the flow fronts are connected. This irregular flow of the ED is attributed to the shifting of individual strands as seen in figure 3.14.

Weld process at the center of the plateau - 500 J

In the middle of the plateau, at an energy of 500 J, the cross section in figure 3.16 reveal that the gaps between the flow fronts observed previously have disappeared. Again the PEEK layer between the CF/PPS substrates is traced and it can be seen that the layer is irregularly distributed. It appears as the PPS resin from the substrate fills the gaps between the PEEK of the Attached ED. This irregular layer is also visible at the cross section of the optimum weld in figure 3.13b.

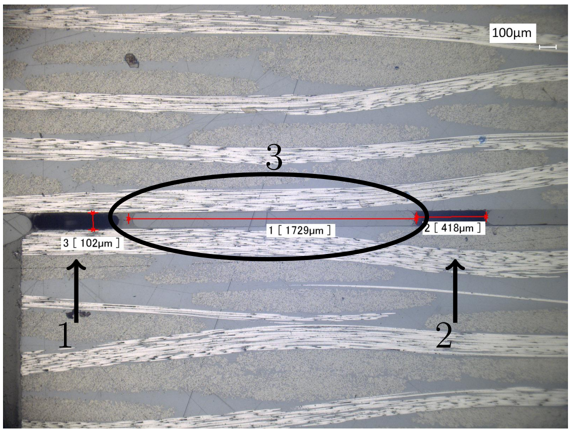
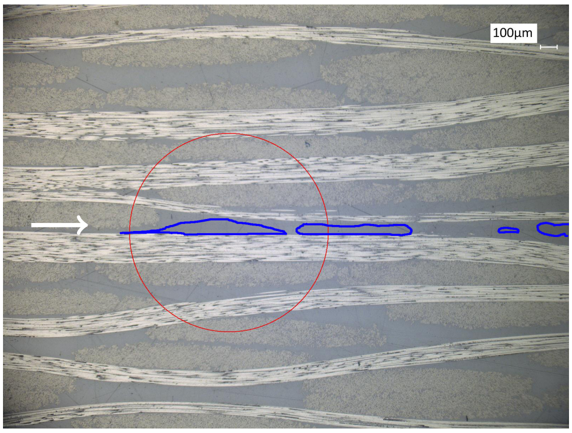
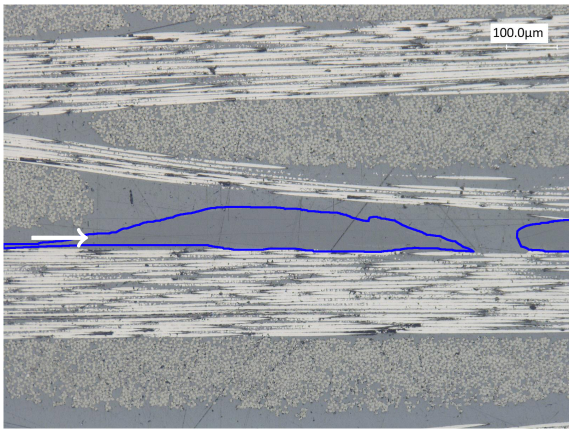


Figure 3.15: *Cross section of the weld with the Attached ED stopped at the onset of the plateau after 120 ms*



(a) *Cross section showing an irregular PEEK layer between two CF/PPS substrates*



(b) *Close-up of cross section*

Figure 3.16: *Cross section with close-up of the weld with Attached ED and CF/PPS substrates stopped at 500 J energy. Blue lines trace PEEK layer between the substrates, arrows indicate the weld line.*

3.3 Concluding remarks on extruded energy directors

This part of the research investigated possibilities and challenges in using Fused Deposition Modeling (FDM) as a means to manufacture the Energy Director for Ultrasonic Welding of Thermoplastic Composites. This is done by first extruding an ED similar to a flat polymer film that covers the entire weld interface, the Extruded Film. After this step, the possibility to manufacture an ED with FDM directly on a consolidated substrate is investigated, where the ED and substrate should bond such that this bond can withstand handling forces and being welded without additional fixation of the ED. The shape chosen is a configuration of parallel narrow strands of 0.4 mm width, positioned 0.6 mm apart with a thickness of 0.20 mm. The width is believed too narrow to integrate this ED in the mould. Manual positioning of this ED will be slow and imprecise.

The main observed possibility of using FDM as ED manufacturing method is that it can simultaneously manufacture and bond a PEEK ED on consolidated CF/PPS substrates. After this, no additional steps are required before welding. The measured single lap shear strength (LSS) of these welds is 34.4 MPa, almost similar as the LSS of the reference weld with CF/PPS substrate and PEEK ED film (33.4 MPa).

In this process, two challenges are encountered, being: 1) An uneven thickness in both the Extruded Film ED and the Attached ED, and 2) insufficient bonding between the ED and the substrates. The uneven thickness presents itself in the Extruded Film as ridges of different height protruding from the surface. For the Attached ED, a sample was only accepted if the thickness was within the set requirement of 0.20±0.01 mm. This requirement is set to minimize the influence of a thickness difference on the weld process. However, 67% of all the manufactured EDs are rejected due to this requirement, indicating a more precise application method is required.

As for the second challenge, no bond between CF/PEEK substrates and the Attached EDs is achieved. The bond between the CF/PPS substrate and Attached ED is barely sufficient as parts of the ED displace at the start of the vibration phase. Research on further increasing the bond between the ED and substrate is required.

An investigation on the effect a thickness variation in the ED has on the weld is the subject of the second part of this research.

Chapter 4

Challenge in FDM: Effect of Thickness Variations within the ED

One of the challenges arising from previous research part on welding with energy directors manufactured with Fused Deposition Modeling, is the variation in thickness of the ED. Earlier research already mentioned that the weld process and final weld quality are affected by difference in ED thickness [13] but a dedicated investigation to this effect has not been done. This part of the research focuses on obtaining a better understanding of the weld process and final weld when the ED has a thickness difference. First the research plan is given, followed by the results and discussion. At the end some conclusions to this research part are stated.

4.1 Research plan

The sub-research question that belongs to this part is:

"How does a variation in ED thickness affect the weld process and final weld quality in the USW process?"

The research starts with selecting a proper ED manufacturing method where an ED with a consistent, deliberate thickness step can be produced. A consistent thickness is important as the influence of differences herein are under investigation. Two methods to manufacture an ED with a thickness step are tried, being extrusion of individual strings at two different thicknesses (Extruded Strings), and combining two PEEK ED films of different thickness to one ED (Split ED). The latter method is chosen due to a better accuracy and consistency in thickness and shape. More information on the Extruded Strings with thickness variation can be found in appendix B.

The EDs with a thickness step, from now on referred to as the Split EDs, are manufactured by pressing a different amount of 0.05 mm PEEK films into one layer according to the manufacturing scheme described in section 2.1. They are applied to the substrate as shown in figure 4.1, where it is believed that this set-up results in simmilar weld conditions for both ED sides. The six different configurations used are summarized in table 4.1, with the 0.25/0.25 mm Split ED is being used as the reference case with no thickness step. The substrate material for all welds is CF/PEEK and the weld settings, which can be found in table 2.2, are kept constant for all configuration. The controlling parameter for all configurations is set as the optimal displacement found for the reference case, determined to be 0.11 mm. By doing so, changes in both the weld process as final weld can be observed between the different configurations.

Table 4.1: *Thickness configurations used as Split ED*

Thickness 1	*Thickness 2*	*Reference name*
0.25 mm	0.25 mm	0.25/0.25 mm Split ED
0.25 mm	0.20 mm	0.25/0.20 mm Split ED
0.25 mm	0.15 mm	0.25/0.15 mm Split ED
0.25 mm	0.10 mm	0.25/0.10 mm Split ED
0.25 mm	0.05 mm	0.25/0.05 mm Split ED
0.25 mm	0.00 mm	0.25/0.00 mm Split ED

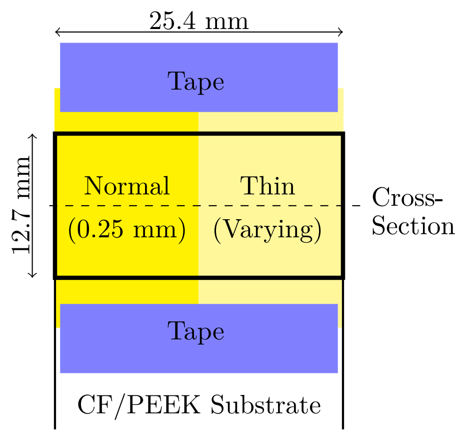


Figure 4.1: *Schematic overview of the positioning of the Split ED on the CF/PEEK substrate*

Of each configuration, displacement controlled welds with a set displacement of 0.11 mm are performed. Changes in weld process, fracture surface, cross section (taken along the dashed line in figure 4.1), and LSS are observed for each individual configuration. From these observations three hypotheses are formulated on the effect of the thickness step on the weld process and final weld. These hypotheses are further investigated to confirm or disprove them by looking at the fracture surfaces of welds deliberately stopped at different weld stages. The displacement of the sonotrode in the Force ramp-up phase is also investigated to see if this significantly influence the weld process.

