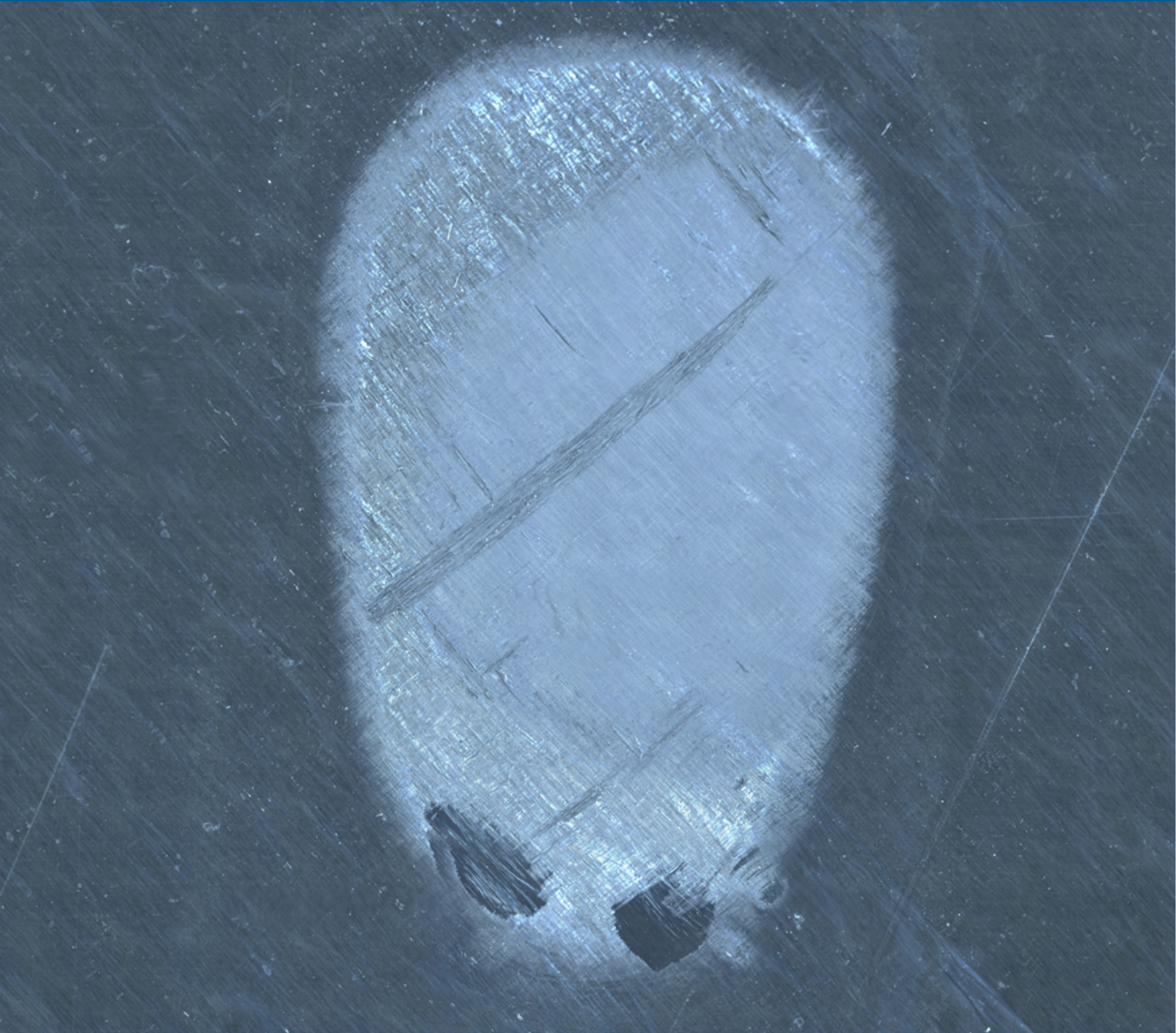


Conduction welding of thermoplastic composites

An experimental study towards specifying the process window for process time and temperature.



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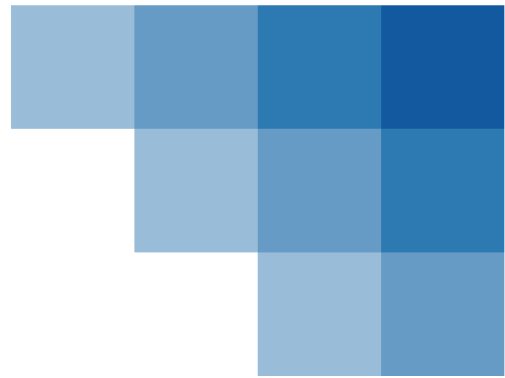
Master thesis

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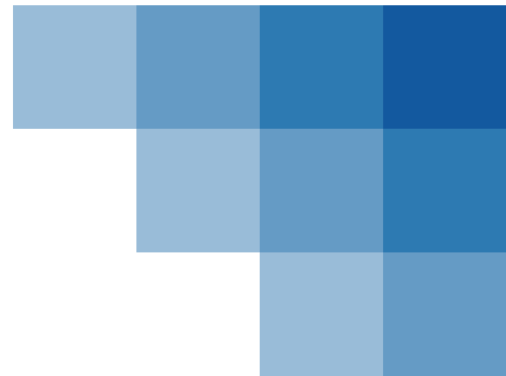
Abstract

The aerospace industry is increasingly incorporating thermoplastic composites into structures to improve the sustainability of the aircraft. These materials offer high strength-to-weight ratios and are weldable, making them preferable over traditional aerospace materials. This study focuses on the effects of the process parameters on the weld quality of conduction welded thermoplastic composites, thereby establishing a process window for consistent weld quality for a range of process time and temperature settings.

Experimental investigations were conducted using a conduction welding setup developed at the TPRC. Spot welds were produced on lap joints using unidirectional quasi-isotropic carbon fibre-reinforced low-melting polyaryl-ether-ketone laminates. Non-destructive and destructive inspections were performed to analyse the weld quality across various process time and temperature settings. This included monitoring temperature cycles during the process, ultrasonic scanning of the welded samples, shearing the welded material, inspecting the outer surface and weld interface, and inspecting the thermal behaviour of the welded material.

The results indicate minimal impact of process time on weld quality, whereas process temperature significantly influences the weld properties and quality. Higher temperatures produce larger, more uniform welds, which may result in thermal degradation of the material. Concluding that to achieve consistent welds on a lap joint of quasi-isotropic CF/LM PAEK laminate with a thickness of 1.2 mm using the current conduction weld setup at a process pressure of 370 kPa, the process window for process time and temperature spans from 0 to 60 s and from 370 to 430 °C. Beyond this window, weld quality may be limited.

This study advances the understanding of conduction welding processes, offering insights for optimising the conduction weld quality of thermoplastic composite joints. Further research avenues include further exploring the effects of process and material parameters, refining the inspection methods, and optimising the welding setup.



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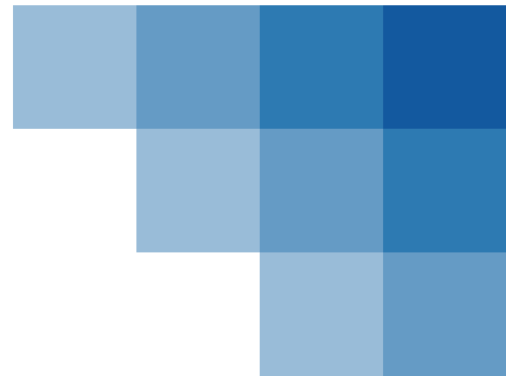
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Abbreviations & Symbols

Abbreviation	Definition
CF/LM-PAEK	Carbon Fibre reinforced Low Melting Polyaryl-Ether-Ketone
CFRP	Carbon Fibre Reinforced polymers
SEM	Scanning Electron Microscope
SLS	Single Lap Shear
TC	ThermoCouple
TPC	ThermoPlastic Composite
WI	Weld Interface

Symbol	Definition	Unit
Cr	Cooling rate	°C/s
Hr	Heating rate	°C/s
P _p	Process pressure	Pa
T _c	Crystallisation temperature	°C
T _g	Glass temperature	°C
T _m	Melting point temperature	°C
T _p	Process temperature	°C
t _p	Process time	s



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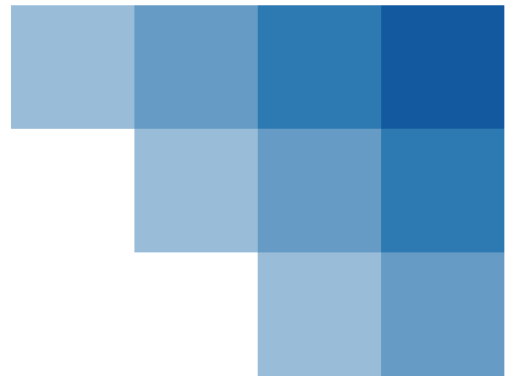
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Preface

Welcome, in front of you is the report of my thesis, which I am pleased to present and share. It presents the key findings of my research journey in the field of conduction welding of thermoplastic composites.

As a master's student of mechanical engineering specialising in Design & Manufacturing, I started the project with the primary objective of optimising a conduction welding setup created. Initially, the aim was to redesign the setup components to enable the production of good-quality conduction welds. However, after conducting preliminary research and experiments, it became evident that the setup could already produce satisfactory conduction welds. Consequently, the focus of the study shifted towards further exploration of the effect of processing parameters and defining a process window of the setup. This change of objective marked a new frontier for me, considering my experience with experimental methods during my bachelor's and master's in mechanical engineering was limited. Nevertheless, I was determined to push my boundaries, broaden my horizons, and acquire new knowledge. It has been a long, challenging journey filled with valuable lessons, resulting in this report.

Acknowledgements

While this report is primarily the result of my work, I am indebted to numerous individuals who supported me along the way, for whom I am deeply grateful.

First and foremost, I would like to thank my supervisors Lars Niens (TPRC) and Wouter Grouve (University of Twente) for their expertise, guidance, and patience throughout this journey. Their mentorship has been crucial in the development of this thesis and my growth as an engineer.

Furthermore, I would like to thank the staff, PhD candidates, researchers, and students at the TPRC and the Production Technology Department at the University of Twente. Their invaluable support, insightful discussions, and diverse perspectives have enriched my understanding and inspired approaches to overcome challenges encountered during the project.

In addition, I also would like to thank the examination committee members for their time and expertise in evaluating this thesis.

Finally, I express my gratitude to my friends, family and teachers for their support, patience, and encouragement during this challenging yet rewarding journey. Special thanks to Charlotte Arenas-Oude Allink, Thom Kuenen, Onno Derkman, Judy Hauser, and Andrea Sterkenburg for their feedback and peer review of this report.

Thank you for taking the time to read my thesis. I hope you will find it both informative and insightful. Please feel free to reach out to me with any questions or feedback. Happy reading!

Yannick van der Wilt,
June 2024, Enschede.

1.1.2 Introduction to composites

Composites contain two or more materials that remain chemically, physically and mechanically distinct. Combining these materials results in enhanced material properties, offering several advantages over using the component materials separately or traditional materials. Composites used in the aerospace industry offer an overall higher specific stiffness, strength, and toughness compared to conventional materials. In addition, the material can be tailored to the application's needs [2].

Commonly used composites in the aerospace industry consist of two materials: a polymer matrix reinforced with glass or carbon fibre. These fibres provide strength to the resulting composite material, bearing most of the applied loads, while the lighter matrix polymers protect the fibres, hold them together and transfer loads between them [3, 4].

1.1.3 Carbon-Fibre Reinforced Polymers

Carbon Fibre Reinforced Polymers (CFRPs) are preferred over glass fibre due to their high specific stiffness in the axial direction. Moreover, carbon is corrosion resistant, unlike some metals, which makes it suitable for harsh environments; high up in the air, marine and chemical surroundings. Furthermore, its thermal stability facilitates excellent mechanical at temperatures of -183 to 1500 °C, so minimal degradation of these material properties occurs [5]. Lastly, carbon's electrical conductivity benefits in some applications and production processes.

Polymers, composed of long polymer chains of repeating atom segments, can be categorised based on their thermal behaviour into thermoset and thermoplastic polymers [6]. Thermoset polymers form cross-links during production, triggered by a catalyst or induced temperature. During the curing, the material solidifies and forms a rigid network of interconnected polymer chains [7]. This irreversible process makes thermoset polymer a strong material that is difficult to reform after production. Thermoplastic polymers on the other hand maintain independent polymer chains upon solidification, allowing them to reshape upon reheating, as Figure 1.2 displays. This reformability offers a whole branch for (post-)production of thermoplastic composites (TPCs) such as reforming, recycling and fusion bonding [2].

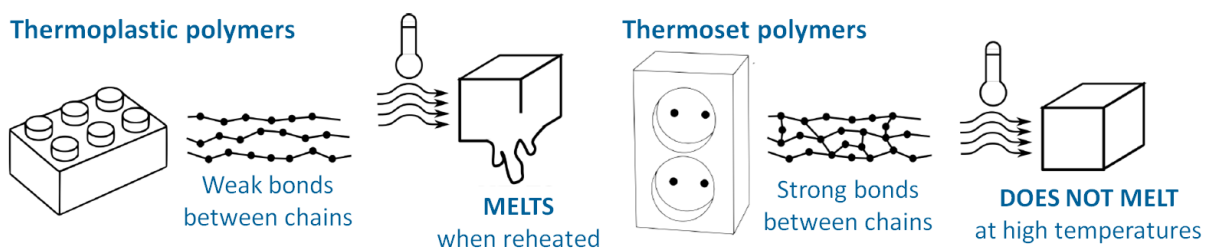


Figure 1.2: *The difference between thermoset and thermoplastic polymers.*

1.1.4 Fusion bonding of TPCs

Fusion bonding, also known as welding, is a bonding method for thermoplastic composites facilitated by the reformability of the TPC matrix [8]. In this process, the matrix material at the joint interface is melted and pressed together, which allows for matrix interaction. Subsequently, the matrix material solidifies and forms a robust joint.

Welding, as a bonding technique, offers several benefits over mechanical and adhesive bonding [9, 10]. Unlike mechanical bonding, fusion bonding does not weaken the laminates by drilling holes for rivets or bolts and introducing local stress. Instead, it preserves component strength and distributes the stresses

over a larger area by line welding. Compared to adhesive bonding, fusion bonding reduces the need for long curing cycles, relying instead on shorter polymer solidification cycles. Various welding techniques use different methods to melt the interface matrix [2, 11–13]. Figure 1.3 displays the welding processes categorised on their primary heat-inducing method. While induction, resistance, and ultrasonic welding are more commonly used and established, conduction welding of TPCs is a relatively unexplored technique [2, 9, 11, 12].

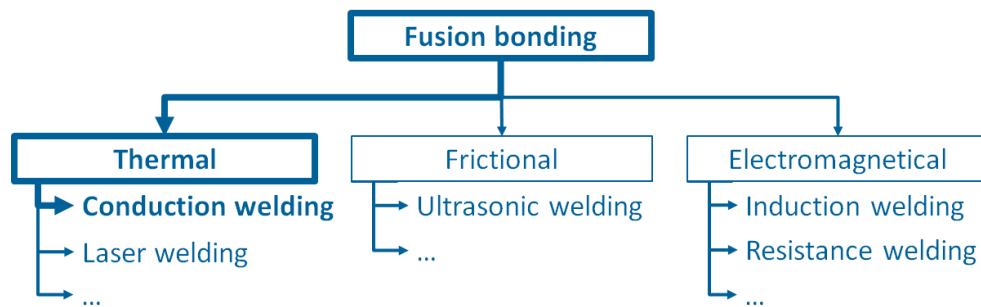


Figure 1.3: Fusion bonding techniques categorised by their primary heat-inducing mechanisms that facilitate the fusion process.

1.1.5 Conduction welding of TPCs

Conduction welding is similar to a press consolidation process [2, 9, 14]. The to-be-joined laminates are clamped between two welding heads. One [9] or both [4] of the welding heads heat up, as displayed in Figure 1.4. Thermal energy is conducted into the laminates by the heated welding heads. Upon reaching the melting temperature (T_m) the matrix material melts, starting from the welding head towards the weld interface. Once the material at the interface melts, the matrix material of both components fuses, followed by cooling to form a solid joint [9]. Compared to the other welding processes, conduction welding is less complex, does not require additional materials at the weld interface or in the composite material, is more scalable for bigger parts, and has a higher production speed [2, 9].

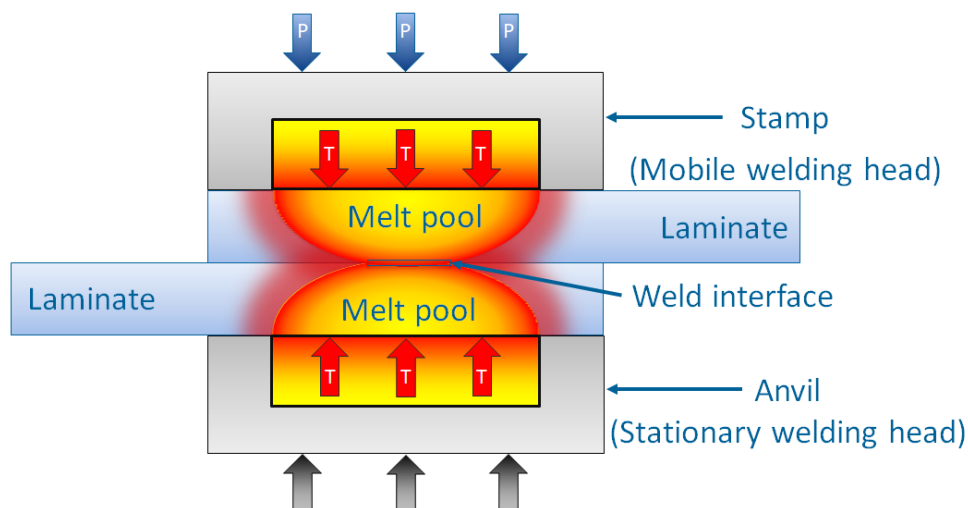


Figure 1.4: Schematic picture of conduction welding.

1.1.6 Previous work on conduction welding

Following the patenting of the TPC conduction welding method in 2017 [14], a few investigations have been conducted into the capabilities and further development of TPC conduction welding, by B. Tijs [9] and Naus [4]. Tijs's research compares the numerical analysis of conduction welds with the produced conduction welds, evaluating the effects of process parameters on TPC welds. Naus's work focuses on designing and evaluating a conduction welding setup at TPRC. Naus concludes that the setup produces welds with strengths comparable to what is reported in literature [13, 15], and recommends the potential for further process investigation and development. Both researchers recommend further research into process parameters (cooling rate, pressure, welding speed, temperature, and time) and their effect on the weld quality (shear strength and matrix material degradation).

1.2 Research objectives

Building further on previous work on conduction welding, this research involves investigating the effects of process parameters on weld quality. The aim is to define process parameter boundaries for consistent weld quality and process reliability bounded by a process window. This initial process window focuses on spot welding of Carbon Fibre reinforced Low Melting Poly-Aryl-Ether-Ketone (CF/LM PAEK, TC1225, Toray) [16], considering the process time and temperature. Both process parameters affect bonding mechanisms and matrix material thermal degradation [9].

This makes the **main objective** for this research:

"Specify the process window of process time and temperature for producing consistent quality conduction spot welds of C/LM PAEK."

Supported by the **sub-objectives**:

- ***"Determine the process time effects on the conduction spot weld quality of CF/LM-PAEK."***
- ***"Determine the process temperature effects on the conduction spot weld quality of CF/LM-PAEK."***

1.3 Thesis outline

The following chapters of this report provide details on TPC conduction welding (Chapter 2), the applied methodology (Chapter 3) and the obtained results (Chapter 4) on the effects of the process parameters on the weld quality. Chapter 5 elaborates further on the results and compares them to literature. Chapter 6 forms a conclusion on the stated objective. Based on this conclusion, an outlook for further development of the conduction welding process, the welding setup and weld assessment is given in Chapter 7.

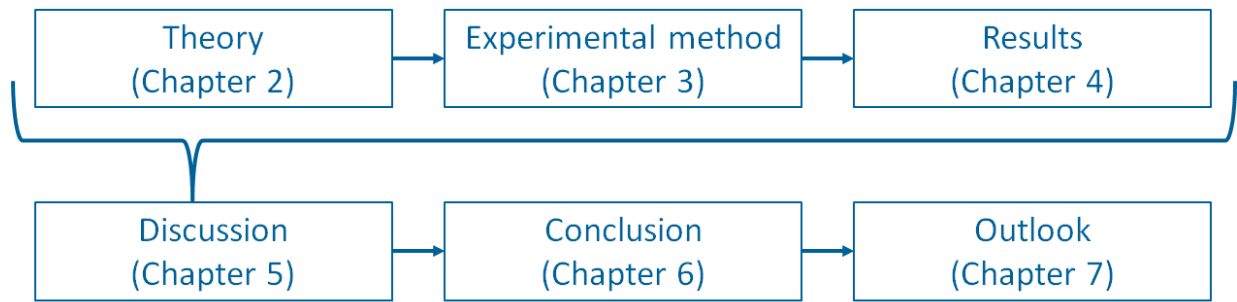
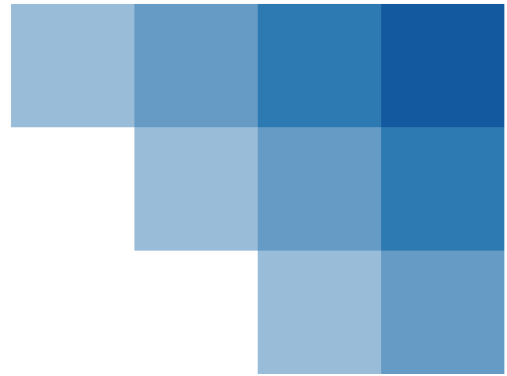


Figure 1.5: *Layout of the report.*



Chapter 2

Theory

Before diving into the experimental research, this chapter provides relevant background knowledge within the domain of TPC conduction welding. Section 2.1 discusses the polymer chain morphology in thermoplastic polymers, followed by Section 2.2, which offers a detailed description of bonding mechanisms, describing the process phases, and thermal behaviour during conduction welding.

2.1 Polymer chain morphology in thermoplastic polymers

In the introduction, it was highlighted that thermoplastic matrix material is essential for welding CFRP. The matrix consists of long polymer chains comprising repeating segments. These chains can lay in a random amorphous or a more structured semi-crystalline structure, as depicted in Figure 2.1 [7, 17]. These chain morphologies play a crucial role in defining the polymer's material properties.

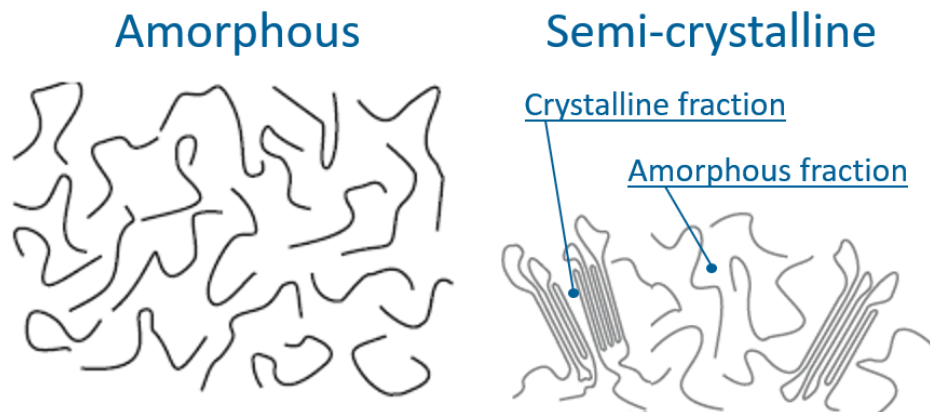


Figure 2.1: *Polymer morphologies: amorphous (left) and semi-crystalline (right).*

2.1.1 Amorphous polymers

Amorphous polymers lack a well-defined crystal structure. The chains are disordered, arranged randomly, and entangled with each other [7, 18]. At room temperature, the polymer typically behaves as a transparent solid material.

Heating the solid material induces thermal energy in the material, allowing the atoms to vibrate at a higher frequency and amplitude. This gives the possibility for the polymer chain to rotate, bend and move back

and forth. However, due to intermolecular bonds, the chains are fixed in place. These bonds start to fail when the material reaches the glass transition temperature (T_g). The chains become mobile so that they can overcome the intermolecular bonds. This allows for molecular motion; the chains move alongside each other and fill up and create the free volume [7]. The back-and-forth movement of the chains lets the chain achieve new positions in the material and construct new entanglements with other polymer chains. This movement of chains through entanglements is called reptation [19].

Beyond the glass transition temperature, the movement of chains occurs more often with the rising temperature, increasing the molecular motion and decreasing the viscosity [20], transitioning the material from the rubbery state to a less viscous liquid.

2.1.2 Semi-crystalline structure

Semi-crystalline polymers, on the other hand, contain both amorphous and crystalline regions in their structure. These polymers feature chains that are partially ordered and randomly laid segments. The presence of crystalline fractions introduces more rigidity to the material. At the glass transition temperature, the amorphous segments undergo the transition as earlier described, however, the crystalline segments stay rigid at this temperature. The preservation of the crystalline regions obstructs the movement of the amorphous segments since the crystalline regions are fixed to each other, and the amorphous segments are fixed to the crystalline segments and surrounded by crystalline regions.

Similar to the amorphous regions, crystalline segments experience increased chain mobility over a temperature range, which happens at higher temperatures than the glass transition temperature. The temperature at which crystals break down into an unordered amorphous phase is known as the melting temperature. Beyond this temperature, the material is considered entirely molten, although some small crystallites may still be present in the melt and obstruct chain mobility when the material temperature is just above the melting point.

Due to the presence of the crystalline regions in semi-crystalline polymers, semi-crystalline polymers tend to be harder and more brittle than amorphous polymers. They find more use in the aerospace industry than amorphous polymers due to their superior strength, stiffness, wear resistance, thermal stability, and chemical resistance [21]. Consequently, the research focuses on semi-crystalline polymers.

2.2 Conduction welding

Conduction welding of TPCs requires precise control of process parameters to achieve optimal bond quality. This section explores the key aspects of conduction welding: Section 2.2.1 focuses on the bonding mechanisms essential for weld formation, while Section 2.2.2 describes the parameter cycles that enable these mechanisms to ensure the weld quality.

2.2.1 Bonding mechanisms

To form an interlaminar joint between two semi-crystalline TPC surfaces, the conduction welding process relies on two critical mechanisms: (1) intimate contact development between the composite substrates, and (2) interdiffusion of polymer chains across the joint interface [18]. These mechanisms are the most effective for semi-crystalline polymers when the material temperature needs to exceed the melting temperature [17, 18].

Intimate contact development

When laying composite laminates on top of each other, the component surfaces create an initial contact. This contact does not stretch over the total surface, because the surface of the laminates is not perfectly smooth and contains asperities. Due to the rough and rigid surface material, intimate contact is established only at some locations, as Figure 2.2a illustrates. Only at these locations where intimate contact is established can interdiffusion between the laminates occur. The degree of intimate contact is defined as the fraction of the total surface area that has reached full contact [22].

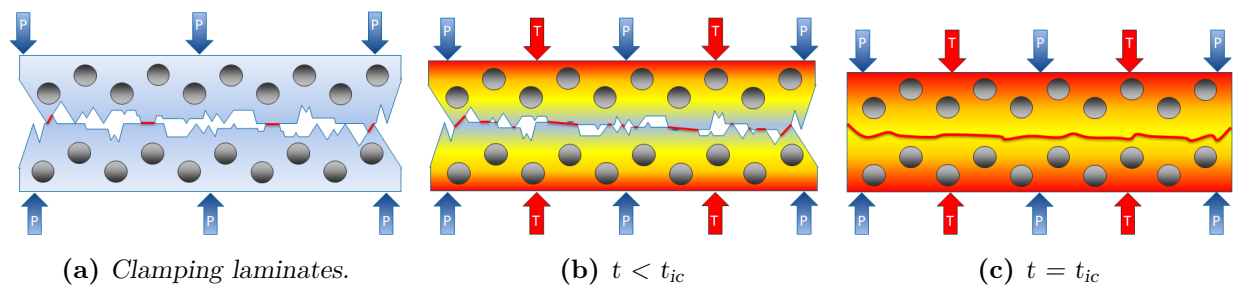


Figure 2.2: Intimate contact development over time.

