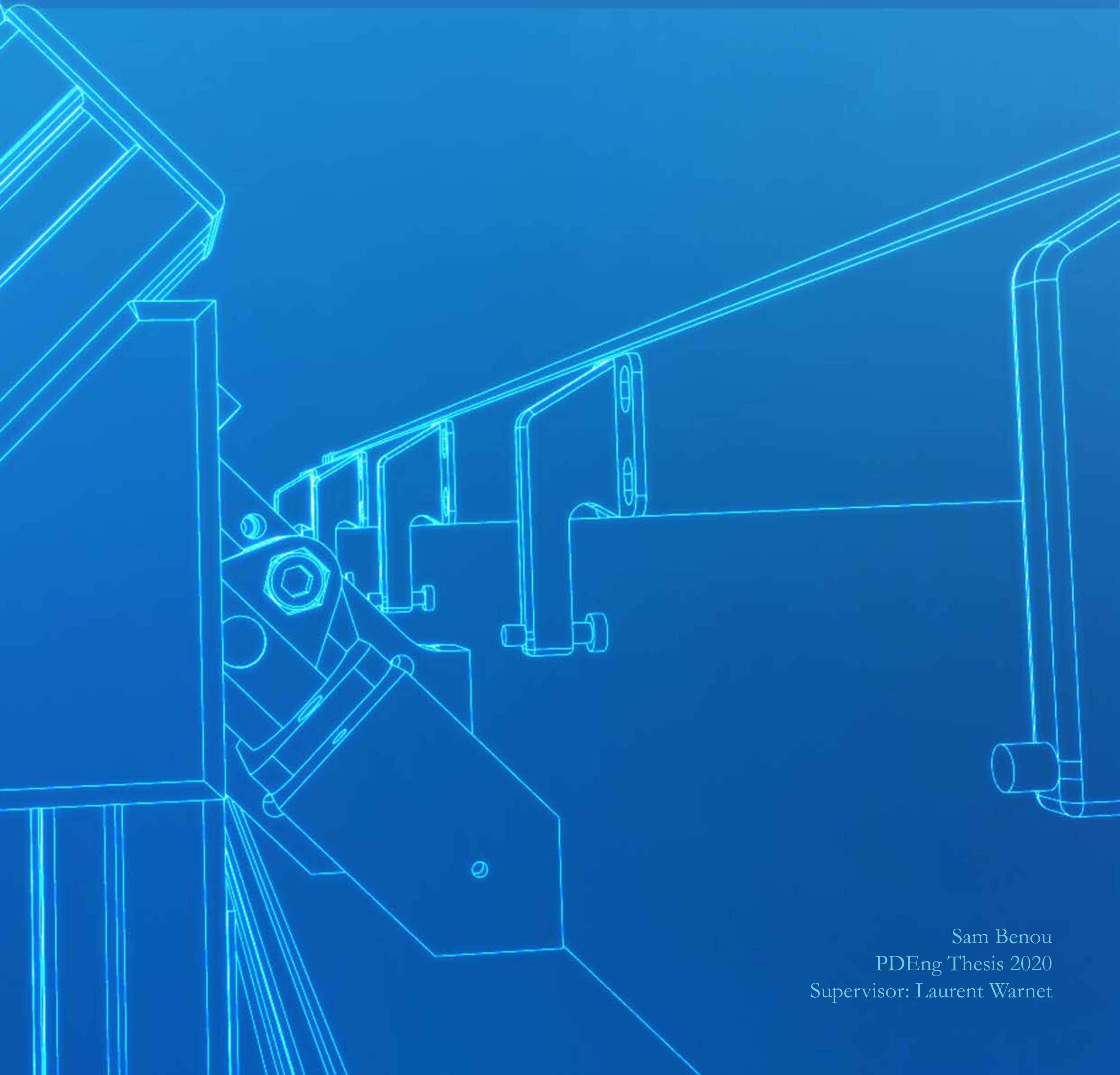
T-CAT

Thermoplastic Composite Automated T-Joints



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Summary

This project builds upon three graduation projects conducted at the University of Twente. The shared goal of these projects is to weld composite T-joints using a local heat input. A T-joint (paragraph Figure 2 on page 3) is nothing more than perpendicular plates that get connected by inserting additional material (metal or polymer) between them. As a starting point, the current manufacturing of these joints out of non-reinforced plastics is used. The manual local welding of non-reinforced plastics is using the matured technique of hot gas heating.

Out of the three studies, the first one was done by Vincent Arzoni in 2015 (Arzoni, 2015). He made the first attempt to automate the hot gas welding process for composite plates. A standard hot gas welding shoe and gun were placed on a tensile tester to lay controlled weld at constant speeds. After these exploring tests, the writers own graduation tried to improve the measurement and control aspect of the welding apparatus with the same standard hot gas welding shoe. The heater of the hot gas was replaced as it was able to reach significantly lower steady state errors and the weld force was measured during welding. Another point of improvement was that the filler wire was driven into the welding volume. This prevented the filler from elongating while being heated.

After the graduation, Mante Sietsma joined the project to help in understanding the heating behavior of the filler and the laminates. Mante developed a model to simulate the heating of the filler and helped in thinking about new ways of designing a welding shoe that could get high performance polymers into melt (Sietsma, 2020).

During this PDEng, four set-ups are build. Three of these set-ups directly follow each other and the graduation set-up in incremental development steps to gain control over identified welding parameters. These parameters came out of literature or self-conducted research. The fourth set-up was build as a sidestep and was purely an exploratory device to get a better understanding of infrared heating and to gain understanding on the influence of laminate and filler temperatures on the resulting weld strength.

The result of this work aims at identifying, measuring and controlling parameters that influence the weld strength. All these parameters relate to the basic welding parameters of heat, pressure and time in some way or another. The challenge lies in the selection of the correct parameters and the ability to design a way of measuring and controlling them.

The final set-up is not perfect, but has made significant progress over the last two years. Not only is it able to produce constant geometry welds with controlled temperatures and material feed rates, it is also able to come much closer to actually measuring the relevant process parameters.

Acknowledgment

First of all I would like to thank the University of Twente and TPRC for making this project possible. Thank you for trusting in the project and giving me the opportunity to learn and build things that interest me. Special thanks to Laurent Warnet for bringing the parties together and putting everything in order for me to do this project. This includes teaching me how to properly engineer and build things in the first place during my graduation project. The same can be said for Erik de Vries and Leo Thiemersma who never said no when I asked for help. Without you guys the set-up would be nothing more than laser cut parts strapped to an Arduino... now we have two Arduinos strapped to something that is indeed worthy of the 'P' in PDEng.

Off course more than two people helped me in the last few years. At first, there is the university staff at the Production Technology group with the always helpful technicians Bert Vos en Nick Helthuis. Than you have the professors and secretary that are always available for discussion or help. Special thanks to Martin van Drongelen for giving advice regarding the rheology of the T-joint. Mante Sietsma has been of tremendous help during his graduation. Thank you for thinking with me during the development of T-CAT. I would also like to thank Ronald Aarts for helping me in the field of control and Henk-Jan Moed for finding suiting actuation hardware for the hot gas flow.

Lastly, thanks to the whole Production Technology group for all your help and providing a great setting to do this PDEng.

Contents

Chapter 1:
Introduction

1.1 Thermoplastic Composites

In most cases, the performance of mechanical structures relies greatly on the balance between weight and mechanical performance. In the aerospace industry, weight savings are heavily rewarded by greater fuel efficiency, while stiffness can improve the dynamic behavior of the vehicle. High performance composite materials offer a way to save weight while gaining stiffness and strength. In the aerospace and automotive sector, the use of composite materials focuses on the combination of polymers with fibers. This is done by specifically reinforcing the direction of loading in a polymer with either glass or carbon fibers. The polymer that connects and protects the fibers is called the matrix material.

The matrix material that is used in most composites is a thermosetting polymer. Using such thermosetting matrices, the recyclability of the matrix material is challenging due to the irreversible cross-linking behavior of the polymers. Also, working with this matrix requires substantially longer processing times than with its counterpart; the thermoplastic matrix. The long processing times of thermosetting matrices enhanced the interest for thermoplastic composites. These polymers can be molten and solidified quickly and repeatedly, which shortens production times and opens up the way for reusing or repairing composite parts. These thermoplastic matrices have the added benefit of increased toughness over thermosetting matrices which, together with their shorter processing times and higher recyclability, make them a realistic future option for the large scale, low cost manufacturing of high performance composite structures. Besides, using thermoplastics as a matrix material also offers alternatives for assembly of composite structures by local fusion bonding.

1.2 Thermoplastic joining methods

When working with a material, specific joining techniques are available to the designer for assembling sub-components. There is a wide range of joining techniques for thermoplastic composites which is itself divided into three categories:

- Mechanical fastening (bolts, rivets, screws)

- Adhesive solutions
- Fusion Bonding (welding)

Currently, mechanical fastening is the most popular joining method for thermosetting matrices in aerospace. The performance of a mechanical fastener joint is highly predictable and lends itself well for quality inspection and placement of parts. The major downside of mechanical fastening is the generally slow and labor intensive assembly process. Another downside of the joint type is the formation of local stress concentrations around each fastener which limits its strength. Its functioning for thermoplastic composites is equal to that of thermosetting polymers.
Adhesive solutions are widely used with thermosetting materials too. Curing of the epoxy or glue requires a lot of time which is a major reason why this joint type does not lend itself well for automated, industrial purposes.
One of the advantages of working with a thermoplastic matrix is the elimination of the long curing time found in its thermosetting counterpart. This arguments carries over to the available joining methods. The use of adhesives is no longer necessary as a thermoplastic material can be heated and brought into melt again and again. With the interface between two surfaces in melt, a weld can be made. For many applications, a weld can be made by locally heating the two structures to be joined.
With the use of mechanical fasteners and adhesives in the thermosetting dominated composite domain, manufacturers will have to invest time and resources to move on to the proposed joining method of welding. A lot of effort goes into characterizing and optimizing the performance of thermoplastic composite welds. Once a weld is made, inspection of the joint quality is not as trivial as a visual inspection typically found with mechanical fastening. Instead, ultrasonic scans have to be made to visualize the weld interface. Another downside of welding is the difficult repair options compared to mechanical fasteners.
Next to a more cumbersome quality inspection, the welding of thermoplastic composites differentiates itself from mechanical fastening by its less accurate processing control. Fasteners can be tightened with precision while controlling direct welding parameters such as temperature and pressure remains difficult to accurately measure and control. Improving the control of thermoplastic composite welding is a major attribute to increase the use of thermoplastic composites. Not only is there potential to decrease processing times, but joint performance could significantly increase as stress concentrations can be toned down.
Welding of thermoplastics has many applications in industry. Multiple joining techniques have been developed for non-reinforced plastics and a selection of these techniques have been under development for the use with reinforced thermoplastics. Two techniques have successfully been adapted and are currently flying as a semi-structural joining method; resistive and inductive welding.

1.3 T-Joints

All joining techniques that are currently under development for thermoplastic composites rely on a similar geometric aspect. Whether the scenario concerns a fastener, adhesive or weld, a common surface or interface is needed to meet the performance requirement of the structure. This area is used to either place bolts or rivets or to create a region where two surfaces are bonded using adhesives or welds.
In the case of producing panels with stiffeners, an inherent weakness is formed due to this common interface. To illustrate the weakness, this project uses a common scenario; the skin-stiffener scenario.

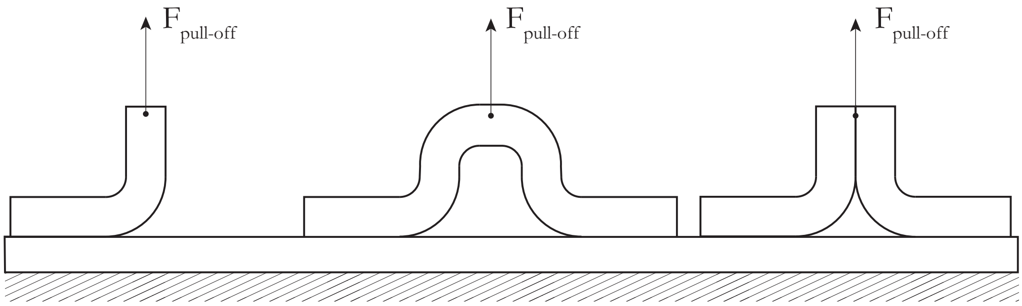


Figure 1: Stiffeners placed on a skin are loaded under pull-off.