4.2 Results and discussion

First the results of the thickness measurements on the Split ED configuration are given, after which the displacement in the Force ramp-up phase is discussed. This is followed by the determination of the optimal displacement for the reference case. Next, the changes in welding process, fracture surface, LSS and cross section of each Split ED configuration will be discussed and three hypotheses are stated. These hypotheses are further investigated next. The chapter ends with some conclusions on this part of the research.

4.2.1 Thickness measurements on Split ED

Thickness measurements on the Split ED are done using the Keyence microscope described in section 2.5. Of each film used, the thickness is measured at eight locations distributed over one ED with an example measurement shown in figure 4.2. The results and further information on the Extruded Strings can be found in appendix B. A summary of the thickness results for the Split ED is given in table 4.2. The difference between the set thickness and actual measured average is 2.3% with a standard deviation of 1.5 μm, which is superior to the values found for the Extruded Strings. With this information, the research continuous using the Split EDs.

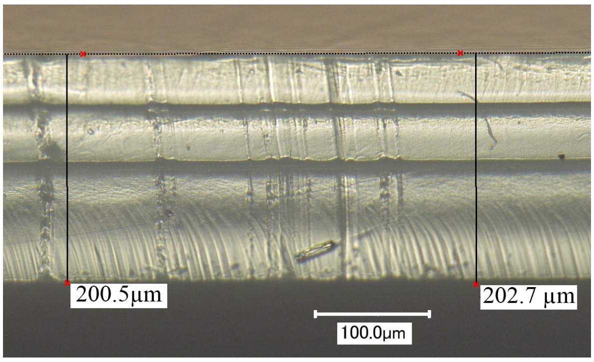


Figure 4.2: *Example measurement of ED film consisting of four layers of 0.05 mm thick PEEK film, with a target thickness of 0.20 mm (200µm) as used in the 0.25/0.20 mm Split ED*

Table 4.2: *Summary of thickness measurements for the Split ED*

Set thickness [μm]	250	200	150	100	50
Avg. thickness [μm]	255	204	153	101	51
Difference w.r.t. set value [%]	1.9	2.2	2.3	1.0	1.5
Std. from average [μm]	0.89	0.92	1.51	0.76	0.46
Std. from average[%]	0.3	0.4	1.0	0.7	0.9

4.2.2 Sonotrode displacement during the force ramp-up phase

Before the vibration phase of the weld the force on the substrates and ED is increased until the set weld force is reached. During this force application, a significant displacement of 0.05 mm at 500 N was measured by the by the USW machine. To rule out that this displacement occurred due to strain in the ED the expected strain in the ED is calculated. At 500 N the stress in the ED is 1.55 MPa (500 N/(25.4mm * 12.7mm)) which with a stiffness of 2.3 GPa [38] would result in a strain of 6.7e-4. With a thickness of 0.25 mm the actual expected displacement due to this force is 1.7e-4 mm which is negligible compared to the 0.05 mm. It is believed that the measured displacement comes from deformation of the machine. This is further confirmed by displacement measurements at different forces and stresses. The results in table 4.3 show that the displacement is independent of the applied stress but linearly related to the applied force.

Table 4.3: *Displacement data at the end of the force ramp-up phase*

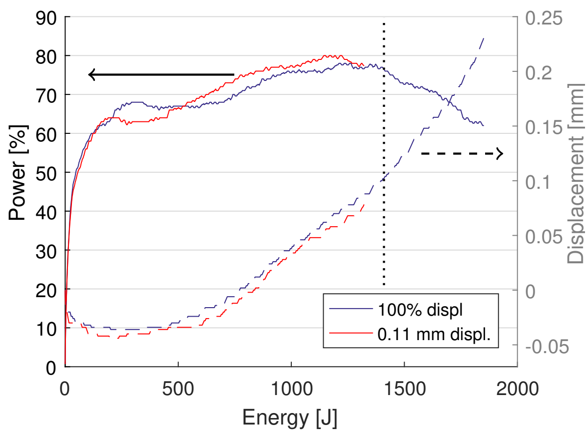
Weld force [N]	Area$_{ED}$ [mm^2]	σ_{ED} [MPa]	Displ.[mm]
500	322	1.55	0.05
500	161	3.10	0.05
250	161	1.55	0.02
1000	322	3.10	0.09

4.2.3 Weld curves, fracture surfacess, and cross section of individual Split ED configurations

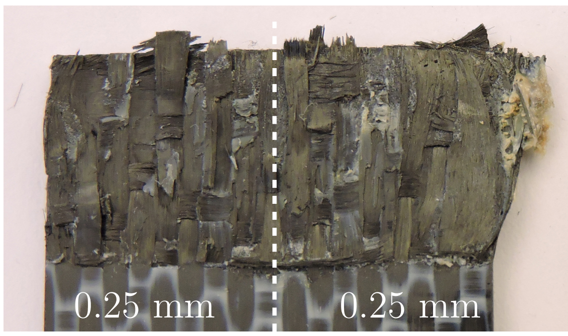
In this section the weld curves, fracture surfaces, and cross sections for each individual Split ED configuration are given. Observed changes in the process lead to three hypotheses stated at the end of this section.

Reference weld: 0.25/0.25 mm Split ED

This configuration is used to determine the optimum weld parameter that will be used to weld the remaining configurations. The optimum is determined along the dotted line in figure 4.3a and set at a displacement of 0.11 mm. The second curve in figure 4.3a shows another weld at the optimum displacement of 0.11 mm. The fracture surface in figure 4.3b, welded at the optimum 0.11 mm displacement, has first-ply-failure indicating that the weld is indeed welded at the optimum. The fibre bundles on the right edge show signs of flattening and outward displacement indicating slight overwelding of this part.



(a) *Weld curves of 0.25/0.25 mm Split ED with the dotted line being at the optimal displacement of 0.11 mm*



(b) *Fracture surface of 0.25/0.25 mm Split ED weld at the optimum displacement of 0.11 mm*

Figure 4.3: *Weld curve and fracture surface of the reference Split ED configuration: 0.25/0.25 mm Split ED*

0.25/0.20 mm Split ED

The weld curves from the 0.25/0.20 mm Split ED shown in figure 4.4 have a different behaviour compared to the reference 0.25/0.25 mm ED configuration. A small displacement plateau occurs around 0.01 mm displacement and a third power peak appears. The onset of increase in power towards this third peak coincides with the end of the displacement plateau. Remarkable is the difference in the power curves of sample 1 and sample 2. Sample 2 has a large drop in power before increasing where sample 1 hardly shows such a drop.

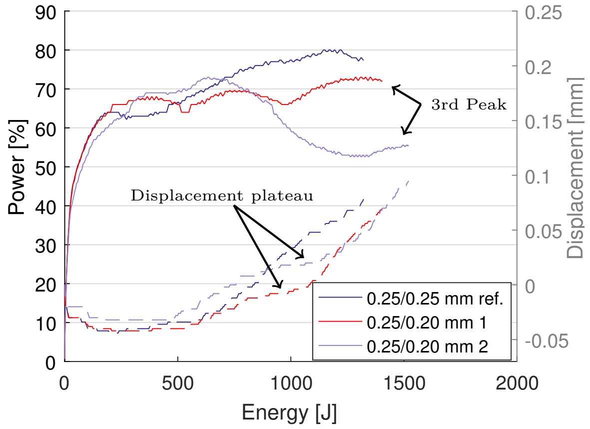
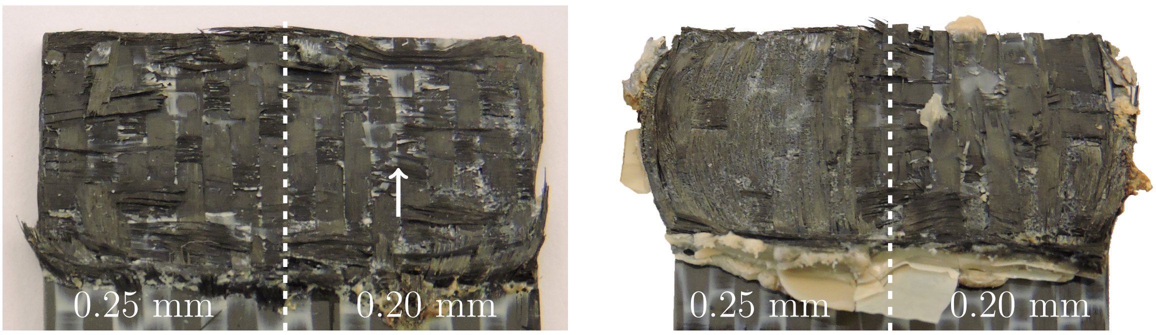


Figure 4.4: *The weld curve of the reference Split ED and two samples of the 0.25/0.20 mm Split ED welded at a displacement of 0.11 mm*