A higher degree of intimate contact is more favourable since it allows for more interconnection between the laminates. The time required to achieve full intimate contact (t_{ic}) depends on the surface roughness, the applied pressure and the temperature-dependent viscosity [23]. By increasing the temperature, the viscosity is decreased, as described in Section 2.1. Under the applied pressure, the viscous polymer surface asperities are flattened and gaps are filled, creating a higher degree of intimate contact to the point that the surfaces are entirely in intimate contact.

Autohesion of semi-crystalline polymers

After achieving intimate contact, an interface between the components is still present rather than a bond. Strong bonding requires autohesion, the interdiffusion of polymer chains across the bond interface. This mechanism fundamentally contributes to the bond strength development, as more chains over the interface create a stronger bond [18].

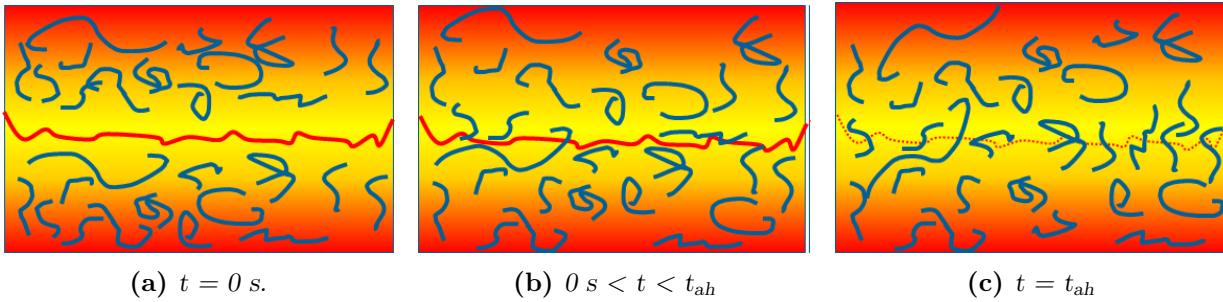


Figure 2.3: Autohesion development over time.

The thermal energy of the material above the melting temperature facilitates reptation of the (previous) semi-crystalline polymer chains. With reptation, the polymer chains move over the interface and entangle with the polymer chains in the other laminate. The time to move the polymer chains over the interface and obtain a full degree of adhesion is temperature-dependent, and it can be calculated using the relaxation or reptation time of the polymer. At a 100 % degree of autohesion, the material at the bond behaves as the bulk material and the maximal attainable bond strength is obtained [17, 18].

2.2.2 Conduction welding process

While intimate contact and autohesion are essential for weld formation, the temperature and pressures can be generated in various ways, as described in the introduction. This section describes the welding process between two semi-crystalline components, using the conduction weld setup designed by Naus [4]. It covers the process phases and process parameter adjustments (as depicted in Figure 2.4).

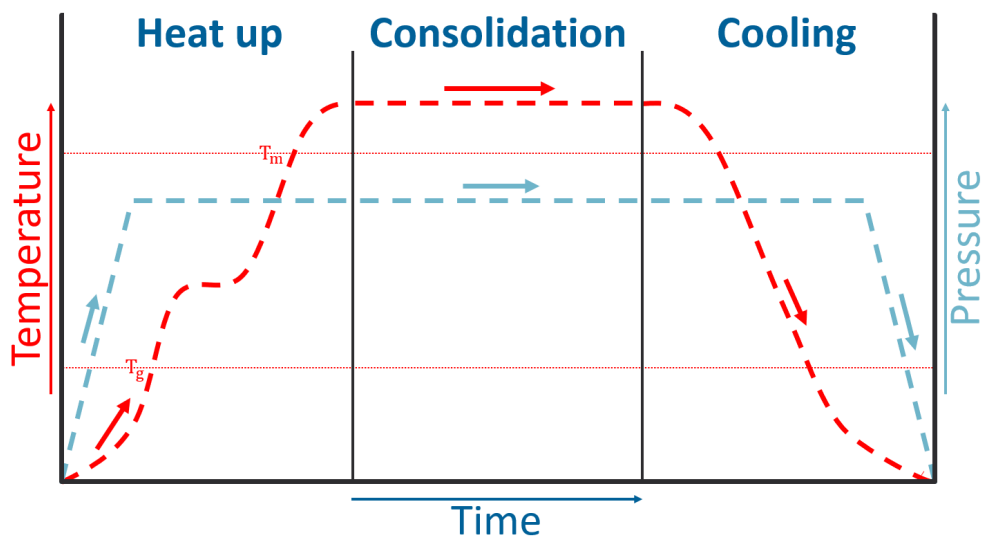


Figure 2.4: The temperature and pressure cycle during conduction welding.

The heat-up phase

The conduction welding process starts with positioning the composite laminates between two welding heads. Air pressure is applied, causing one welding head to move towards the other welding head, securing and clamping the composite material. This clamping pressure remains constant throughout the

process.

Following the positioning and clamping, the preheated welding heads transmit heat into the composite, elevating the laminate temperature through conduction. The first stage of the heating phase preheats the material to a temperature between the glass transition temperature and the onset of the melting range. Consequently, the material remains at a constant temperature to minimise thermal gradients across the components. Upon reaching an almost uniform temperature over the components, the welding head temperature increases beyond the polymer's melting point.

The consolidation phase

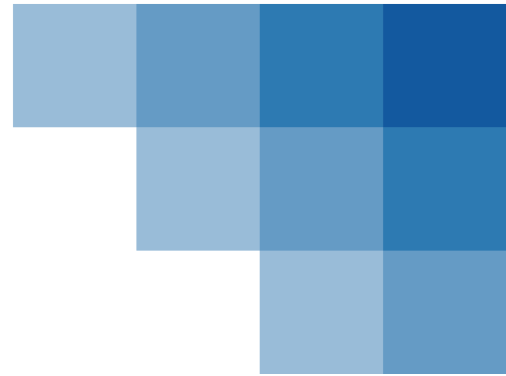
The melting of semi-crystalline matrix material marks the start of the consolidation phase. In this phase, the temperature remains constant, ensuring sufficient time to realise a full degree of intimate contact and autohesion.

Welding with temperatures above the melting point and with extended duration risks thermal degradation of the materials [24–26]. While higher temperatures provide the necessary energy for the polymer chains to bond, they also increase the atomic excitation. If the atom's energy state reaches a critical value, bonds within the polymer chains can break, leading to chain scission. Consequently, the polymer chain shortens in length, and cross-links between polymer chains and impurities form, altering the material properties. Therefore, the process time is not set too long and the process temperature is not set too high.

The cool-down phase

Subsequently, when sufficient time has expired to form a bond, the cooling phase begins. The cooling systems are activated, lowering the temperature of the weld welding heads and the material.

The lower temperature reduces the atomic energy, diminishing the chain mobility to the point that the movement is too low to overcome the intermolecular bond energy. The polymer segments start to entangle. From these nuclei, crystallites form, with an alternating pattern of crystalline and amorphous regions. The number of nuclei and the size of the crystallites depend on the cooling rate. Slower cooling rates allow polymer chains time to organise and form nuclei or form around them, whereas quicker cooling rates create more nuclei simultaneously. For semi-crystalline polymers, e.g. LM-PAEK, a cooling rate of 100 °C/min and above is typical to form fewer crystalline regions than are formed at lower cooling rates [27].



Chapter 3

Materials & Methods

The preceding chapters highlighted the challenges, bonding mechanisms, and the process of conduction welding. This chapter outlines the experimental approach to investigate the process parameters and their effects on the weld quality. Figure 3.1 displays the experimental approach with the material preparation, welding experiments and weld inspection methods.



Figure 3.1: *Experimental Approach.*

3.1 Sample preparation

For this study, a unidirectional carbon fibre tape pre-impregnated CF/LM PAEK (TC1225) is used [16]. Table 3.1 provides an overview of material properties. A total of 28 laminates are manufactured with a quasi-isotropic $[45\ 0\ -45\ 90]_s$ layup for experimental work. Using a consolidation press (thermoplastic press 200T, Pinette Emideau Industries) four laminates are simultaneously produced in a $30.48 \times 30.48\text{ cm}^2$ ($12 \times 12\text{ inch}^2$) picture frame. During the consolidation, the press applies a pressure of 1500 kPa and a temperature of 365 °C. These conditions are maintained for a dwell time of 30 minutes. Subsequently, the laminate is cooled down to room temperature with a rate of 5 °C/min.

Table 3.1: Material properties [16] and press consolidation settings.

Material property	Value	Unit			
T_g (glass transition)	147	°C			
T_m (melt)	305	°C			
T_c (crystallisation)	263	°C			
T_p (processing)	340-385	°C			
Resin content by weight	34	%			
Consolidated ply thickness	0.14	mm			
Tensile strength 0°	2.41	GPa			
Tensile modulus 0°	135	GPa			
Compressive strength 0°	1.3	GPa			
Tensile strength 90°	86	MPa			
Tensile modulus 90°	10	GPa			
			Consolidation process setting	Value	Unit
			T_p	365	°C
			P_p	15	bar
			t_p	30	min
			CR_p	5	°C/min

After consolidation, the laminates were cut into halves using a diamond-coated and water-cooled saw. Subsequently, the edges were deburred with sandpaper, and the surfaces were cleaned with water and isopropanol. The right-side laminates were flipped to achieve a 45° -45° fibre orientation at the interface, as is depicted in figure 3.2. Thermocouples were positioned at the interface of the selected samples to measure the interface temperatures. With the help of polyamide tape, the thermocouples and the plates are fixed in place. Lastly, the sample plates are placed in an oven to dry for 16 h at 120 °C before welding.

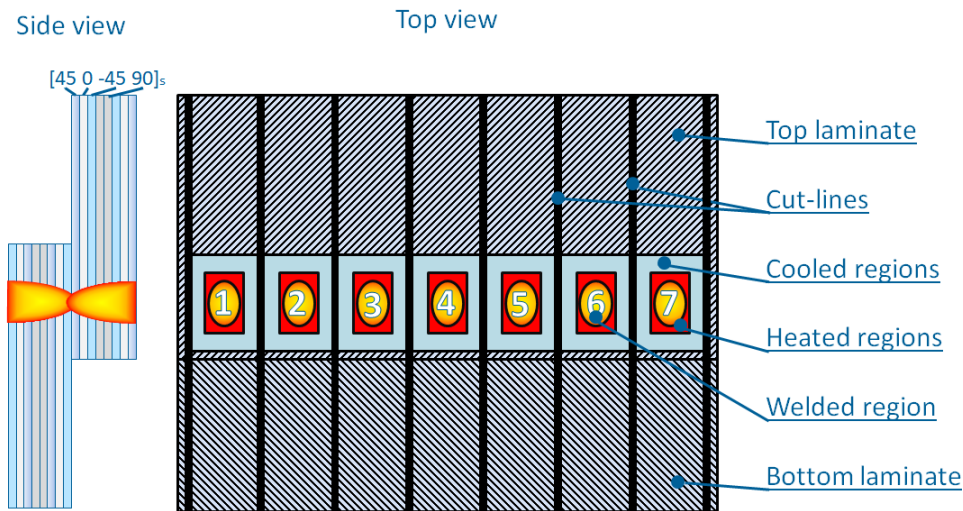


Figure 3.2: Laminate layup and sample plate layout. The welds are positioned in the width of the composite plates and in the length of the sample strips.

3.2 Welding setup

The welding experiments aim to investigate the effect of the various process times (t_p) and temperatures (T_p) on the weld quality. For the production of conduction welds, the setup created by Naus is used [4].

The setup uses two welding heads: one stationary and one vertical moving welding head as displayed in Figure 1.4. These welding heads clamp the components and induce heat into the composite material to facilitate the correct welding conditions. Through a user interface, the process time and temperature are specified. During welding, the PID controller heats the welding head surface to the set process temperature and remains at that temperature for the specified process time.

With thermocouples placed within the welding heads at the cooled and heated surfaces, thermocouple feedback is applied to monitor the welding process. Figure 3.3 illustrates the locations of these thermocouples. Next to process monitoring, these thermocouples also provide temperature data at 4 Hz during welding. Placing an extra thermocouple at the weld interface allows obtaining temperature data about the weld interface during welding [4, 7]. This data is used for further analysis on the effects of the process parameter on the weld quality.

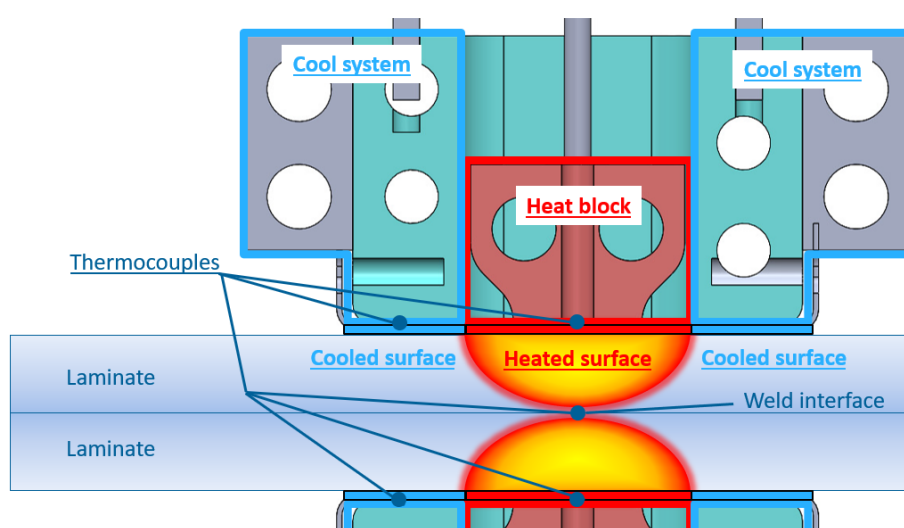


Figure 3.3: A cross-sectional overview of the welding heads during welding.

3.3 Weld production

To investigate the effect of process parameters on the weld quality, welds were produced with various settings, as shown in Table 3.2. The parameter values are based on previous research findings and preliminary experiments on process parameters to ensure correct weld conditions [4, 9, 16, 17, 28]. The process temperature, T_p , is the set temperature for during the consolidation phase. The process time, t_p , is the time that the setup maintains the process temperature during consolidation. The air pressure of the dynamic welding head is set at 500 kPa, which results in an effective pressure on the sample of 370 kPa [4]. For the cooling system, the air pressure is set at 500 kPa and the valves are fully opened. The full argumentation for the used parameter settings and the achieved cooling rate calculations are given in Appendixes B.2 and C.1.3.

Table 3.2: *Process parameter values and the number of samples per process parameter set.*

Quantity	Value	Unit
T _p	315, 320, 345, 370, 400, 430	°C
t _p	0, 10, 60	s
P _p	370	kPa
SLS sample amount	10	Samples/PP-setting
TC sample amount	2	Samples/PP-setting

The welding process follows the process as described in Section 2.2. The weld head surfaces preheat the sample material to just above 190 °C. This is followed by further heating to the specified process temperature. Subsequently, the surfaces maintain the set temperature for the designated process time before cooling to 210°C. Then the clamps open, a sign of the completion of the welding process. Figure 3.2 illustrates the layout of the sample plates and the positioning of the welding heads on them.

3.4 Weld inspection

After welding, the produced welds are inspected using non-destructive inspection methods (surface microscopy, ultrasound scanning) and destructive inspection methods (single lap shear experiments, fractography and differential scanning calorimetry).

3.4.1 Outside surface inspection

Using a Keyence 5000-series microscope, images of the outside surfaces are created. The surfaces are analysed and the size of the heat-affected zone is determined.

3.4.2 Ultrasound inspection

The ultrasound scanning setup, a Sonatest Rapidsan 2, uses ultrasound waves to inspect the dampening coefficient and time of flight of the weld specimen. This inspection is used to inspect the weld for delamination or void in the weld and depending on the depth of the reflecting surface, full welds are indicated.

3.4.3 Bond strength analysis

The samples are tested on their bond strength using single lap shear (SLS) experiments using an Instron 5982 Universal Testing System. Before testing, the samples are dried in an oven for 16h at 120 °C. ASTM D3165 is used for SLS, which prescribes a weld of 25.4 x 25.4 mm² (1x1 inch²). However, the welded areas vary in size and from the prescribed weld dimensions of the standard. To test all samples equally and be able to analyse the heat-affected zone of the weld, a sample width of 40 is used. The new dimensions of a sample are displayed in Figure 3.4.

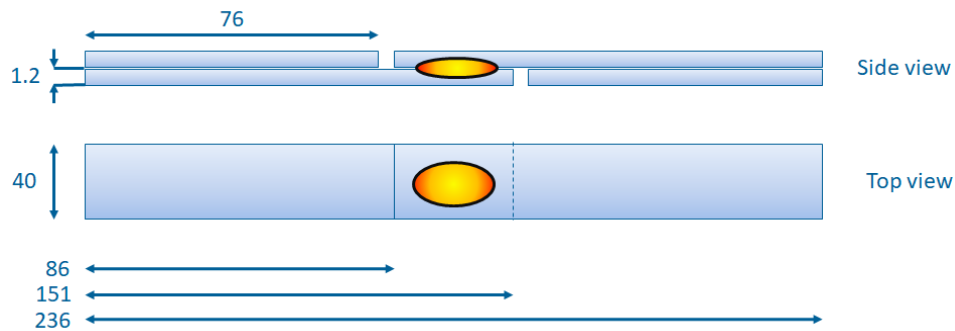


Figure 3.4: SLS sample dimensions in mm.

The specimen is clamped in the Instron 5982 Universal Testing System, fitted with a force cell of 600 kN. The samples are pre-tensioned at 40 N after which the clamps move at a speed of 1 mm/min during the experiments. This movement stops when the applied force drops 25% when the sample breaks. Time, cross-head displacement, and force results are obtained. The bond strength is calculated from the tensile force and the weld area, which is determined using fractography. Combining these results with the area results calculated using fractography, the maximal bond strength of the weld can be determined.

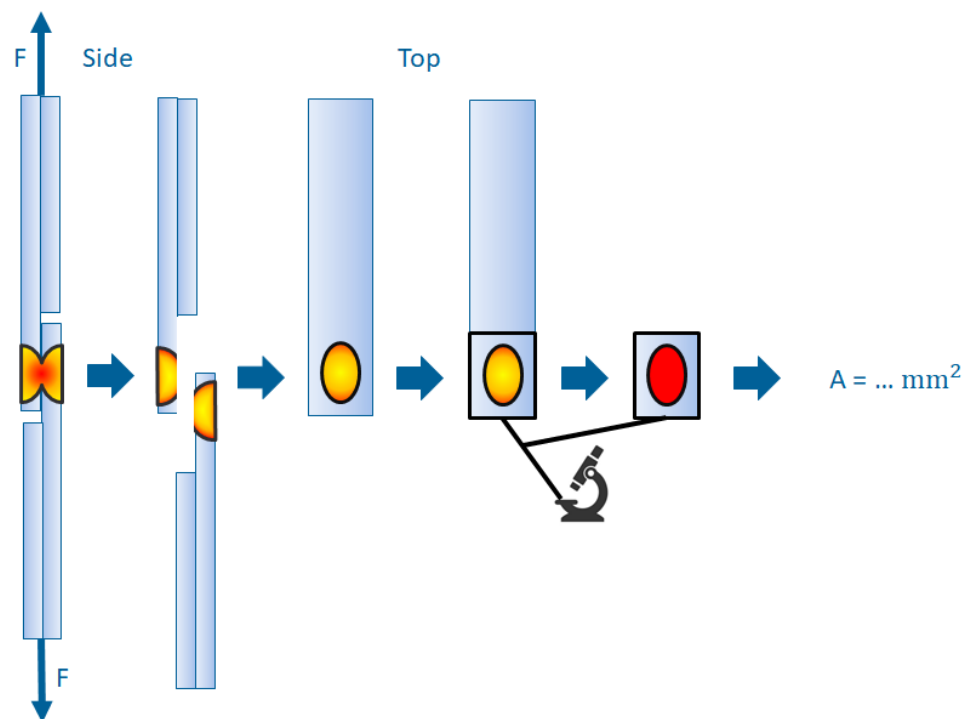


Figure 3.5: SLS experiments overview. The samples are torn apart, and microscopy images are used to determine the weld area.

3.4.4 Fractography inspection

After the SLS experiments, the samples are analysed on the bond interface using a Keyence 7000-series light microscope and a scanning electron microscope (SEM). In addition to calculating the weld area, the

interfaces are analysed, and different interface structures are identified.

3.4.5 Differential scanning calorimetry inspection

At last, two samples with process times of 0, 10, and 60, with temperatures of 315, 345 and 430 °C are analysed using Differential scanning calorimetry (DSC) to assess their thermal behaviour. Circular samples are milled from the welded volume using a milling machine [29]. The DSC samples have a diameter of 4.9 mm and a height of 0.7 mm (~ 5 plies closest to the welding head surface are extracted from the laminate). After sanding and cleaning the samples with isopropanol, the specimens are weighed and placed in an aluminium pan. Subsequently, the DSC machine, TA instruments DSC 250, conducts two heat-cooling cycles spanning from 100 to 345 °C and back down. During the experiment a heating and cooling rate of 10 °C/min and an isotropic break between heating and cooling of 5 min was used. The detailed procedure is discussed in Appendix C.7.

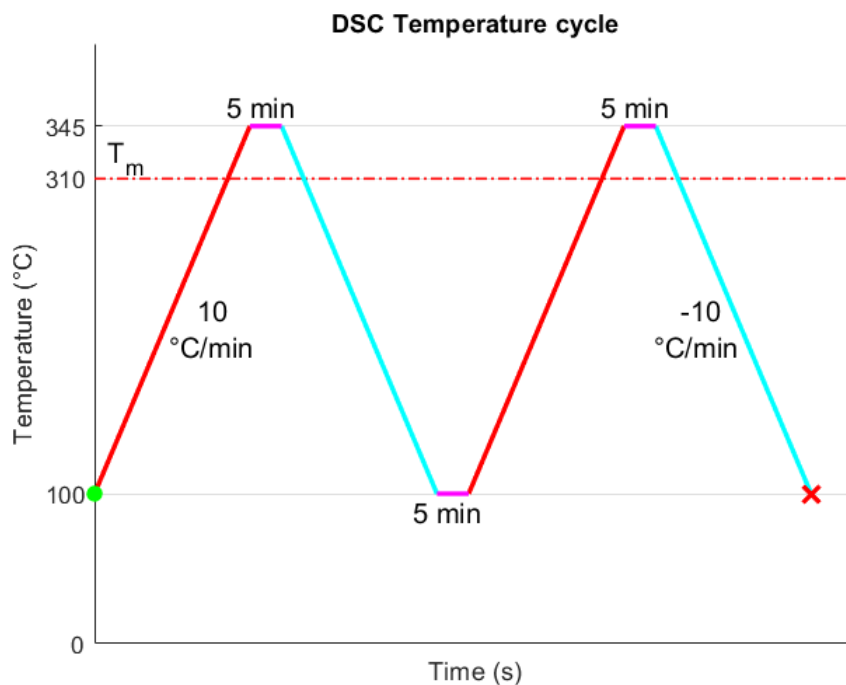


Figure 3.6: Heating curve of the DSC experiments.



Chapter 4

Results

This chapter presents and discusses the experimental results, beginning with a section on the thermocouple measurements conducted during welding, followed by non-destructive and destructive weld inspections.

4.1 Process analysis

Thermocouples were placed in the welding heads and at the weld interface, providing temperature data during welding. Two experiments per parameter setting were performed. As a result of corrupted and incorrect temperature, the temperature cycle with the highest interface temperature is used to calculate parameters such as time in a molten state, heating and cooling rates, and the relation between the heated welding head surface and weld interface temperatures. The detailed heat and cooling rate analysis is available in Appendix C.1

Figure 4.1 illustrates the temperature profiles of the thermocouples during two welding processes: one with a process time of 0 s and a process temperature of 315 °C, and the other with a process time of 60 s and a process temperature of 430 °C.

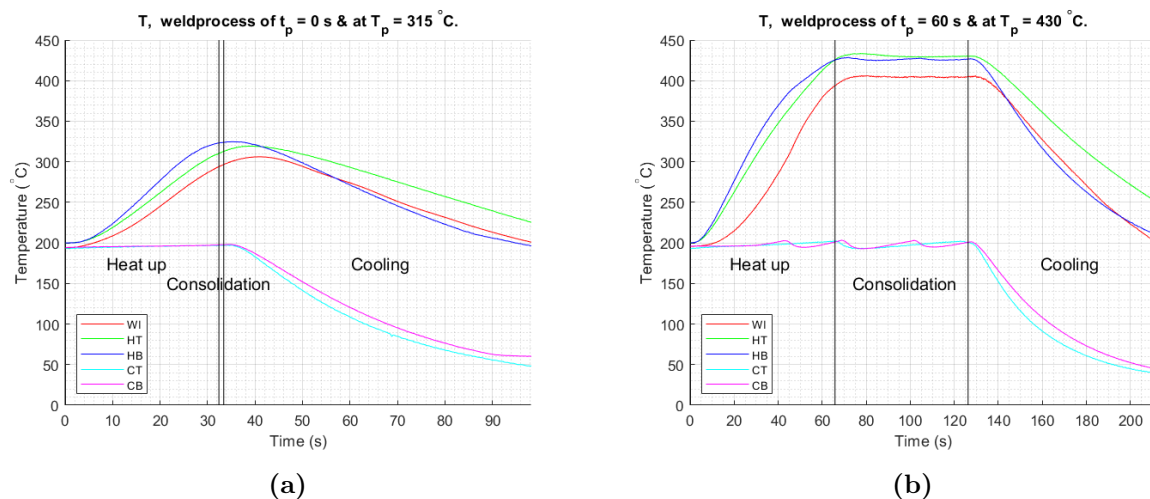


Figure 4.1: Temperature profiles of two welding processes.

WI is the weld interface HT is the heated top surface, HB is the heated bottom surface, CT is the cooled top surface and CB is the cooled bottom surface.

4.1.1 Time in melt

The time of the material in molten state (t_m) was calculated using temperature data of the weld interface thermocouple. This time is the duration at which the interface temperature is above the melting temperature of LM PAEK (305 °C [16]). Figure 4.2 shows the time in melt per process parameter setting, indicating that an increase of the process temperature extends the time in melt. However, for the process time, no clear relation is observed between time in melt and process time. The exact values for the time in melt are provided in Table C.1 in Appendix C.1.