Stiffeners are structures that are placed perpendicularly onto thin 'skin' plates to increase the skins bending stiffness. The stiffeners geometry can vary, but the connection between skin and stiffener is always based on achieving a large common interface, aimed at transferring the load between the two components. To do this, the stiffener laminate bends in a 90-degree angle. The fibers go 'around the curve' from the perpendicular section into the flange. The flange is nothing more than additional material used for creating the common interface. Three common stiffeners are shown in Figure 1.

The skin-stiffener scenario can be loaded in many ways, but its weakness shows under pull-off loading. Here, the stiffener is pulled off from the skin along its perpendicular plane. When the joint is examined under this loading condition the problem is located at the end of the flange. Here, the stiffener bends away from the skin and a stress concentration is formed at the junction. Loading in pull-off is common in aircraft stiffened panels and is often combined with a shear loading condition in some sort. Pull-off loading is considered a mode-I loading scenario and shear loading a mode-II. The flanges perform well under mode-II due to the large common surface of the joint, but poorly under mode-I due to the stress concentrations.

The junction with its stress concentration is a weakness of the flanged joint. Unfortunately, the designer is often limited to only this joint type when welding two thermoplastic composites together perpendicularly. And the stress concentration is not the only downside of using flanges. Structures also gain extra weight due to the flanges (in some cases, to maintain laminate symmetry, the flanges have to be mirrored) and in autoclave molding flanged designs increase the mold costs significantly (Offringa, 2012). As the flanged joint is clearly not perfect, alternatives to the flanged joints are explored to investigate if additional joint types can be found that provide added value.

In order to find alternatives, it is possible to find inspiration in the non-reinforced thermoplastic industry to use a joint that is commonly available there; the T-joint (Figure 2). The T-joint does not make use of a flange, but instead places additional polymer between the skin and stiffener plate. This polymer fills the volume between the plates to create a stress alleviating joint. The resulting geometry has a smaller common interface, but can possibly perform better under pull-off loading. The downside of the smaller common interface is the likely reduction in shear strength over a flanged joint type, but many applications require only sufficient pull-off performance and can benefit from using the T-joint.

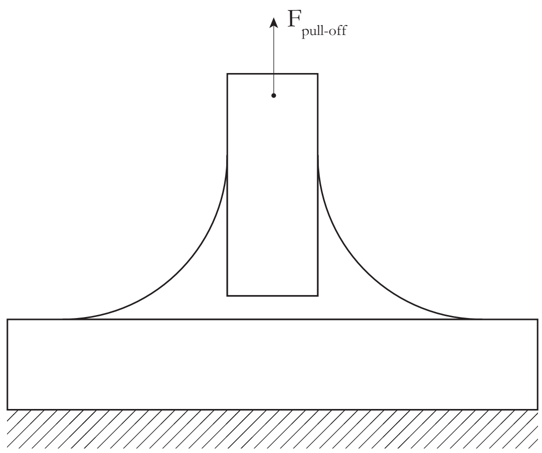


Figure 2: Ideal filler deformation from circular filler wire to tangent geometry.

Experiments of Fokker concluded that the T-joint can outperform its flanged alternatives under pull-off loading (Offringa, 2012). This principle has been applied by Fokker by placing skin and stiffener in a mold with a previously injection molded filler, and letting the lot 'co-consolidate' in an autoclave. Even though the fibers were discontinued between skin and stiffener and the laminates were only joined by the pure matrix polymer filled with short fibers, the alleviation of stress proved to have a drastic effect on performance. The T-joint structure created was stronger, and lighter, while mold costs were reduced as recesses for the flanges no longer had to be milled.
With the potential of the joint mapped, the question rose whether the joint could be made using a guided welding head instead of an autoclave. The welding head would be placed on a positioning system and made to move over the welding line. Instead of globally heating the complete product as in the Fokker concept, local heat inputs would heat the skin and stiffener laminates only just before they are welded to create a flexible welding tool that could reduce costs by automation. Automating this welding concept in order to control the weld quality is the basis of the design proposed in this report.

1.4 Project Objective

This project aims to develop a set-up with a control system for the local welding of thermoplastic composite T-joints with additive filler. The name of the control system is T-CAT (Thermoplastic Composite Automated T-joint). This control system will have the task to control a select amount of process parameters that come forward out of a fundamental analysis of the welding of thermoplastics. These fundamental parameters are heat, pressure and time. A machine that controls these parameters should produce consistent weld quality, but it proves to be difficult to accurately measure these parameters, let alone control them. The relation between parameters and performance is not derived within the framework of this project.
The machine will be used in a lab setting where it will allow for research into the impact of process parameters on weld performance. The welds that will be made will be around 0.6 meters long. This is long enough to take around 30 samples out of a weld and determine the variance of the weld quality along the weld.
The goal is to produce consistent PPS welds at a rate of 3 mm/s that have a constant geometry and pull-off performance along the weld line. This speed will allow for welding a sample in around 200 seconds. The machine will be developed in stages where incrementally control over a certain process parameter will be added. This project follows a graduation project where PP joints were welded using a, automated, standard welding shoe (basic manual tooling from the non-reinforced thermoplastic industry as shown in Figure 7). Welding time and temperatures could be held stable during the welding of these joints, but pressure could not be controlled simultaneously. Speeds and feedrates of materials could be controlled accurately. Material temperatures remained stable but exact processing temperatures remained unknown. The experience gathered during the production of this machine is used as the base for this new project.
To reduce development time, the decision was made to only make single-sided welds until consistent weld quality and geometries could be made (Figure 3). This prevents the double machining of components and saves time and costs. If a single-sided weld is made that fits the requirements, the machine can be doubled. The doubling of the device is not part of this PDEng project.

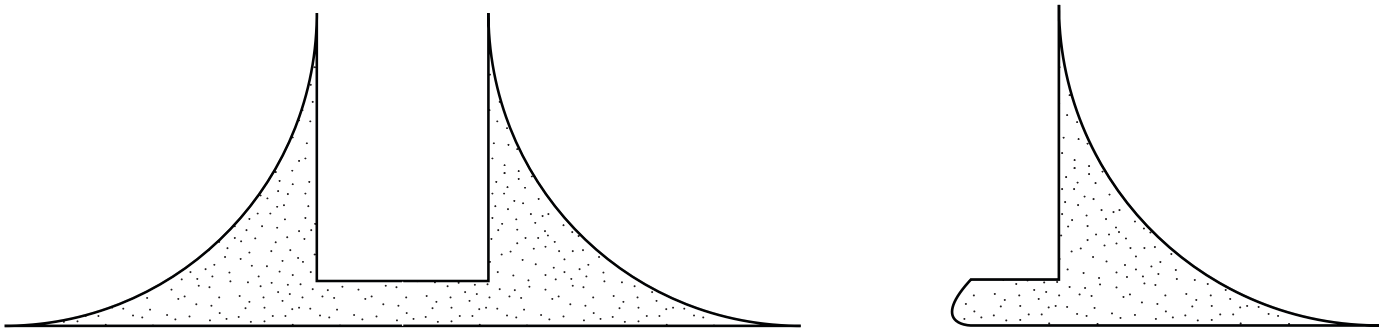


Figure 3: Double and single sided weld.

Multiple versions of the welding machine were developed. Based on the master graduation machine mentioned earlier, two more subversions gradually added controlled process parameters. The complexity and capability of each iteration increased until the welding head did not fit on the same frame anymore. For the last version of the machine a new frame was made and a new linear guide allowed for the heads movement. This complete redesign was the final version of the machine that was the main delivery of this project.
This report focusses on the development of this last version, an overview of the three revolutions of the welding head that enabled the design of the fourth revolution can be found in appendix B.

1.5 Project Perspective

The industry of thermoplastic composites partly builds upon serial robotic arms fitted with heads to perform activities such as automated tape-laying or inductive welding. Ideally, these robots can produce a wide range of products without any adjustment to their hardware. Just like CNC-machines, their tool path dictates the workpiece geometry which allows for high flexibility.
Robotic arms can be combined in production lines where they process and assemble simpler parts to produce a complex product. The arms can be fitted with different end-effectors to facilitate the production. The welding head developed in this project could well be used for such an arrangement. This concept is shown in Figure 4 where the welding head is given an arbitrary shape.

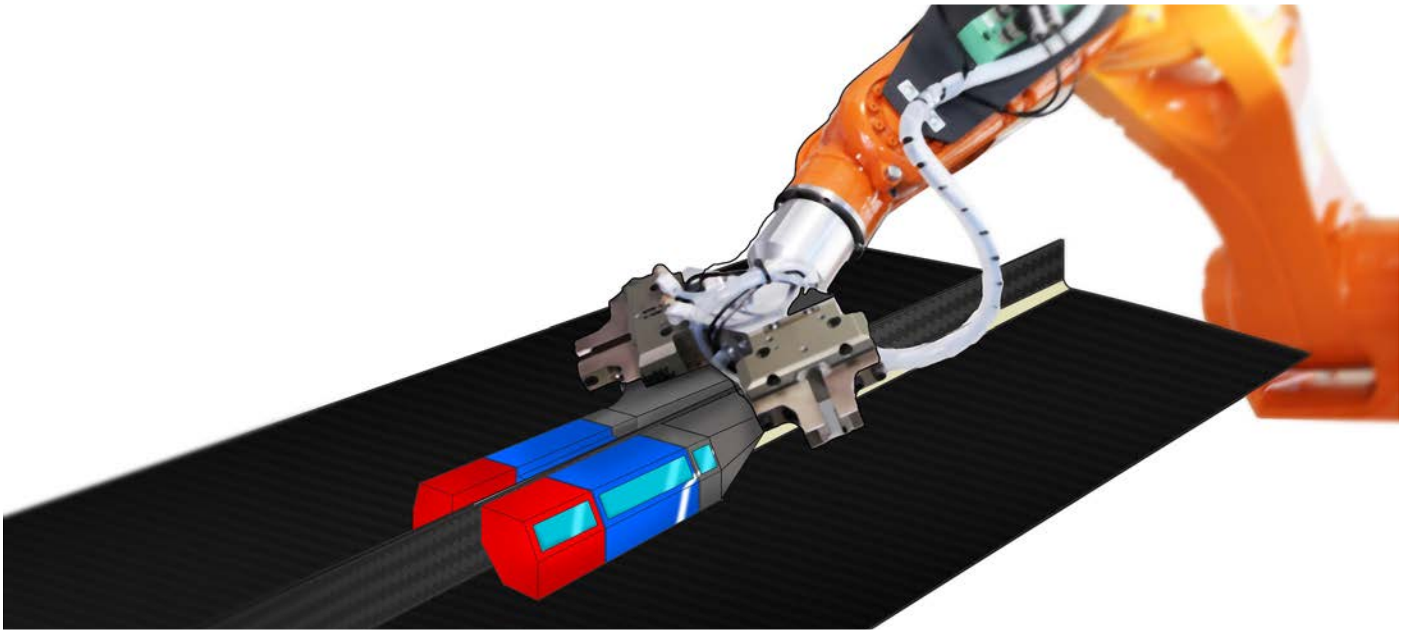


Figure 4: Artistic Rendering of a serial welding robot.

But in some cases flexibility will be of less importance than standardization. This will hold especially for the standard skin-stiffener scenario, because many stiffeners will have to be welded in a parallel fashion. This allows for simultaneous welding and thus an increase in cost and time efficiency. The goal here is to make stiffening a skin less expensive over time and to make this technology available to a large sum of thermoplastic composite structures. The rise of the standardized robotic systems will most definitely contribute to this progress. A concept is drawn using an arbitrary shape of the actual welding head in Figure 5. Seven stiffeners are welded at once using 14 single-sided welding heads.