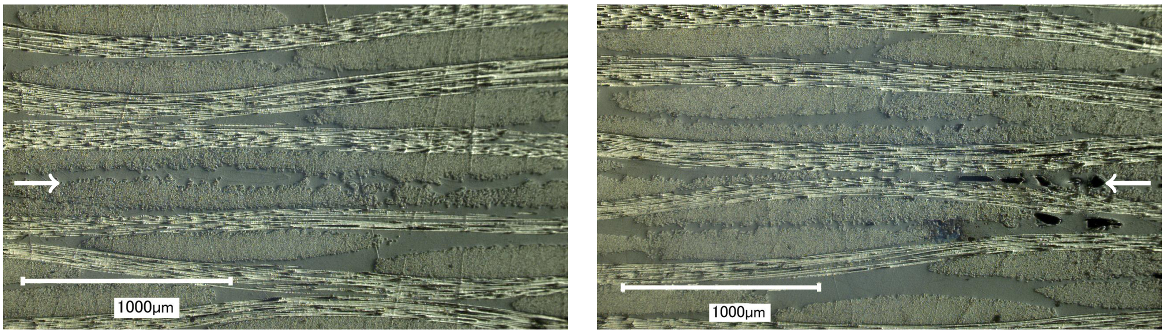
This difference in weld curves translates in differences in the fracture surface of the welds. The fracture surface of welds that resemble the curves of sample 1 (figure 4.5a) show broken fibres and little fibre distortion. The arrow points at a patch of fibres that originated from the other substrate, indicating failure in the second layer. The surface of sample 2 shown in figure 4.5b has severe damage to the 0.25 mm area, with flattened fibre bundles that are squeezed to the outside of the weld. These are indications of a stage 5 weld, welded beyond the optimum and overheated. On the other hand, the 0.20 mm side has first-ply-failure and only slight distortion of the fibres indicating that his area welded near its optimum.



(a) *Fracture surface of sample 1* **(b)** *Fracture surface of sample 2*

Figure 4.5: *Fracture surface of sample 1 and 2 of the weld with 0.25/0.20 mm Split ED welded at a displacement of 0.11 mm*

The cross section of a weld with 0.25/0.20 mm Split ED weld is shown in figure 4.6 which has welding curves similar to sample 1. In figure 4.6a the cross section is located at the 0.25 mm ED part whereas the cross section in figure 4.6b is taken from the 0.20 mm half. There are some small voids present in the 0.20 mm cross section, which occur at the edge of the weld due to additional heating in this location.



(a) *Cross section of the weld line from the 0.25 mm ED side* **(b)** *Cross section of the weld line from the 0.20 mm ED side*

Figure 4.6: *Cross section of weld with 0.25/0.20 mm Split ED welded at 0.11 mm displacement, with the arrows indicating the weld line*

The observations is made that an elongated displacement plateau results in overwelding of the 0.25 mm side of the weld.

0.25/0.15 mm Split ED

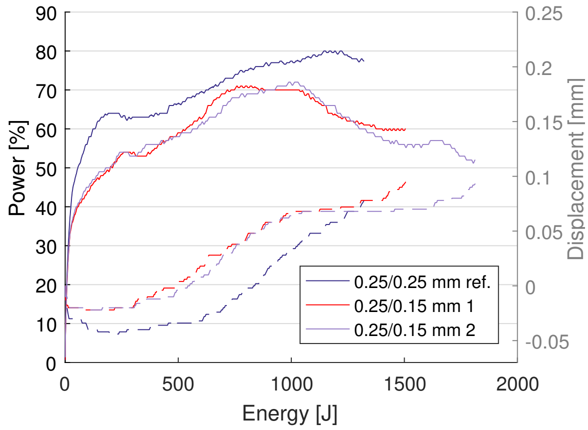
The weld curves for this configuration are shown in figure 4.7a along with the weld curves of the reference Split ED. While the weld settings are similar for both configurations, the power used for the 0.25/0.15 mm Split ED configuration is lower compared to the reference Split ED configuration. This decrease in power is an indication that initially only the 0.25 mm ED area is welded, with the 0.15 mm ED area remaining unaffected. It is believed that the drop in power due to this is partly compensated by the higher stress initially present in the ED, as the same weld force (500 N) acts at only 50% of the original area.

Again a displacement plateau occurs, now more dominant than with the 0.25/0.20 mm Split ED. The displacement plateau has shifted to a displacement of 0.06 mm and a higher energy level. During the displacement plateau the power decreases, followed by an increase of both power and displacement near the end of the plateau. The curves are more consistent with each other compared to the 0.25/0.20 mm Split ED configuration, although difference in plateau length are present.

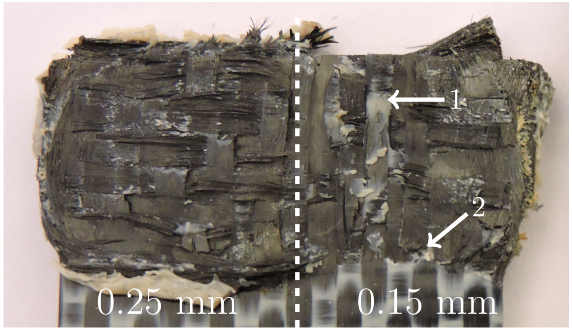
It is believed that the displacement plateau is caused by unmelted ED present in the 0.15 mm area. This hypotheses is further discussed in section 4.2.4.

The fracture surface of the 0.25/0.15 mm Split ED is given in figure 4.7b where it appears as two separate fracture surfaces are combined to one. The 0.25 mm half has broken fibres, but also some distortion of the fibre bundles. On the 0.15 mm side resin rich areas are present (1) and the weld has not affected the entire overlap area as can be at the bottom of the weld with an irregular weld line (2). Again at the right edge the fibre bundles show distortion.

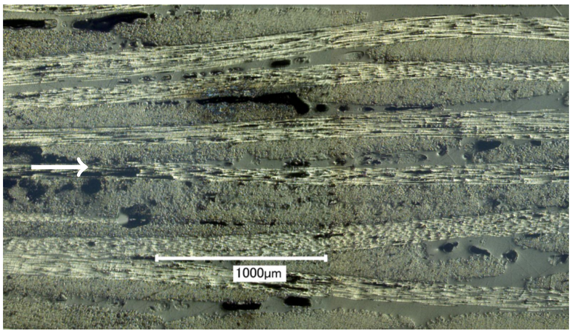
The cross section in figure 4.7c taken from the 0.25 mm half reveals numerous voids present appearing several layers in the substrate. This is an indication that the substrate is heated beyond the first layer which is a sign of overwelding. The cross section from the 0.15 mm half only has a few small voids near the edge.



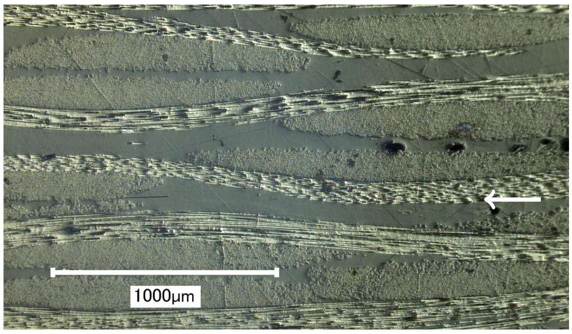
(a) *Weld curves of the reference Split ED and two samples of the 0.25/0.15 mm Split ED*



(b) *Fracture surface of 0.25/0.15 mm Split ED*



(c) *Cross section of the weld line from the 0.25 mm ED side, with the arrow indicating the weld line*



(d) *Cross section of the weld line from the 0.15 mm ED side, with the arrow indicating the weld line*

Figure 4.7: *Weld curve, fracture surface, and cross section of weld with 0.25/0.15 mm Split ED welded at a displacement of 0.11 mm*

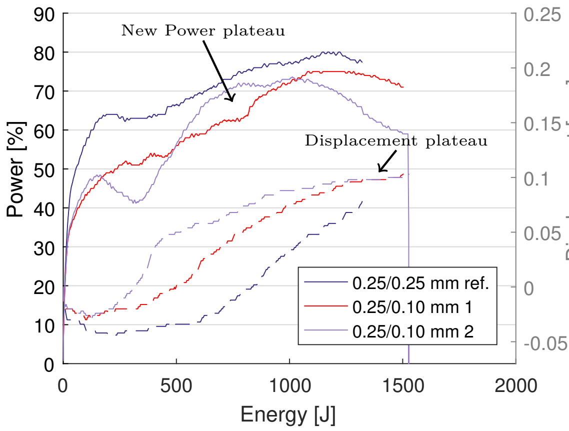
The appearance of the displacement curve, now later in the weld process and more dominant than in the 0.25/0.20 mm Split ED configurations, gives rise to the idea that this plateau occurs due to the presence of the thin ED layer. The believe is that at the plateau, some area of the thin ED is solid, preventing further displacement of the sonotrode. Furthermore, the believe that an elongated plateau overheats the 0.25 mm ED area is strengthened, as the fracture surface of the 0.25 mm ED area has signs of overwelding.