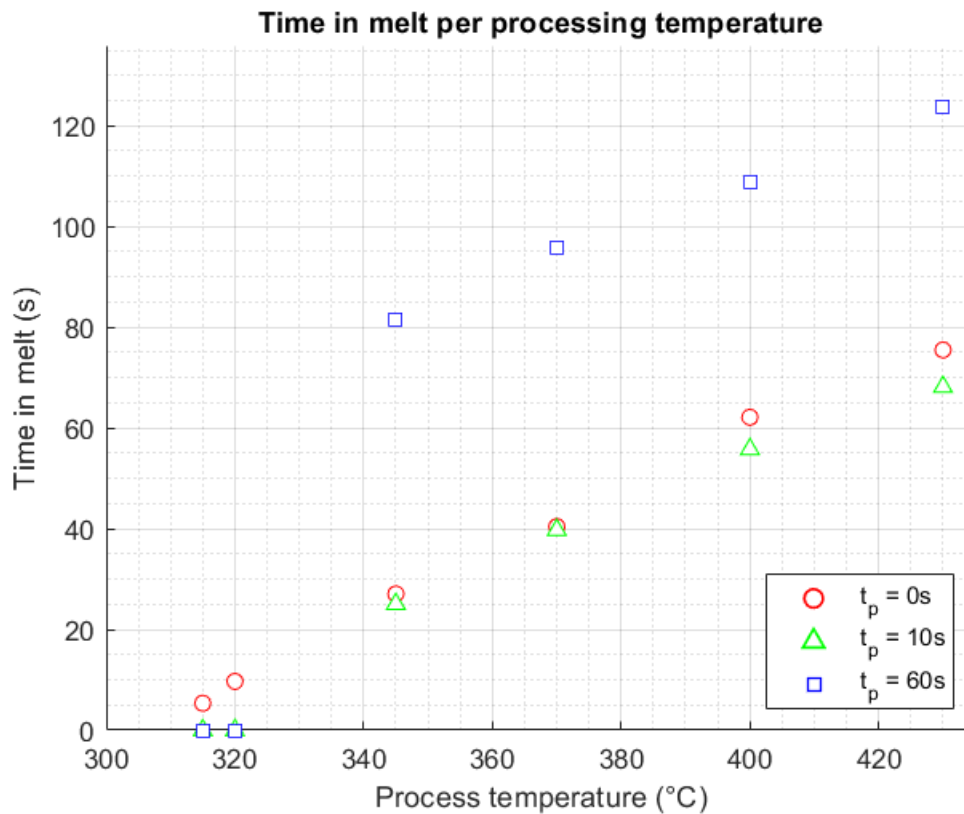


Figure 4.2: The time in melt per processing parameter setting.

The lack of correlation of the times in melt for varying process times results from changing the samples during the experiments with thermocouples. The three process times were measured with three different thermocouple samples, affecting multiple parameters simultaneously, such as heat source-to-thermocouple insulation. This discrepancy resulted in significantly different weld interface temperatures despite the similar heated weld head surface temperature, as Figure 4.3 illustrates. Additionally, due to varying interface temperatures, only the data with the highest interface temperature per process setting was selected for calculations, which gives more realistic and precise values than using all the data with varying interface temperatures. Moreover, the thermocouple misplacement led to lower measured interface temperatures for process times of 10 and 60 s. For the experiments with process temperatures of 315 and 320 °C, this resulted in measured temperature below the melting temperature of LM PAEK, falsely indicating a 0 s time in melt. However, as demonstrated in Section 4.2, these process parameter settings are capable of producing welds. Therefore, due to the high-temperature gradient at the weld interface, accurate positioning of weld interface thermocouples is crucial for measuring accurate weld interface temperatures.

4.1.2 Heated surface and weld interface temperature relation

The average temperatures of the heated welding head surfaces and those of the weld interface were calculated. The relation is different for the various process times since the placement of the weld interface thermocouple also affects this data. Figure 4.3 illustrates the average heated weld heat surface and weld interface temperatures, demonstrating that the weld interface temperature increases with higher heated welding head surface temperatures. The difference between the heated surfaces and weld interface is 19 ± 4 °C, 31 ± 1 °C, and 22 ± 2 °C, respectively for the process time samples of 0 s, 10 s, and 60 s. These values are in detail displayed in Figure C.9 in Appendix C.1. In Figure 4.3 the relation between the surface and interface for the 10 s is indicated in the diagram. This relationship can help approximate the maximum weld interface temperature in later experiments when the heated weld head surface temperatures are known. Ultimately, the smallest temperature difference would be the best since this gives a better view of the maximum weld interface temperature.

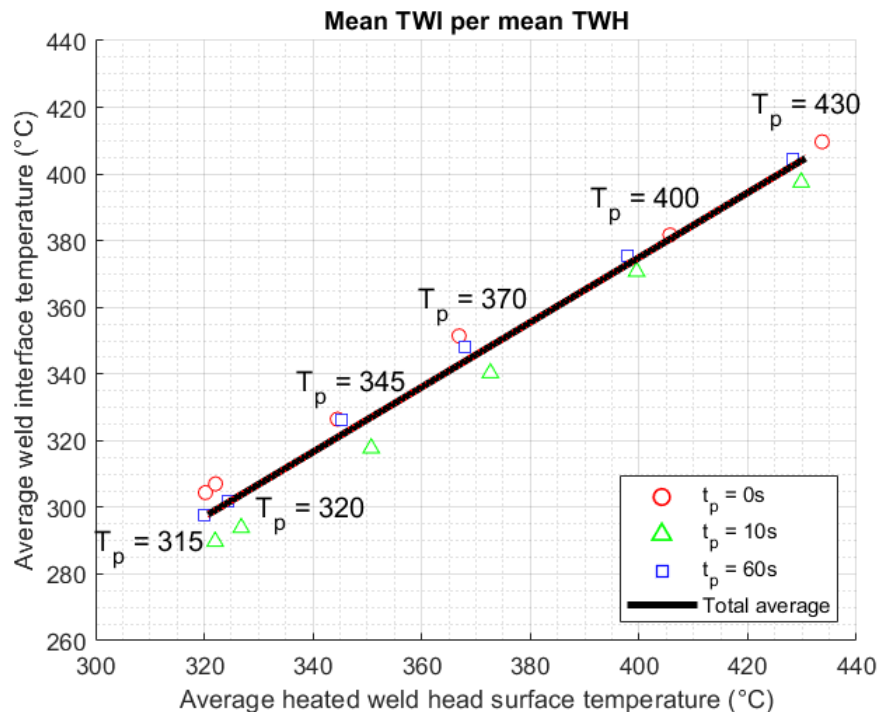


Figure 4.3: Averaged weld interface temperature per averaged heated welding head surfaces during the consolidation phase with the average line of the total sample set.

4.1.3 Conclusion of the process inspection

During welding, the welding head surfaces and weld interface temperatures were measured. Based on the temperature data, the following key findings can be concluded:

- Higher process temperatures result in higher heated welding head surfaces, higher interface temperatures, and a longer time in melt.
- Slightly imprecise placement of the weld interface thermocouple significantly affects the measured weld interface temperature, resulting in incomparable temperature data for the various process time values.

- For the process with a process time of 0 s and a temperature of 315 °C, the time in melt is 5 s. For other welding processes, with a longer process times or higher process temperatures, the time in melt is longer.
- The difference between the heated welding head surfaces and the weld interface temperature is at minimum 24 ± 1.5 °C.

Additional analysis and conclusions are provided in Appendix C.1.

4.2 Weld analyses

After welding, the weld specimens underwent an inspection as described in Section 3. First, they are inspected non-destructively through surface inspection and ultrasound scanning, followed by destructive inspection methods: SLS, fractography and DSC analysis.

4.2.1 Outside surface analysis

To examine the impact of the process parameters on the outer surfaces of the composite components, the top surface weld marks are inspected and compared per process parameter setting. A comparison with the weld marks of the bottom surface is made in Appendix C.2.

Figures 4.4 and 4.5 display weld marks on the top surfaces. Figure 4.4 illustrates the weld marks for a constant processing time and a rising processing temperature, while Figure 4.5 shows the weld marks for a constant processing temperature with an increasing processing time.

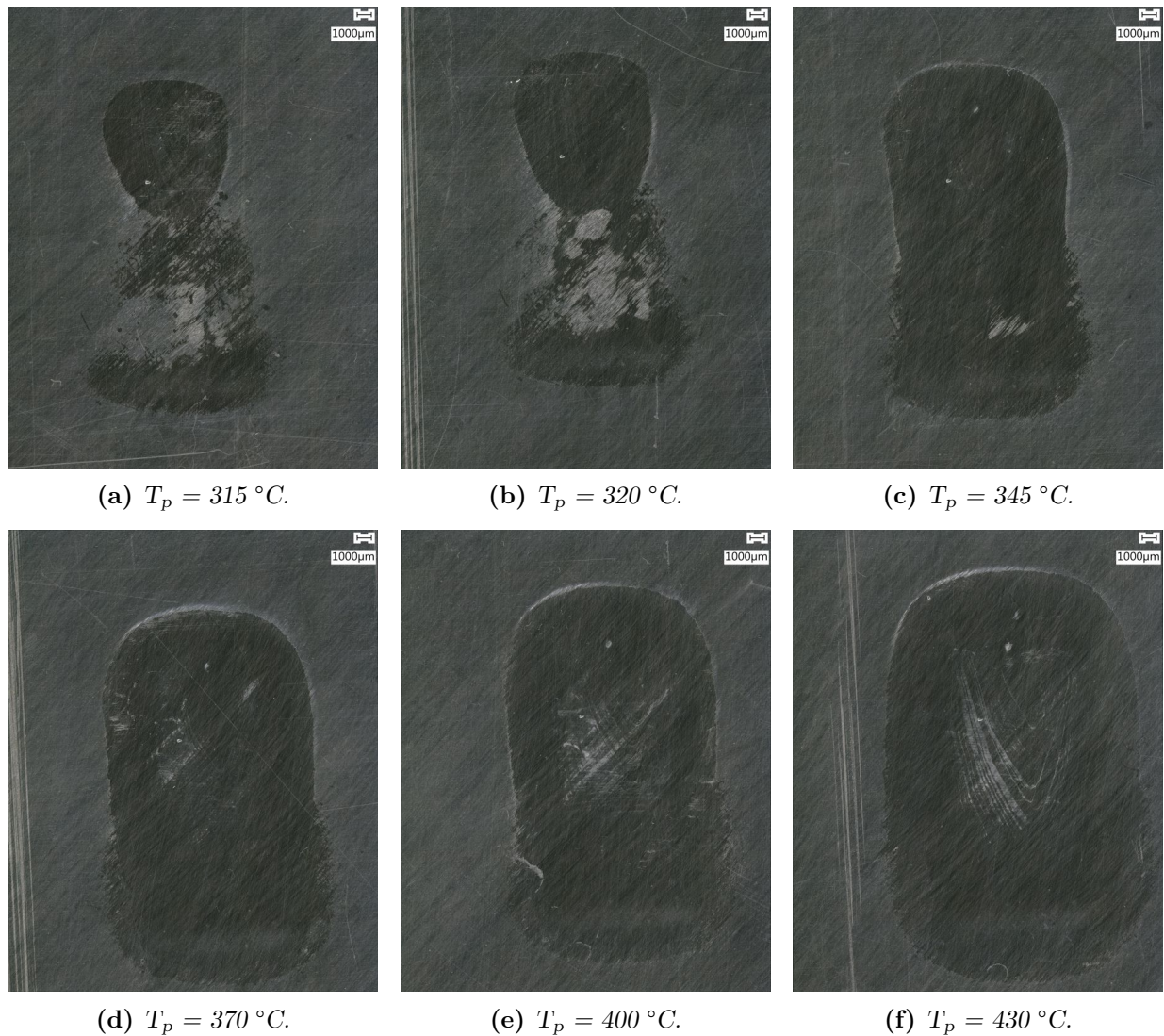


Figure 4.4: Top weld surfaces at $t_p = 0$ s.

Observing Figure 4.4, a growth of the weld mark is evident. Starting at $T_p = 315^\circ\text{C}$ two weld marks are seen. In between the areas, an incomplete molten area is observed. At $T_p = 320^\circ\text{C}$, these areas expand, and at $T_p = 345^\circ\text{C}$ the areas merge into one molten region. This area continues to grow larger over the temperature range from $T_p = 345^\circ\text{C}$ to 430°C .

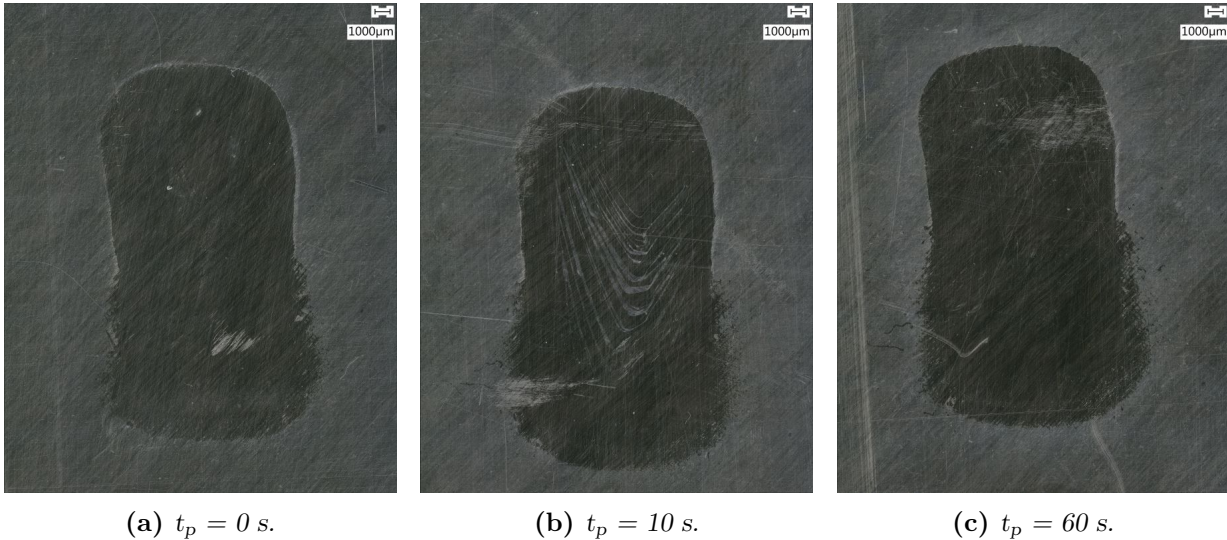


Figure 4.5: Top weld surfaces at $T_p = 345^\circ\text{C}$.

Figure 4.5 shows images of weld marks produced by a process temperature of 345°C and an increasing process time of 0 s to 60 s. No significant effect of the process time on the weld marks is observed.

Conclusion of the surface inspection

Based on the images of the outside weld marks, it can be concluded that:

- The weld mark sizes increase for higher process temperatures.
- The weld marks do not grow significantly for longer process times.

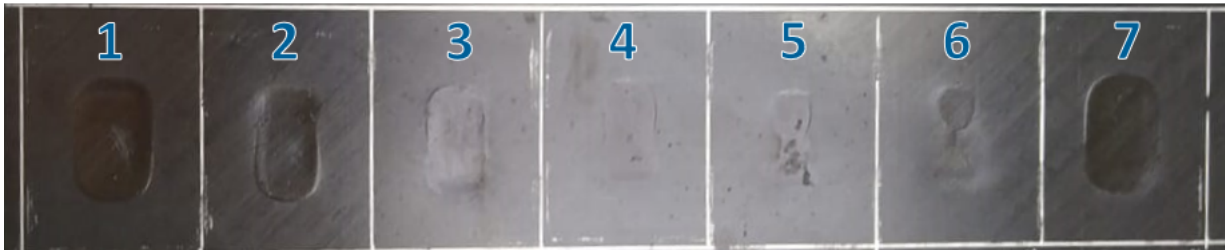
4.2.2 Ultrasound scanning analysis

In addition to the surface inspection, the welds underwent ultrasound scanning to visualise the weld non-destructively: visualise potential voids or delamination, material dampening coefficient, and reflection distance in the material, as given in Section 3. This section presents the results and observations obtained from the ultrasound scans.

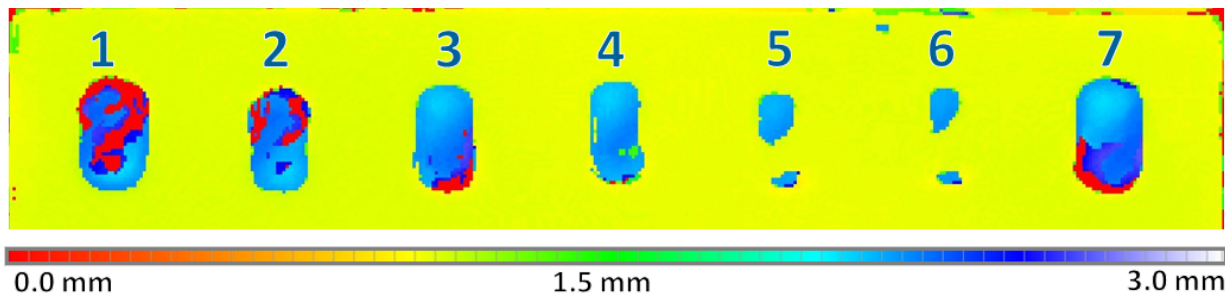
Figures 4.6 and 4.7 display representations of two sample plates, displaying a photograph of the top surface, an ultrasound scan of the reflection distance, and a scan of the signal dampening. The scans reveal the pattern of the spot welds (1 to 14), with an increase in weld size observed over temperature increase (sample 6 to 1). The reflection distance scan indicates a depth of approximately 1.2 mm outside the welds and approximately 2.4 mm inside the welds, suggesting signal penetration into adjacent laminates. Inspecting the dampening percentage of the welded areas reveals varying levels of damping. The white areas indicate fully welded regions and darker areas are areas that dampen the signal in the material and indicate potential voids or delamination. However, comparing the dark regions with the same regions in the reflection distance scan suggests that the signal is dampened at the surface of the laminate and not in the material, where voids and delamination occur. The signal was dampened due to the rough surface that the welding heads left behind. This hinders the signal from being transmitted in the material, obstructing definitive conclusions about the underlying material, as the scan from the bottom side was also obstructed. This is discussed in Appendix C.13.

However, for some samples, the scan of the weld displays a full scan of the weld (samples 4-6, 8, 10-12). Here in sample 4 two green areas in the weld are visible. These two spots at approximately 1.5 mm and show a slight dampened signal in Figure 4.6c, which could indicate voids or delamination. During the inspection of other ultrasound scan, these green areas were also visible for samples with a process temperature of 345 °C (whenever the surface roughness did not obstruct the ultrasound signal). Further inspection of these regions is performed during the fractography of the interface in Section 4.2.4.

Figures 4.6 and 4.7 show no, one and two welds at a process temperature of 315 °C. At this process temperature, the interface temperature was simply too low to create a full weld.

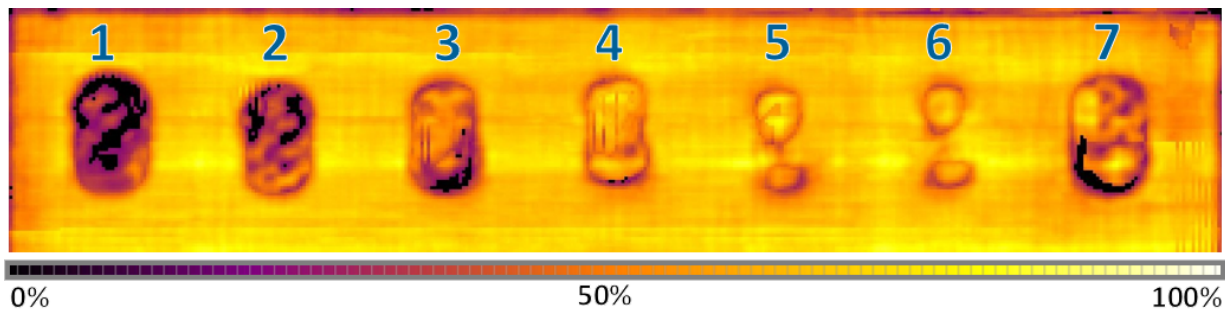


(a) Photograph of the top showing the visual weld marks. Sample 1 to 6 are the same samples displayed in Figure 4.4.



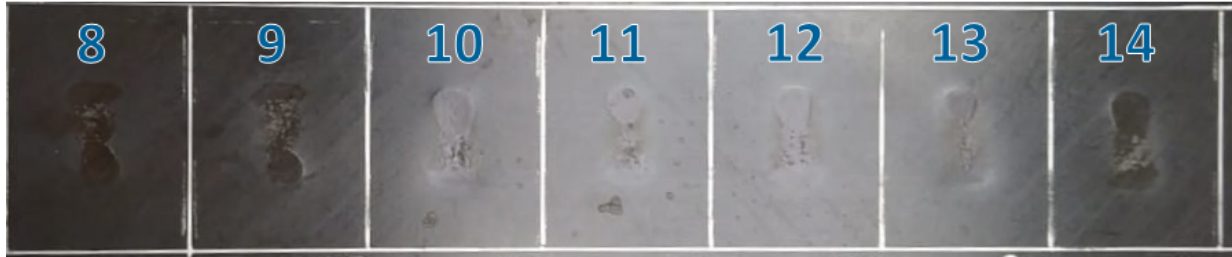
(b) Reflection distance ultrasound scan.

The colours indicate at what distance in the material the ultrasound signal is reflected. In the welds, blue is at approximately 2.0 to 2.5 mm, green at 1.1 to 1.6 mm, yellow 0.9 to 1.0 mm, and red 0.0 to 0.3 mm.

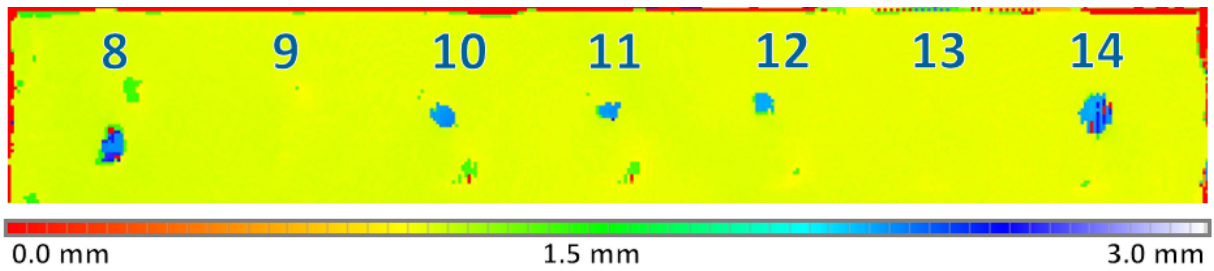


(c) Ultrasound signal dampening scan. White areas mean that 100 % of the signal is received (not damped), darker-coloured means that it is damped, and black means that 0% of the ultrasound signal is received.

Figure 4.6: Photograph and ultrasound scans of the top side of sample plate 25. $t_p = 0s$, from left to right (samples 1 to 7) T_p values: $430^\circ C$, $400^\circ C$, $370^\circ C$, $345^\circ C$, $320^\circ C$, $315^\circ C$, $430^\circ C$. Samples 1 & 2 are up-side-down compared with the other weld-samples.

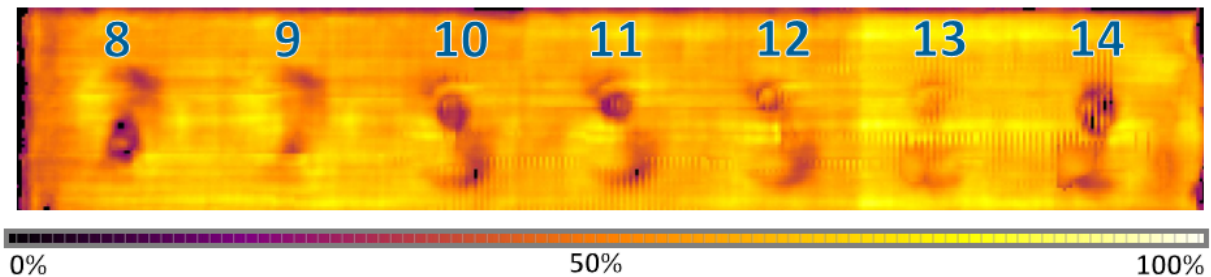


(a) Photograph of the top showing the visual weld marks. Samples 1 & 2 are "up-side-down" compared with the other weld-samples.



(b) Reflection distance ultrasound scan.

The colours indicate at which distance the ultrasound signal is received back. In the welds, blue is at approximately 2.0 to 2.5 mm, green at 1.1 to 1.6 mm, yellow 0.9 to 1.0 mm, and red 0.0 to 0.3 mm.



(c) Ultrasound damping scan. White areas mean that 100 % of the signal is received (not damped), darker-coloured means that it is damped, and black means that 0% of the ultrasound signal is received.

Figure 4.7: Photograph and ultrasound scans of the top side of sample plate 15. From left to right (samples 8 to 14) $t_p = 10s \ \& \ T_p = 320^\circ C$, $t_p = 60s \ \& \ T_p = 315^\circ C$, $t_p = 60s \ \& \ T_p = 320^\circ C$, $t_p = 10s \ \& \ T_p = 315^\circ C$, $t_p = 10s \ \& \ T_p = 320^\circ C$, $t_p = 60s \ \& \ T_p = 315^\circ C$, $t_p = 60s \ \& \ T_p = 320^\circ C$

Conclusion of the ultrasound inspection

Based on the ultrasound scans of the weld samples, it can be concluded that:

- The welds do not increase in size with an increasing processing time.
- The weld size depends on the process temperature setting.
 - At a process temperature of 315 °C, inconsistent small welds are produced.
 - At a process temperature of 320 °C, inconsistent small welds are produced.
 - At a process temperature of 345 °C, voids or delamination may be present in the weld.
 - At a process temperature bigger than 345 °C, it is one fully welded area.

For further observations, discussions and conclusions regarding the ultrasound scans, refer to Appendix C.3.

4.2.3 Bond strength analysis

Following the non-destructive inspection, the welds underwent destructive inspections. This involved conducting SLS experiments, microscopy inspection of the fractured weld surface, and performing differential scanning calorimetry to measure the thermal history effects of the processing parameters. First, the welds are individually assessed on their maximal shear force in SLS experiments. The results of these experiments and the corresponding shear strength of the samples are described in this section. Figure 4.8 illustrates the shear force at failure per parameter setting, derived from the SLS results presented in Figure C.19a in Appendix C.5. Figure 4.8 indicates that increasing the temperature leads to a higher shear force at failure. Notably, welds produced at process temperatures of 315 °C & 320 °C exhibit a significantly lower shear force at failure than those produced at 345 °C and higher. Upon looking at the shear force at failure for a constant process temperature and varying process times, the shear force at failure does not display significant changes.

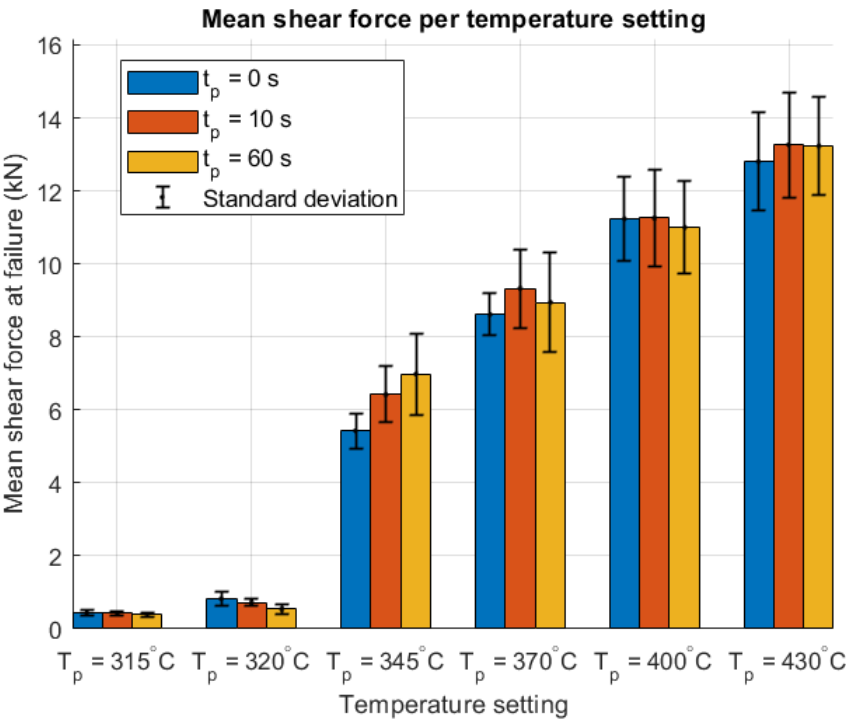


Figure 4.8: Mean shear force at failure per process parameter setting.