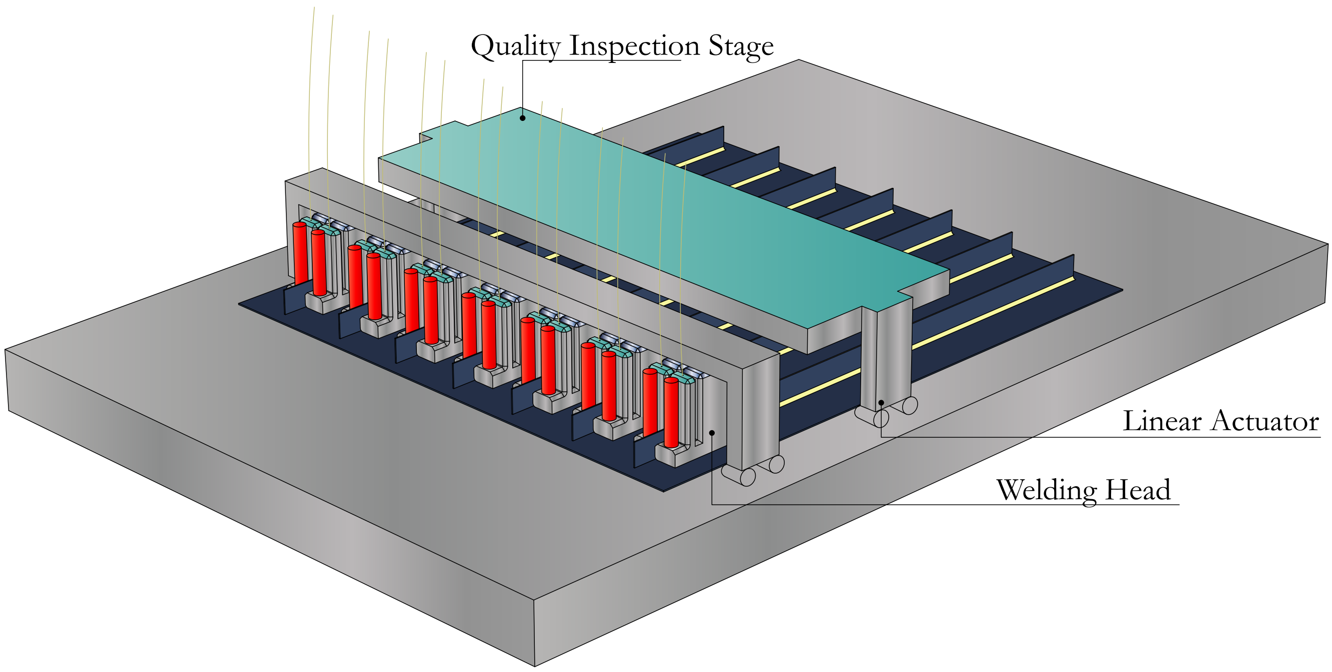


Figure 5: Artistic rendering of simultaneous welding of stiffeners.

Whatever the future will bring is unclear, but what is needed now is to get a clear view of what such a single-sided welding head needs to control to produce consistent welds. Once the requirements for such a machine are defined, two such welding heads can be used to create simultaneous double-sided welding heads and these can find their place in industry on different actuators.

1.6 Report Overview

As the reader is now familiar with the reasoning behind a thermoplastic T-joint, the next chapter will elaborate on the welding process and its parameters. Current knowledge on fusion bonding is applied to generate a set of requirements for the functions and parameter ranges. From this theory, the likely candidates for process parameters of welding T-joints are derived. These process parameters are then captured in requirements for the welding machine. Those requirements will be used to develop the set-up, reported in chapter 3. Control design results are presented in chapter 4, and the resulting preliminary welds are analysed in chapter 5. Insights gathered during the development will be shared that can be the base for a next iteration.

Chapter 2:
The T-Joint Welding Process

The aim of this project is to develop a research set-up with control system that is capable of producing T-joints with consistent performance and geometry. To create an understanding on how the process works and which parameters are of importance an analysis of the process and the parameters involved in the technology is presented in this chapter. Where possible, parameters have been given valid ranges for their expected set-points during welding. The parameters and their ranges will form a process window that is based on knowledge gathered in the thermoplastic community or more specifically the reinforced thermoplastic industry. The relation between parameters and performance is not performed within the framework of this work.

2.1 Available Matrices & Fibers for High Performance

As new types of fiber and matrix materials come to market, it is up to research institutions to test and compare the characteristics of these materials. Until recently, the application of thermoplastic composites was predominantly focusing on the aerospace sector. This brought forward a limited selection of materials that conform to the high performance standards of the industry.

High performance thermoplastic composite solutions use the following matrices: PEI (for interior application only), PEEK, PEKK and PPS. These matrices are qualified for multiple (semi-)structural and interior applications at aerospace producers Airbus and Boeing and are often used for their toughness and excellent chemical and solvent resistance (except PEI).

Research at Fokker Technologies (Offringa, 2012) into globally joined T-joints was carried out using carbon and glass reinforced PEKK. This project aims to weld PPS welds first as this polymer has a lower melting point than PEKK, which will make it probably easier to design a set-up for. Typical properties influenced by the choice of the matrix are the processing temperature, and viscosity of the filler. This last property can also be influenced by the presence of fillers, as short carbon fibers, in the filler. Options for fibers generally come down to glass (heat insulator) or carbon (heat conductor) fibers as these are commercially available in standard composite plates manufactured by, for example, Toray Advanced Composites. The impact on the process parameters of the fibers is smaller than that of the matrix. Still, fibers can restrict the flow of the filler wire in regions where they are closely packed and fibers impact the heat conductance of the laminate.

2.2 Manual Hot Gas Welding

For making a standard, non-reinforced T-joint, the only equipment needed by the user is a hot gas fitted with a speed welding shoe and a filler rod. The resulting quality and speed of the process are in this case completely dependent on human factors. A speed welding shoe (Figure 6) is used in order to ease the welding process and increase weld consistency. This piece of equipment directs hot gas towards the welding interface and heats, guides and pressurizes the filler rod. Using a speed welding shoe, the filler wire is melted to deform from a cylindrical shape to the desired shape, while both sub-structures are locally melted as well.

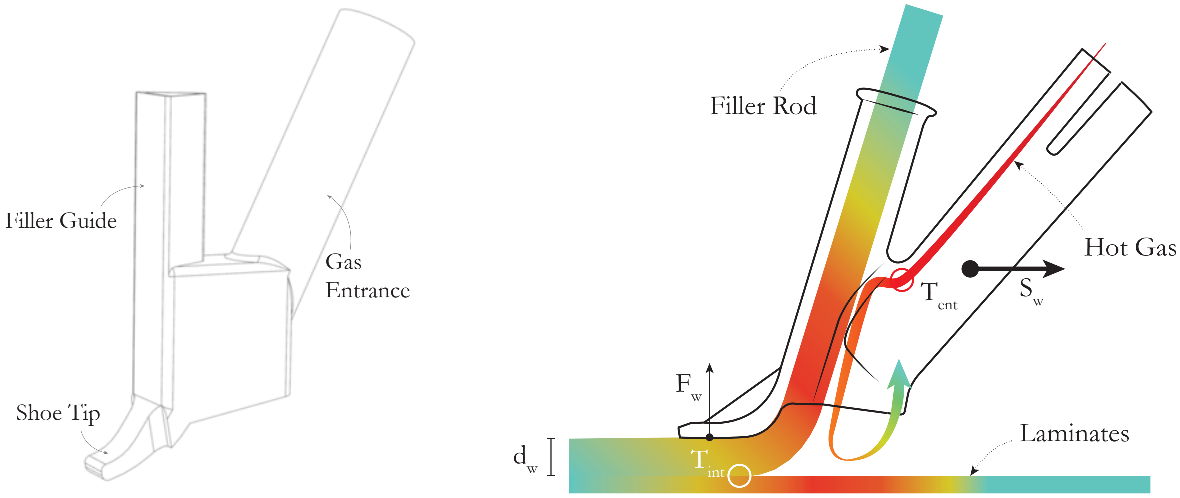


Figure 6: Speed welding shoe for manual hot gas welding.

Higher gas entrance temperatures (T_{ent}), increase the filler's ability to flow. The force used to press down onto the filler wire is called the welding force. The welding force (F_w) is, although not actually measured, in case of a constant weld thickness, the result of the filler wire's ability to resist deformation. The welder tries to achieve constant weld thickness and notices whether the weld force is too high or low. This indicates whether the heat input is sufficient for correct filler flow and whether the shoe tip has the right distance to the two substructures. By adjusting the T_{ent} or the welding speed (S_w), the welder alters the heat input (E_w). F_w can be adjusted using the heat input or, in case of absolute necessity, the distance between the shoe tip and the workpiece (d_w). The welder tries to achieve a constant interface surface area over each weld as this is the first indicator of a constant weld strength. To prevent environmental flow disturbances, the flow of gas should be set high enough to make environmental flows have an insignificant impact. The welder makes sure the filler does not elongate while welding by carefully driving the filler into the weld volume by hand (Figure 7).

Hot gas locally transfers heat to the weld surfaces by means of convection. When F_w is applied through the welding shoe tip onto the filler wire, intimate contact at the interface is achieved through deformation of the filler material and interdiffusion takes place if the interface temperature (T_{int}) is high enough. As the heat source moves away, the heat input through convection approaches zero while the joint area is kept under pressure and some heat input is still applied by the welding shoe through conduction.

The most commonly used carrier gas for convection is environmental air, which is often filtered to eliminate contamination. To prevent thermal degradation and oxidation, nitrogen or carbon dioxide can be used.

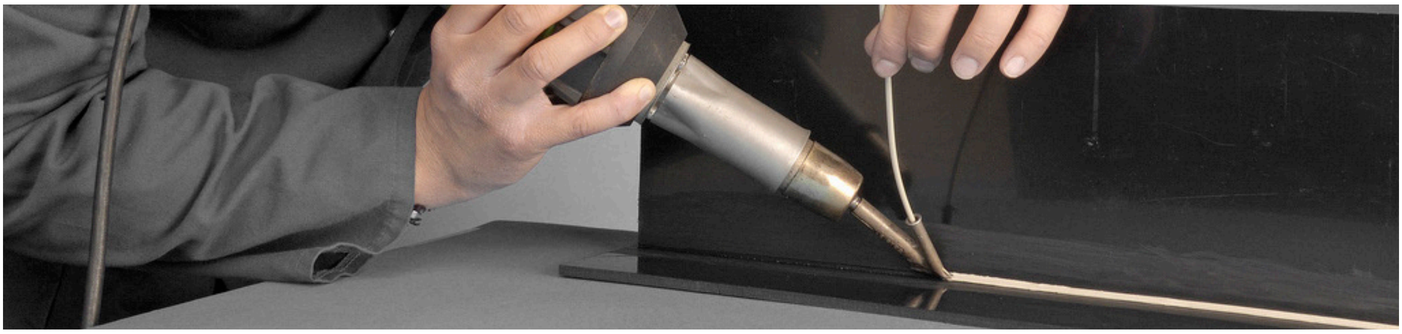


Figure 7: Manual Hot Gas Welding

2.3 Butt-Joints using Automated Hot-Gas welding

Heavy-duty machinery is already available for producing automated T-joints in the non-reinforced industry. These machines use an extrusion based head that fills the concealed space between two sub-components with molten filler. These devices do not use hot gas based convection for heating the filler, but instead use conduction throughout an extruder head. The parts to be connected are still pre-heated using hot gas.
Automated hot gas welding using a filler rod has the potential to be smaller, lighter and cheaper than extrusion based machines. This opens up the use on smaller workpieces or in confined spaces.
There is only one documented case of an effort towards automated welding using hot gas convection and a filler rod (Marczis, 2006). The welding set-up is shown in Figure 8 and is made for non-reinforced polymers. The welding force was passively controlled by placing free weights on a welding shoe to supply a constant pressure. Moving the shoe at a constant speed allowed for the heat input to be easily passively controlled. The gas was supplied at a constant flow and controlled at a constant temperature before it hit the workpiece. The machine was able to produce in-plane butt-joined welds with repeatable ultimate tensile strengths.

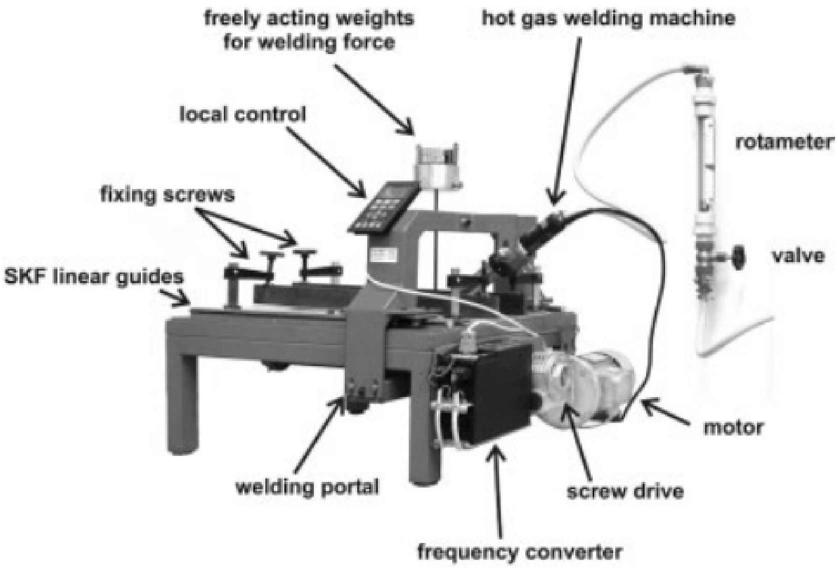


Figure 8: Automated hot gas welding with a filler rod. Taken from (Marczis, 2006).