0.25/0.10 mm Split ED

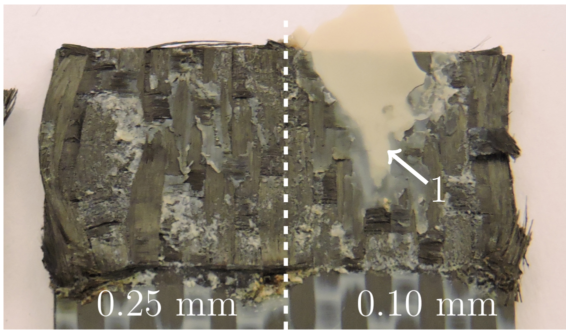
As can be seen from the weld curves in figure 4.8a an increase in thickness difference does not have a significant impact on stage 1 of the weld process compared to the 0.25/0.15 mm Split ED configuration. This strengthens the believe that at first only the 0.25 mm ED side is being heated and melted. The displacement plateau is still visible but again shifted to a higher displacement and energy. It now is located near the end of the weld at a displacement around 0.10 mm.

A new phenomena that occurs is an additional power plateau after which the power increases further. Noticeable is that the displacement of the sonotrode at this plateau is similar to the displacement of the sonotrode at the second power peak of the reference case. This gives rise to the idea that this power plateau represents the second power peak of the 0.25 mm ED side. It occurs at a lower power and energy due to the reduction in area. The increase in power is then caused by interference from the 0.10 mm ED side. As this phenomena not occurred with the previous configurations it is believed that the thin ED sides interfered at a lower displacement. As the rise in power appears before the displacement plateau it appears as the thin ED area affects the weld before the displacement plateau as well.

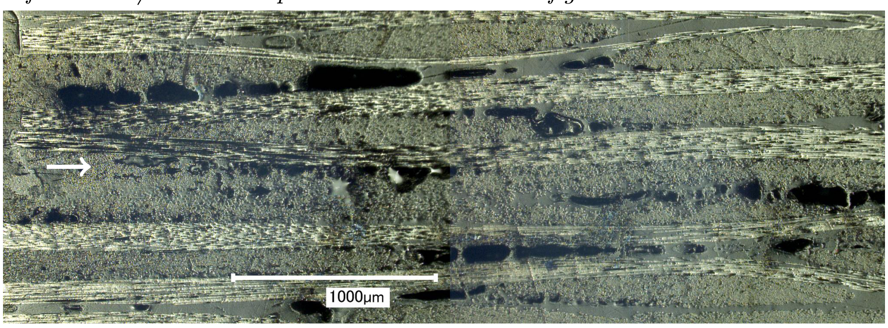
The fracture surface of a weld with 0.25/0.10 mm Split ED with welding curves as sample 1 is given in figure 4.8b. A large unmelted ED area is visible at the 0.10 mm ED side (number 1), indicating that this half of the weld did not surpassed stage 2 of the weld process. The 0.25 mm ED side appears to be welded near the optimum, with some signs of overwelding near the edge.



(a) *Weld curve of the reference Split ED and 2 samples of the 0.25/0.10 mm Split ED*



(b) *Fracture surface of 0.25/0.10 mm Split ED configuration*



(c) *Cross section at the weld line of the 0.25 mm ED area with numerous voids present. The arrow indicates the weld line*

Figure 4.8: *Weld curves, fracture surface, and cross section of welds with the 0.25/0.10 mm Split ED configuration, welded at a displacement of 0.11 mm.*

The cross sectional image in figure 4.8c is of the weld line on the 0.25 mm ED side and displays numerous voids beyond the first layer. This indicates overheating of the substrate well beyond the substrate as seen in welds of stage 5. This severe overheating is not clearly seen from the fracture surface in figure 4.8b. This can be explained by the weld curves, where the weld curves of sample 2 from figure 4.8a belong to the cross section and sample 1 to the fracture surface. It appears that a large decrease in power overheats the 0.25 mm ED side, as was already observed in in the 0.25/0.20 mm Split ED configuration.

The observation from this configuration and the configuration from before, lead to the believe that with difference in thickness within the ED, the thick ED side goes through the normal weld stages until the thin ED side interferes with the process. This interference happens just before the displacement curve. The solid ED visible on the fracture surface strengthens the believe that such a layer causes the displacement plateau by preventing sonotrode displacement. Finally, the difference in observed weld stage between the cross section and fracture surface along with the difference in their weld curves agree with the earlier observation that an elongated plateau and large power drop are signs of overheating of the 0.25 mm ED side.

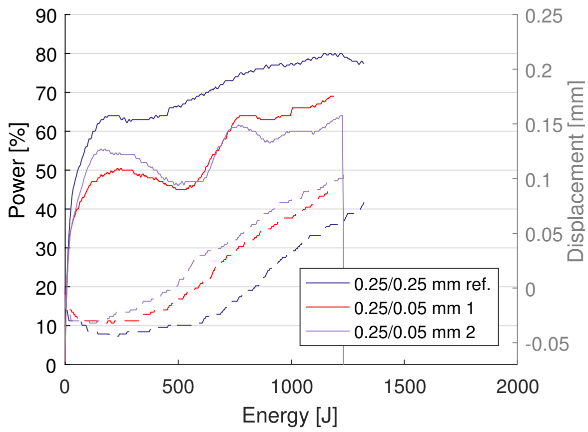
0.25/0.05 mm Split ED

From the weld curves in figure 4.9a it can be seen that again the power during stage 1 of the weld is similar as in the 0.25/0.15 mm ED and 0.25/0.10 mm ED welds. As with the 0.25/0.10 mm Split ED configuration a lower power peak is observed. The shape of the power curve and displacement curve until this peak are similar compared to the reference weld. Interesting is the more dominant decrease in power after the first power peak and a kink in the displacement curve coinciding with the power valley.

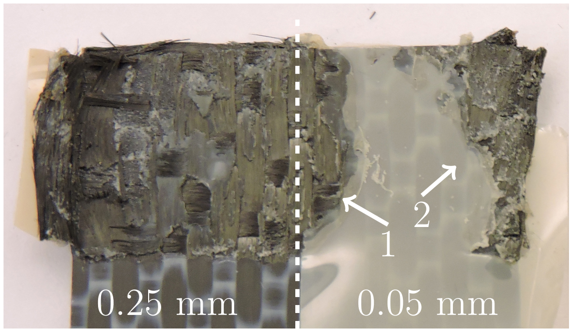
No displacement plateau is present, which indicates that the 0.05 mm ED side is not pressed by the substrates and will not be affected by the weld process. From the fracture surface in figure 4.9b this appears to be largely true. Only the edge contacting the 0.25 mm ED half (1) and the complete right edge (2) show signs of welding. It is believed that during the squeeze flow of the 0.25 mm ED side, some material is pushed between the 0.05 mm ED and the substrates, welding this area as well. This will slow the displacement of the sonotrode, causing the kink in the displacement curve and the welded area at number 1 in figure 4.9b.

The cross section of the weld line at the 0.25 mm ED half in figure 4.9c has some small voids present in the ED. The cross section in figure 4.9d shows the transition from the welded section to the unwelded ED. This transition is smooth as part of the 0.05 mm ED near the edge with the 0.25 mm ED is welded as already observed in the fracture surface.

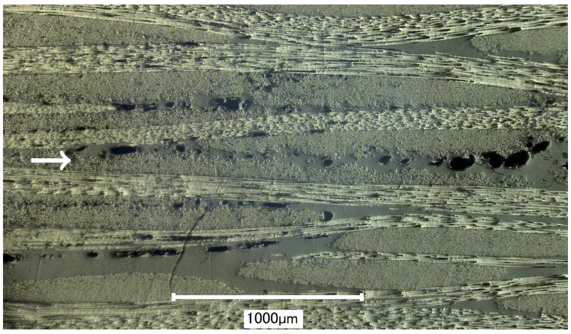
The absence in displacement curve and the 0.25 mm ED side showing signs of first-ply-failure with some resin rich areas present is another confirmation that a plateau causes the 0.25 mm side to overheat. The largely unaffected 0.05 mm side confirms that until a certain displacement, the thin ED side is unaffected by the weld. The relatively normal shape of the weld curves until this point indicate that indeed the 0.25 mm ED side goes through the normal 5 stages of a weld.