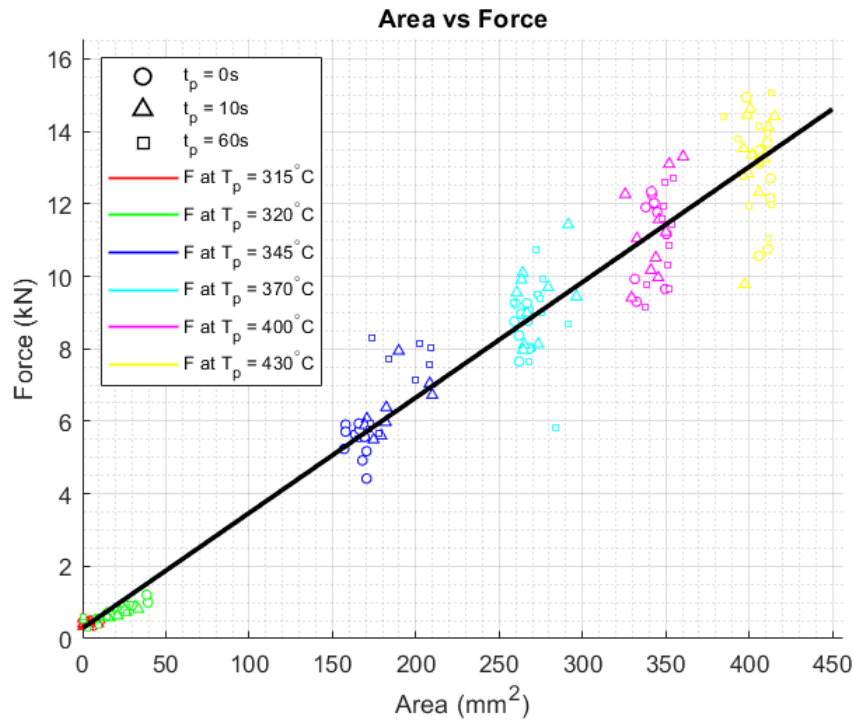


Figure 4.9: Weld area vs. Shear force.

After the experiments, the size of the welded areas at the interface is determined. Section 4.2.4 will describe this process in more detail. Figure 4.9 depicts the maximum shear force per weld area, indicating a linear proportionality between the welded area and the maximum shear force. The line does not go through 0.0, as also Figure C.20b displays in Appendix C.5. The reason for this lies in the method of conducting the SLS experiment; during the clamping of the samples, the pretension in the sample was already ~ 200 N breaking some of the samples' bonds. Therefore, there was no data on those samples with a small force. Figure 4.10 displays the shear strength per process setting. The shear strength is calculated by dividing the maximal shear force by the weld area. Due to the small areas of the samples produced with a process temperature of $315^\circ C$ and $320^\circ C$, the shear strengths are unrealistically high. Therefore, these values are excluded from further shear strength analysis.

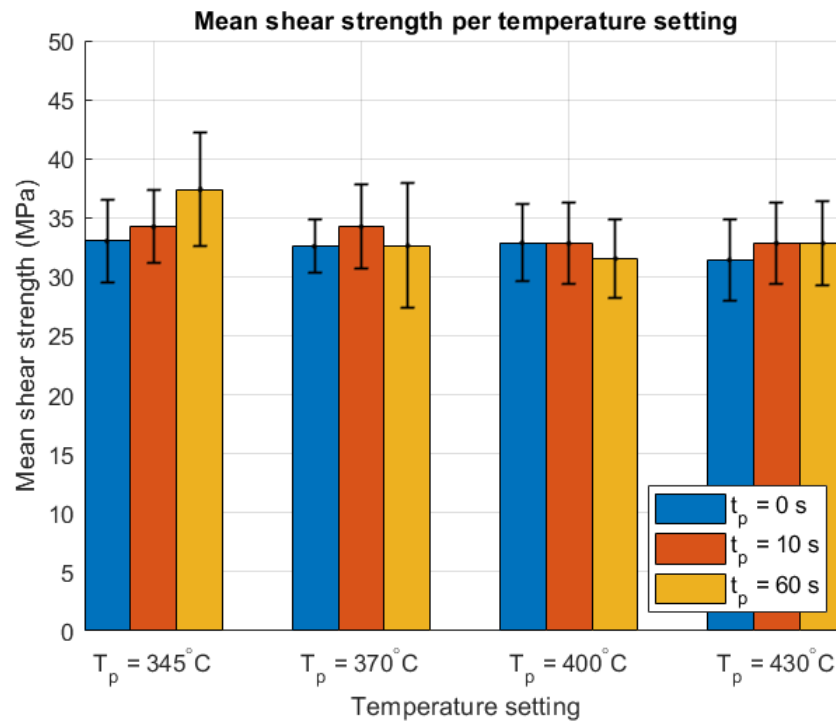


Figure 4.10: *Shear strength per processing parameter setting.*

Figure 4.10 indicates no significant difference in shear strength for both process parameters. Therefore, the shear strength remains unaffected by the process time and temperature within the tested range.

Conclusion of the SLS-experiments

Based on the SLS experiments and analysis, it can be concluded that:

- The maximal shear force is temperature-dependent and proportional to the weld area.
- The maximal shear force is not time-dependent.
- The maximal shear strength of the welds is constant for the tested time and temperature settings.

4.2.4 Fractography analyses

The weld interfaces are inspected on their weld size and failure fracture structure. This fractography involves a light microscope and SEM to analyse the interface structure of the weld, identifying irregularities and fail mechanisms. Detailed images of notable areas are created with the SEM.

Weld sizes

Figure 4.11 presents the weld interface surfaces of six welds produced with a processing time of 0 s and all the processing temperatures. The size of the weld areas is similar to the weld size on the outer surface (Section 4.2.1) and in the ultrasound scans (Section 4.2.2). The weld size per parameter setting is visualised in Figure 4.12.

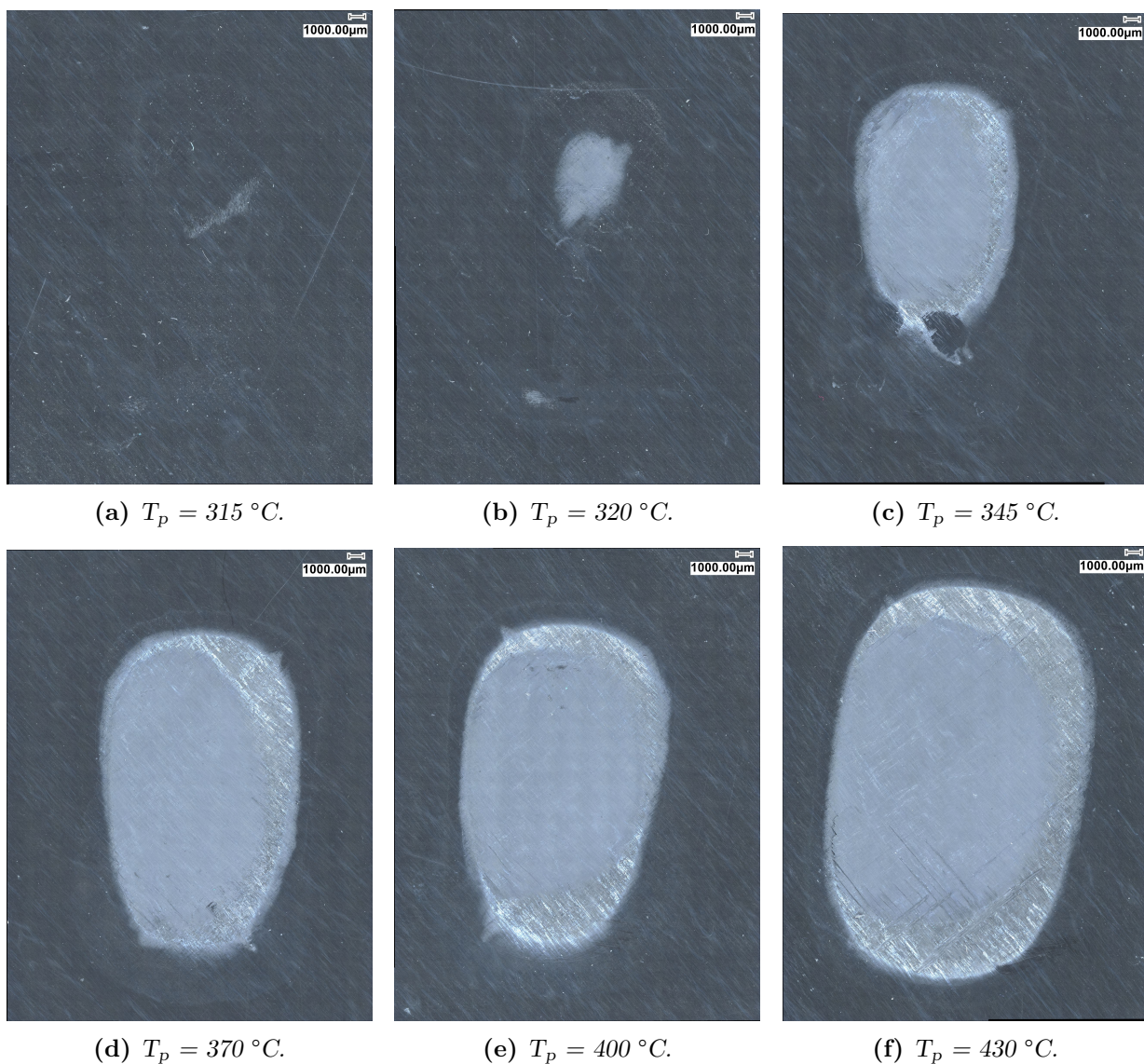


Figure 4.11: Weld interface surfaces of $t_p = 0\text{ s}$.

In Figure 4.12 it is evident that the process temperature significantly affects the weld size and the process

time does not influence the size of the weld area. However, at a processing temperature of 345 °C the standard deviation does not overlap for the processing times of 0 and 10 s, suggesting an increase in weld size during this period. However, the weld size increase is not significant between specimens welded for 0 and 60 s at 345 °C. This variation in weld area between the 0 and 10 s sample is likely due to a small measurement error, as the area and shear force at failure are proportionally related, see Figure 4.9, and the shear force at failure is constant over time.

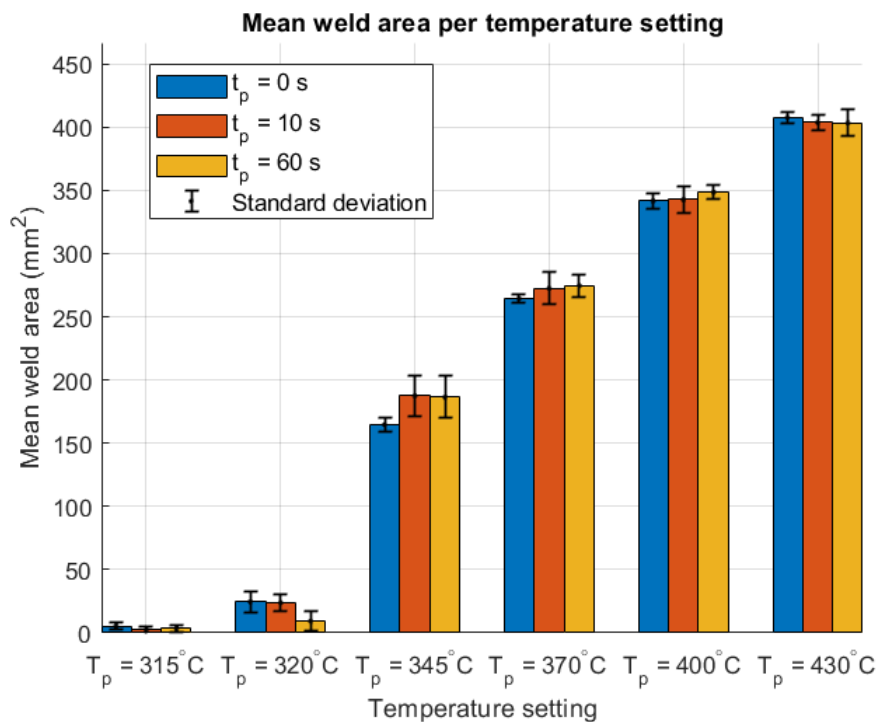


Figure 4.12: Bar plot of the weld area at the weld interface vs. T_p .

At a process temperature of 315 °C, the values are approximately 0 mm², as observed in the ultrasound scans. Figure 4.13 displays this on the interface. Welds at 315 °C consist of no, one or two spots, which indicates that around this temperature creates a measurable weld area. From there, the weld size increases with an increasing process temperature as demonstrated in Figures 4.12 & C.22 in Appendix C.5

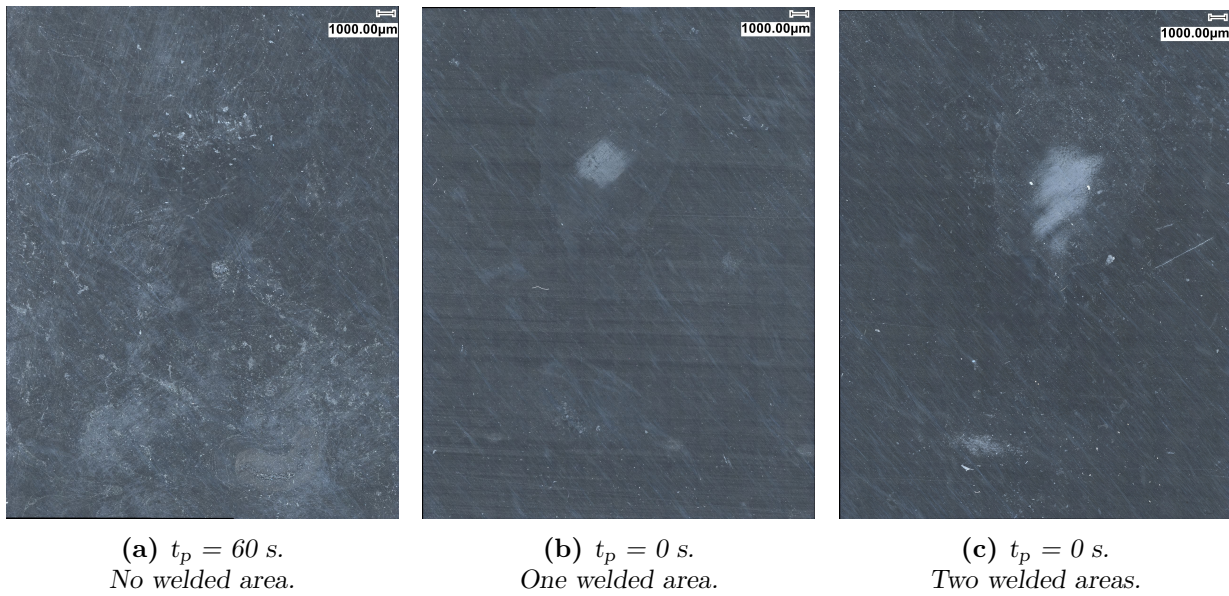


Figure 4.13: Weld interface surfaces of $T_p = 315$ °C.

Weld area inspection

For further weld inspection, two samples are examined using a SEM, providing information on different areas at the weld interface. The microscope images of these samples are displayed in Figure 4.14 and C.24 in Appendix C.6.

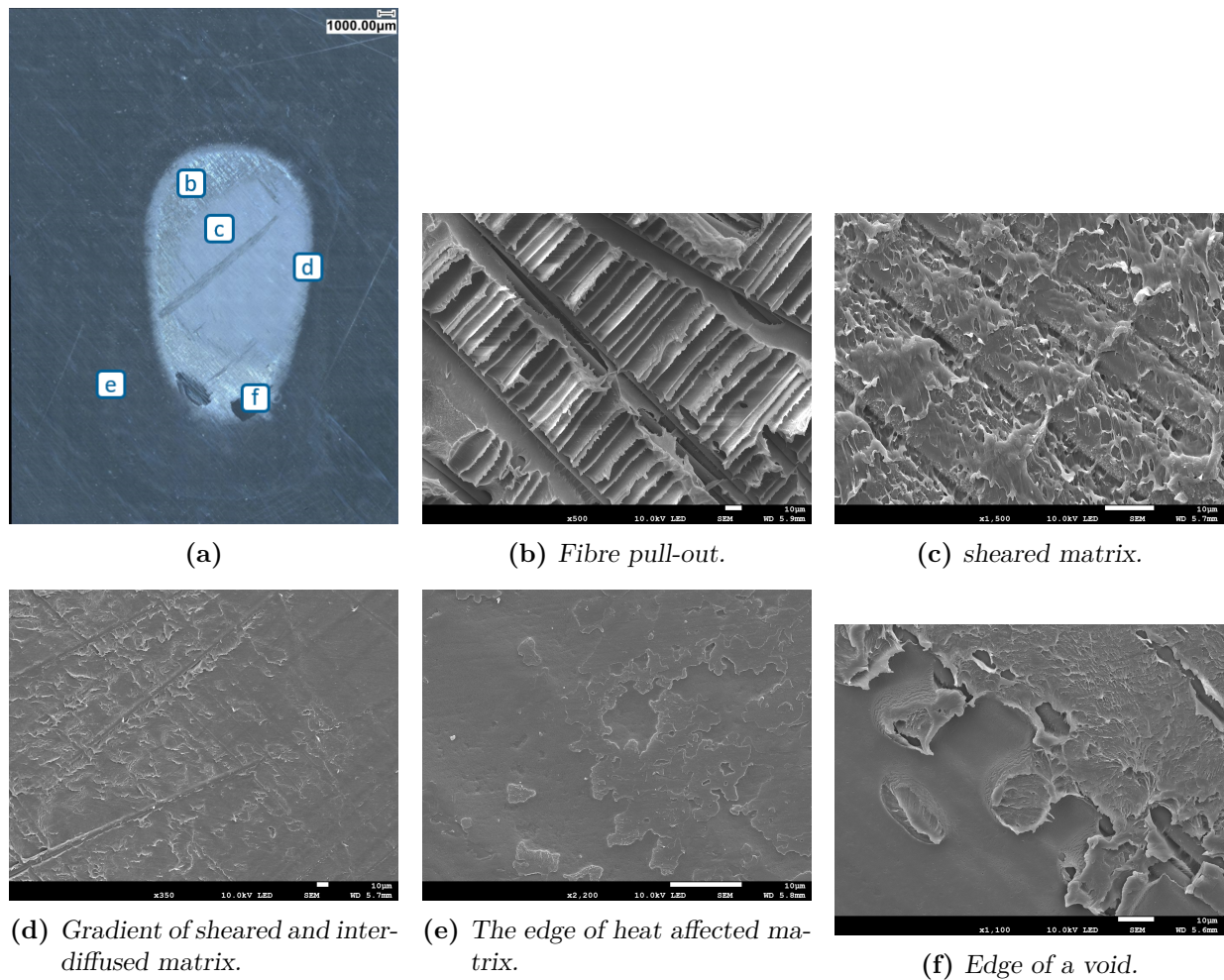


Figure 4.14: SEM images of the weld interface of sample 9.2, a weld produced at a process temperature of 345 °C at a process time of 60 s.

Figure 4.14a showcases the weld interface of a weld created at a process temperature of 345 °C and a process time of 60 s. Various failure modes within the weld area are visible, including fibre breakage, fibre pull-out, sheared matrix, a gradient of the sheared matrix, a gradient of the heat-affected matrix material, and voids. Some of these failure modes are further magnified in Figures 4.14b to 4.14f. The voids, visible as dark holes in Figure 4.14a, are primarily located at location 'f' in welds produced at a temperature of 345°C, although smaller voids are observed in other samples. Figure 4.14f magnifies the edge of a void, where the matrix material outside the void has failed due to shearing, while the material inside the void appears smooth. This observation suggests insufficient intimate contact, and thus insufficient pressure at the weld interface, preventing proper interdiffusion. A SEM image of the whole void can be seen in Figure C.23 in Appendix C.6

Conclusion of the fractography

The fractography results show:

- Similar results as the earlier inspections of the outside surface microscopy and Ultrasound scans:
 - The weld size increases with increasing process temperature.
 - The weld size does not depend on the process time.
 - Around 315 °C, welds initiate, although the weld formation is small and inconsistent.
 - At 320 °C, one or two small inconsistent areas are present in the joint.
 - At 345 °C, welds consist of one area, but all samples contain voids.
 - At 370 °C, 400 °C and 430 °C, consistent areas are observed, but contain small voids.
- That the tested welds were not purely tested on matrix shearing, as they contain fibre pull-out (peeling) and fibre breakage.

4.2.5 Thermal behavioural analysis

In the final step of the weld inspection, samples underwent testing in a DSC setup to analyse the thermal behaviour (Appendix C.7) and thermal degradation of the welded material. Figure 4.15 shows the crystallisation temperature during cooling, serving as a measure for thermal degradation of the matrix material [24]. A decrease in crystallisation temperature indicates reduced chain mobility, potentially due to polymer chain branching or crosslinking, indicating thermal degradation of the polymer.

Figure 4.15 illustrates the crystallisation temperatures of samples welded at 315 °C, 345 °C, and 430 °C for 0s and 60s, along with consolidated samples as reference. At process temperatures of 315 °C and 345 °C, the process parameter setting does not significantly affect the crystallisation temperature. However, at 430 °C, there is a significant decrease in crystallisation temperature, indicating potential thermal degradation of the matrix material. Further experiments, as shown in Figure C.27 in Appendix C.7, show that the crystallisation temperature decreases further by extended heating of the material, as shown by Overmars [30].

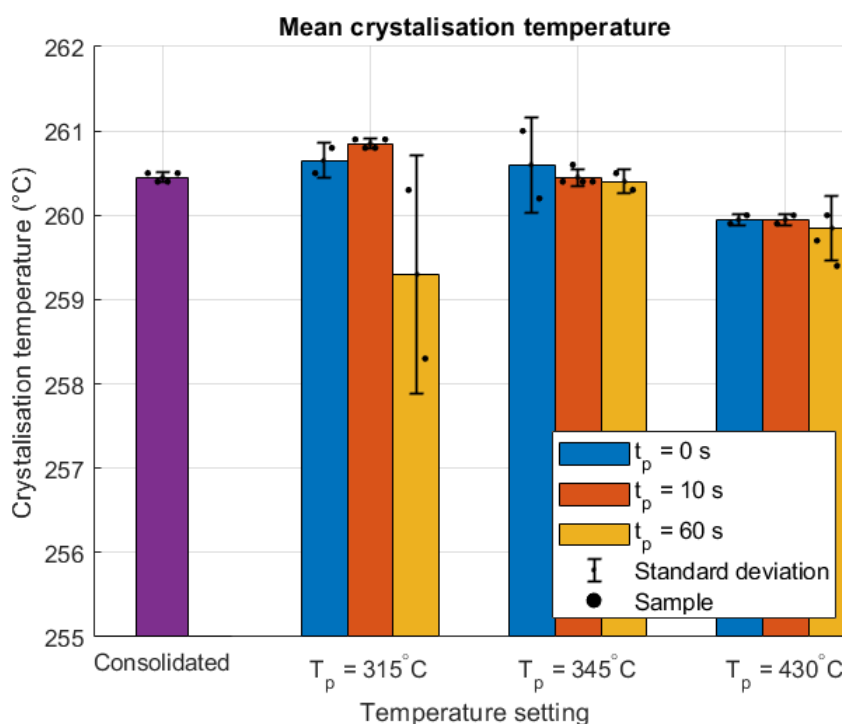
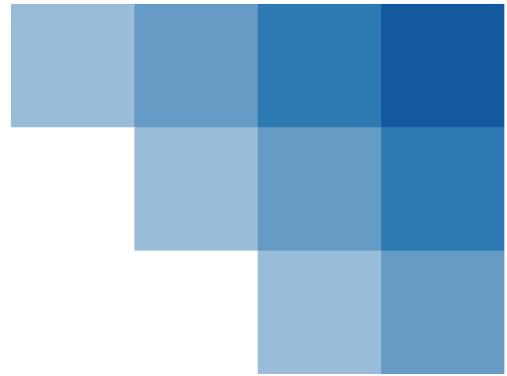


Figure 4.15: Measured crystallisation temperatures per process setting.

Conclusion of the DSC analysis

Based on the results of the DSC scans, it can be concluded that:

- A minor crystallisation temperature decrease is measured at a processing temperature of 430 °C, which could indicate thermal degradation.



Chapter 5

Discussion

The objective stated in Section 1.2 was to specify the process window for the conduction welding of CF/LM-PAEK in terms of the process time and temperature, as the parameters affect the bonding mechanisms as described in Section 2.2. This chapter combines the experimental results, presented in the previous chapter, defining the effects of the process time and temperature on the weld quality, and links them to the literature. Subsequently, based on these findings, a process window is described for consistent weld quality production using the conduction weld setup and sample design.

5.1 Process time effects

The experimental results indicate that the process time has minimal effect on the weld quality. Over the tested process times while maintaining a constant process temperature, no significant differences in maximal shear force, shear strength and degradation are observed. The experimental results showed that the weld force was directly proportionally related to the weld area, as Figure 4.9 depicts, resulting in the constant shear strength.

5.2 Process temperature effects

On the other hand, the process temperature appears to have a more significant influence on the weld properties, compared to the process time on the weld properties. Altering the process temperature resulted in notable variations in weld size, maximum shear force, weld quality, and crystallisation temperature degradation. Increasing the process temperature led to the transition of the weld area from a small inconsistent weld at 315 °C to a larger more uniform weld at 345; which contains large voids, and finally to a larger weld with consistent weld quality at process temperature values of 370, 400, and 430 °C.

The maximal shear force increased proportionally with the weld area increase, maintaining a constant shear strength, which is equivalent to Naus's values [4] and in line with the literature [17, 18]. Literature suggests that the required welding time of CF/LM-PAEK is 2 s just above the melting temperature at 310 °C, and even less than 1 s at 345 °C [20, 28, 31], suggesting an almost direct full degree of intimate contact and healing after melting. As the measured time in melt at minimal process settings, a process time of 0 s and a process temperature of 315 °C, is 5 s. And with time in melt increasing per process setting increase. All samples will have a full degree of autohesion.

Furthermore, a minor decrease in crystallisation temperature observed at 430 °C remains consistent across process times, which could indicate thermal degradation, as additional experiments and literature suggest [24, 30]. The "thermal degradation" did not affect other measured weld properties, like the shear strength.

5.3 Process window

Based on the experimental results and literature, an initial process window is established for process time and temperature, illustrated in Figure 5.1. The window spans from a process time of 0 to 60 s and from 370 to 430 °C for process temperature, representing the parameters for which consistent weld quality was achieved. Outside this window, the weld quality is lacking or unknown.