Two parameters are used that can be tuned to optimize the weld strength. One is the welding force and the other the heat input into the joint. The welding force was set by the free weights which directly impacts the weld geometry. A clear relation between weld force and weld strength was found. It is expected that this relation was caused by the ability of the welding head to vary its distance to the plates and force intimate contact between all materials.
The heat input was derived from the gas flow rate and the difference between entering and leaving temperatures of the gas flow over the weld. Whether this represents the true heat input is under discussion, but it can surely

be used to tune the weld performance. Again a clear relation was found between this parameter and the weld performance.
The research presented by Marczis confirms that parameters related to heat input, pressure and time will have to be controlled to allow for weld strength optimization. Working with reinforcements will bring with it more challenges that will be discussed in the following paragraph.

2.4 Applying Polymer Knowledge to Composites

The typical, in-plane, butt-joint (considered by Marczis (Marczis, 2006)) has no practical adaptation for composites. Welding composites with pure polymers is only useful to out-of-plane joints like the T-joint. Fibers are crucial to the strength and stiffness of a laminate. They also impact the welding process significantly. Deforming fibers outside their axial loading direction is done with relative ease once the matrix looses viscosity. When there is little resistance to keep the fibers in place, they will deform under the pressure of the filler wire. This deformation can be kept within boundaries by limiting the heat penetration through the laminates depth. This asks for a tight temperature control of the composite laminates.
When fibers are woven into a fabric, the local variation in fiber density in the fabric impacts the flow of matrix material. As the matrix melts, the fiber bundles remain in place because they offer greater resistance to deformation than the matrix. This can cause local dips in the welding force required to achieve the filler geometry.
The changing ratio between fibers and matrix in the material can also cause temperature gradients which might affect weld strength. More on this in paragraph 3.1.4 on page 20.
Processing thermoplastic based composites introduces an important failure mode called deconsolidation. When thermoplastic composites laminates are produced, the matrix is forced under pressure and heat to flow between the fibers. This causes stresses in the laminates that will remain once the part cools down and solidifies. When a thermoplastic laminate is then reheated during welding, the stresses are released. This process leads to deconsolidation and shows when melt temperature in the matrix is reached but pressure on the fibers and matrix is lacking, allowing the plies to delaminate.
Deconsolidation causes the void content in a matrix to increase. This has a negative impact on the structure's stiffness and strength. Mechanical properties of the matrix should be retained as much as possible during welding. This can be done by tuning the amount of pressure and heat input into the laminates. An important requirement is therefore to limit the heating of the laminates to their surfaces and to the area where the filler will be placed, without dissipating too deep into the thickness of the plate.

2.5 Non-Isothermal Welding Experiment

During the production of a T-joint, the filler is fed into the heating zone as a solid rod. This rod is molten, because it has to deform and flow into a stress-alleviating shape between the pre-heated laminates. This process bares a similarity with injection molding, where polymer suppliers provide temperature ranges for (Celanese, 2020). The filler can be seen as injected polymer in a heated mold consisting of the laminates and the welding head.
In a short experiment to support the development of T-CAT, simple welds are made to evaluate the impact of temperature on weld strength. It is assumed that the required processing temperature for the filler in a T-joint will also lay in the injection molding range, bt the set-up did not allow for these high temperatures. Instead, a temperature of 285ºC is chosen as a set-point for the filler material. With a set temperature of the filler, the temperature of the laminates is varied to study the effect on weld strength.
Two specimen, a carbon PPS laminate and a pure PPS plate, are heated and pressed together in a cantilever set-up. More information can be found in "Appendix A: Non-Isothermal Welding" on page 66. The temperature of the joint interface is assumed to equal the average of the surface temperatures of both specimen just before contact is made. The strength of the joint is evaluated using a three points bending test, designed to let the weld interface fracture under shear conditions. A sketch of the setup is reproduced in Figure 9. The data in Figure 9 shows the

interface temperature plotted against the joint strength. A significant increase in the joint strength is found around 260ºC. Specimen welded above this tipping point of 260ºC show fractures in the laminate. Samples welded below the tipping point showed fracture at the weld interface. Therefore, the tipping point of 260ºC is taken as a first estimation for the minimum interface temperature for the T-joint as well. Using the final T-CAT set-up, similar types of experiments can be performed for the T-joint.
This would provide knowledge about the optimal laminate temperature at a certain filler temperature. The filler temperature may first need to optimized. That step was skipped under the injection molding conditional assumption in the experiment described here.

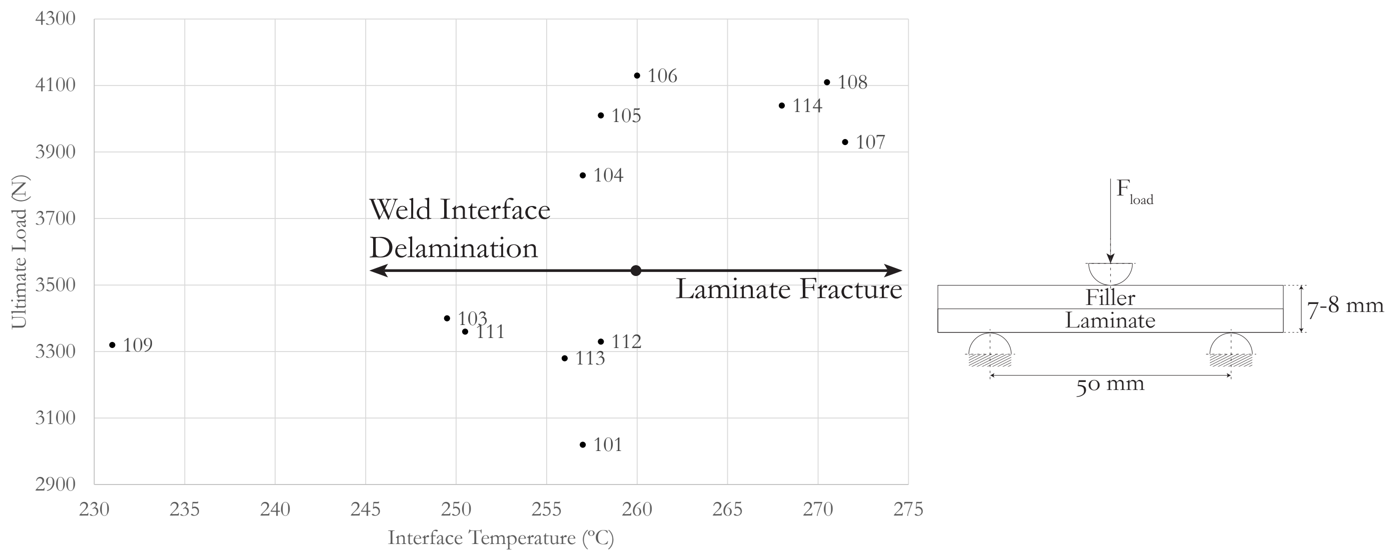


Figure 9: Interface temperature versus joint ultimate load (labels indicate specimen number). Fracture stress is not indicated as the mode of fracture changes.

2.6 Process Parameters Overview

A weld between two laminates using filler material needs to have predictable performance. What passes as margins for predictability is under discussion for every design the joint is used in. This PDEng uses a selection of seven parameters to be monitored and/or controlled based on the analysis of the welding technology. The selected parameters are illustrated in the cross-section of a single-sided T-joint in Figure 10 and are listed in Table 1. These parameters are concerned with both the laminates to be connected and the filler material. These are selected based upon their relation to the basic welding parameters; temperature, pressure and time. It remains unknown if these parameters can actually be measured and controlled. This list may be under or over complete, but is used as a framework for developing the welding head. Completing the list is the aim of project, but evaluations of weld performance consistency can also be done without control over all parameters.

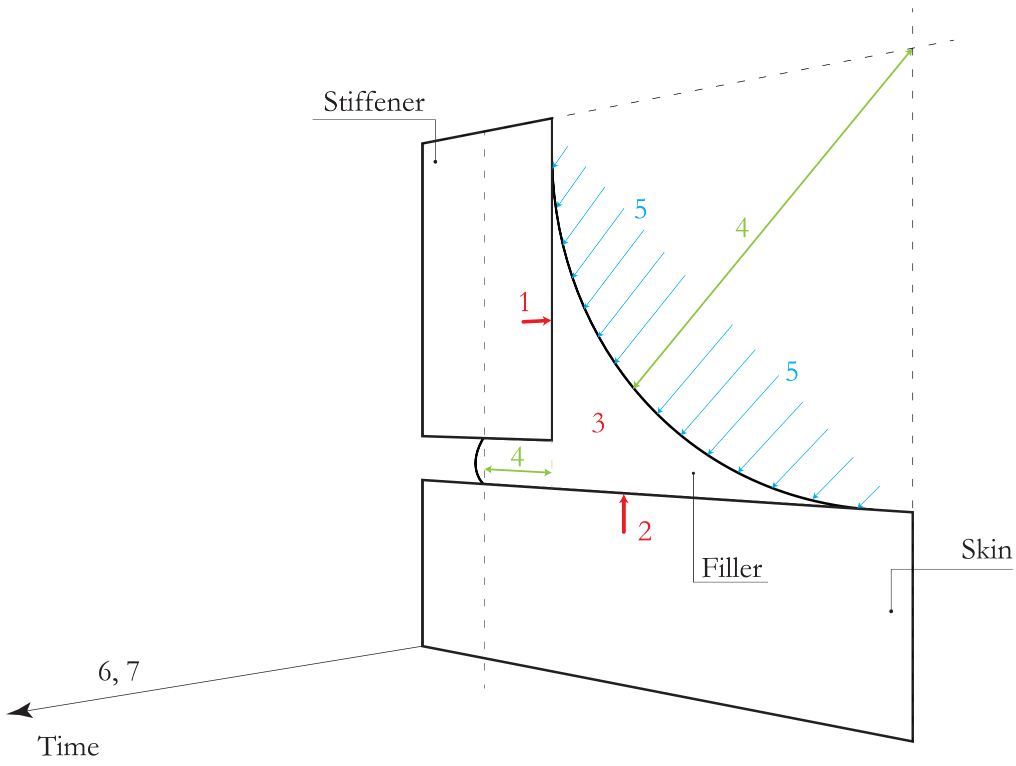


Figure 10: Cross-section of single-sided T-joint.

Process Parameter	Figure 10 #	Process Category
Stiffener Surface Temperature	1	Temperature
Skin Surface Temperature	2	Temperature
Filler Temperature	3	Temperature
Deformed Filler Geometry	4	Pressure, Temperature, Time
Joint Pressure	5	Pressure
Welding Speed	6	Time
Cooling Rate	7	Temperature, Time

Table 1: T-joint welding process parameters.

Controlling these parameters may produce sufficiently predictable welds while also giving the process engineer ways of tuning the process. Optimizing weld strength, would thus become an exercise of finding the optimal combination between these parameters by gradually developing an understanding of the process.

A summary of the current understanding of the process is given in a 2D representation of the process focusing on the skin and filler. The numbers used follow a chronological logic of the process (Figure 11). It is specific to skin-stiffener welding using a polymer filler rod and shows the filler moving over the laminates. The latter is coincident with the page plane and would show almost identical behavior to that of the depicted skin laminate.

The process summarized in the figure includes several functions necessary to perform the bond. It starts with the heating of the filler from room temperature to melt processing temperature (points 1 to 2); In parallel, both laminate and skin are heated up to create a situation where a bond can be realized (point 3). A welding shoe (point 6) bring both laminates and filler in contact and applies pressure. The same shoe also induces the cooling down phase of the weld (point 7). Some requirements on the design of the setup and its control are derived from this analysis.