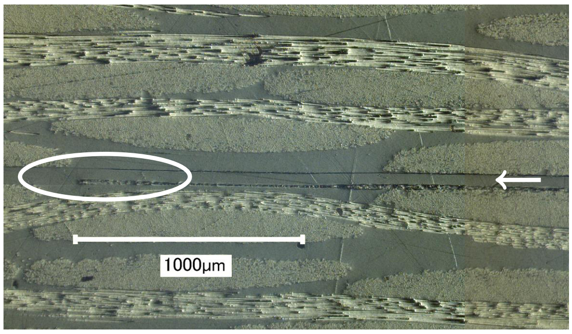
(a) *Weld curves of reference Split ED and two samples of the 0.25/0.05 mm Split ED*



(b) *Fracture surface of 0.25/0.05 mm Split ED configuration, with the arrow indicating the weld line*



(c) *Cross section of the weld line at the 0.25 mm ED part with the arrow indicating the weld line*



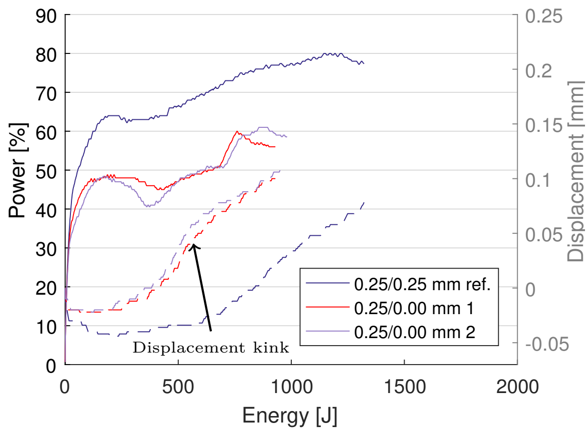
(d) *Cross section where the transition of welded ED to unwelded ED is encircled and the arrow indicates the location of the weld line*

Figure 4.9: *Weld curve, fracture surface, and cross section of weld with 0.25/0.05 mm Split ED configuration welded at a displacement of 0.11 mm*

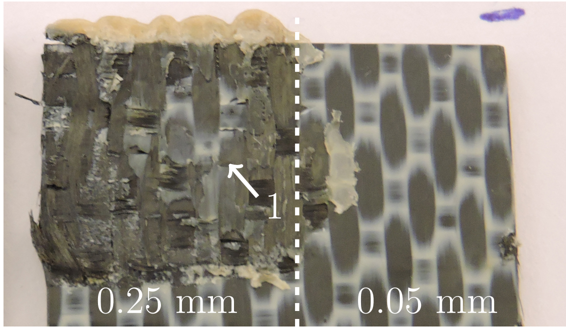
0.25/0.00 mm Split ED

The weld curves for the welds with 0.25/0.00 mm Split ED shown in figure 4.10a show that the power curve returned to a familiar shape seen at the reference Split ED and other ED films. No displacement plateau is visible but again a small kink appears. The fracture surface in figure 4.10b has, similar as the 0.25/0.05 mm ED configuration, an area next to the 0.25 mm ED which is welded, giving similar reasoning to the kink as with the 0.25/0.05 mm Split ED configuration.

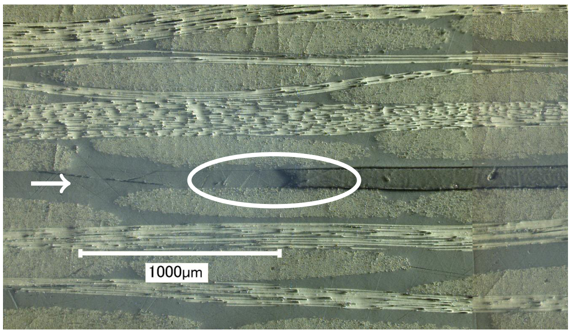
The fracture surface in figure 4.10b furter reveals that the weld has failed in both first-ply-failure for the most part and weld interfacial failure in a resin rich area (1). The cross section in figure 4.10c shows a clean flow front (encircled) where the ED flow stopped. The remaining weld line is unaffected by the weld.



(a) *Two example weld curves for 0.25/0.00 mm ED*



(b) *FS of 0.25/0.00 mm ED weld at the optimum*



(c) *CS at the flow front of the ED in the 0.25/0.00 mm ED weld*

Figure 4.10: *Weld curve, fracture surface and cross section of welds with 0.25/0.00 mm ED*

LSS of individual configurations

Of each configuration described above 5 samples were tested for their LSS and the average values are shown in figure 4.11 and table 4.4. The LSS is calculated over the entire weld interface of 25.4 x 12.7 mm to have a correct comparison with the reference configuration. The error bars represent the maximum and minimum measured LSS. An increase in thickness difference result in a decrease in LSS and inincreae in dispersion.

The decrease in strength can be attributed to the different weld stages found for welds with a varying thickness in the ED. Some areas were suddenly overheated, while others showed no sign of welding at all. Especially the decrease in welded area caused a big decrease, as can be seen between the LSS for the 0.25/0.10 mm Split ED configuration and the 0.25/0.05 mm Split ED configuration. The large drop in LSS between the 0.25/0.20 mm and 0.25/0.15 mm Split ED configurations appears to be caused by the consistent overheating of the 0.25 mm ED half in the latter configuration.

The increase in dispersion is caused by the variation in weld process within one configuration. Inconsistent plateau lengths and welded areas result in large difference between the measured LSS of one configuration.

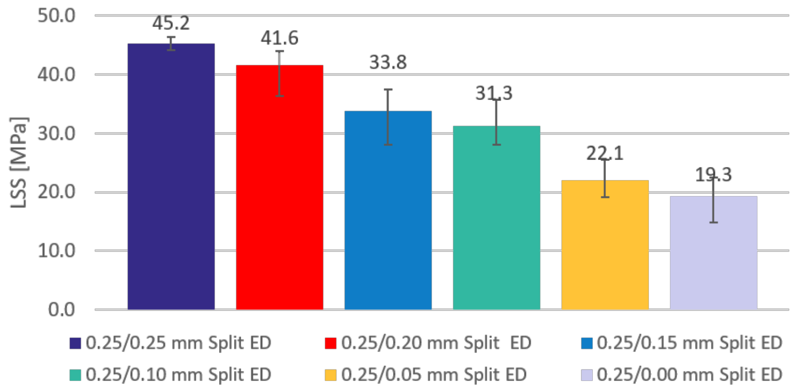


Figure 4.11: *Average LSS of the 6 Split ED configurations, with the error bars representing the maximum and minimum measured LSS*

Table 4.4: *Summary of LSS of the Split ED configurations in numbers*

ED configuration	Avg. LSS [MPa]	Drop [%]	Dispersion [MPa]	Dispersion [%]
0.25/0.25 mm	45.5	0	1.9	4.2
0.25/0.20 mm	41.6	8.6	7.6	18.3
0.25/0.15 mm	33.8	25.7	9.5	28.1
0.25/0.10 mm	31.3	27.3	7.5	24.0
0.25/0.05 mm	22.1	51.4	6.4	29.0
0.25/0.00 mm	19.3	57.8	7.5	38.9

Summary formulated hypotheses

From the observations of the welds with the individual Split ED configurations some hypotheses are formulated describing the effect of a variation in the ED thickness on the weld process and final weld quality. These hypotheses are summarized below:

1. Before the displacement plateau is reached the thin ED area (0.20 mm, 0.15 mm, 0.10 mm) is unaffected by the weld process.
2. The displacement plateau in the 0.25/0.20 mm, 0.25/0.15 mm, and 0.25/0.10 mm Split ED configuration is caused by the thin half (0.20 mm, 0.15 mm, 0.10 mm) still being solid preventing the sonotrode to displace until this area is fully melted.
3. An elongated plateau and large power drop result in overheating of the 0.25 mm ED side of the weld.

4.2.4 Investigating formulated hypotheses

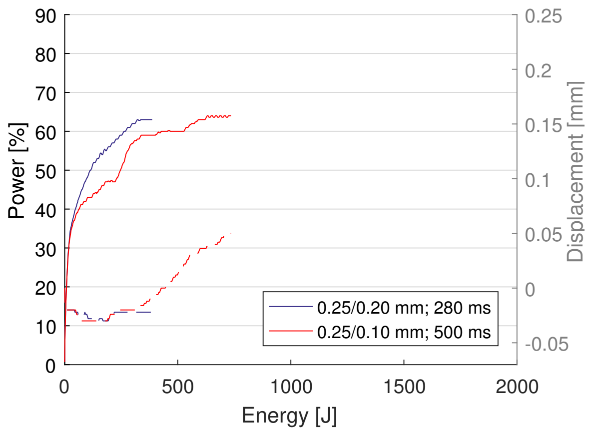
From the investigation on the different thicknesses in EDs with a thickness steps some hypotheses are formulated which are further tested. The results of this research are shown below. At the end the are linked together.

Hypotheses 1: The thin area is unaffected before the displacement plateau is reached

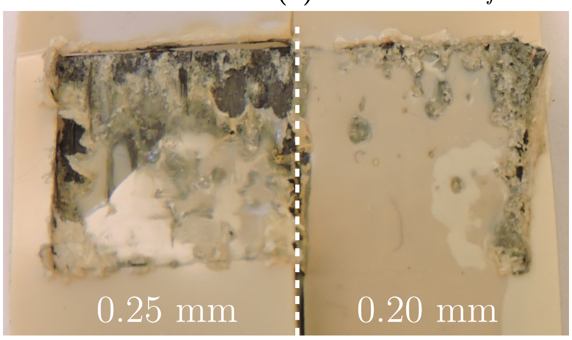
This hypotheses is tested by welding two additional substrates, one with the 0.25/0.20 mm Split ED and one with the 0.25/0.10 mm Split ED configuration, deliberately stopped well before the displacement plateau is reached. To achieve this the welds are time controlled, with 280 ms for the 0.25/0.20 mm Split ED and 500 ms for the 0.25/0.10 mm Split ED. Time is chosen as the energy and displacement had a to great dispersion. The resulting weld curves are shown in figure 4.12a.