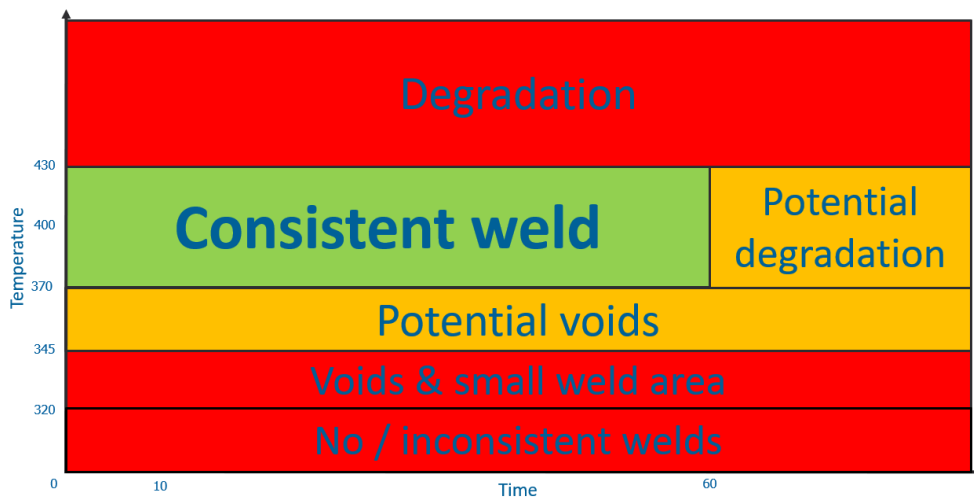
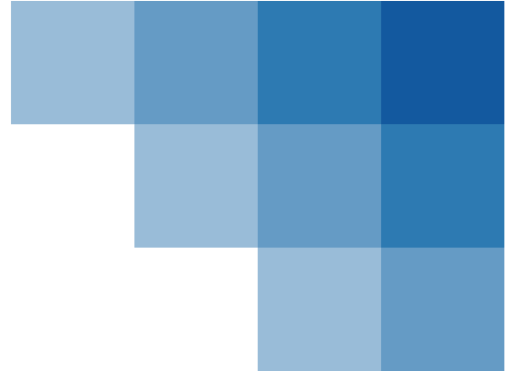


Figure 5.1: The process window of process time and temperature for producing a conduction spot weld on two quasi-isotropic CF/LM PAEK laminates with a thickness of 1.2 mm at process pressure of 370 kPa.

The window is based on the following key findings:

- At a process temperature of 430 °C, a decrease in crystallisation temperature was observed, which could indicate thermal degradation.
- Process times exceeding 60 s at temperatures 370 °C to 430 °C, may lead to degradation of the matrix material [24].
- Between a process temperature of 345 and 370 °C, voids may be present. At a process temperature of 345 °C, voids are present, and at a process temperature of 370 °C, these voids are absent.
- At process temperatures 320 and 345 °C, the small welded areas with low maximal shear forces were observed.
- At the process temperature of 315 °C, inconsistent welds were produced.



Chapter 6

Conclusion

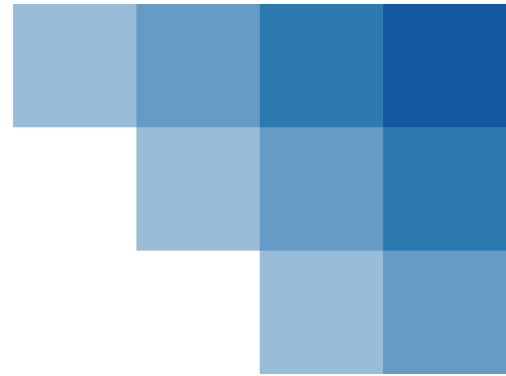
The objective of this work was to specify a process window for producing CF/LM-PAEK conduction welds, with a focus on the influence of process time and temperature settings on the weld quality. Utilizing Naus's conduction welding setup, spot welds were produced to make lap-joints on quasi-isotropic laminates. Subsequently, non-destructive and destructive weld inspections were performed to analyse the effects of process parameters on the weld quality. Based on the results and discussions of the process and weld analyses, conclusions were drawn regarding the impact of the process time and temperature on the weld quality. Consequently, a process window for producing consistent quality conduction spot welds was established for the setup and sample material.

The key conclusions that are drawn from this study are:

- **The effects of the process times on the weld quality are insignificant for the range studied in this work.**
- **The effects of the measured process temperatures on the weld quality are significant.**
In the experiments, the temperature was found to have an evident effect on the weld properties.
 - Higher process temperatures increase the weld area and the proportionally coupled maximal shear force.
 - Welds produced with process temperatures of 315 and 320 °C resulted in inconsistent, small welds.
 - Welds produced with a process temperature of 345 °C contained voids.
 - Welds produced with process temperatures of 370 and 400 and 430 °C resulted in consistent welds.
 - Welds produced with a process temperature of 430 °C showed a small decrease in crystallisation temperature.
- **The process window for this experimental configuration; setup and sample material, spans over the process time 0 to 60 s and process temperature 370 to 430 °C.**
 - For process time values exceeding 60 s, the effect on the weld quality is unknown as no tests were performed at longer process times, which may lead to degradation of the matrix material.
 - Process temperatures exceeding 430 °C increase thermal degradation beyond the observed levels in the experiments.

- Process temperatures of 320 °C and below pose challenges in obtaining consistent welds, as the melting point at the weld interface is not or barely obtained, resulting in small joint areas with low maximal shear forces.
- Process temperatures of 315, 320, and 345 °C produce insufficient welds, the welds are inconsistent, have small welded areas or contain voids, which leads to weak unpredictable welds.

To achieve consistent welds on a lap joint of quasi-isotropic CF/LM PAEK and laminate thickness of 1.2 mm using the current conduction weld setup at a process pressure of 370 kPa, the process window for process time and temperature spans from 0 to 60 s and from 370 to 430 °C.



Chapter 7

Outlook & Recommendations

Conduction welding offers significant benefits over alternative TPC welding methods; such as it is relatively simple, it does not require additional materials at the weld interface or in the composite material, it is more scalable for bigger parts, and has a higher production speed [2, 9]. Therefore, further development of this welding technique should be considered. This development should focus on parameters, setup and weld assessment optimisation used in this research. This section describes areas with considerable potential for improvement of conduction welding. Appendix D provides an extensive list of recommendations.

7.1 Outlook for further development of conduction welding process

Focussing on the further development of the conduction welding process and expanding its application, promising avenues include the development of predictive simulations on weld development and more testing of process parameters and material parameters. These investigations will offer more and deeper insights into the process capabilities and limitations, further defining the process window.

7.1.1 Thermal modeling implementation

Using the dataset generated in this research, computational models for conduction welding can be validated, facilitating the simulation of the process. These models serve multiple purposes: determining the process window virtually to minimise the need for extensive experimental trials, and aiding in the development of tools (the welding heads), for larger and more complex welds. The simulations provide insight into weld development under varying parameters. With the current dataset, the process temperature and the relation with the weld interface temperature would be essential, as it affects the weld area and quality, while process times would only affect thermal degradation. Experimental validation will be again crucial to confirm the simulation results.

7.1.2 Process and material parameter testing

The experimental investigation that follows should contain unexplored process parameter values, out- and inside the current measured process parameter regions. This will validate the simulation results but also give more insight into their impact on weld development and quality. Parameters include process and material parameters.

Process parameter testing

Further exploration of the process parameters: temperature, pressure and cooling rate is essential for further understanding their effects on conduction spot welding. Process temperatures should be investigated between 320, 345 and 370 °C, revealing the void formation and presence. The effects of process pressure are uncertain, however, literature and preliminary experiments (not displayed in this report) indicate that varying the process pressure leads to differences in weld quality therefore optimal values could be obtained for the process pressure. When the boundaries for spot welding parameters are identified, weld speed could be investigated to define optimal line welds.

Material parameter testing

In addition to the process parameters, the material parameters that affect the weld formation, like material thickness, the fibre and matrix material and the matrix volume fraction, are interesting to investigate their effect on the weld properties. The laminate thickness would be interesting to research since thicker laminates need higher process temperatures at the outer surfaces to facilitate weld formation. However, the higher temperature will degrade the outer layer material, limiting the processability. The results of these experiments could help in computational modelling as well.

7.2 Recommendations for improving the experimental setup and method

In addition to the process development, the experimental setup and assessment should also be more robust, to create more consistent research outcomes. Therefore, it is recommended to adjust the used setup and assessment methods. These are described below.

7.2.1 Setup

Based on the experience with the current welding setup, modifications to the setup are recommended, particularly positioning the heat block of the bottom welding head correctly. Different results were observed regarding the bottom and top welding heads. It was observed that the heat block was misaligned, Figure 7.1. Correcting the heat block's position would minimise these differences.



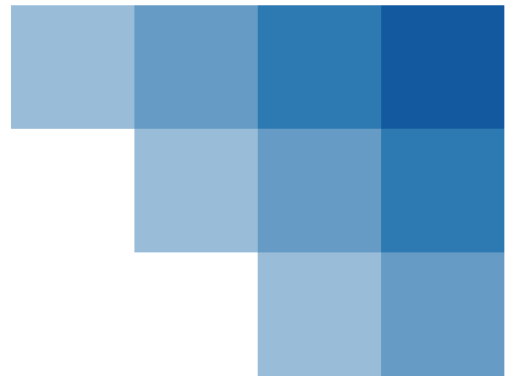
Figure 7.1: Misaligned heat block (right edge downwards) at the bottom welding head.

7.2.2 Experiments

Noteworthy changes to the experimental procedures are recommended to ensure consistent and accurate results. To enable meaningful comparisons between process parameter effects on the temperature of the weld interface, the thermocouple at the weld interface should remain at a fixed location during the process

analysis. This allows for an accurate comparison of the interface temperatures across different process settings.

In addition, for accurate shear strength determination, Double Lap Shear or Short Beam Shear experiments with an interface layup of slight fibre direction difference (e.g. 0 to 5°) should be considered. This should result in no fibre bridging [9] and no fibre breakage, leading to more representative shear strength values.

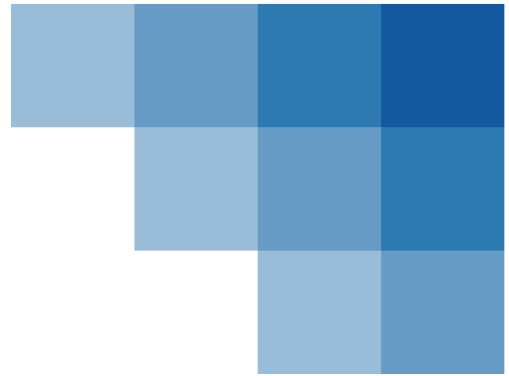


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Appendix A

Tools

A.1 Report writing tools

Chat.GPT

During the preparation of this work, the author used chat.GPT in order to improve the readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

<https://www.chat.openai.com/>

Grammarly

During the preparation of this work, the author used GrammarlyGrammarly in order to improve the English grammar and the readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

<https://app.grammarly.com/>

Languagetool

During the preparation of this work, the author used Languagetool plug-in for Latex in order to improve the English grammar and the readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

<https://www.languagetool.org/>

Thesaurus

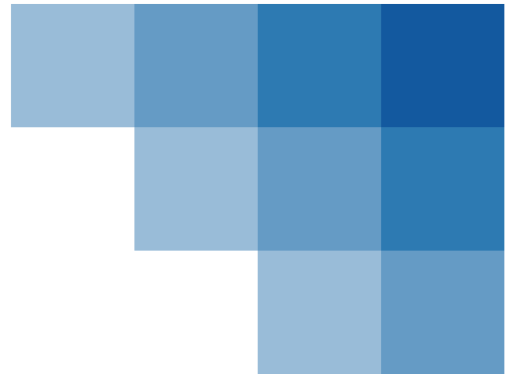
During the preparation of this work, the author used Thesaurus in order to improve the English word use and the readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

<https://www.thesaurus.com/>

Google Translate

During the preparation of this work, the author used Google translate in order to improve the English grammar and the readability of the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

<https://www.translate.google.nl/>



Appendix B

Methodology

B.1 Material argumentation

LM PAEK is a semi-crystalline polymer. Due to its designed molecule structure, it has lower T_m than PEEK, but a similar T_g [21]. Due to its lower melting point, the material has a lower processing temperature than PEEK, up to 60 °C [16] (up to 40 °C according to Vitrex [21]). And since the T_g is similar to that of PEEK the performance up to 140 °C is the same [21]. In addition, due to the lower processing temperature, the time to reach the processing temperature is decreased and the thermal gradients during partly laminate processing are smaller. Decreasing the potential effects of internal stresses during and after the process. [] Next to the benefits of the lower melting point, CF/LM PAEK is chosen because of relatively simple processability, and forgiveness in using somewhat wrong parameters (processing: range 340 - 385 °C). Therefore, it is also widely used in the industry. In addition, the material was also used in previous experiments with the setup[4]. So, to be able to make well-founded comparisons with the previous experiments, these experiments use also CF/LM PAEK.

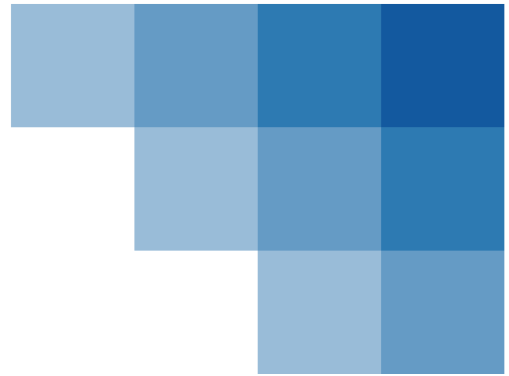
B.2 Weld parameter settings

The process time of 60 s was selected to align with the same process time as Naus used. Process times of 0 and 10 s were included to assess the impact of process time, considering that the weld time is less than 1 s according to Brandt [28]. The process temperatures of the 315 and 320 °C were chosen based on preliminary experiments indicating minimal bonds. The temperature of 345 °C represents the lower limit of the processing temperature suggested by Toray [16]. Additionally, 370 °C corresponds with advised process temperature, while 400 and 430 °C were selected to investigate the effects of temperatures above the recommended range as Tijs advised to do [9].

Preliminary experiments indicated that a pressure of 500 kPa for the movable welding head yielded satisfactory welds without matrix material expansion or signs of squeeze out. This process pressure setting results in a 370 kPa pressure on the weld interface according to Naus' results of the pneumatic actuator testing.

For the cooling system, the same pressure of 500 kPa bar is used with a full open air-valves. This last setting would make it simpler to reproduces with the current setup instead of "closing the valve with three turns" This yielded a cooling rate of 1.5 °C/s according to the results C.1.3.

The welds were positioned with the length in the length of the SLS samples, enabling more samples on a single sample plate without majorly affecting the adjacent weld samples.



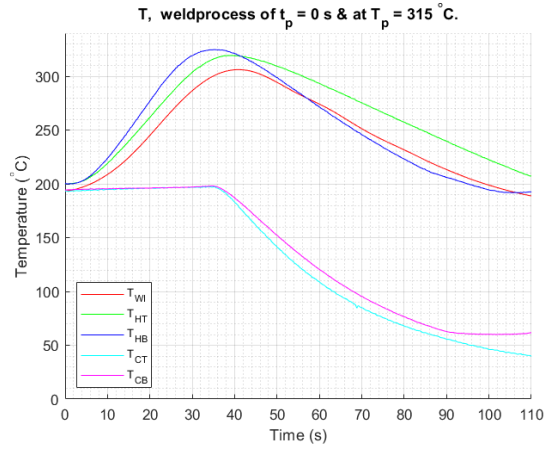
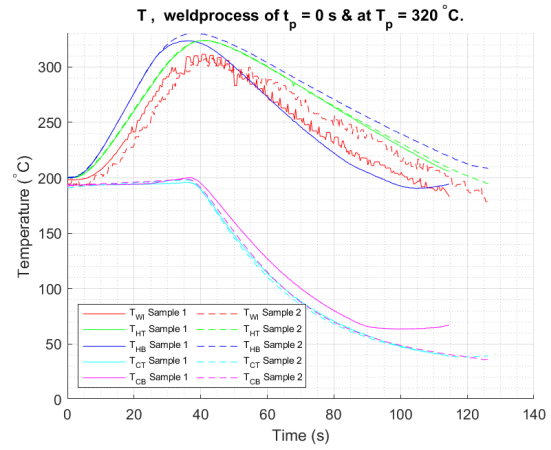
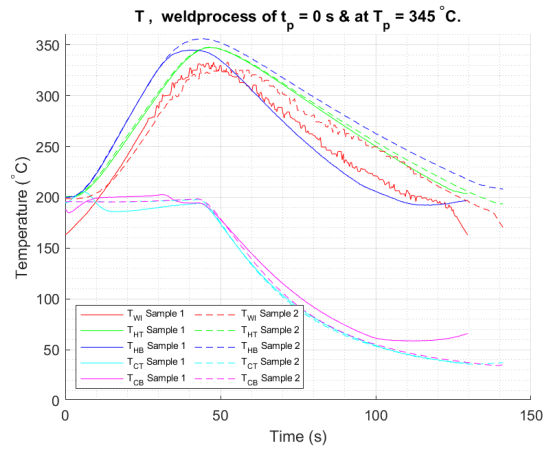
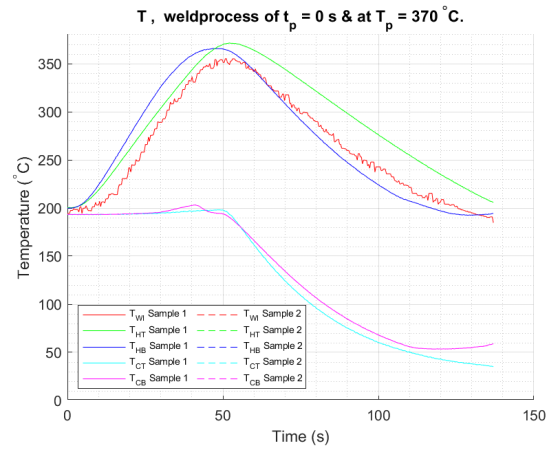
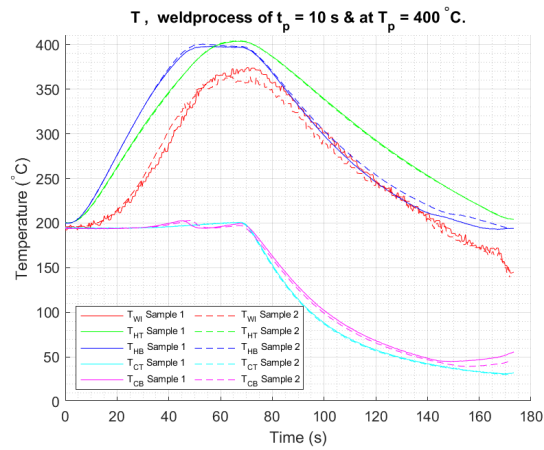
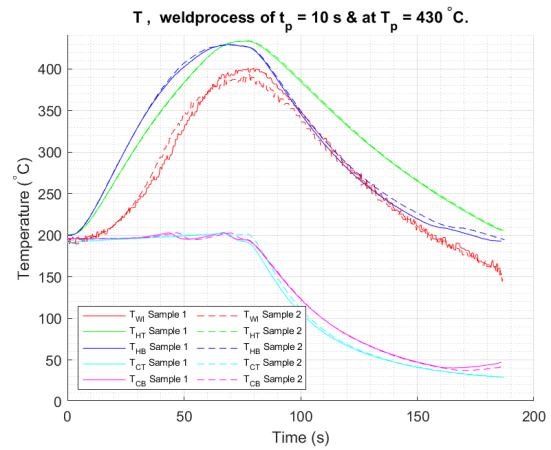
Appendix C

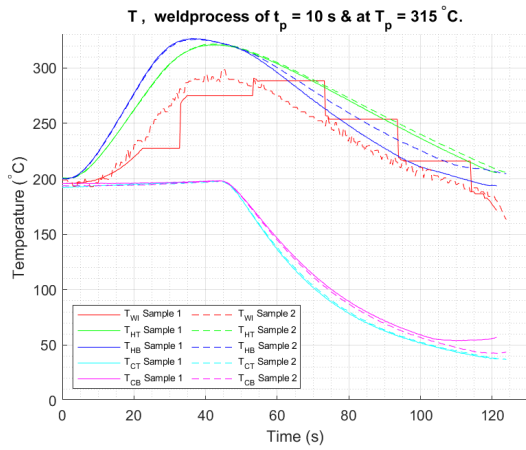
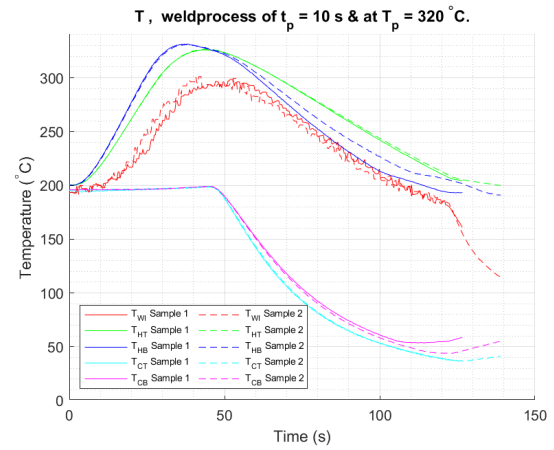
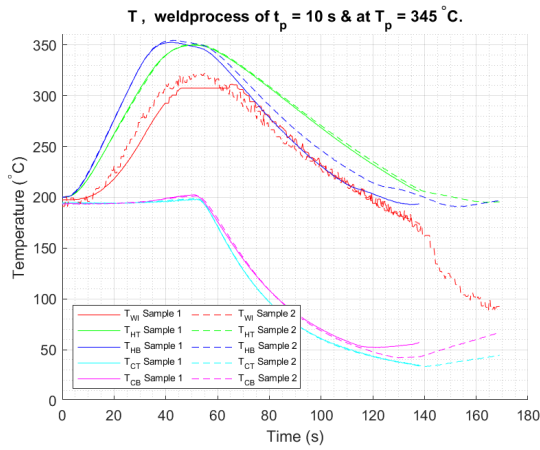
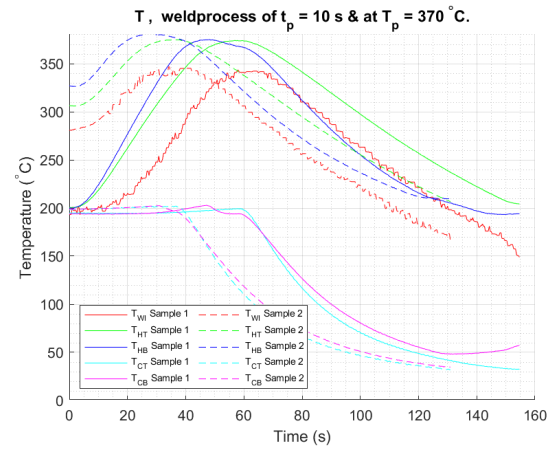
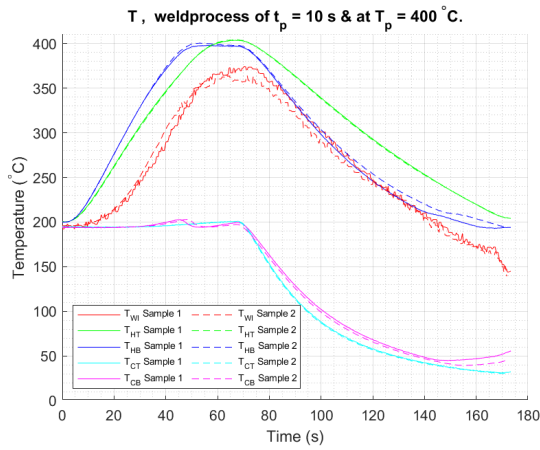
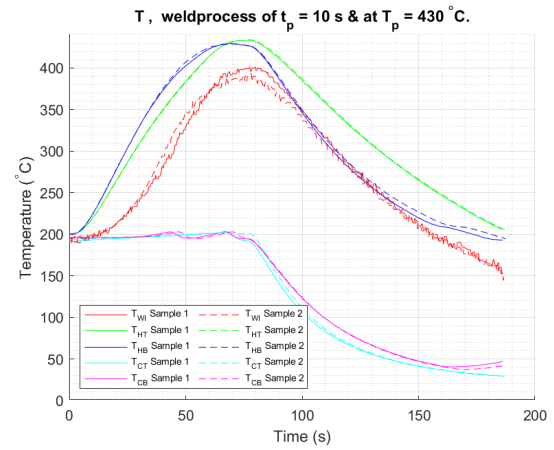
Results

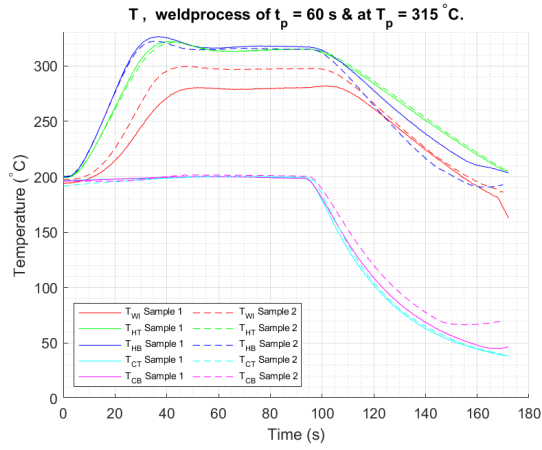
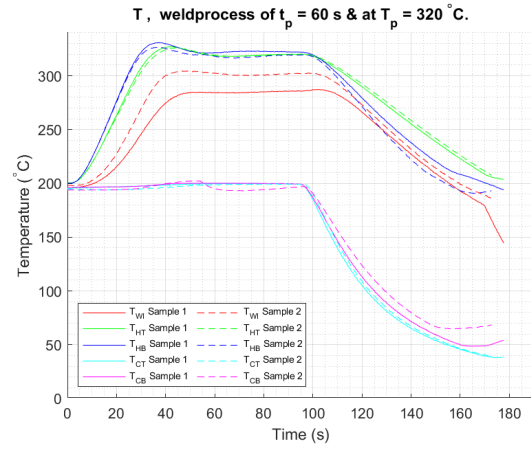
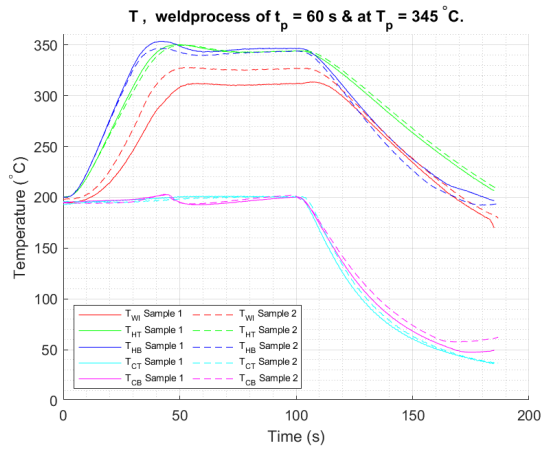
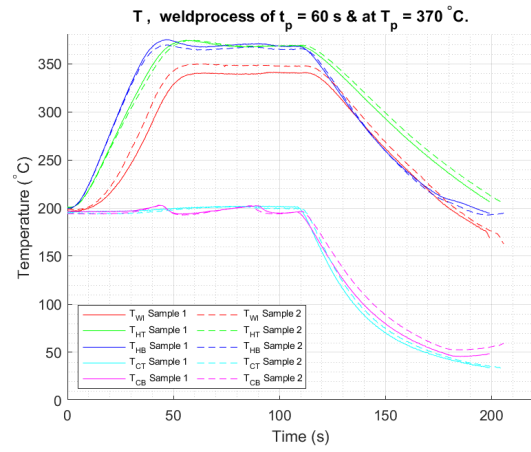
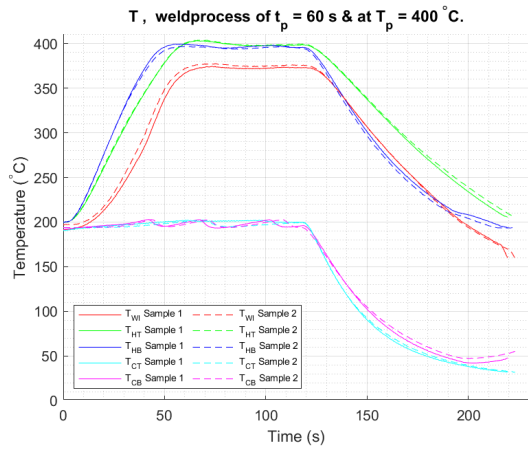
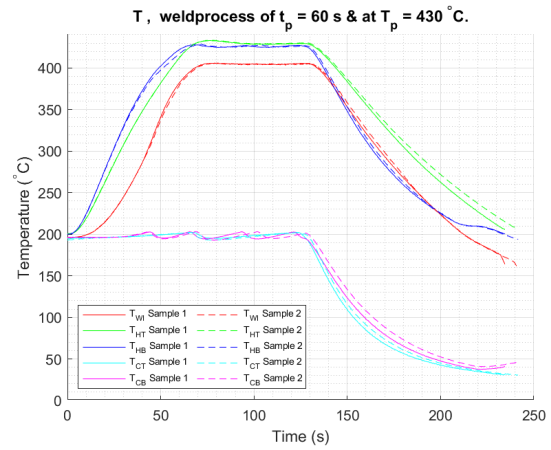
C.1 Process analysis

C.1.1 Measured temperature cycles

Figures C.1, C.2 & C.3 display the measured temperature cycles during welding using the temperature and time settings.