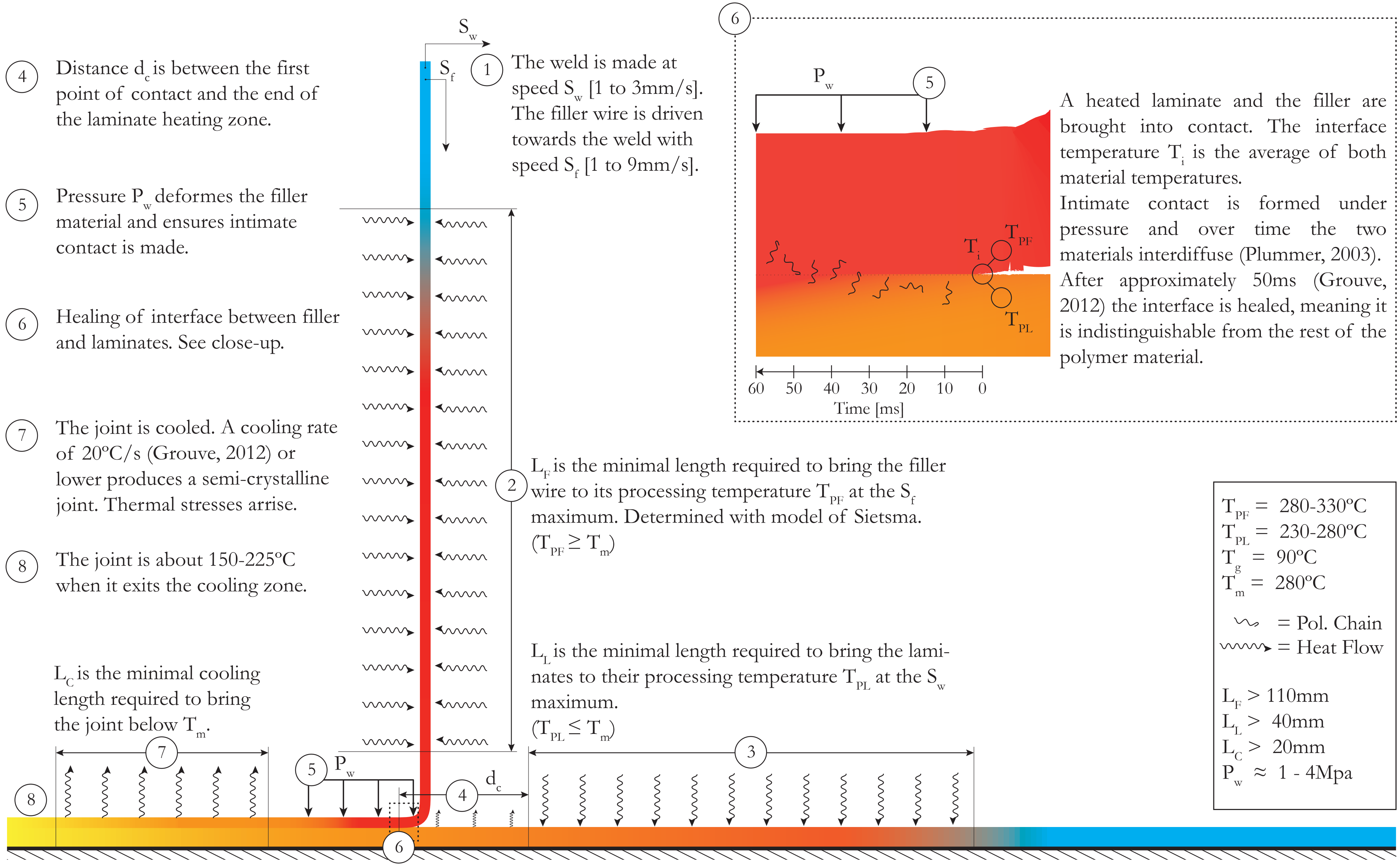


Figure 11: Process Overview with belonging parameters.

This picture visualizes where a set-up should be build around. It also contains control ranges of some process parameters and the order of processes required to produce a weld (ordered by the number bullets). The set-up should be able to lay PPS welds up to 3mm/s. Carbon and glass laminates of up to 4mm thickness should be heated up to 280ºC and the filler material up to 330ºC (Celanese Database, 2019). These temperatures should be controlled as close as possible to the point of first contact between filler and laminates. The time that laminates and filler material spend in the hot gas flow after temperature control impacts the accuracy of the measurements. Basic time domain controller performance such as rise time and settling time are not specified, because they have neglectable importance in a research-oriented set-up.

An important point of remark is the temperature difference between skin and stiffener due to end-effects with single-sided welding. During a single-sided weld, the skins heated zone is surrounded by a colder laminate area. The stiffener is heated on a free end, where the heat input can not dissipate in all directions. This will create a hotter stiffener than the skin. This effect is simply accepted for now, as a double-sided welding head is expected to largely cancel the heat dissipation of the skin under the stiffener as the other side of the skin is then also heated.

The aim is to measure the welding force and see if quality boundaries can be found for this process parameter. The welding force could indicate whether the filler feed rate or heat input is within a normal range. Filler feed rate could be adjusted to ensure intimate contact.

The cooling block should be able to cool the joint under pressure with a rate lower than 20 ºC/s to about 225ºC using the relative crystallinity of PPS versus temperature relation (Wijskamp, 2005). Recrystallization on cooling appears roughly between 255 and 225ºC.

All of these functions should work on a repeatable basis. After cooling down the machine and solidifying all the molten polymer inside the heaters should be able to remelt the left-over polymer and free the filler path again.

Further requirements are for the geometry to be constant after welding. This means a consistent filler radius upon visual inspection with even flow under the stiffener. The polymer should flow further than half-way under the stiffener. This is to ensure that double welds leave no voids between the laminates.

Some extra technology - and control - specific requirements will be defined in chapter 3, following the detailed development of the setup. The full set of requirements used during the design can be found in "Appendix C: Complete Requirement Overview" on page 79.

2.7 Visual Inspection and Physical Testing of Weld Quality

Weld quality can be assessed using optical and mechanical means. By means of the naked eye, a camera or, somewhat more sophisticated; a microscope, the local failure or global consistency of a weld can be assessed. Quality can be visually inspected by checking the filler deformation and checking how close it came to an ideal deformation. A distinction can be made between destructive and non-destructive evaluations.

On a microscopic and non-destructive level, wetting of the polymer can be observed. Using a microscope on sliced section of weld, void content in the filler material or deconsolidation induced delamination in laminates can be evaluated on section views (thus destructive). These section views will also offer a better insight into the flow behavior of the filler and possibly the matrix belonging to the laminate. The effect of laminate deformation on weld performance is still unknown, but as the filler and matrix material are equal, the effect of the matrix disturbance is assumed to be of a low order as long as the fibers remain in their designated position.

Visually inspected weld characteristics such as filler radius continuity or void content relate to weld quality, but are not part of a mechanical testing method. They can be used to improve upon process input settings, but will not suffice for more detailed numerical analysis regarding weld strength consistency.

Another non-destructive measurement is the ultrasonic scanning of the interface between skin and filler. A scanner can visualize voids at this interface. Such a scanner could also check for delamination of the skin.

Double-sided T-joints weld strength consistency can be assessed by pull-off testing. T-joints can also be evaluated under shear conditions as that also needs to be at least predictable if not optimized. A short beam shear test can later be implemented to check the strength of the joint in a shear loading direction. Future research should go into this loading case to compare the performance between flanged and hot gas welded T-joints. As flanged L-joints rely on a larger interface surface, they are expected to perform better under a shear loading condition. The relative importance of the tests is application dependent, but with the current project (which focuses on controlling the process, not optimizing it) any test will suffice as long as it evaluates the strength of the T-joint for consistency. The set-up for pull-off testing is shown in Figure 12. This test (Baran, 2018) will be able to accurately compare weld strength between double-sided joints. The data gathered on co-consolidated T-joints (Baran, 2018) will probably be used to compare to the locally heated T-joint of T-CAT in the future. Therefore, the same radius is used of six millimeters for the filler.

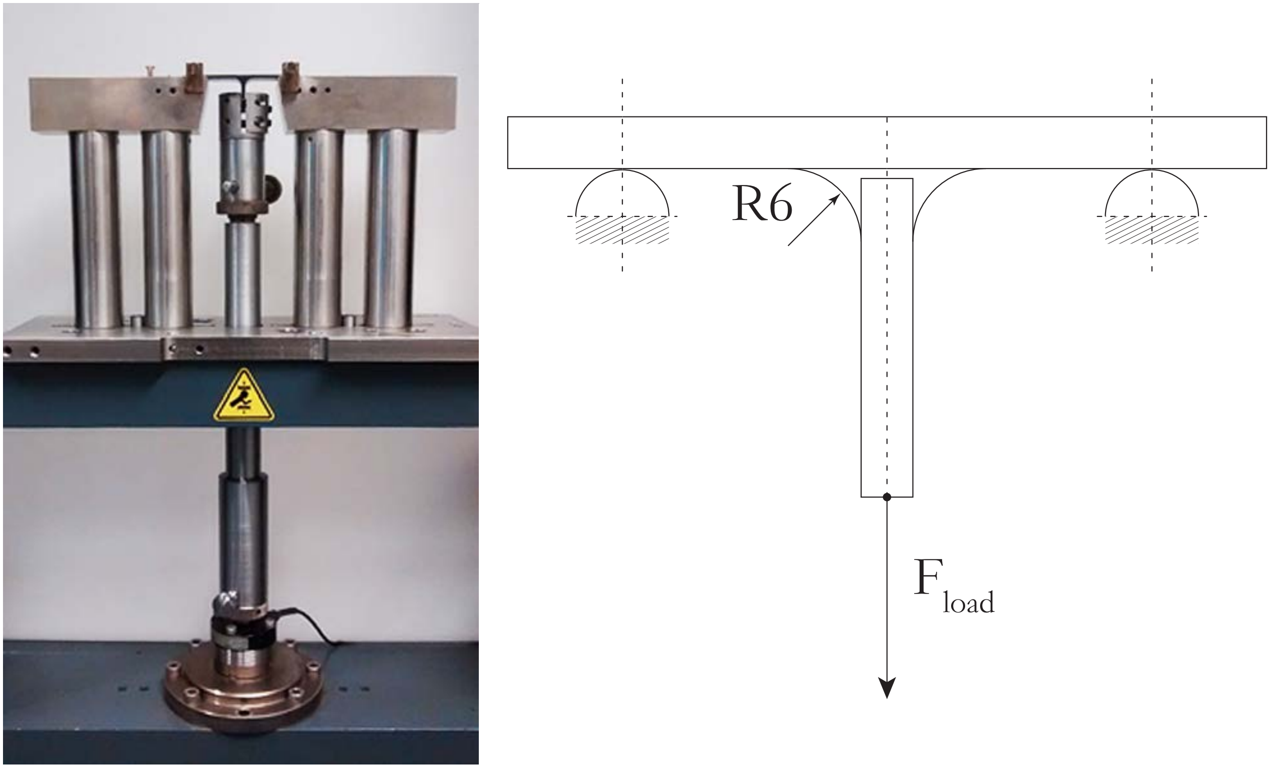


Figure 12: Photograph and schematic of pull-off set-up

Within the framework of this report, samples will be welded on one side using the single-sided welding head to produce a weld for testing. The testing procedure used to evaluate the consistency of single sided welds will be presented later on in the report. For the majority of the welds performed, the skin and stiffener will be in contact. This makes sure the weld volume under the machine is closed just as with a simultaneous double-sided set-up. In that way the flow behavior of the filler is consistent and the joint can be pressurized. The geometry would look like configuration one on the left in Figure 13 though welded on one side only.

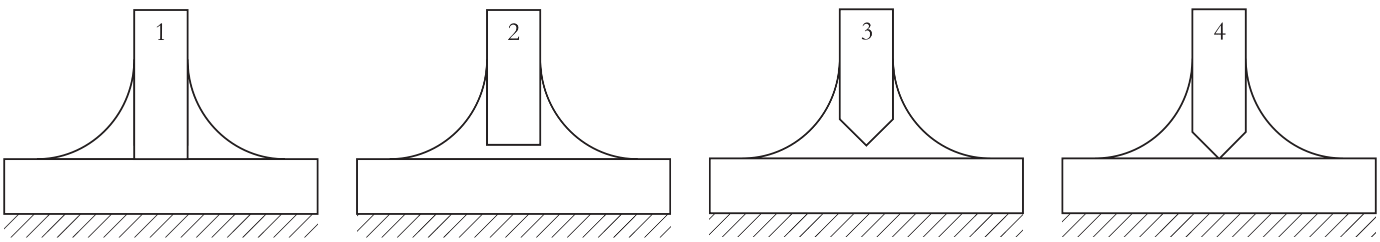


Figure 13: Different skin-stiffener configurations.