The fracture surfaces of the resulting weld are shown in figures 4.12b and 4.12c. Two observations can be made: 1) The thin areas (0.20 mm and 0.10 mm) appear to be unmelted and still be in stage 1 of a weld, and 2) the 0.25 mm areas are either in stage 2 of a weld (figure 4.12b) or stage 3 of the weld (figure 4.12c). Looking back at the fracture surface of the weld with 0.25/0.05 mm Split ED (figure 4.9b) the 0.25 mm ED half is almost at stage 4, whereas the 0.05 mm half is not even in stage 1.

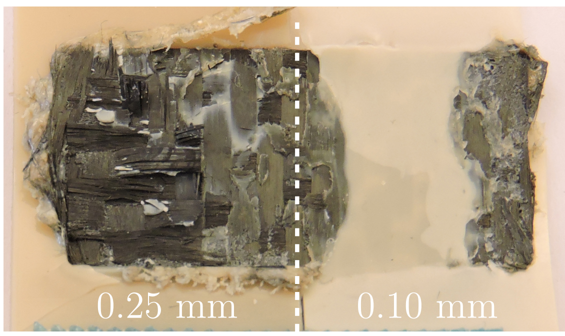
It is concluded that with a thickness step, the thick area (in this case 0.25 mm) melts and welds almost normally at least until the displacement plateau. The process does change due to the reduction in area and, because of this reduction in area, a higher initial stress in the ED.



(a) *Weld curves of welds stopped before their plateau*



(b) *FS of weld with 0.25/0.20 mm ED stopped after 280 ms, just before the plateau*



(c) *FS of weld with 0.25/0.10 mm ED stopped after 500 ms, just before the plateau*

Figure 4.12: *Weld curve and fracture surface of welds stopped before the displacement plateau*

Hypotheses 2: The displacement plateau is caused by the solid ED still present at the area with a thinner ED

With previous hypotheses confirmed, this hypotheses is tested in similar manner by stopping a weld at their displacement plateau. The two additional welds are again time controlled and consist of one weld with 0.25/0.20 mm Split ED at 550 ms, and one weld with the 0.25/0.15 mm Split ED at 650 ms. The weld curves for both welds are given in figure 4.13a. The displacement of both welds is close to the displacement where the plateau is previously observed, being around 0.01 mm for the 0.25/0.20 mm Split ED and 0.06 mm for the 0.25/0.15 mm Split ED.

The fracture surface of the welds (figures 4.13b and 4.13c) partly confirm this hypotheses. In both cases large areas of solid ED are still present on the thin half of the weld (number 1 in both figures). The areas are smaller than observed in figures 4.12b and 4.12c indicating that some areas are already melting before the plateau is reached and the surface are in stage 2 of the weld. A resin rich area in the 0.25 mm half of the 0.25/0.20 mm Split ED is present (number 2 in figure 4.13b), but the color difference indicates that this part has already been melted. Both 0.25 mm half appear to be in stage 3 of the weld, although the 0.25/0.15 mm Split ED configuration is closer to stage 4.

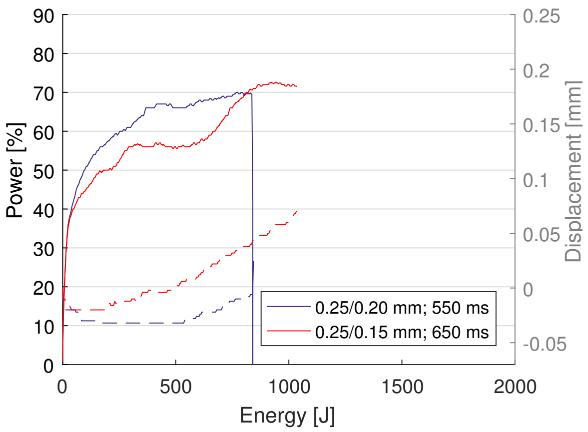
The fracture surfaces shown here are similar as seen before in the weld with the 0.25/0.10 mm Split ED at a displacement of 0.11 mm shown in figure 4.8b. The displacement curve of this weld (sample 1 in figure 4.8a) show that this weld also is near the onset of the displacement plateau. Here the 0.25 mm ED half has reached stage 4 of the weld.

With the combination of results it is confirmed that the sonotrode is not able to displace further upon contact of the solid areas present at the thinner areas in the ED, causing the displacement plateau in the welds.

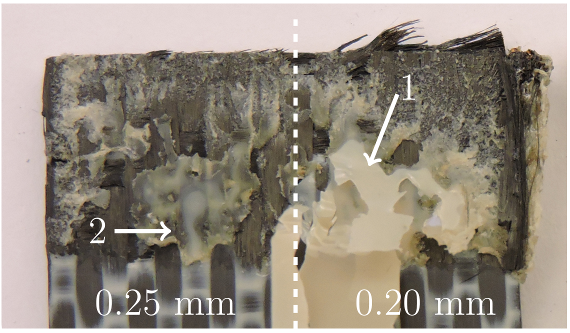
Hypotheses 3: An elongated plateau and larger power drop causes the 0.25 mm ED area to overheat, while the thinner area is being melted

As confirmed before, the movement of the sonotrode is limited by the presence of a solid ED area at the weld interface. It is observed that an elongated plateau results in more overheating of the 0.25 mm ED half, for example by the difference in fracture surface of the weld with 0.25/0.20 mm Split ED configuration between sample 1 (figure 4.5a) and sample 2 (figure 4.5b). This hypotheses is further tested by deliberately overwelding a weld with the 0.25/0.10 mm Split ED configuration, by setting the welding time to 1050 ms, longer than any of these welds took.

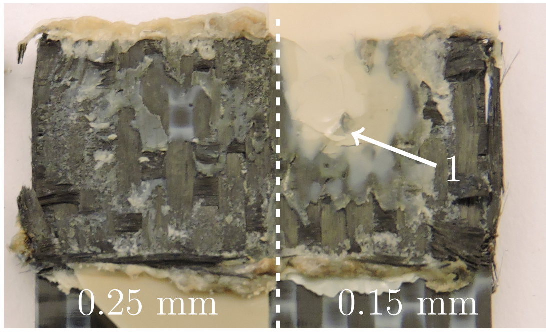
The resulting curve is shown in figure 4.14a, along a curve shown as reference from similar Split ED configuration with 0.11 mm displacement as before. The fracture surface of this weld shown in figure 4.14b confirms the set hypotheses. The 0.25 mm ED area has severe flattening and distortion of the fibre bundles over the entire area indicating severe overheating and being welded to stage 5. The 0.10 mm ED half still has unmelted ED visible and appears to be welded to stage 2. This observation can be linked to weld curve of sample 2 in figure 4.8a and the cross section which showed signs of overheating as well. This observation is also in agreement with the observations of the fracture surfaces of sample 1 and sample 2 for the 0.25/0.20 mm Split ED configuration figure 4.5.



(a) *Weld curves of two welds stopped just before their plateau*



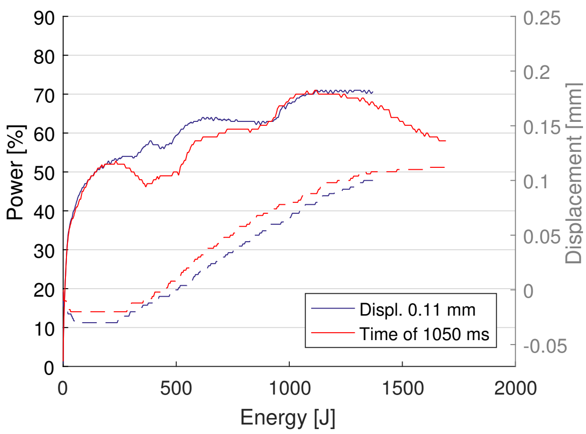
(b) *FS of 0.25/0.20 mm ED stopped after 550 ms at the onset of the displacement plateau*



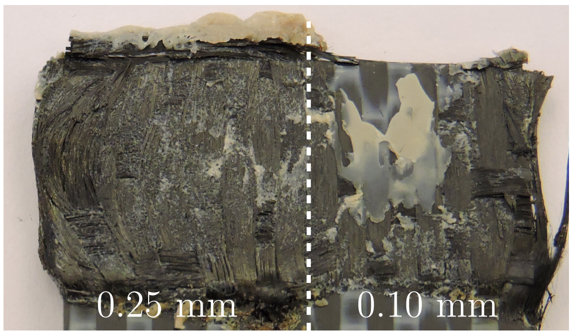
(c) *FS of 0.25/0.15 mm ED stopped after 650 ms at the onset of the displacement plateau*

Figure 4.13: *FS of welds stopped at their displacement plateau*

The hypotheses that the 0.25 mm ED area continuous to heat up the surrounding substrate and overheats at an elongated displacement plateau is confirmed.