(a) $T_p = 315^\circ\text{C}$.(b) $T_p = 320^\circ\text{C}$.(c) $T_p = 345^\circ\text{C}$.(d) $T_p = 370^\circ\text{C}$.(e) $T_p = 400^\circ\text{C}$.(f) $T_p = 430^\circ\text{C}$.**Figure C.1:** Temperature cycles of $t_p = 0$ s.

(a) $T_p = 315$ °C.(b) $T_p = 320$ °C.(c) $T_p = 345$ °C.(d) $T_p = 370$ °C.(e) $T_p = 400$ °C.(f) $T_p = 430$ °C.**Figure C.2:** Temperature cycles of $t_p = 10$ s.

(a) $T_p = 315$ °C.(b) $T_p = 320$ °C.(c) $T_p = 345$ °C.(d) $T_p = 370$ °C.(e) $T_p = 400$ °C.(f) $T_p = 430$ °C.**Figure C.3:** Temperature cycles of $t_p = 60$ s.

C.1.2 Time in melt

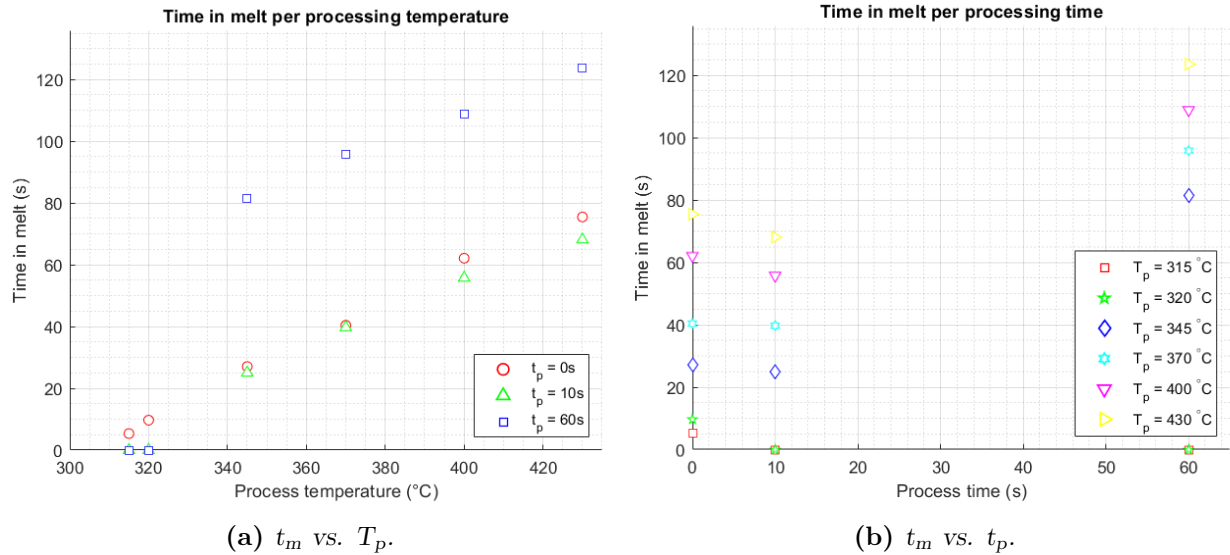


Figure C.4: The t_m per processing parameter setting.

Table C.1: Measured time in melt of WI per process setting.

	$T_p = 315\text{ °C}$	$T_p = 320\text{ °C}$	$T_p = 345\text{ °C}$	$T_p = 370\text{ °C}$	$T_p = 400\text{ °C}$	$T_p = 430\text{ °C}$
$t_p = 0\text{ s}$	5.3 s	9.7 s	27.1 s	40.4 s	62.1 s	75.5 s
$t_p = 10\text{ s}$	0 s	0 s	25.1 s	39.8 s	55.8 s	68.1 s
$t_p = 60\text{ s}$	0 s	0 s	81.5 s	95.9 s	108.9 s	123.6 s

C.1.3 Heat and cooling rates

In addition to the time in the melt phase, the heat and cooling rates are extracted. These cool rates are calculated over the time period that the weld interface temperature is above T_g . According to the theory, Section 2, crystallisation can take place during cooling until the glass transition temperature is reached. So the cooling rate should be calculated up and until this temperature to also discuss and be able to link the thermal history. However, the temperature is measured to the end of the process. And looking at the weld interface temperature is at this point not below T_g , the process stops sooner. Therefore, the thermocouple measurements up to the end of the process are included to indicate the cool rate of the system. The mean and maximal cool rates per process time and temperature-settings are given in Figures C.5 & C.6. The mean and maximal calculated Cr-values per process setting are shown in Tables C.3 & C.4.

Table C.2: Mean heat rates of the weld interface per process setting.

	$T_p = 315\text{ °C}$	$T_p = 320\text{ °C}$	$T_p = 345\text{ °C}$	$T_p = 370\text{ °C}$	$T_p = 400\text{ °C}$	$T_p = 430\text{ °C}$
$t_p = 0\text{ s}$	3.0 °C/s	3.0 °C/s	4.0 °C/s	3.3 °C/s	3.2 °C/s	3.2 °C/s
$t_p = 10\text{ s}$	2.4 °C/s	2.5 °C/s	2.8 °C/s	2.5 °C/s	2.8 °C/s	2.9 °C/s
$t_p = 60\text{ s}$	2.5 °C/s	2.6 °C/s	2.7 °C/s	2.8 °C/s	2.9 °C/s	2.9 °C/s

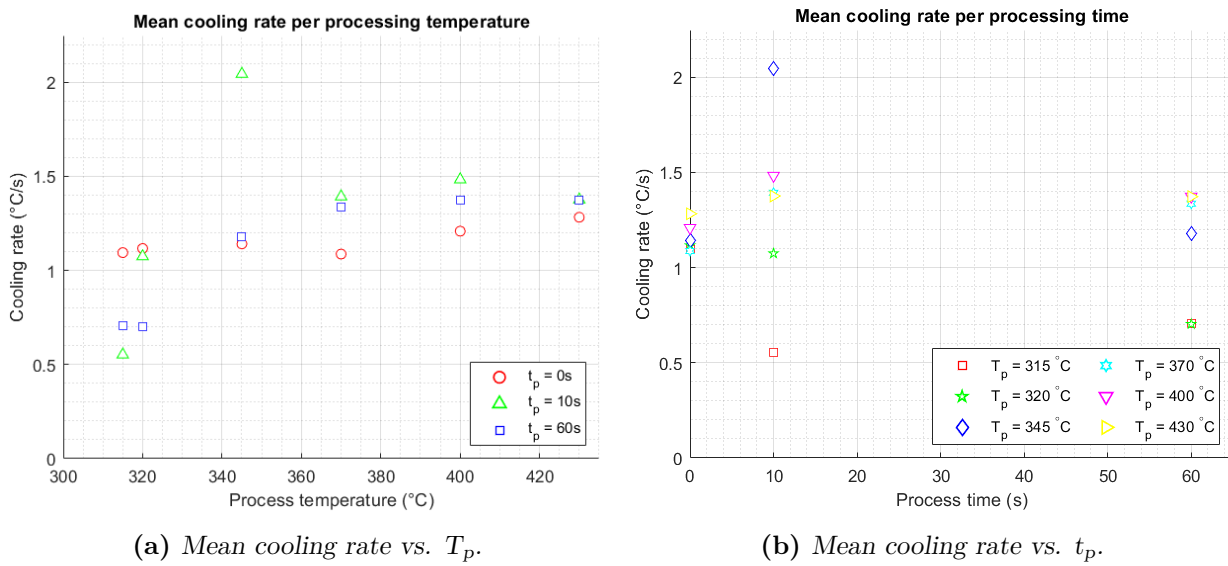


Figure C.5: Diagrams of the average cooling rate per processing parameter setting. On the x-axis is the processing parameter and on the y-axis is the means calculated cooling rate during crystallisation.

Table C.3: Mean cooling rates of weld interface per process setting.

	$T_p = 315^{\circ}\text{C}$	$T_p = 320^{\circ}\text{C}$	$T_p = 345^{\circ}\text{C}$	$T_p = 370^{\circ}\text{C}$	$T_p = 400^{\circ}\text{C}$	$T_p = 430^{\circ}\text{C}$
$t_p = 0\text{ s}$	-1.1 $^{\circ}\text{C/s}$	-1.1 $^{\circ}\text{C/s}$	-1.1 $^{\circ}\text{C/s}$	-1.1 $^{\circ}\text{C/s}$	-1.2 $^{\circ}\text{C/s}$	-1.3 $^{\circ}\text{C/s}$
$t_p = 10\text{ s}$	-0.6 $^{\circ}\text{C/s}$	-1.1 $^{\circ}\text{C/s}$	-2.0 $^{\circ}\text{C/s}$	-1.4 $^{\circ}\text{C/s}$	-1.5 $^{\circ}\text{C/s}$	-1.4 $^{\circ}\text{C/s}$
$t_p = 60\text{ s}$	-0.7 $^{\circ}\text{C/s}$	-0.7 $^{\circ}\text{C/s}$	-1.2 $^{\circ}\text{C/s}$	-1.3 $^{\circ}\text{C/s}$	-1.4 $^{\circ}\text{C/s}$	-1.4 $^{\circ}\text{C/s}$

In Figure C.5 displays the effect of the specified process parameters on the mean cooling rate. The mean cooling rate is relatively constant for the process time 0 s, visible in both diagrams. For the other processing times, 10 s and 60 s, the value deviates more. Figure C.5a shows the cooling rates seem to converge to $\approx 1.3^{\circ}\text{C/s}$ for higher temperatures. So the average cooling rate equals approximately 1°C/s , regardless of the process settings.

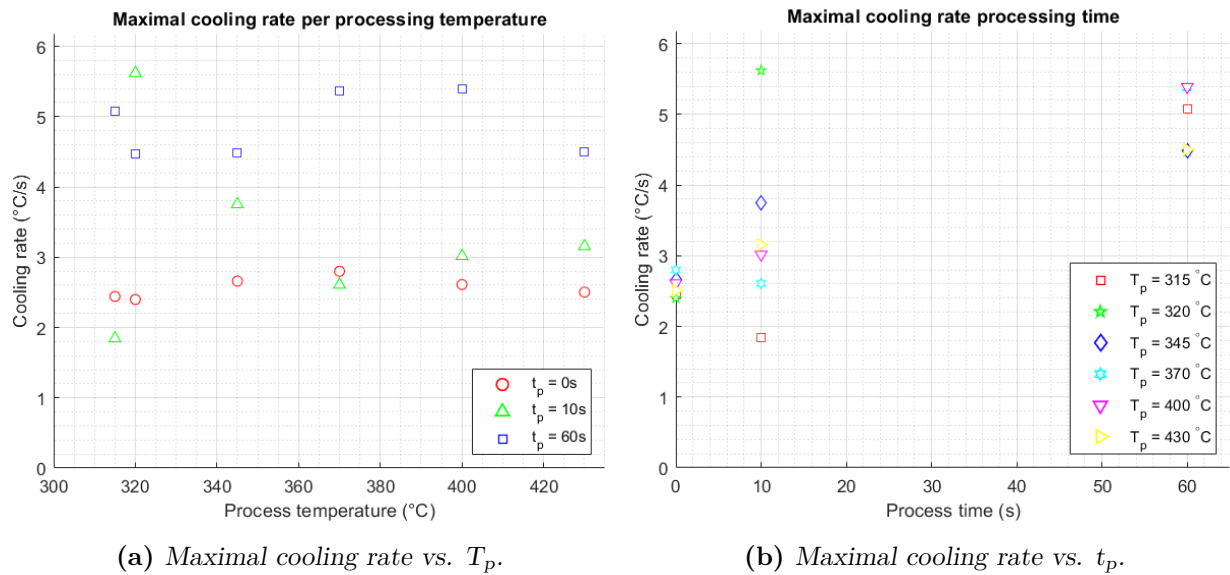


Figure C.6: Diagrams of maximal cooling rate per processing parameter setting. On the x-axis is the processing parameter, and on the y-axis is the maximal-calculated maximal cooling rate during crystallisation.

Table C.4: Maximal cool rates of the weld interface per process setting.

	$T_p = 315\text{ °C}$	$T_p = 320\text{ °C}$	$T_p = 345\text{ °C}$	$T_p = 370\text{ °C}$	$T_p = 400\text{ °C}$	$T_p = 430\text{ °C}$
$t_p = 0\text{ s}$	-2.4 °C/s	-2.4 °C/s	-2.7 °C/s	-2.8 °C/s	-2.6 °C/s	-2.5 °C/s
$t_p = 10\text{ s}$	-1.8 °C/s	-5.6 °C/s	-3.8 °C/s	-2.6 °C/s	-3.0 °C/s	-3.2 °C/s
$t_p = 60\text{ s}$	-5.1 °C/s	-4.5 °C/s	-4.5 °C/s	-5.4 °C/s	-5.4 °C/s	-4.5 °C/s

In Figure C.6 is for a process time of 0 s the maximal cooling rate is again constant, similar to the average cooling rates. The value of the maximal cooling rate is approximately two times the value of the mean cooling rate. The other maximal cooling rates differ again a lot in their values. Whereby a process time of 10 s again the most. The values of maximal cooling rate are 2 to 6 times higher than the average corresponding cooling rate.

Furthermore, when comparing Figure C.5b with Figure C.6b, the order of highest cooling rate is also not the same order as that of the average CR. Here the effect of hold time is stronger. The mean maximal cooling rate for longer holding time is higher.

C.1.4 Temperature measurements

Table C.5: Average top heat block temperature during consolidation phase per process setting.

	$T_p = 315\text{ °C}$	$T_p = 320\text{ °C}$	$T_p = 345\text{ °C}$	$T_p = 370\text{ °C}$	$T_p = 400\text{ °C}$	$T_p = 430\text{ °C}$
$t_p = 0\text{ s}$	317.5°C	322.3°C	345.6°C	369.6°C	399.5°C	427.9°C
$t_p = 10\text{ s}$	320.0°C	324.7°C	349.0°C	372.3°C	402.2°C	432.0°C
$t_p = 60\text{ s}$	319.3°C	324.0°C	347.7°C	370.1°C	400.0°C	430.5°C

Table C.6: Average bottom heat block temperature during consolidation phase per process setting.

	$T_p = 315\text{ }^{\circ}\text{C}$	$T_p = 320\text{ }^{\circ}\text{C}$	$T_p = 345\text{ }^{\circ}\text{C}$	$T_p = 370\text{ }^{\circ}\text{C}$	$T_p = 400\text{ }^{\circ}\text{C}$	$T_p = 430\text{ }^{\circ}\text{C}$
$t_p = 0\text{ s}$	323.0 $^{\circ}\text{C}$	321.8 $^{\circ}\text{C}$	343.4 $^{\circ}\text{C}$	364.1 $^{\circ}\text{C}$	411.9 $^{\circ}\text{C}$	439.5 $^{\circ}\text{C}$
$t_p = 10\text{ s}$	324.1 $^{\circ}\text{C}$	328.9 $^{\circ}\text{C}$	352.4 $^{\circ}\text{C}$	373.0 $^{\circ}\text{C}$	396.9 $^{\circ}\text{C}$	427.7 $^{\circ}\text{C}$
$t_p = 60\text{ s}$	320.5 $^{\circ}\text{C}$	324.5 $^{\circ}\text{C}$	342.6 $^{\circ}\text{C}$	365.9 $^{\circ}\text{C}$	395.5 $^{\circ}\text{C}$	426.1 $^{\circ}\text{C}$

Table C.7: Average heat block temperature (top & bottom) during consolidation phase per process setting.

	$T_p = 315\text{ }^{\circ}\text{C}$	$T_p = 320\text{ }^{\circ}\text{C}$	$T_p = 345\text{ }^{\circ}\text{C}$	$T_p = 370\text{ }^{\circ}\text{C}$	$T_p = 400\text{ }^{\circ}\text{C}$	$T_p = 430\text{ }^{\circ}\text{C}$
$t_p = 0\text{ s}$	320.2 $^{\circ}\text{C}$	322.1 $^{\circ}\text{C}$	344.5 $^{\circ}\text{C}$	366.9 $^{\circ}\text{C}$	405.7 $^{\circ}\text{C}$	433.7 $^{\circ}\text{C}$
$t_p = 10\text{ s}$	322.0 $^{\circ}\text{C}$	326.8 $^{\circ}\text{C}$	350.7 $^{\circ}\text{C}$	372.6 $^{\circ}\text{C}$	399.5 $^{\circ}\text{C}$	429.8 $^{\circ}\text{C}$
$t_p = 60\text{ s}$	319.9 $^{\circ}\text{C}$	324.2 $^{\circ}\text{C}$	345.2 $^{\circ}\text{C}$	368.0 $^{\circ}\text{C}$	397.7 $^{\circ}\text{C}$	428.3 $^{\circ}\text{C}$

Table C.8: Average weld interface temperature during consolidation phase per process setting.

	$T_p = 315\text{ }^{\circ}\text{C}$	$T_p = 320\text{ }^{\circ}\text{C}$	$T_p = 345\text{ }^{\circ}\text{C}$	$T_p = 370\text{ }^{\circ}\text{C}$	$T_p = 400\text{ }^{\circ}\text{C}$	$T_p = 430\text{ }^{\circ}\text{C}$
$t_p = 0\text{ s}$	304.4 $^{\circ}\text{C}$	307.0 $^{\circ}\text{C}$	326.5 $^{\circ}\text{C}$	351.4 $^{\circ}\text{C}$	381.7 $^{\circ}\text{C}$	409.7 $^{\circ}\text{C}$
$t_p = 10\text{ s}$	289.8 $^{\circ}\text{C}$	293.9 $^{\circ}\text{C}$	317.8 $^{\circ}\text{C}$	340.3 $^{\circ}\text{C}$	370.8 $^{\circ}\text{C}$	397.5 $^{\circ}\text{C}$
$t_p = 60\text{ s}$	297.5 $^{\circ}\text{C}$	301.9 $^{\circ}\text{C}$	326.1 $^{\circ}\text{C}$	348.0 $^{\circ}\text{C}$	375.6 $^{\circ}\text{C}$	404.5 $^{\circ}\text{C}$

Table C.9: Average temperature difference between the weld interface and heated welding heads during consolidation phase per process setting.

	$T_p = 315\text{ }^{\circ}\text{C}$	$T_p = 320\text{ }^{\circ}\text{C}$	$T_p = 345\text{ }^{\circ}\text{C}$	$T_p = 370\text{ }^{\circ}\text{C}$	$T_p = 400\text{ }^{\circ}\text{C}$	$T_p = 430\text{ }^{\circ}\text{C}$
$t_p = 0\text{ s}$	15.8 $^{\circ}\text{C}$	15.0 $^{\circ}\text{C}$	18.0 $^{\circ}\text{C}$	15.5 $^{\circ}\text{C}$	24.0 $^{\circ}\text{C}$	24.0 $^{\circ}\text{C}$
$t_p = 10\text{ s}$	32.3 $^{\circ}\text{C}$	32.9 $^{\circ}\text{C}$	33.0 $^{\circ}\text{C}$	32.4 $^{\circ}\text{C}$	28.8 $^{\circ}\text{C}$	32.3 $^{\circ}\text{C}$
$t_p = 60\text{ s}$	22.4 $^{\circ}\text{C}$	22.4 $^{\circ}\text{C}$	19.0 $^{\circ}\text{C}$	20.0 $^{\circ}\text{C}$	22.2 $^{\circ}\text{C}$	23.8 $^{\circ}\text{C}$

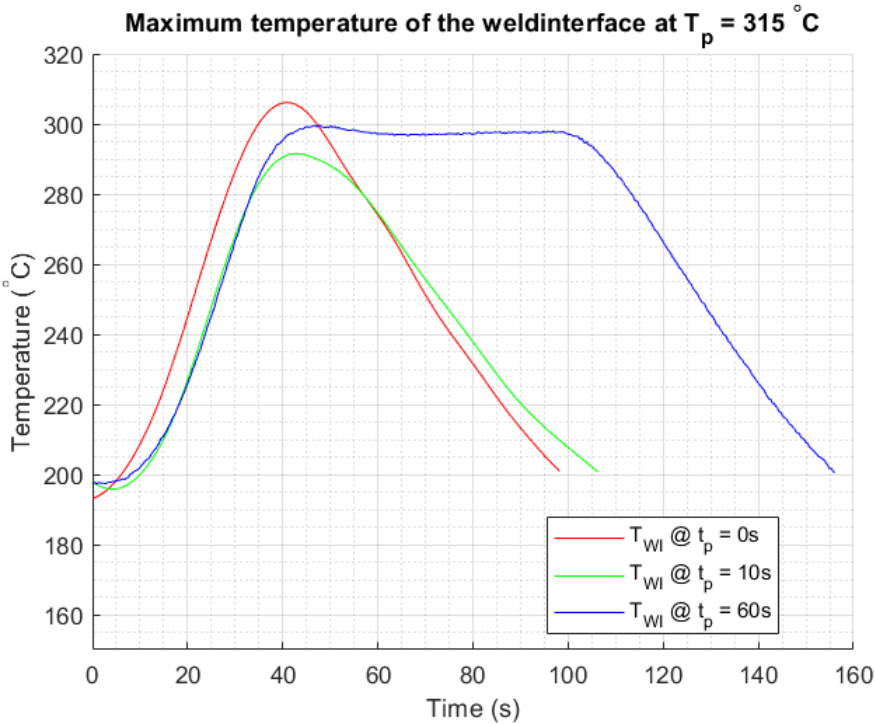


Figure C.7: The difference in measured temperature at the interface.

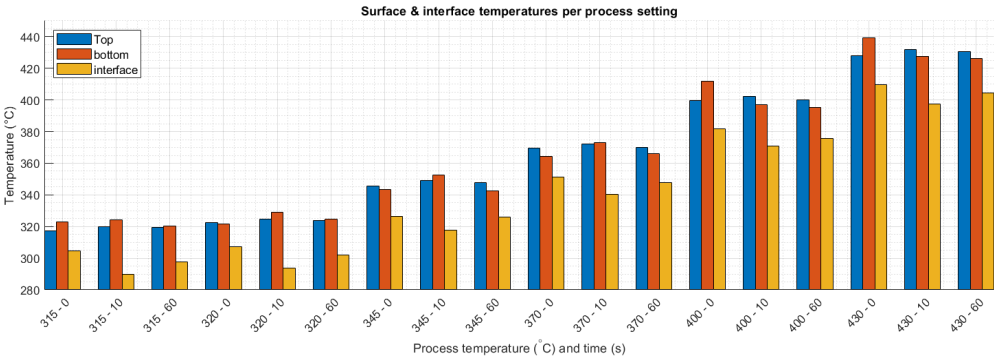


Figure C.8: Average heated welding head surfaces and interface surface temperature during welding processes.

Average Welding head and weld interface temperature difference per t_p setting

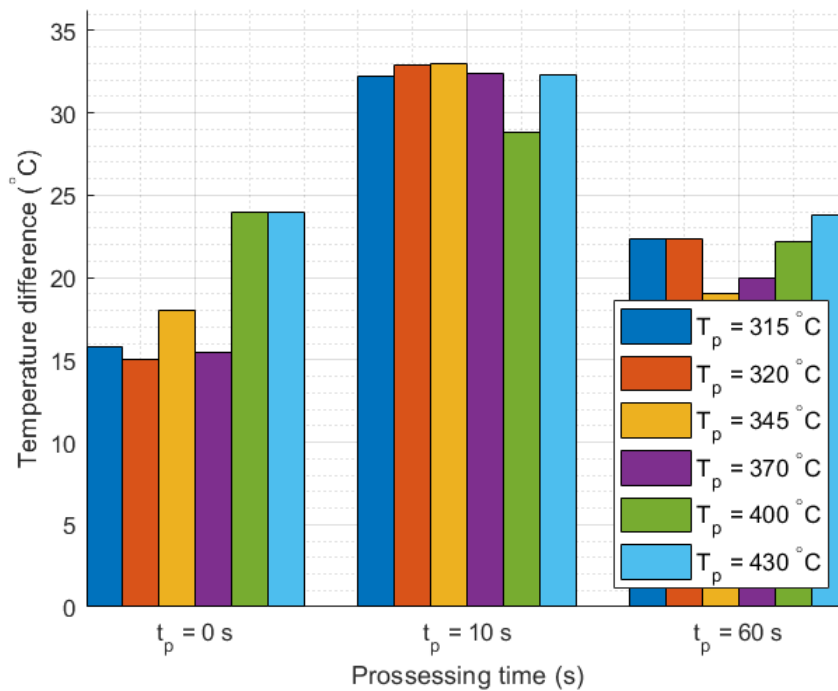


Figure C.9: Temperature difference of the heated welding head surface and the weld interface per process setting.

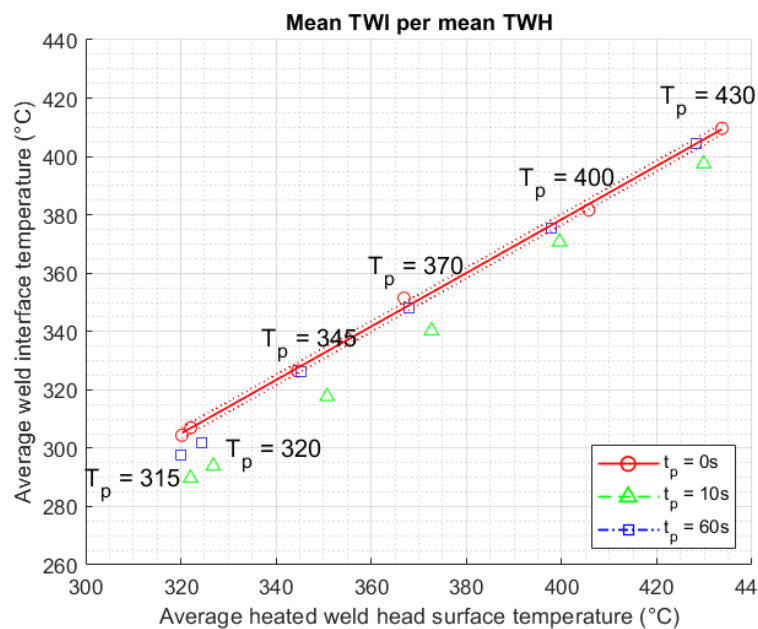


Figure C.10: Averaged weld interface temperature per averaged heated welding head surfaces during the consolidation phase with the average line per process time = 0 s. A difference of 18.718 ± 4.2092 °C.