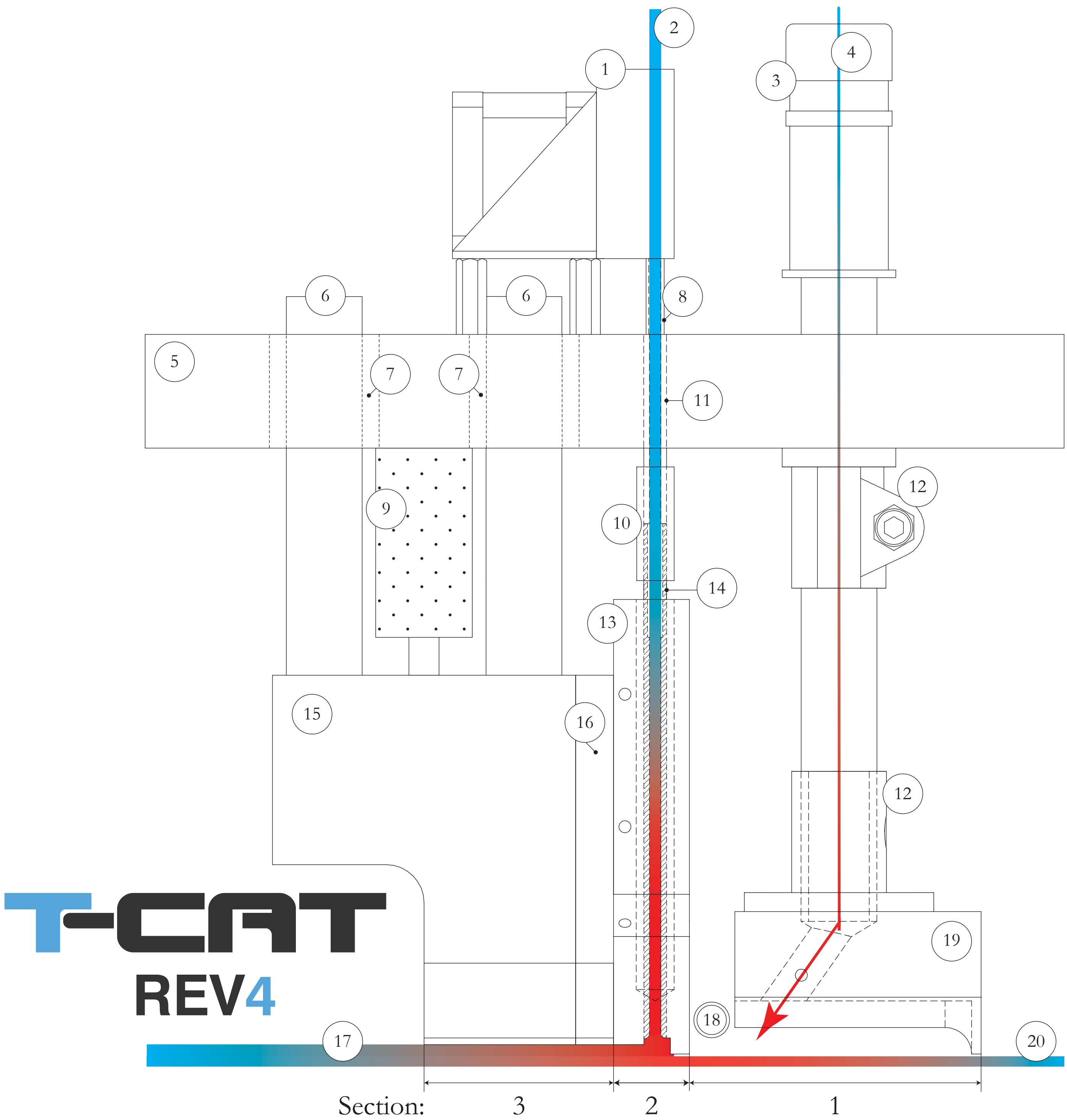
When a double-sided welding head is available, joint two and three in Figure 13 can be used. Joint three will allow for increased heating of the underside of the stiffener and will allow for better flow between the laminates. It would also be interesting to see the strength increase compared to the single-sided serial welds with configuration two and three or to adjust configuration three so that it touches the skin laminate (configuration four). The difference between two and three is the improved heating of the laminates and filler flow in three. The last configuration, configuration four, can be used to make the positioning of the laminate easier, but it requires (just as configuration three) a preprocessing step to create the double chamfer on the laminate. Configuration four would also provide the closed off weld volumes needed for consecutive single-sided welding. A laminate can be preprocessed using a conventional milling machine and be used to evaluate configuration three's performance compared to configuration one.

Chapter 3:
Welding Head Development

This project aims to control the welding of two perpendicular laminate plates with or without a small distance between them using additional matrix material called the filler. This scenario is a variant of the regular skin-stiffener application found in industry. The skin-stiffener scenario in this project is a simplification of many real world applications where large skin plates are reinforced with stiffeners. These skins and stiffeners do not have to be straight, rectangular plates, but can possess curvatures along multiple axis. By simplifying the welding scenario, the complex problem of taking corners is postponed until straight consistent, double-sided welds are produced. Therefore, the welding device under development always goes along a straight welding line where a longer design would still comply to all requirements. So to smoothen the eventual transition towards cornering, the welding head is made as short as possible.

The complete welding head of T-CAT REV4 consists of three sections (Figure 14). One for heating the laminates (section 1), one for heating and deforming the filler material and gaining intimate contact with the laminates (section 2) and one for cooling the joint (section 3). Each of the sections will be discussed in detail in the coming chapter. The previously derived process parameters are each measured and possibly controlled in one of the three sections and will be discussed section by section. After this discussion its requirements will be presented. Not all requirements belong to a section that is discussed in detail in this report. A complete overview of all requirements for T-CAT revolution four are given in appendix C.

On the next page the developed welding head is drawn with numbered components. The table holds all part numbers (P.#) and the section the part belongs to (S.#). Pictures of the real set-up are presented in appendix D on page 81 to give the reader a better picture of how the set-up functions and how the welding head is moved over the clamped laminates.



P.#	S.#	Description	P.#	S.#	Description	P.#	S.#	Description	P.#	S.#	Description
1	2	Filler Driver	6	2	Shaft	11	2	Guide Tube	16	3	Isolator
2	2	Filler Rod	7	2	Linear Bearing	12	1	Gun Clamp	17	-	Complete Joint
3	1	Hot Gas Gun	8	2	Teflon Guide	13	2	Filler Heater	18	1	Pyrometer
4	1	Gas Flow	9	2	Load Cell	14	2	Runner	19	1	Gas Nozzle
5	-	Frame	10	2	Heatsink	15	3	Cooling Block	20	1	Skin Laminate

Figure 14: T-CAT REV4 assembly overview. (P.# = Part Number, S.# = Belongs to Section Number)

3.1.1 Section one: Laminate Heating Source

This is the first section of the machine that interacts with the two plates to be welded. Here, both laminates are heated into their processing range between 230 to 280 degrees Celsius. It takes some time to get the laminates up to the required temperature so it is easiest to speak of a heating zone where the laminates are exposed to the heating source. This source could be either a laser or a hot gas flow that is aimed onto the welding line. Both sources have their pros and cons, but with this machine the choice was made to use hot gas heating for the ability of the gas to flow between stiffener and skin to heat the material in this volume which is difficult to reach. With a laser, these surfaces would be harder to reach as the light can not travel to it directly and quickly loses its energy after being reflected. It has to be noted that stiffener laminates can be adapted to lose their parallel lower face with the skin to solve this inherent problem (Figure 13). The flat surface could be made angular by machining chamfers on both sides. This would allow for better heating of both laminates using laser or hot gas heating sources. Another advantage of using hot gas is the fact that it can easily provide an inert environment to heat the polymers which prevents thermal degradation. This method is used in the welding of metals already and would simply replace the gas supply of pressurized air with an (semi-)inert gas.
A laser system would become of better value with increasing welding speeds. By increasing the welding speed, the heating zone using hot gas stretches which limits the maneuverability of the welding head. Let alone the mass increase and its impact on dynamic modes, the heads increase in sheer size would make it harder to go around a corner. A laser can bring higher energy input densities into the lamina and thus could shorten the heating zone significantly. The problem of cornering is only valid starting at a certain curvature level, as both the laser and hot gas heating do not require direct contact between the head and the laminates. This leaves space between the two to act as a buffer for light curvatures.
Whether a laser or hot gas heating source is chosen, the actual heat transfer coefficient into either the skin or stiffener laminate is not trivial to acquire. For a laser system, the energy traveling into one of the laminates is determined by not only the power of the laser system, but also the materials wavelength dependent absorption, transmittance and reflectance behavior of the light. This data is already available for most pure polymers, but placing fibers in these polymers can significantly alter the behavior. Not only the use of fiber reinforcements limits the understanding of heat transfer by laser light, but also the reflectance off a complex geometry such as the skin-stiffener scenario. As a beam of light reflects on the surface of, for example, the skin, it loses a substantial part of its energy. When it hits the stiffener afterwards, this beam can reflect further into the weld geometry before losing most of its energy. Understanding the heat transfer into the joint would require tracing the rays of light. In this project laser heat is not required yet as welding speeds are kept relatively low and welding lines are kept straight. Understanding the heat transfer with hot gas is therefore much more relevant at the moment and will be discussed in the next paragraph.

3.1.2 Hot Gas Heating: The Heater

Hot gas heaters require a minimal gas flow rate to make sure the complete device is uniformly heated and that the temperature of the gas that exits the gun lays close to the temperature measurement inside the gun. Increasing the flow rate helps averaging out the temperatures of the individual heating spirals in the device and prevents them from burning out. The minimal flow rate is given by the manufacturer in liters of gas per minute (LPM) and increases linearly with the power of the heater. In case of the chosen brand for this project, the minimal flow rate is seven to eight percent of the heater power in watts. As with most components, the trade-off for finding a suitable heater is between power and size. As the welds that need to be made only have a radius of six millimeters, the gas heater requires a small package to come as close as possible to the weld line. In that way, the gas temperature does not drop so much before it hits the workpiece. A small, 20 millimeter, diameter heater is found in the XS20 series from Hertz. This heater comes in power ratings ranging from 450 to 2000 watts. As the 2kW version has the same dimensions as the 450W version, the highest power heater is chosen as it allows for higher heat transfers and thus smaller time constants of the heating process. A high power heater can supply higher flow rates of the same gas at the same temperature, allowing it to heat laminates quicker. Future systems could be developed with lower power ratings based on the findings with this heat gun, but the higher power heater always has the highest change of delivering robust control. The downside of high power heaters is the loss of resolution in the exit temperature of the hot gas. If the loss of resolution will have a significant effect on the temperature controller precision has to be determined experimentally as this is system dependent (mainly on the power regulation towards the heater which will be discussed further on).

3.1.3 Hot Gas Heating: The Laminates

Once the hot gas exits the heater, it enters the nozzle. The nozzle directs the gas towards the laminates and sets boundaries to the heating zone. It is important to aim the flow of gas towards the end of the laminate heating zone. This allows the heater to gradually increase the temperature of the laminates. If the gas flow was aimed at, for instance, the middle of the heating zone, the laminates would first increase in temperature and slowly cool down afterwards before they leave the zone. As there will always be a sensor to check the temperature of the laminates after leaving the heating zone, it is required that this measured end temperature is the maximum temperature of the laminates. Knowing the maximum temperature of the laminate together with the exposure time in the heating zone helps in understanding the thermal degradation of the laminates. Aiming the hot gas flow in the measuring spot of the sensor at the end of the heating zone allows for the maximum temperature measurement. More sensors are installed to measure the temperatures of the hot gas in the heating zone. This could later be used to model the heating behavior of the laminates.
Sietsma (Sietsma, 2020) made an effort to model the heating of the laminates with a hot gas flow in his master thesis. Next to filler heating, the thesis focused on the modeling of a single laminate exposed to a perpendicular, impinging jet of gas. What was found, was that if the laminate is isolated while heating, the heat transfer rate within the laminates is insignificant compared to the transfer rate of the gas to the laminates. Therefore the materials and dimension of the laminate are of little influence to the surface temperature of the laminate during local heating. Only when the laminates are clamped to a conducting metal block (as it probably will be a metal clamp) the thickness of the laminates starts to play a role in maintaining the surface temperature. In his recommendations, Sietsma expressed the importance of computational fluid dynamics (CFD) analysis of the turbulent hot gas in the nozzle. Understanding the turbulent behavior of the flow together with measurements of it temperature gradient, should allow for modeling the complex skin-stiffener nozzle flow.