(a) *Weld curve of 0.25/0.10 mm Split ED at a weld time of 1050 ms*



(b) *Fracture surface of 0.25/0.10 mm ED welded at 1050 ms*

Figure 4.14: *Weld curve and fracture surface of overwelded substrates*

4.3 Concluding remarks on the varying thickness energy director

The affect a thickness variation in the Energy Director has on the weld process and final weld depends on the difference in thickness. In this chapter, a total of six configurations of EDs with different thickness steps are tested. Changes in the weld curves, fracture surfaces, and cross sections are observed which result in some general conclusions on the changes in the weld process.

For welds with a thickness variation it is determined that the thin ED area is unaffected by the weld process until a certain displacement is reached. Up to this displacement the thick ED area is being welded as a normal weld going through the different weld stages. The weld curves show a decrease in required power due to the lower area, but this is also partly compensated by the higher stress occurring in the ED. Depending on the thickness difference present, a number of things can happen.

A plateau in the displacement can occur. This displacement plateau is caused by solid ED material in the thin ED area, preventing further displacement of the sonotrode until it is fully molten. In this research such a displacement plateau is most dominantly visible in the 0.25/0.15 mm Split ED configuration figure 4.7a. In the 0.25/0.10 mm Split ED it was located near the set displacement and barely visible figure 4.8a. With a deliberately long weld time for this configuration, the plateau is as visible as in the 0.25/0.15 mm ED configuration figure 4.14a. Only a small plateau was visible in the 0.25/0.20 mm Split ED configuration figure 4.4. This indicates that the plateau will decrease in size and impact with smaller thickness differences. This is not investigated in this research.

An elongated plateau results in overheating of the 0.25 mm ED area. This area is at least in stage 3 of the weld, with a fully molten ED that is being squeezed. During the plateau heat is transferred to the substrate material which heats up more than normally is the case. This results in a stage five weld, well beyond the optimum, with a lot of voids between the substrate layers and fibre displacement.

At larger difference in thickness, the displacement plateau disappears as is the case for the 0.25/0.05 mm Split ED configuration. The displacement set as controlling parameter was insufficient for the substrates to press the thin ED layer and this area remains unaffected. This can be observed from the fracture surface of the 0.25/0.05 mm split ED in figure 4.9b, and also from the two welds stopped before their displacement plateau, the 0.25/0.20 mm ED stopped after 280 ms (figure 4.12b) and the 0.25/0.10 mm ED configuration stopped after 500 ms in figure 4.12c. In each the thin area is barely affected by the weld process whereas the 0.25 mm ED area is already in stage 2 (0.25/0.20 mm ED) or even further along the weld process for the 0.25/0.10 mm ED and 0.25/0.05 mm ED configuration.

With increasing thickness difference in the ED the single lap shear strength of the bond decreases while the dispersion within one configuration increases. This decrease in LSS is attributed to the different weld stages that occur for welds with relative small difference with a displacement plateau, or decrease in welded area for larger differences where the thin ED is completely unaffected by the weld process. Differences within the weld process of an individual Split ED configuration lead to the greater dispersion of the measured strength.

Chapter 5

Conclusions and Recommendations

As the research objective stated the goal is to further automate the USW process by introducing FDM as application method for the ED. Chapter 3 covered the process of welding with an extruded ED. In chapter 4, one of the occurring challenges of using extruded EDs is investigated, being the variation in thickness that occurs within the ED. This chapter will summarize the conclusion from this research and give some recommendations for future research on this subject.

5.1 Conclusions

This report describes the research on implementing the Fused Deposition Modeling (FDM) manufacturing technique for the application of the Energy Director (ED) for in the Ultrasonic Welding (USW) of Thermoplastic Composites (TPCs). The research is split in two parts, one investigating the possibilities and challenge of using an ED manufactured with FDM in the USW process, and the second part investigates an occurring challenge encountered in the first part, being research on the influence of a variation in thickness of the ED on the weld process and final weld.

The research in part 1 resulted in a successful weld with a PEEK ED manufactured directly on a consolidated CF/PPS substrate. After the extrusion on the CF/PPS no additional steps are required to further fixate the ED, as the formed bond can withstand the forces arising by handling of the substrate and during welding. The shape of the ED, consisting of 0.4 mm wide, 0.20 mm thick parallel strands placed 0.6 mm apart, are too narrow to be integrated on the substrates during consolidation, and impractical for manual application, but not difficult for manufacturing with FDM. The weld process resembled that of welds with a triangular ED. The single lap shear strength of the final weld was similar as the weld with CF/PPS substrates and a loose, flat PEEK ED film, around 34 MPa. This direct positioning and bonding of the ED on a consolidated substrate is the main possibility for using FDM as application method.

Challenges in using FDM to manufacture the ED are encountered as well. Insufficient bonding between consolidated CF/PEEK substrates and a PEEK ED manufactured on this substrate is one of these challenges. The ED could be moved over the CF/PEEK surface without resistance. The bond between the CF/PPS and PEEK ED should also be improved as some parts of the ED had shifted slightly at the start of the weld.

The second challenge is an irregular final thickness of the extruded EDs. For the ED extruded on the CF/PPS, a sample was accepted only if the thickness is between 0.20±0.01 mm to minimize the influence of a thickness difference on the weld process. This resulted in the rejection of 67% (29 of 43) of the EDs manufactured in this manner. The second part of the research is dedicated to determine the influence of such a thickness difference in the ED on the weld process and final weld.

For this, six configurations of ED with a deliberate thickness step are welded and the weld process observed. The ED configuration consists of two equal areas each having a PEEK film with a different thickness. The used configurations are: 0.25/0.25 mm ED as reference case, 0.25/0.20 mm ED, 0.25/0.15 mm ED, 0.25/0.10 mm ED, 0.25/0.05 mm ED, and 0.25/0.00 mm ED. They are all welded with as controlling parameter the optimum displacement found in the reference case, being 0.11 mm. From the observations of the individual configurations three hypotheses are formulated and investigated further to be confirmed or disproved.

The main conclusion for part 2 of the research is that an increase in thickness difference results in a decrease of the LSS, but an increase in dispersion between the measured values. The LSS of the reference case is 45.2 MPa, where a difference in thickness of 0.05 mm decreases this strength by 8.6% to an average of 41.6 MPa, while the difference between the maximum and minimum value increases from 1.9 to 7.6 MPa. Larger differences in thickness reduce the LSS further, to a reduction of 51.4% for difference of 0.20 mm (0.25/0.05 mm Split ED configuration).

The weld process is affected by a thickness difference as well, visible from changes in the weld curves and fracture surfaces. For the used ED configurations it was found that, depending on the thickness difference present, several changes occur. It is determined that at first the thin ED area is unaffected by the weld process and the thick ED area is welded normally, going through the normal weld stages. At a certain displacement, that depends on the thickness variation present, a displacement plateau in the weld curve appears. This plateau is caused by a solid ED area in the thin ED area. At the displacement plateau two processes occur simultaneously: 1) The thin ED is being melted, and 2) the substrate surrounding the thick ED area is being heated. The plateau ends if the entire thin ED area is melted, which elongates the weld process. This results in, sometimes severe, overwelding of the thick ED area.

The displacement plateau is smaller for small thickness differences. It is seen that the thin ED is affected by the weld process earlier in the process than the displacement plateau appears. For large difference, the thin ED area remains fully intact and again no displacement plateau occurs. It this case, the thick ED area went through all the weld stages normally.

The fracture surfaces and cross sections reveal the different weld stages and failure modes present within one weld with an ED with thickness step. A clear distinction between the thin and thick areas is visible for all the welds having a thickness step in the ED.

5.2 Recommendations and Future Research

This research made a first effort to implement FDM as application method for the ED, but more research towards this goal is required. One of the subjects that needs more research is obtaining better adhesion between the ED and the consolidated substrates. Research towards applying a surface pre-treatment, bringing the substrate to a higher temperature or extruding with a different material can be done.

With the concept proven to work, further research can optimize the shape of the ED for the weld process and to decrease the extrusion time. A possibility is to extrude an ED for use in a continuous USW process.

The research on the effect of a thickness difference in the ED was limited in step size by the availability of films. Smaller steps in thickness can be an interesting topic to find at which difference there is no measurable effect. One can also decrease the area of the thickness step to find when it is not noticeable anymore. This could be interesting for new ED designs having less material as well. It is also interesting to investigate what the effect of such a difference is on other ED shapes such as the strings presented in this research. Since for now displacement controlled welds are performed it might be interesting to look at energy controlled welds as well.