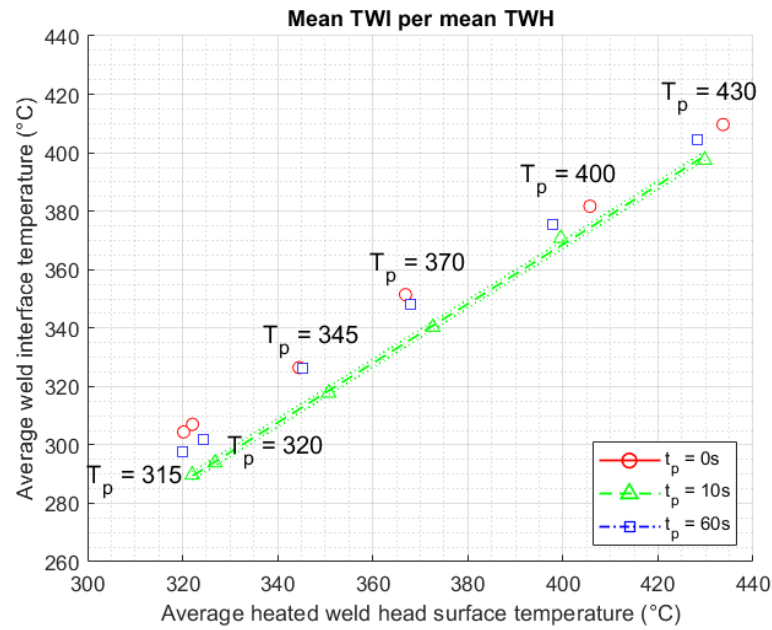


Figure C.11: Averaged weld interface temperature per averaged heated welding head surfaces during the consolidation phase with the average line per process time = 10 s. A difference of 31.932 ± 1.5795 °C.

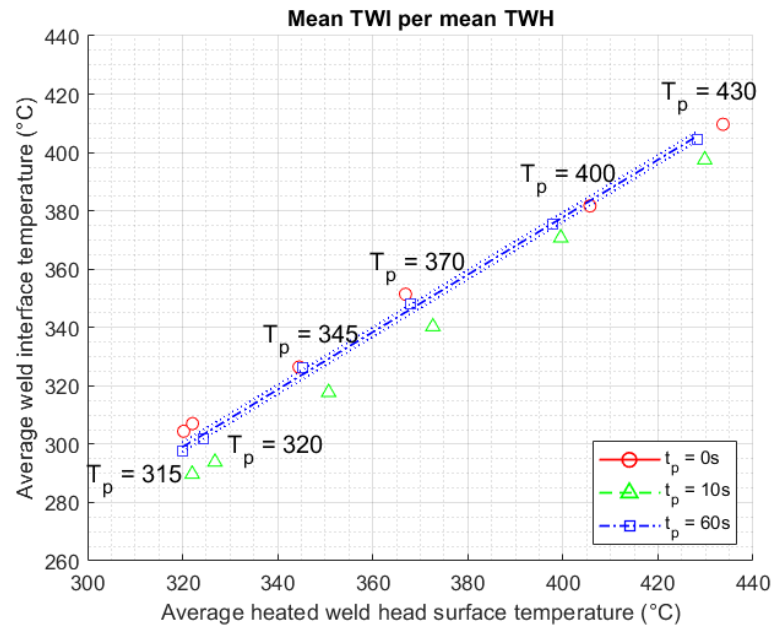


Figure C.12: Averaged weld interface temperature per averaged heated welding head surfaces during the consolidation phase with the average line per process time = 60 s. A difference of 21.624 ± 1.766 °C.

C.1.5 Additional conclusions on the process analysis

- During consolidation, the temperature deviation of the outside surface to the set process temperature is within the range of ± 5 °C.
- The measured weld interface temperatures are 15 to 25 °C lower than those of the outside surfaces for process temperatures ranging from 315 to 430 °C.
- The consolidation time of the weld interface differs from that of the welding heads.
- In the bottom welding head, the cooling system affects the heated surface. Due to the heat sink, a lower heating rate and temperature at the outer surface is established, causing a possibility to extend the dwell time of the process.

C.2 Bottom surface analysis

Figure C.13 displays the weld marks on the bottom surface for increasing temperatures at a constant processing time of 0s.

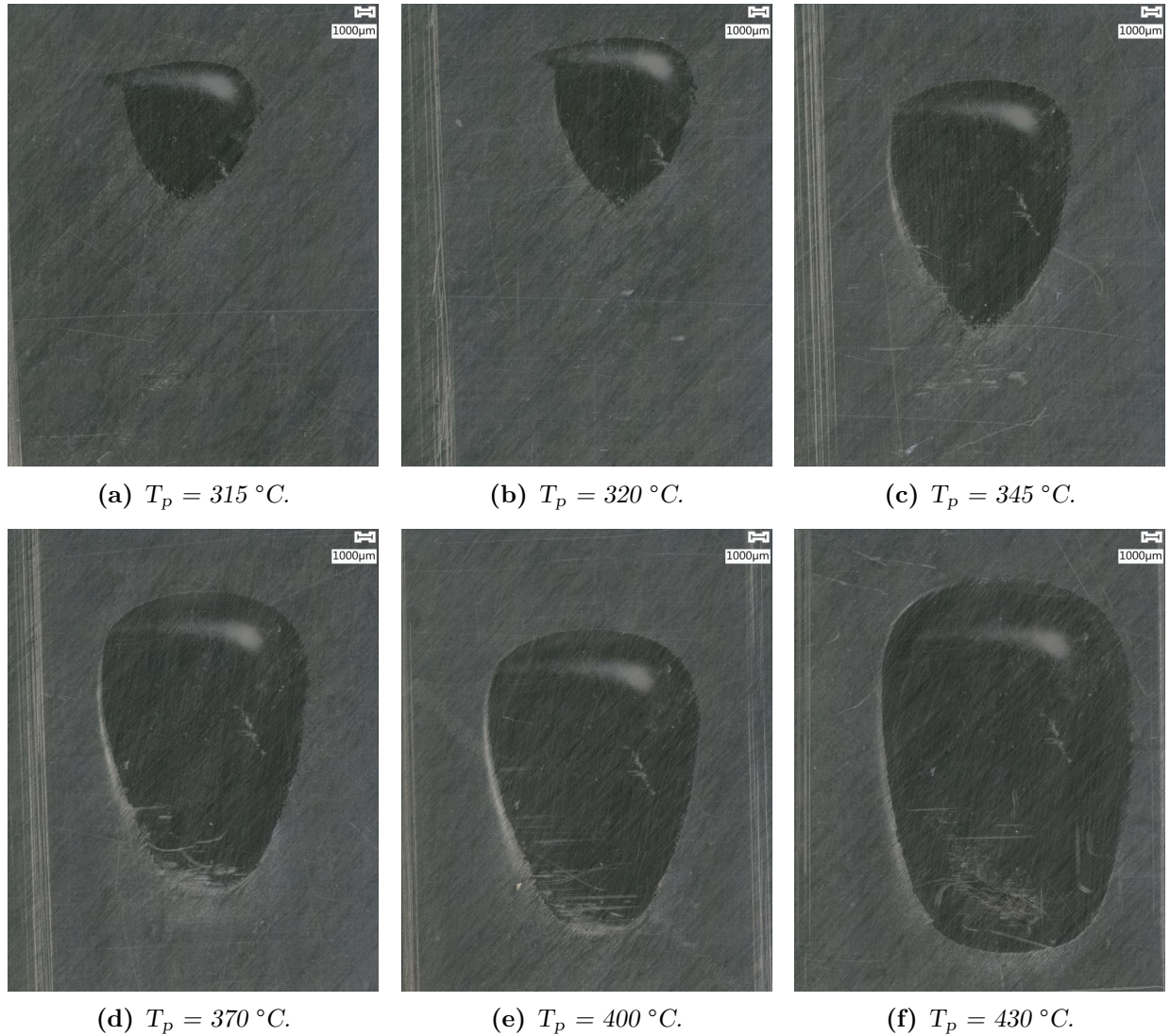


Figure C.13: Bottom weld surfaces at $t_p = 0\text{ s}$.

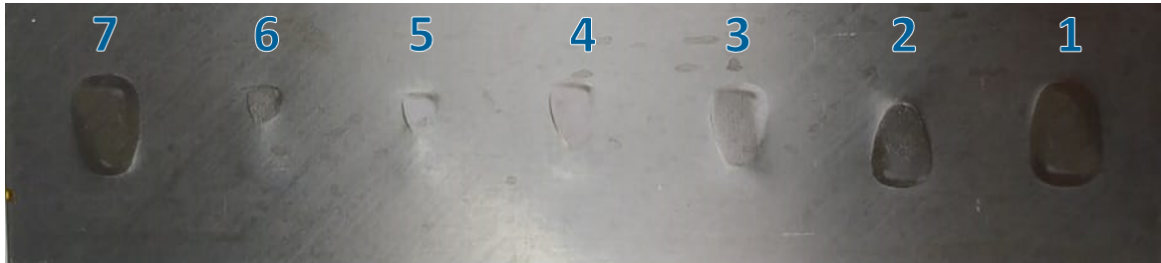
Figure C.13 illustrates once again the growth of the weld mark over an increasing processing temperature with a constant process time. This time of the bottom side of the weld.

Comparing Figure 4.4 with Figure C.13, differences in the weld mark shape are noticeable. In Figure 4.4 the marks consist of either two separate areas or one single rounded rectangle, while the marks in Figure C.13 consist of a single droplet-shaped area.

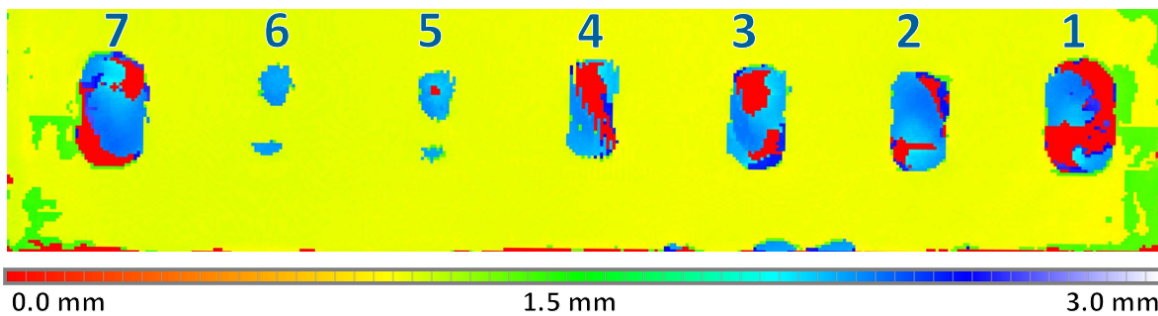
C.2.1 Additional conclusions on the surface inspection.

- The weld mark shape on the top and bottom surfaces differs.
- The bottom surfaces contain an indent in the surface. (Also visible in the microscopy images.)

C.3 Ultrasound observation

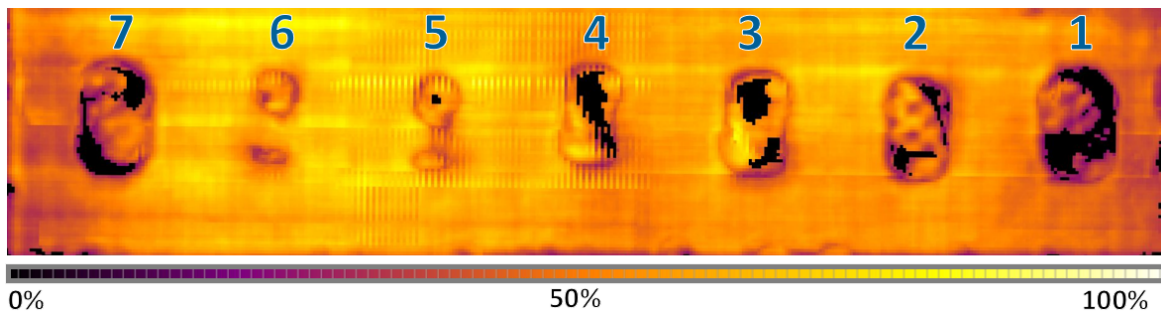


(a) Photograph of the bottom showing the visual weld marks.



(b) Depth ultrasound scan.

The colours indicate at which distance the ultrasound signal is received back. In the welds, blue is at approximately 2.0 to 2.5 mm, green at 1.1 to 1.6 mm, yellow 0.9 to 1.0 mm, and red 0.0 to 0.3 mm.



(c) Ultrasound dampening scan. White areas mean that 100 % of the signal is received back (not damped), darker-coloured means that it is damped, and black means that 0% of the ultrasound signal is received back.

Figure C.14: Photograph and ultrasound scans of the bottom side of sample plate 25. $t_p = 0s$, from left to right (samples 1 to 7) T_p values: 430 °C, 400 °C, 370 °C, 345 °C, 320 °C, 315 °C, 430 °C. Samples 1 & 2 are up-side-down compared with the other weld-samples.

The black areas of the dampening scans are similar to the red areas in the depth scans. Therefore, Ultrasound signal that is dampend is dampend by the surface indicating a surface defect or no connection between the signal transmitter and the surface. Indicating that the surface is too rough to get a sufficient signal back to say something about the composition of the weld.

The measured thickness of the samples is more than measured. the sample thickness is approximately

2.6 mm thick while the two laminates are 2.4 mm thick, and with the impression of the welding head on the weld even less. In addition, the “voids” have a back wall deeper than the weld interface, from the top surface as well as from the bottom surface. Therefore, the measured weld depth is too deep and the set **speed of sound** should be lowered.

The edges of all welds are darker and display therefore dampening of the weld. Indicating that there is dampening in the material, in other words potential voids.

C.4 Cross-sectional area inspection

Some samples ($T_p = 345, 370, 400, 430\text{ }^{\circ}\text{C}$) were cut open over the length or width of the weld. The cross-sections are inspected on their structure and impurities using microscopes so statements about the weld quality can be made.



Figure C.15: *Cross-sectional-area over the length of a weld.*

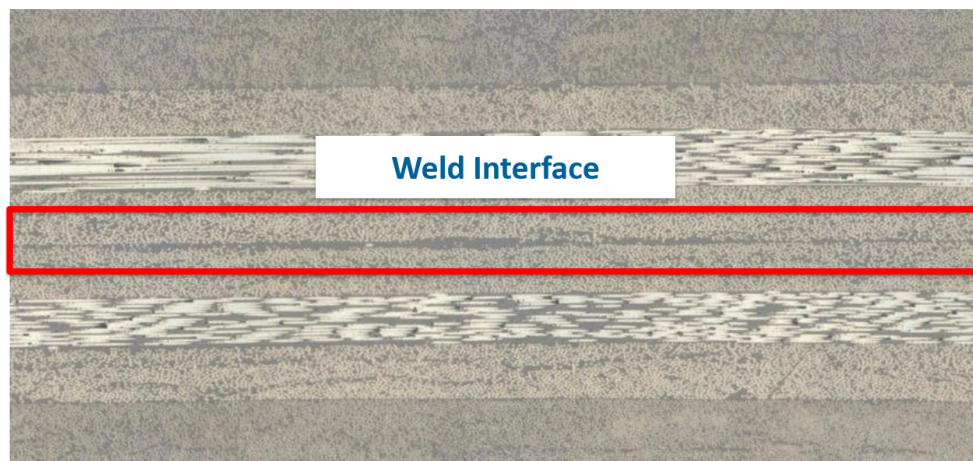


Figure C.16: *Middle of Section of the weld displaying the matrix line between the weld.*

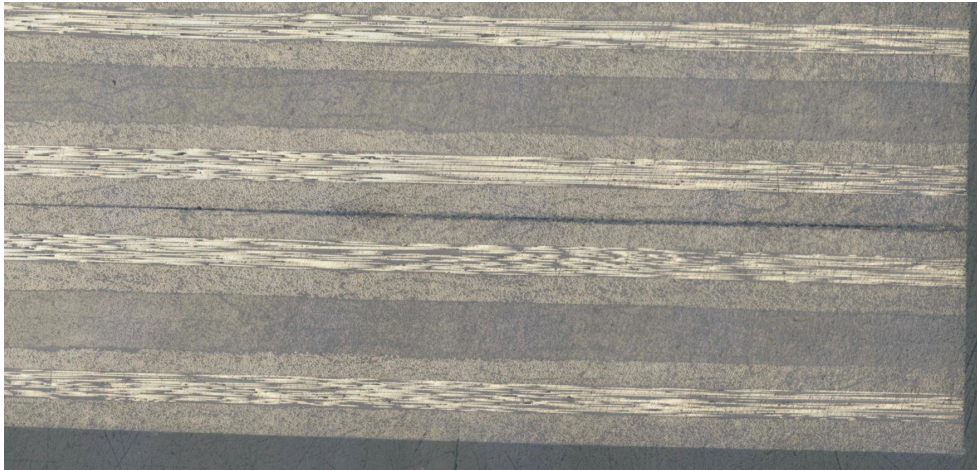


Figure C.17: *Edge section of the weld displaying the opening of the material.*

Figure C.15 showcases the cross-section over the length of a weld. Figures C.16 and C.17 are close-ups of the sample.

In Figure C.15 the laminate is not fully straight. The laminates have a small bent at the top left of the image and the bottom right.

Looking at Figure C.16 the section the layup of the composite layup of the two laminates is visible. The weld interface between the laminates is visible. It is a thick line of matrix material in between the laminates. The line is not everywhere even thick.

Looking at the edge of the weld, Figure C.17, the distance between the two laminates increases towards the rightside of the image. The weld interface consists of more matrix material. And toward the edge black spots are visible on the weld interface.

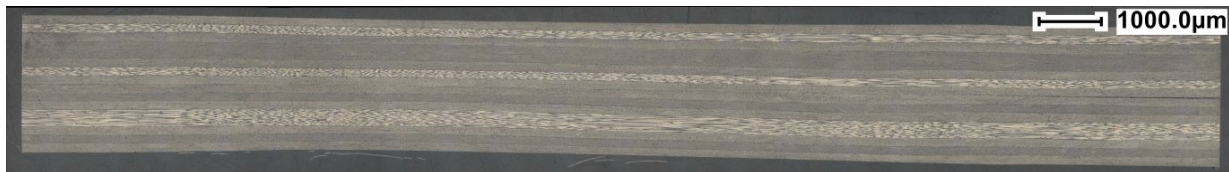


Figure C.18: *Cross-sectional-area over the width of a weld.*

Figure C.18 displays a crosssectional sample over the width of the weld. Here again, the laminates are not fully horizontally straight. A small bend over the weld is visible. The weld interface and edges over the width are similar as that of the length sample, Figures C.16 & C.17.

No, voids were observed in the cross-sectional cuts. Only less and more matrix-rich regions. The quality of the samples should be consistent, therefore.

C.5 Weld strength evaluation

Figures C.19a & C.19b display shear forces at a respective claw displacement of the welds per process parameter setting, Figure C.19a for all samples and Figure C.19b displays the average. All the averages come down to a similar stiffness. $T_p = 315$ & 320 °C samples have a small maximal shear force compared to the other samples.

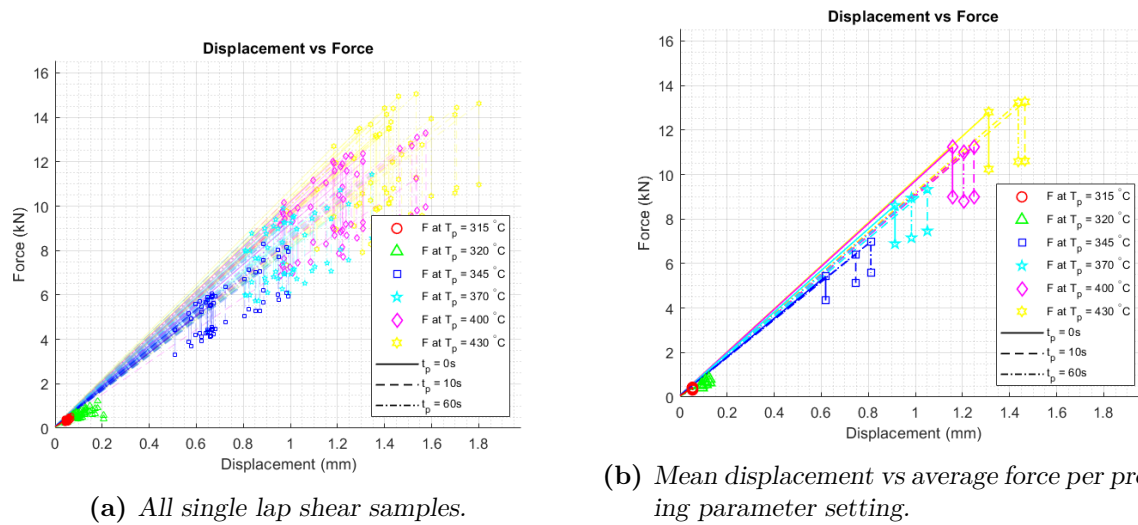


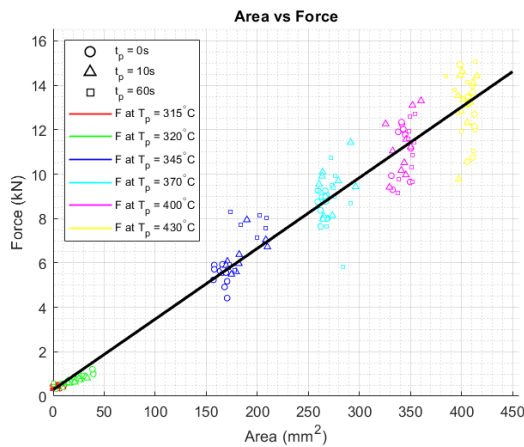
Figure C.19: Displacement vs shear force per processing parameter setting.

Table C.10: Clamp displacement, yield shear force, and Shear strength per process temperature and time.

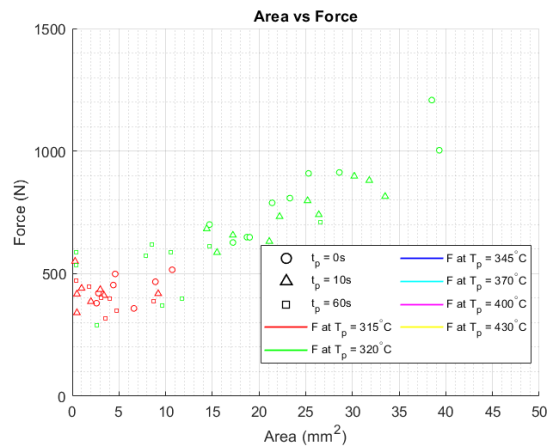
T_p ($^\circ\text{C}$)	t_p (s)	ΔL (mm)	S_y (kN)	A (mm^2)	τ_y (MPa)
315	0	0.053 ± 0.006	0.44 ± 0.06	5.8 ± 3.1	90.0 ± 43
315	10	0.051 ± 0.009	0.42 ± 0.06	2.5 ± 3.0	550.0 ± 584
315	60	0.053 ± 0.006	0.4 ± 0.05	3.7 ± 2.6	270.0 ± 406
320	0	0.12 ± 0.03	0.8 ± 0.19	24.6 ± 8.5	34.9 ± 5.6
320	10	0.11 ± 0.03	0.7 ± 0.09	23.0 ± 6.8	31.5 ± 8.6
320	60	0.09 ± 0.05	0.54 ± 0.1	9.0 ± 8.2	320.0 ± 526
345	0	0.62 ± 0.05	5.4 ± 0.5	164.7 ± 5.3	33.0 ± 3.5
345	10	0.7 ± 0.13	6.4 ± 0.8	187.5 ± 15.9	34.2 ± 3.1
345	60	0.8 ± 0.14	6.9 ± 1.1	186.4 ± 16.7	37.4 ± 4.8
370	0	0.91 ± 0.08	8.6 ± 0.6	264.5 ± 3.6	32.6 ± 2.3
370	10	1.0 ± 0.17	9.3 ± 1.1	272.5 ± 12.6	34.2 ± 3.6
370	60	1.0 ± 0.16	8.9 ± 1.4	274.7 ± 8.6	32.6 ± 5.3
400	0	1.2 ± 0.12	11.2 ± 1.2	341.6 ± 6.3	32.9 ± 3.3
400	10	1.2 ± 0.23	11.3 ± 1.3	342.7 ± 10.8	32.8 ± 3.5
400	60	1.2 ± 0.19	11.0 ± 1.3	348.5 ± 5.8	31.5 ± 3.3
430	0	1.3 ± 0.10	12.8 ± 1.3	407.7 ± 4.4	31.4 ± 3.5
430	10	1.5 ± 0.24	13.3 ± 1.4	403.7 ± 6.4	32.8 ± 3.4
430	60	1.4 ± 0.12	13.2 ± 1.3	403.3 ± 10.3	32.8 ± 3.6

C.5.1 Shear strength determination

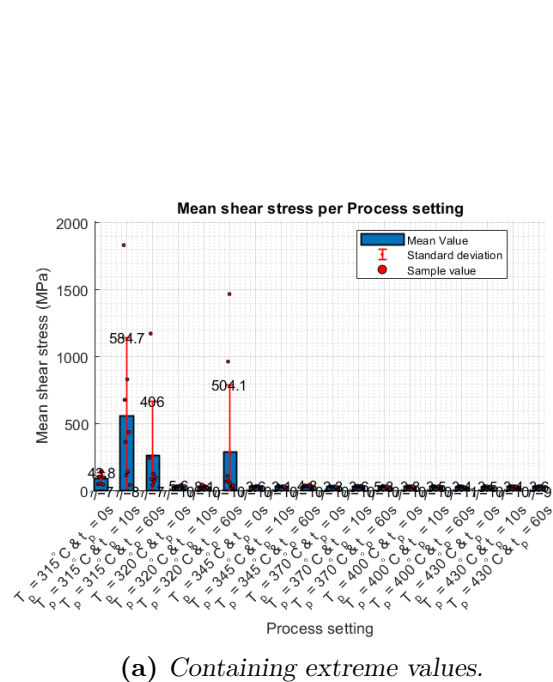
Figure C.20a Displays the shear force at failure per unit area, similar as Figure 4.9. The slope is not going through 0.0. However, it shows that the weld area is linearly proportional to the maximal shear force. A zero-value for the weld area would suggest a zero value for the force, however this is not the case. Weld areas of with approximately 0 mm^2 have a shear force of approximately 0.5 kN , as displayed in Figure C.20b. In the first instance, this can be explained by clamping the samples a pre-load of 200 N was observed at which some weld samples with a process temperature of 315°C and 320°C failed. Removing samples with a low shear force and a potentially large shear area from the data set to calculate the slope. Furthermore, kissing bonds can be produced during welding. The weld or diffused areas can be so small that it can not be observed. Producing a small area, but able to withstand a small shear force. Furthermore, there is a noticeable difference in the sample set produced at a process temperature of 345°C . Between the process time of 0 and 60s , there is a clear difference. It is unclear what caused this deviation.



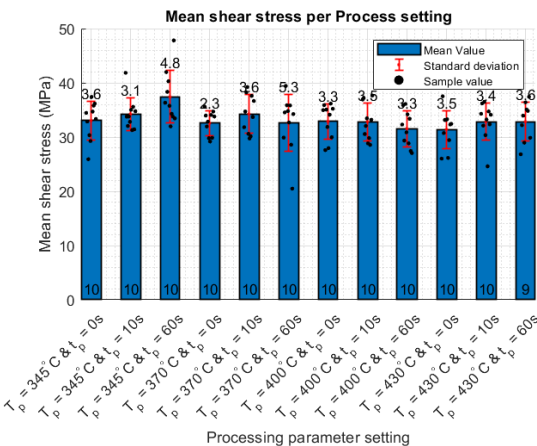
(a) Weld area vs. Shear force at failure.



(b) Area vs force for $T_p = 315$ and 320°C .



(a) Containing extreme values.



(b) Shear strength vs. process setting. The (extreme) values of $T_p = 315^\circ\text{C}$ and 320°C are removed. The blue bar displays the mean shear strength value, the red bar the standard deviation with it named there above, and the black dots the various calculated shear strengths. Per bare also the sample size per setting is given.

Figure C.21: Shear strength vs. process setting.

Figure C.21b displays a bar plot of the shear strengths per processing parameter setting. All setting have a mean value between 30 and 40 MPa. The standard deviation is in the same order of magnitude, thereby resulting in a coefficient of variance is roughly 10 %. Most samples lie around their mean value, however, there are some outliers.