3.1.4 Hot Gas Heating: Measurement and Control

From a processing perspective, two parameters need to be controlled. These are both the stiffener- and skin laminate surface temperatures at the moment before contact is made with the filler material. Assuming no sensor can be fitted into the laminates during welding as this would require holes to be drilled into a structural component, the control system has to be made non-destructive. There are two proposed, non-destructive options for controlling the two parameters: one partly open- and one closed loop control system. Both will be discussed in this paragraph.

Measurment and Actuation Options:

Open-loop control systems are based on empirical or pure modeling efforts to find a fixed output value of an actuator that results in a reasonably stable process parameter. In case of hot gas heating, this could entail fixing the power and gas flow into the heating element while driving over the laminates with a fixed speed after a fixed heating time of the apparatus in a consistent environment. This would, in theory, leave the laminates at a stable temperature. Supported by experiments, the correct settings for all the parameters can be found and the system would work. These experiments will require a sensor that measures the laminate temperature before they come into contact with the filler. For open-loop empirical studies, this sensor can be placed in the laminates (destructive measurements). It is impossible to have an in-line, non-destructive measurement that exactly captures this temperature as there will always be some distance between the measurement point and the point of contact between filler and laminates. This implies that the cooling behavior of the laminate will have to be understood in any accurate control system. The destructive sensors can be used to understand the cooling of the laminates. The uncertainty caused by the cooling of the laminate can be reduced by decreasing the distance between the points of measurement and contact. Minimizing this distance was therefore an important goal during development.

The measurement of laminate temperatures can be carried out non-destructively using infrared camera's (IR-camera) or pyrometers ('single pixel' IR-camera). Dragging surface thermocouples were investigated, but adapting (isolating the sensor from the heated gas flow) these for the skin-stiffener scenario makes them bulky which increases their thermal mass which, in turn, increases their heating time constant. Use of the thermocouples dragging over the surface of the laminate would therefore cause control delays. Infrared measurements have fast responses as they do not heat themselves and are flexible in the measurement spot size, which is extremely beneficial in measuring non-uniform temperatures at woven laminate surfaces. Depending on the fiber weaving geometry, a laminate has distinct surface temperature patterns. These patterns form depending on the volume between the fibers and the laminate surface which is filled with matrix material. Under uniform heating of the laminate, when this local matrix volume is large, the surface temperature rises. For low local matrix volumes (when fibers are close to the surface), the surface temperature will show a local valley as the heat dissipates through the carbon fiber. Having a measurement area which is small enough to detect these local valleys and peaks in the surface temperature will only provide the control algorithm with unnecessary noise as it does not have the precision and the response time to compensate for these local phenomena. Therefore, the measurement spot is best left adjustable for different types of fiber weavings. It can then be set large enough to average out the local temperature pattern and provide a smooth input for the controller. A schematic example is given in Figure 15. Here three IR-measurements are taken of a woven laminate. Measurement A would pick up on the local temperature valley and upcoming peak. Measurement B would average out a complete period of temperature fluctuations and is the best input for hot gas temperature control. Measurement C also takes an average, but this might not be as representative as B. All these measurements can be taken with a single pyrometer set at varying distances from the target.

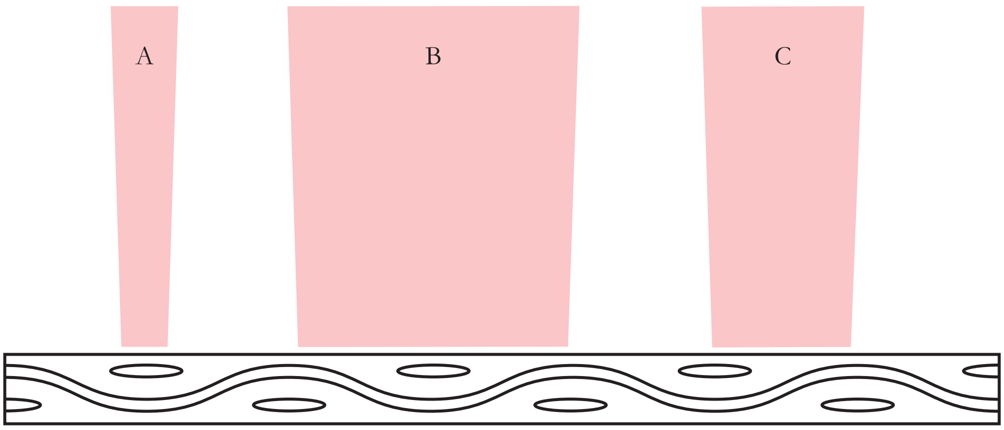


Figure 15: Woven laminate with IR-measurements.

Infrared cameras can be used to evaluate the patterns, while pyrometers can be used to do in-line measurements without the need for image processing of multiple pixels. Because pyrometers are costly, only one of the two laminates is monitored while welding for now. In single-sided welding, the infrared camera might show the stiffener heating up more due to end-effects. To avoid thermal degradation, the stiffener is therefore controlled and not the possibly cooler skin. A set-up could be designed that heats each laminate individually, but this would mean doubling both actuators and sensors to create a bulky, expensive package. Therefore, a single pyrometer is aimed at the stiffener with a measuring spot that is large enough to average out fiber dependent noise in the surface temperature.

If the move to a laser heating system is ever undertaken it would open up the way to individual measurement and control of both laminates in a compact package. This is made possible by the fact that two radiative energy flows can cross each other, while convective flows cannot. A concept drawing of such a laser heater is found in Figure 16 in the bottom right corner. Such a system would be able to overcome the temperature difference between stiffener and skin, but requires the laminate to be chamfered to heat the underside of the stiffener. The much simpler system that is currently under development (top left) may possibly be adapted by rotating or shifting the hot gas flow to make sure that the skin is exposed to more air flowing over its surface. This will have to be investigated further once the set-up is completed. This system would therefore be expanded by monitoring both laminates to collect data on the temperature difference between the two (bottom left of Figure 16). If the current design is not able to reach required welding speeds, the design could first be updated by only replacing the hot gas source with a laser (top right Figure 16). These four configurations all rely on the same principle of using heating power to regulate a surface temperature and therefore do not add individual controller complexity.

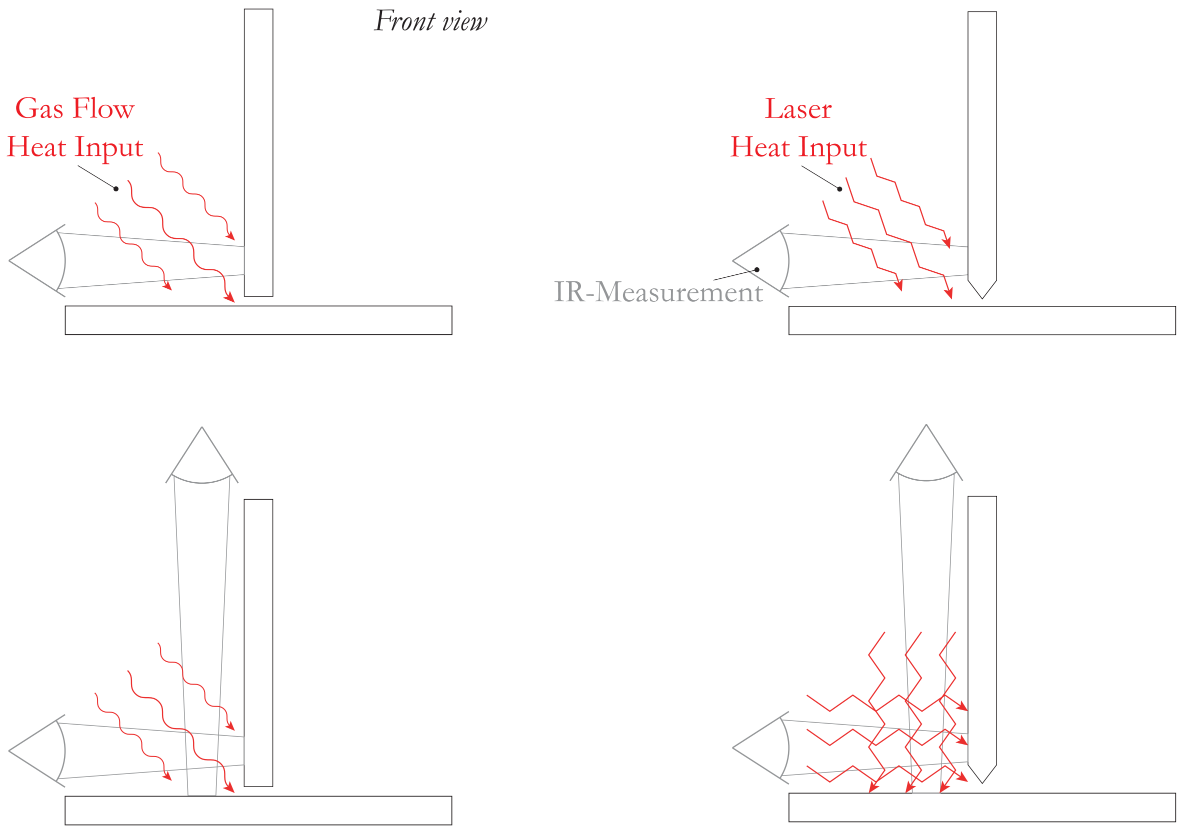


Figure 16: Measurement and control options of the skin-stiffener scenario.

Summarizing, a complete open-loop control system is described that can be tuned using an infrared camera or pyrometer. In practice, such an open-loop system could be adapted just slightly and become easier to work with.

Partly Open-Loop Control:

By controlling the temperature of the hot gas inside the nozzle and fixing the gas flow rate plus welding speed parameters, a welding head is made that does not have to reach a thermal equilibrium to function (Figure 17). At the start of a weld, as the welding head components are still increasing in temperature, the power into the heater is increased to compensate for this heat loss and keep the gas temperature stable. The temperature of the gas in the nozzle will have to be measured. Therefore, sensors are installed in the welding head to capture the gas temperature gradient inside the nozzle. The heating of a set flow of gas is very common in industry and can be handled with off-the-shelf components or simple control systems. These control systems are however closed-loop systems. So the system proposed here is, in essence, a system that acts as an open-loop system while regulating one indirect parameter with a closed-loop controller. A closed-loop system is simply a controller that is directly monitored by a sensor input that guides the output value of an actuator. The algorithm that transfers the sensor value into the correct actuator output can be tuned empirically or by analytical models of the system under control or plant. Empirical or heuristic tuning is a common practice in process heating and is perfectly capable of sufficiently tuning a controller for gas temperature control in the nozzle.

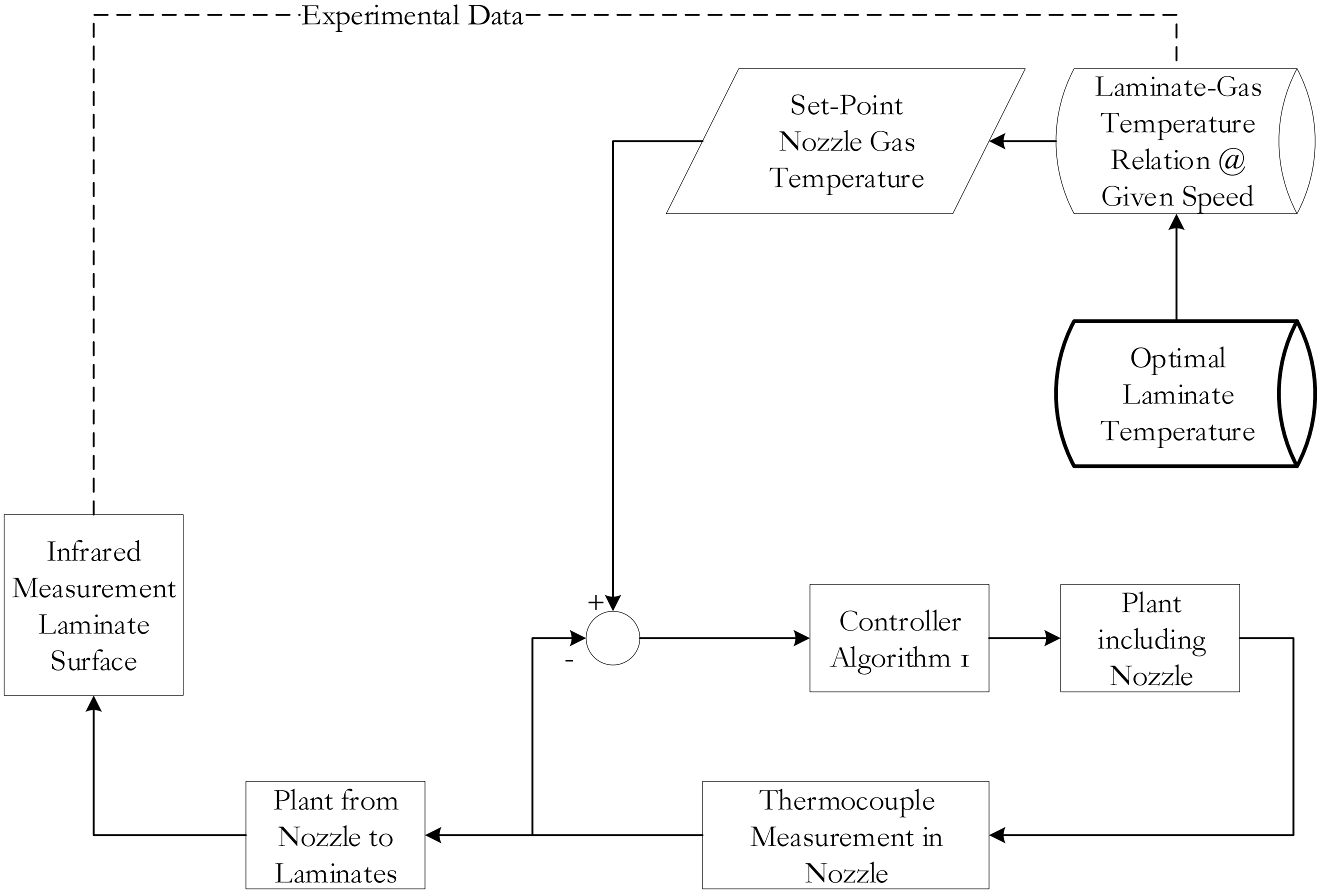


Figure 17: Controlling only the gas temperature according to welding speed.