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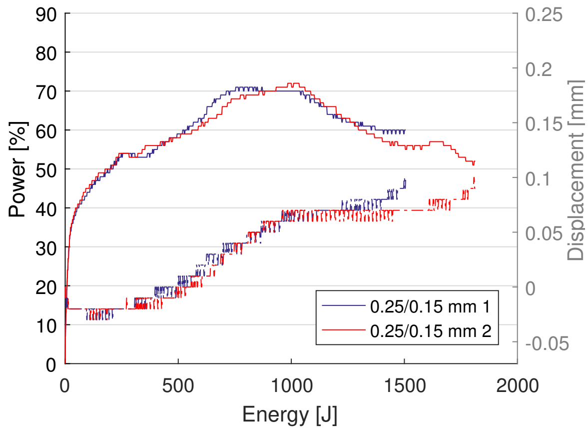
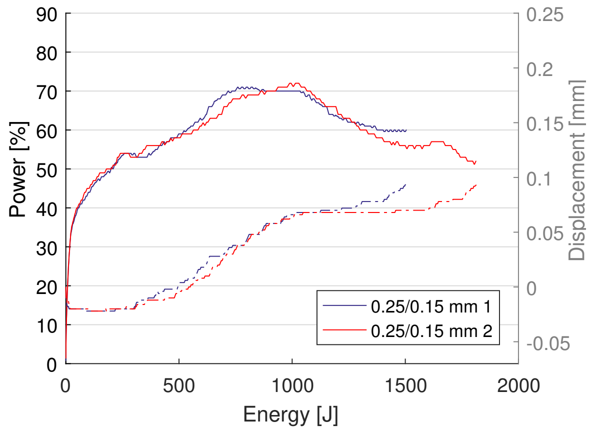
Appendix A

Smoothing of the Weld curves

The ultrasonic welder measures the displacement of the sonotrode in 0.01 mm increments at a sampling rate of around 1 ms. The required power is given in whole percentages also at a sampling rate of 1 ms. This results in a very jagged curve where the data switches from one value to another and back repeatably as shown in figure A.1a. For clarity the remaining plots are shown with the data smoothened by the moving mean function from Matlab. For the power curve the mean is calculated from 5 surrounding data points, the displacement curve from 9 points. In figure A.1b the new, smooth graphs are shown used to replace the jagged curves.



(a) *Example weld curves of original data from the ultrasonic welder*



(b) *Weld curves that are smoothened with the moving average function*

Figure A.1: *Example weld curves show the smoothening of the curves for a weld with CF/PEEK substrates with a 0.25/0.15 mm Split ED, 500 N of weld force, and 86.2 μm amplitude*

Appendix B

Thickness measurements of the Extruded String ED

This appendix elaborates on the Extruded Strings ED with variation in thickness, how the thickness is measured and why it is rejected for further use in the research. The ED is shaped as shown in figure B.1 with individual strings connected by two transverse bars. The top half has a varying thickness (0.30 mm, 0.25 mm, 0.20 mm, and 0.10 mm) and the bottom half has thickness of 0.30 mm. The width of each string is 0.4 mm and the distance between the strings 0.60 mm. It is extruded on the build platform to minimize the influence of the substrate on the extrusion process.

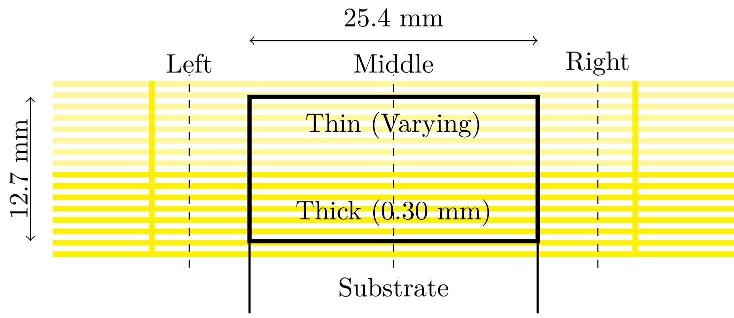
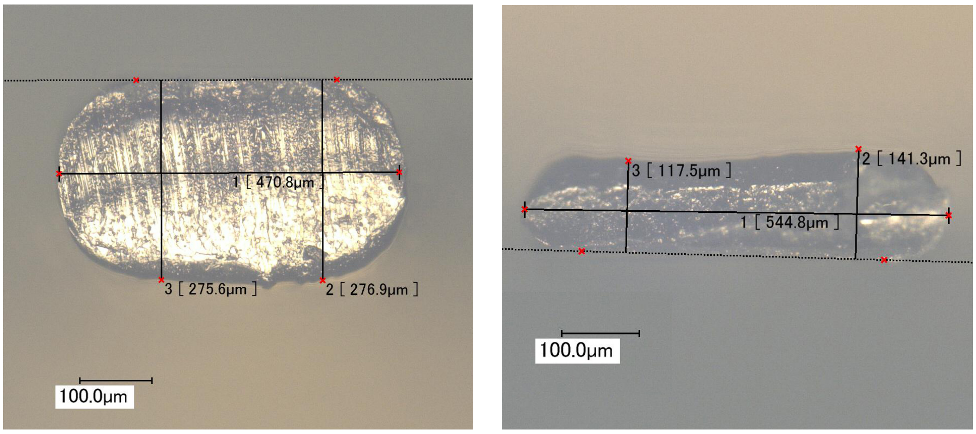


Figure B.1: *Extruded String ED with varying thickness. The dashed lines represent the locations (Left, Middle, Right) where the thickness is measured.*

From each of the configurations (0.30/0.30 mm, 0.30/0.25 mm, 0.30/0.20 mm and 0.30/0.15 mm) the thickness is measured at the three locations shown in figure B.1. Each string is individually measured using the Keyence OM described in section 2.5. Example measurements of twi individual strings can be found in figure B.2. From this pictures it can be seen that the shape of the strings is irregular, especially for the 0.15 mm string (figure B.2b). This string is not only more than 30% wider than expected, the thickness varies from 0.11 to 0.14 mm over the width of the string. The varying thickness within an Extruded String ED is visualized in figure B.3 where it can be seen that at all three locations the measured width is greater and measured thickness is smaller than the set value.

This is the case for all the Extruded String EDs as can be observed from table B.1 where the average measured thickness is compared to the set thickness. Not only is the difference between the set and measured value greater than for the Split ED, the standard deviation is larger as well. The greater variation in thickness, difference from the target value, and irregular shape are all a reason to reject the Extruded String ED for further use.



(a) *Example measurement of individual string with a set thickness of 0.30 mm.*

(b) *Example measurement of individual string with a set thickness of 0.15 mm.*

Figure B.2: *Two example measurements of individual strings from the Extruded String ED. The dotted line represents the side where the build platform was located.*

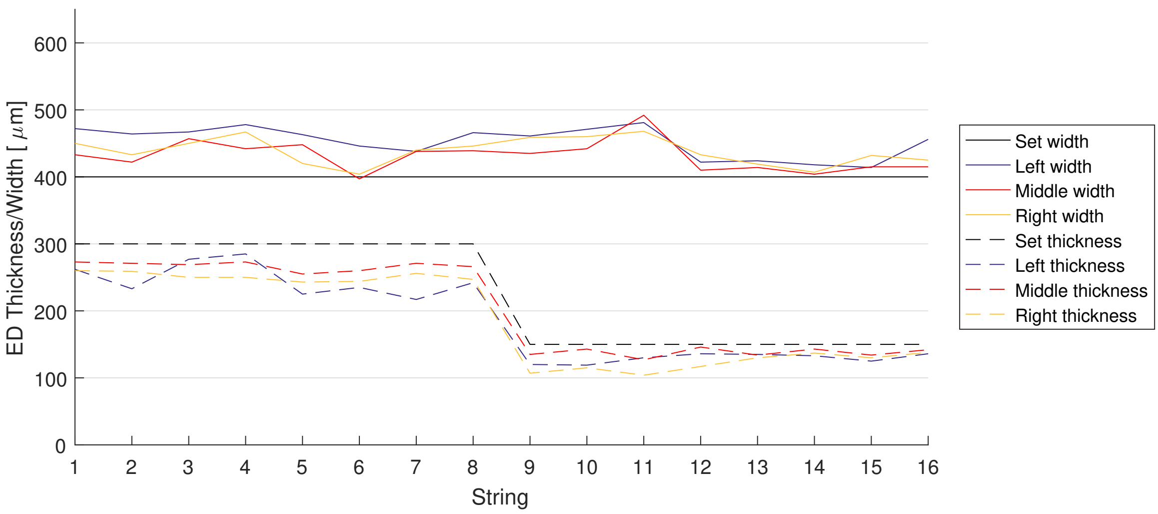


Figure B.3: *Set and measured dimensions of an Extruded String ED with 0.30/0.15 mm configuration. The numbers represent the individual strings from bottom to top.*

Table B.1: *Summary of thickness measurements for extruded and pressed ED*

	Extruded String ED				Split ED				
Set thickness [μm]	300	250	200	150	250	200	150	100	50
Avg. thickness [μm]	268	222	195	123	255	204	153	101	51
Difference [%]	-17.8	-2.75	-11.2	-10.6	1.9	2.2	2.3	1.0	1.5
Std. [μm]	8.7	11.3	13.0	8.1	0.89	0.92	1.51	0.76	0.46
Std. [%]	3.2	5.1	6.7	6.6	0.3	0.4	1.0	0.7	0.9