As said in Section 4.2.3 the 315 and 320 °C shear strengths were removed since these gave no realistic shear strengths, As Figure C.21a

C.6 Fractography

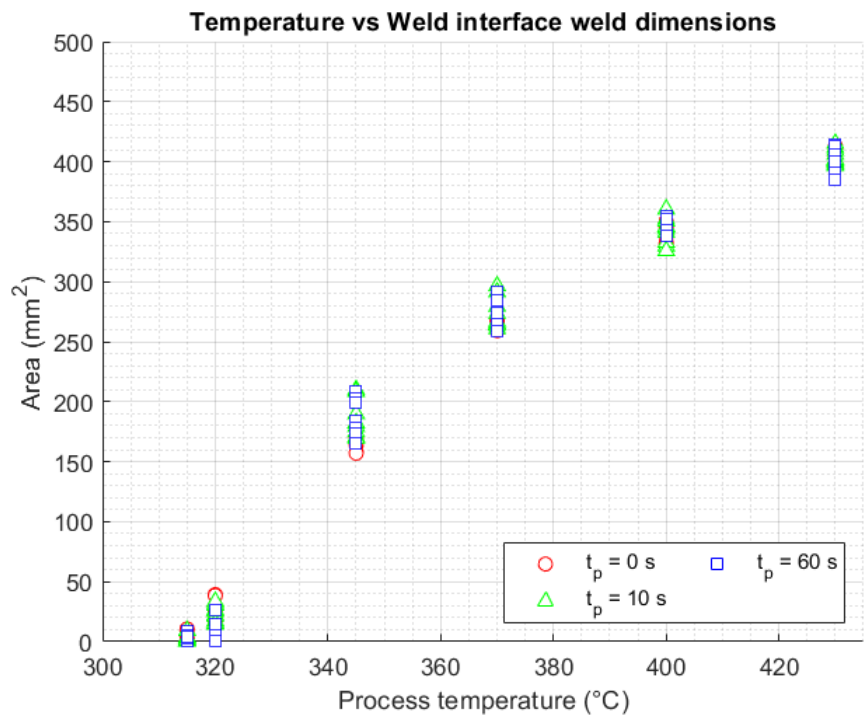


Figure C.22: Scatter plot of the weld area at the weld interface vs. T_p .

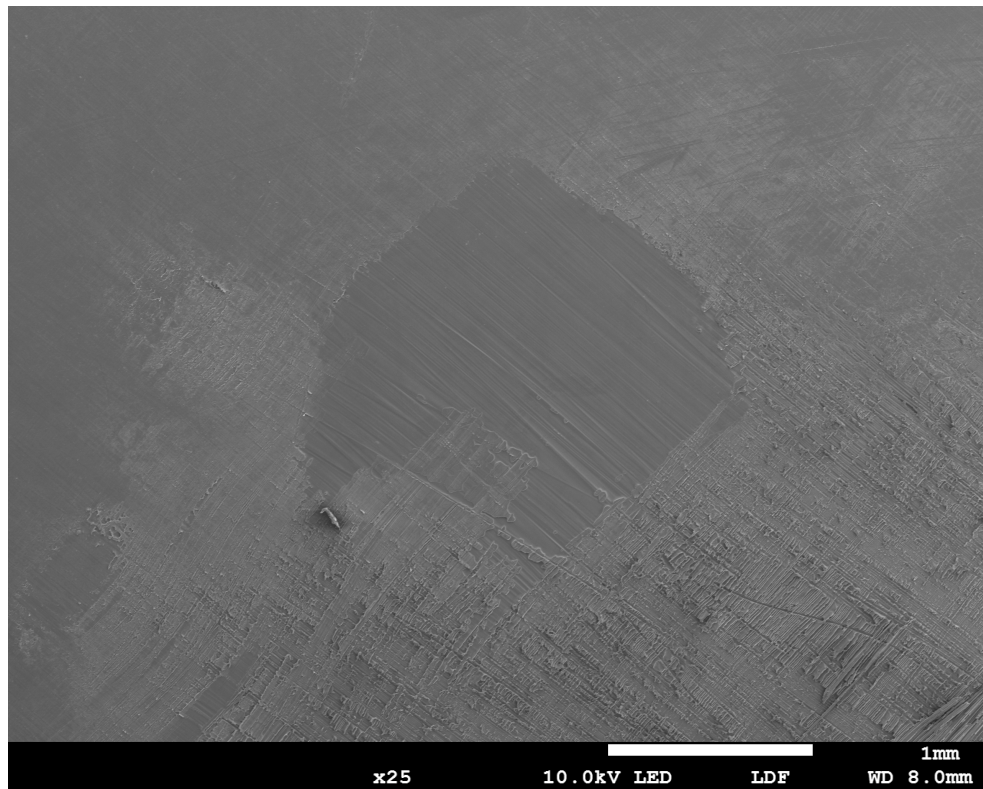


Figure C.23: SEM image of the void.

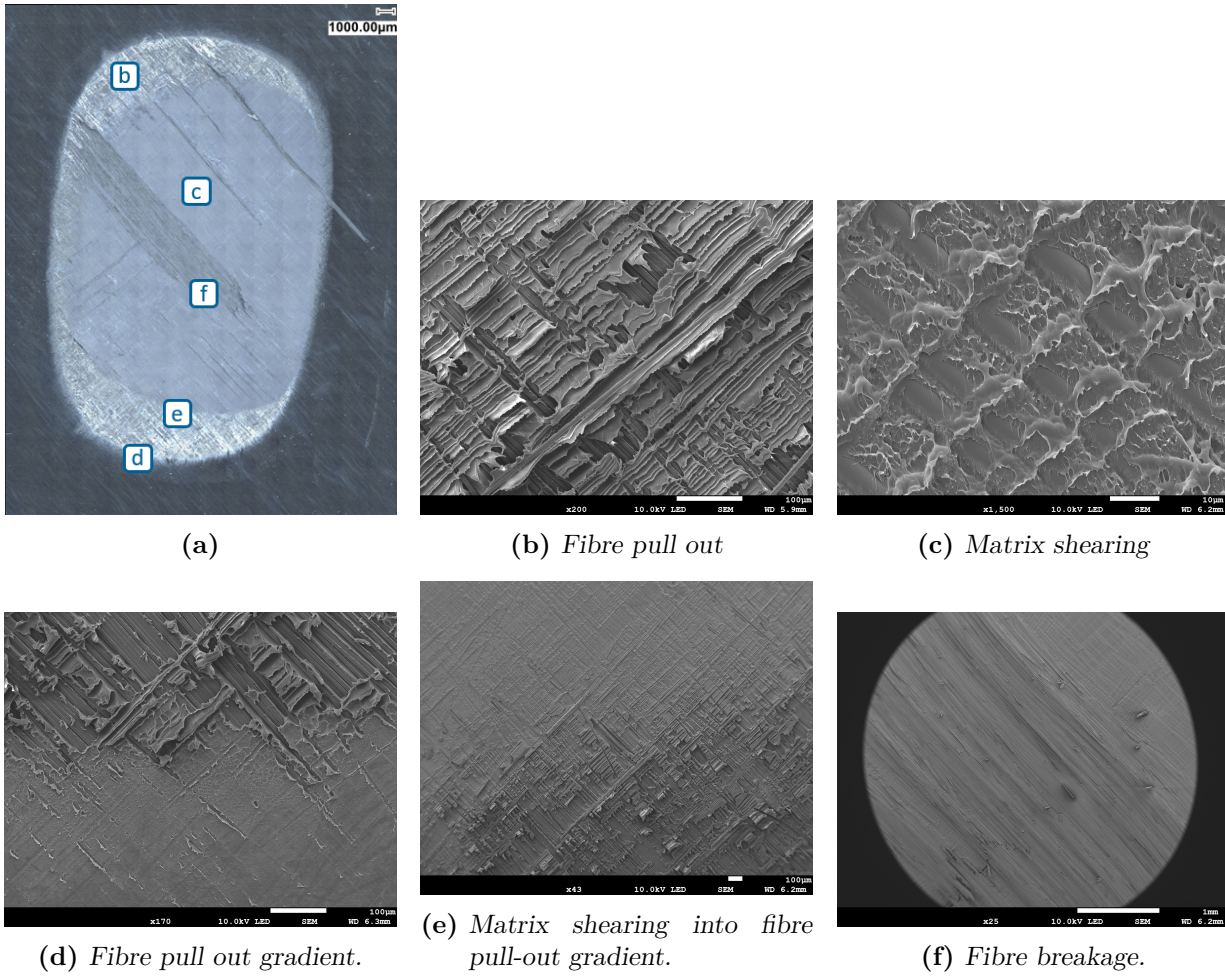


Figure C.24: SEM images of the weld interface of a sample produced at $t_p = 0s$ and $T_p = 430\text{ }^{\circ}\text{C}$.

C.7 DSC inspection

Material crystallinity

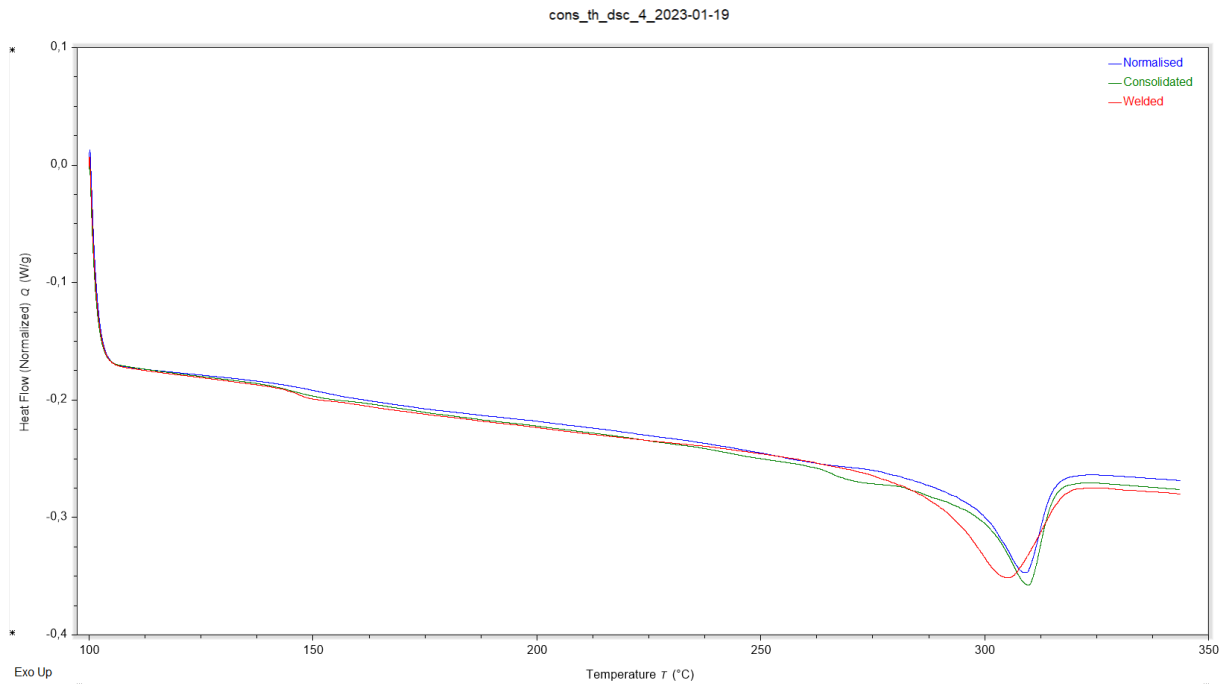


Figure C.25: The temperature path of a normalised, consolidated and welded sample. X-axis shows the temperature and the y-axis normalised heat flow.

To analyse the crystallinity, analyse the heat up of the material. The Tg changes a bit but no cold crystallisation. All data in the Appendix. The Tm is lowered a bit so smaller crystals are created in the weld. the material is not homogenous. Therefore, the used cooling rate did not create too much amorphous structures and so the cooling rate is not too high.

Glass transition temperature shifts.

Table C.11: Measured glass transition temperatures.

Sample	Baseline	Consolidated	315-0	315-10	315-60	345-0	345-10	345-60	430-0	430-10	430-60
1	150.7 °C	143.9 °C	148.6 °C	148.6 °C	148.72 °C	145.3 °C	144.2 °C	150.6 °C	147 °C	148.8 °C	145.7 °C
2	151 °C	144.3 °C	149.2 °C	150 °C	143.2 °C	145.6 °C	145.9 °C	145 °C	146.2 °C	150.3 °C	145.2 °C
3	150.1 °C	144.5 °C		150.4 °C			150.9 °C				146.2 °C
4	149.8 °C			149.9 °C			153.5 °C				146.1 °C
Mean	150.4 °C	144.2 °C	148.9 °C	149.7 °C 5	146.0 °C	145.5 °C	148.6 °C	147.8 °C	146.6 °C	149.6 °C	145.8 °C

Melting temperature shifts.

Table C.12: Measured melting temperatures.

Sample	Baseline	Consolidated	315-0	315-10	315-60	345-0	345-10	345-60	430-0	430-10	430-60
1	309 °C °C	309.3 °C	310.4 °C	310.2 °C	310.7 °C	304.8 °C	305.4 °C	304.8 °C	306.1 °C	304.6 °C	303.8 °C
2	308.5 °C	310.2 °C	310.1 °C	310.1 °C	313.7 °C	306 °C	304.4 °C	305.3 °C	304.3 °C	304.7 °C	304.8 °C
3	309.4 °C	309.5 °C		309.8 °C			305 °C				306.2 °C
4	308.5 °C			310.9 °C			305.4 °C				305 °C
Mean	308.9 °C	309.7 °C	310.3 °C	310.3 °C	312.2 °C	305.4 °C	305.1 °C	305.1 °C	305.2 °C	304.7 °C	305.0 °C

Crystallisation temperature degradation.

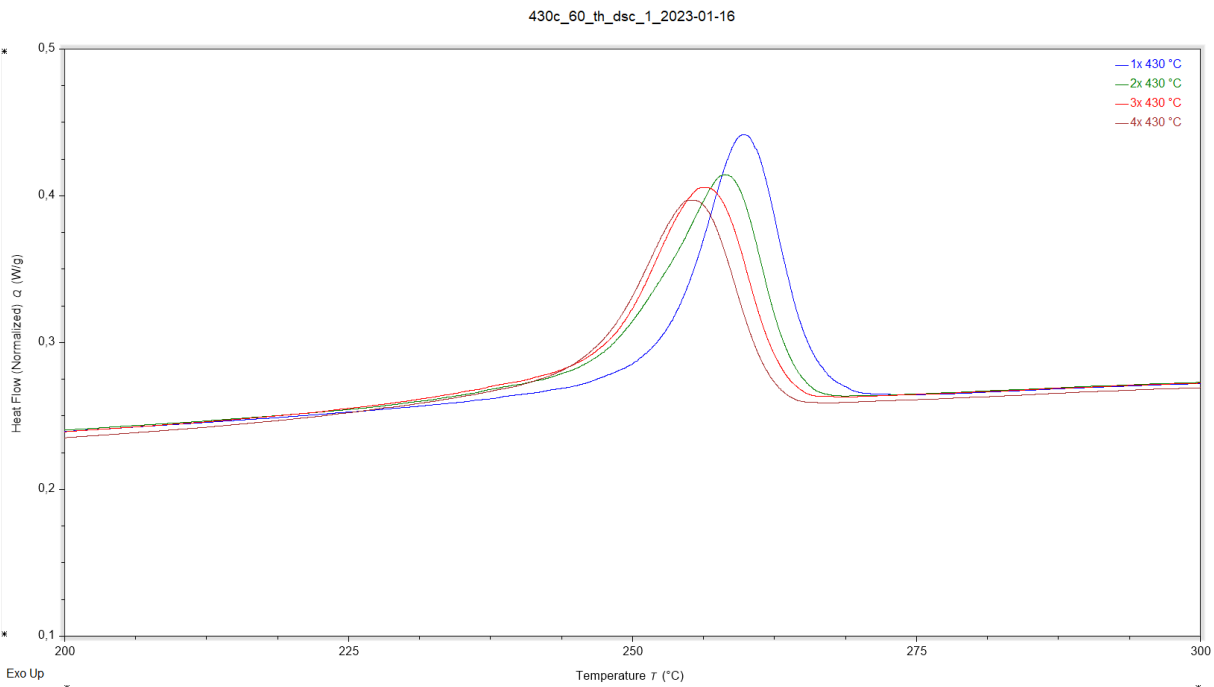


Figure C.26: The temperature path of a normalised, consolidated and welded sample. X-axis shows the temperature and the y-axis normalised heat flow.

Table C.13: Measured crystallisation temperatures

Sample	Consolidated	315-0	315-10	315-60	345-0	345-10	345-60	430-0	430-10	430-60
1	260.5 °C	260.5 °C	260.9 °C	260.3 °C	261 °C	260.4 °C	260.5 °C	259.9 °C	259.9 °C	259.7 °C
2	260.4 °C	260.8 °C	260.8 °C	258.3 °C	260.2 °C	260.6 °C	260.3 °C	260 °C	260 °C	260 °C
3	260.4 °C		260.8 °C			260.4 °C				259.4 °C
4	260.5 °C		260.9 °C			260.4 °C				260.3 °C
Mean	260.45 °C	260.7 °C	260.85 °C	259.3 °C	260.6 °C	260.5 °C	260.4 °C	259.95 °C	259.95 °C	259.9 °C
σ	0.05 °C	0.15 °C	0.05 °C	1 °C	0.4 °C	0.075 °C	0.1 °C	0.05 °C	0.05 °C	0.3 °C

Looking at Table C.13, for all the samples the T_c is approximate 260 °C +
 For some samples of $T_p = 430$ °C this lays a little bit lower at 259.7 °C, 259.4 °C. Figure C.26 displays the

crystallisation peaks of a welded sample at 430 °C and other samples that had 2, 3, and 4 cycles at 430 °C for 5 min. In the further cycles the T_c decreases with 1.5 °C per cycle

In an additional experiment, multiple heat cycles to 430 °C are performed on one sample, revealing further degradation of the crystallisation temperature. These results are depicted in Figure C.27.

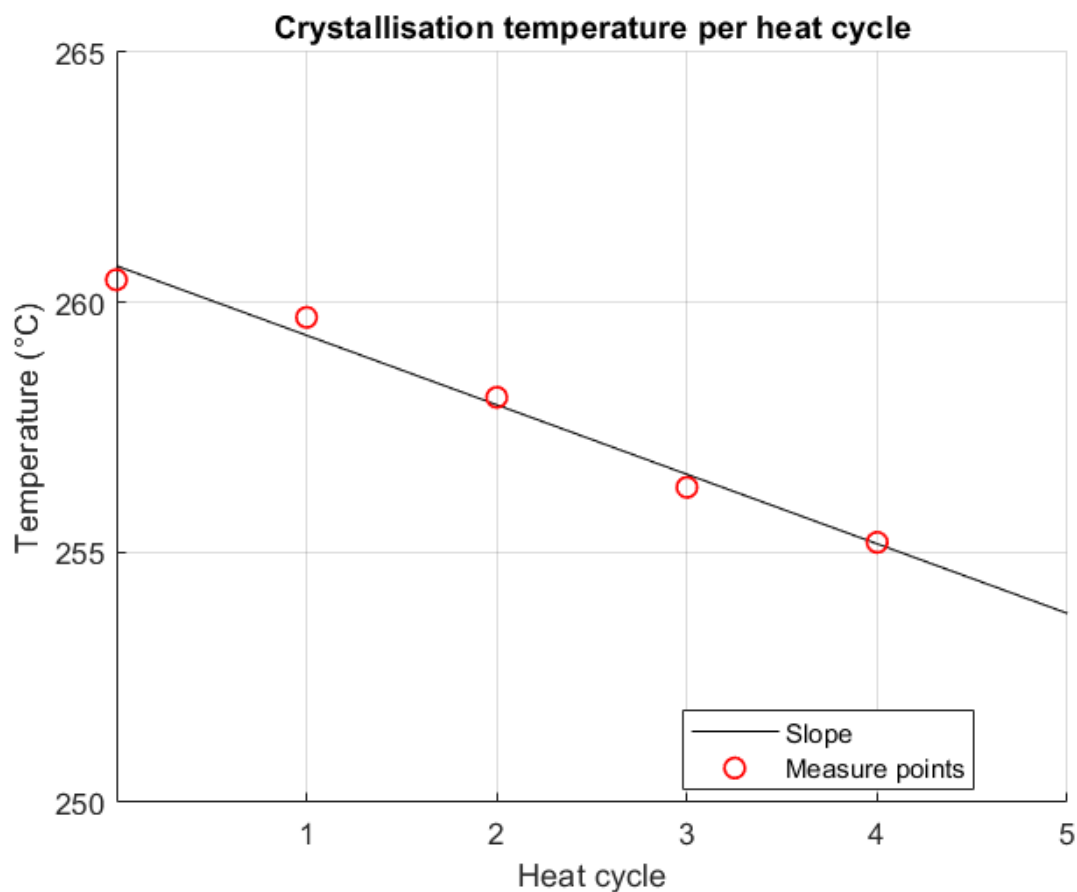
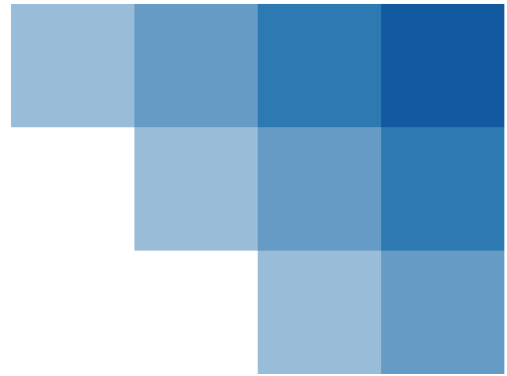


Figure C.27: Measured crystallisation temperatures after various heat cycles to 430 °C, with heat and cooling rates of 10 °C/min and 5-min isothermal breaks.



Appendix D

Recommendations overview

D.1 Further development of conduction welding process

D.1.1 Thermal modeling

- Simulating conduction spot welds in the design space.
- Modeling the conduction sport weld of other welding head designs.

D.1.2 Process parameter testing

For further development, the following material parameters should be (further) evaluated in terms of their effects on the weld quality.

- Temperature;
 - Determine the minimal temperature between 345 and 370 °C at which welds without big voids are produced.
 - Determine the cause of the void formation and minimise this.
- Pressure; in terms of 1 to 10 bars. Preliminary results showed delamination at 1 bar and squeeze out at 10 bars.
- Cooling rate, test the possibility of increasing the cooling rate and minimise the total time of the process.
- Welding speed.

D.1.3 Material parameter testing

For further development, the following material parameters should be evaluated regarding their effects on the weld quality.

- Laminate / ply thickness.
- Ply lay up.
- Fibre material.

- Matrix material.
- Fibre volume fraction.
- Weld configurations, double lap, scarf joint, etc.

D.2 Weld setup optimisation

D.2.1 General

- Make an alignment tool to position the welding head at the right position for a weld.
- Make the setup more safe. For example, a hand can come between the welding heads during the process, leading to skin burns.

D.2.2 Control

- Make it more reliable.
 - The heat and cooling rates differ between processes.
 - The maximum temperature of the welding heads between processes differ with 10 °C (over and undershoots of the process temperature).
 - Due to undershoots of the process temperature, the total process takes more time. See Section D.2.3.
- The cooling phase is potentially dependent on many variables surrounding temperature in winter and summer, blowers in the production hall, the thermal mass of the laminates, etc.
- Add a “Temperature” knob indicating temperatures instead of the material name.
- Weld time and distance turning knob are too sensitive, make it less sensitive.
- First press the setting then be able to change it. For example “weld” or “material” is blinking. By clicking it the value can change.
- The process should stop after reaching T_g and not earlier.

D.2.3 Heat rate decrease

Lastly, a noteworthy observation was made on a welding process with a process time of 0 s at a temperature of 430 °C. Sample 1 in Figure D.1 displays the process in which the phenomenon occurred: during the heating phase, the heat rate of the bottom welding head decreases, first at 30 s and a second time at 70 s. This phenomenon resulted in the delayed achievement of the set point temperature, extending the total process duration. This was the only case of the phenomenon. The cause of the heat rate decrease is unknown, but it seems that the activation of the cooling system of the bottom welding affected the heated surface's heat rate. By activation of the cooling system, T_{CB} decreases and the heating rate of the heated surface decreases. Due to the discrepancy, this data is not used in calculations.

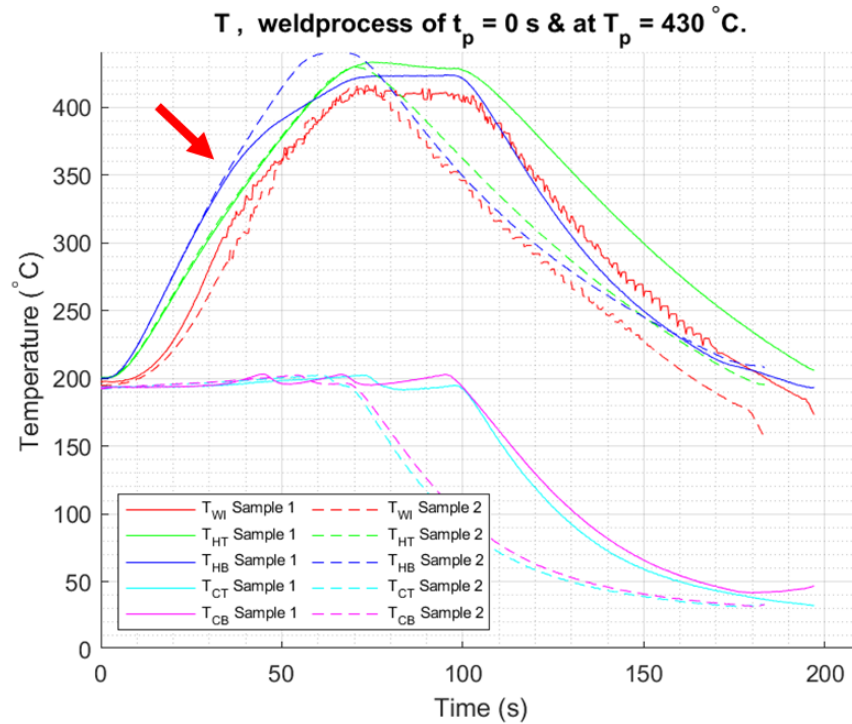


Figure D.1: During the heating phase the heat rate of T_{HB} Sample 1 decreases compared T_{HB} Sample 2. Therefore, the setpoint for T_{HB} Sample 1 is reached just before the 100 s after which cooling is started. 30 s after the cooling of Sample 2 is started.

Inconsistent temperature behaviour is observed in the welding setup for the same process parameter settings, process time = 0 s and process temperature of 430°C . In other temperature data, this inconsistency is not observed. However, during the production of the non-thermocouple samples, the temperature values were not measured, and this phenomenon could have happened during the production of the other samples.

D.2.4 Welding heats

- Reposition the bottom heat block. So the weld shape of bottom and top have a similar weld shape, heat rate and cooling rate.
- Make it possible that 1 x 1 inch welds can be produced so the ASTM standards can be achieved.
- Make a line welding setup with a stronger linear motor and linear stage. Motor deform stage and motor can not make line welds at 3 bar and above, due to too high clamping of the welding heads.

D.3 Experimental method

D.3.1 general

- Determine the heat gradient. Use multiple TCs around the weld at various distances from the "centre". How does this affect the temperature over the interface and cooling rate there.

D.4 Microscopy

- Taking microscope pictures of the welds took a lot of time. Try to make them with a camera and a ruler, it will be less precise however, it saves a lot of time to photograph the welds simultaneously.

D.5 Single lap shear

- Determine the amount of shear versus peel and how this determines the shear strength of the weld.
- Perform Double lap shear tests, to minimise the peel effect observed during SLS
- Use a 1 to 10° layup, Where the fibres are in a tensile direction. This should test the matrix more and cause fewer fibre breakages and interlaying.