The downside of a system with controlled hot gas nozzle temperature and set gas flow rate is that it still forces a deeper understanding of the impact of changing welding speeds on the resulting laminate temperatures. However, collecting the empirical evidence to predict how the welding speed influences the laminate temperatures is a realistic undertaking. Three tests are scheduled to find this relation for a specific laminate thickness in Table 2. This data will be used to schedule certain gas temperature set-points based on a constant or varying welding speed (Figure 34). This would deliver stable laminate temperatures in a consistent welding environment.

	Test 1	**Test 2**	**Test 3**	**Test 4**
Gas Temperature	330 °C	340 °C	350 °C	360 °C
Welding Speed	3 mm/s	3 mm/s	3 mm/s	3 mm/s

Table 2: Testing matrix for welding speed - gas temperature relation for set laminate thickness.

Closed-Loop Laminate Temperature Control:

To compensate for smaller disturbances such as environmental temperature deviations, different laminate lay-ups, fiber materials and clamping set-ups, the laminate temperature could be directly controlled. A control algorithm should then transform the laminate temperature error into gas heater power. It can have its parameters scheduled depending on welding speed. This is shown in Figure 18.

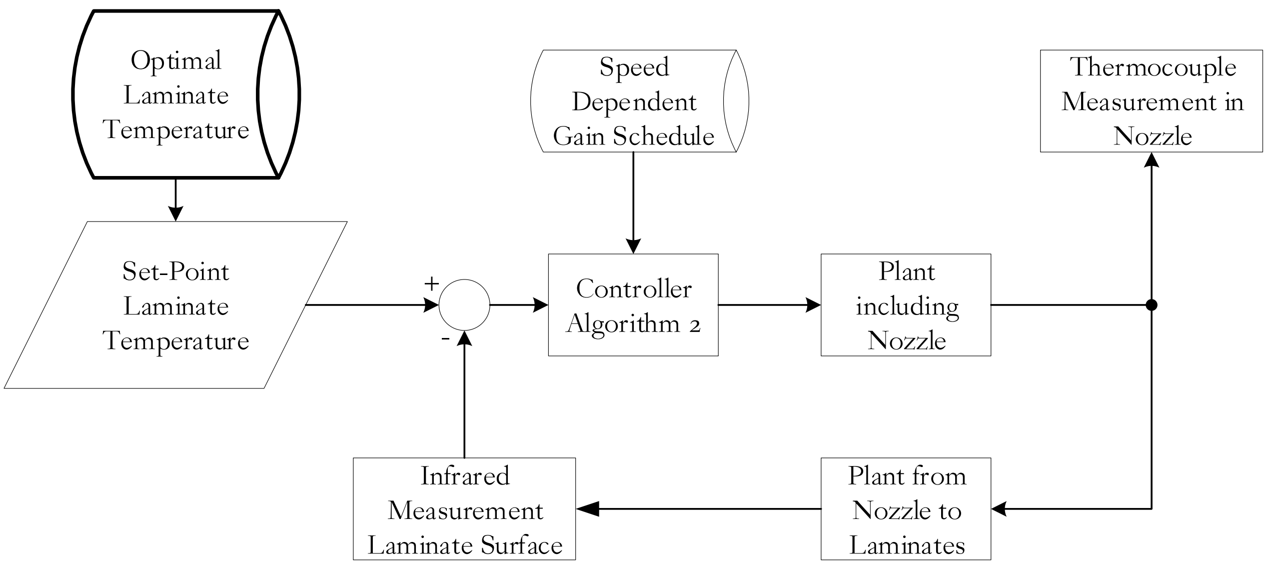


Figure 18: Closed-loop control over laminate temperature using power regulation into the heater directly.

The problem with this technique is the fact that at the start of the weld, only environmental temperatures are registered by the infrared sensor as it is not aimed at the laminates jet (Figure 19). This would result in maximum power going into the heater during start-up, burning the laminates.

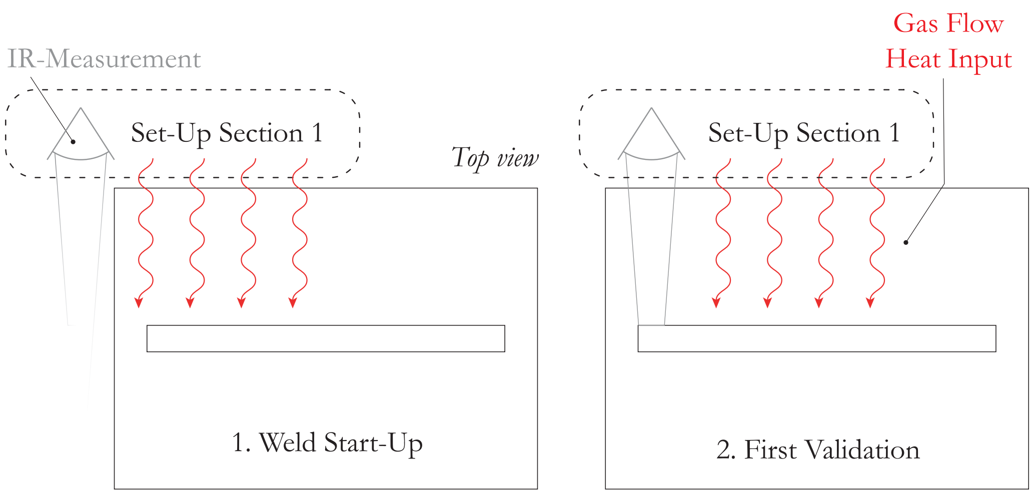


Figure 19: Start-up problems arise when only using IR-measurements for control.

This problem can be solved with empirically determined relations between welding speed, gas temperature in the nozzle and resulting laminate temperatures. When the infrared sensor does not register a value belonging to the heated laminate, the control system starts controlling the hot gas temperature to be at the corresponding temperature for the chosen welding speed and laminate temperature. The algorithm shown in Figure 20 would thus first determine whether the infrared sensor is pointed at heated laminates. If not, the gas is heated towards an empirically determined nozzle temperature to limit start-up effects once the infrared sensor detects a heated laminate. Once the sensor does detect the laminates, the control system uses this sensor value to hold the laminates to their set-point.

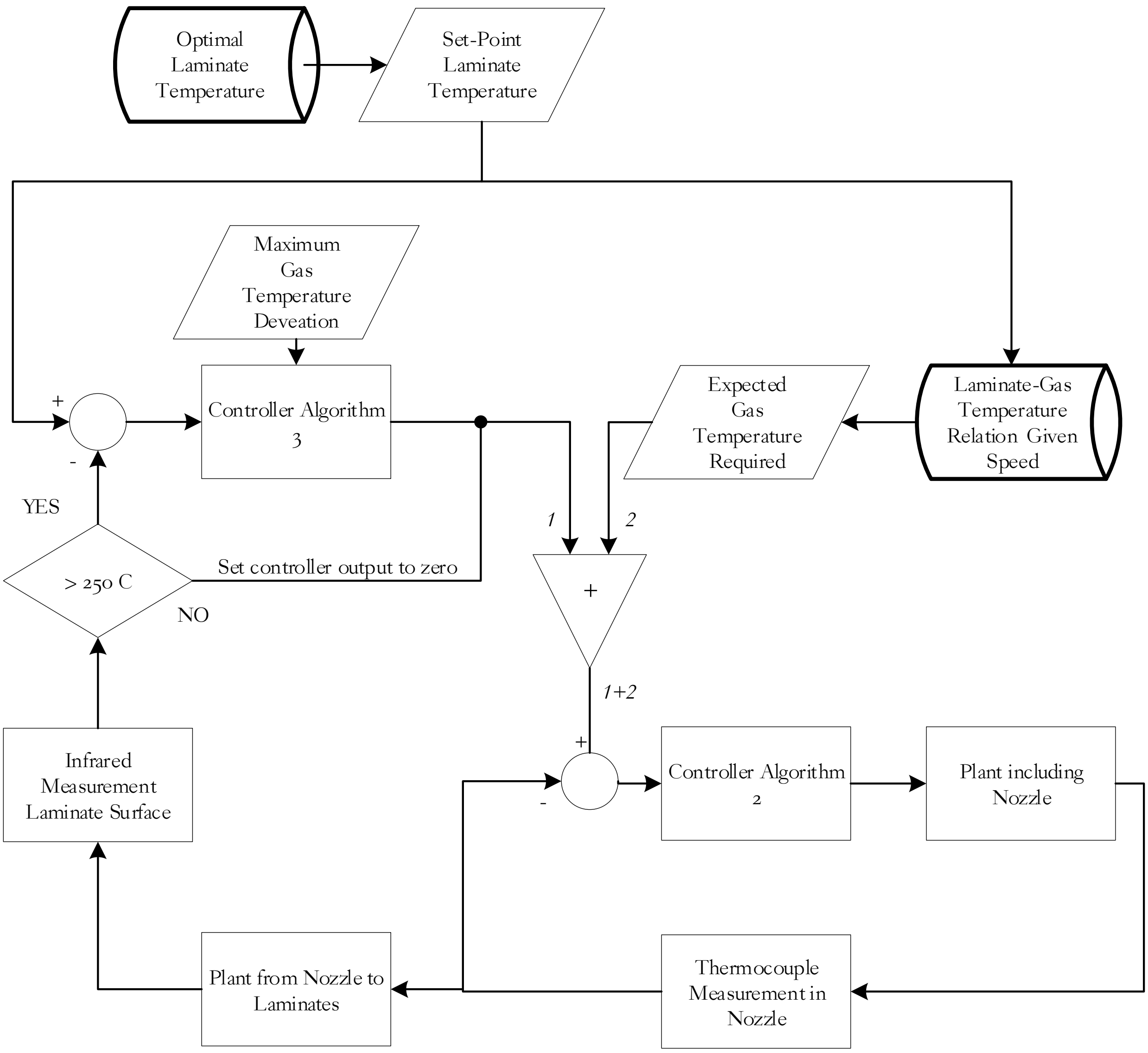


Figure 20: The cascaded controller design prohibits laminate burning at welding start-up.

The closed loop system could be made more robust by using the empirically found data as a baseline for control. Knowing the welding speed, the laminate temperature error is used to tune the gas temperature controller set-point. So two controllers are cascaded to first measure the laminate temperature and then use the laminate temperature error to adjust the gas temperature controller set-point. The adjustment of the gas temperature is using the experimental data as a baseline. The cascaded controller has the ability to set minimum and maximum gas nozzle temperatures and limit start-up effects. The gas temperature set-point can be adjusted for small deviations such as changes in the materials or welding environment.

This cascaded design will be used in the set-up and will be made to work at speeds of three millimeters per second. More welding speeds can be added later, but for now only baseline information is gathered of this speed. The allowable gas temperature range will be estimated and can be fine tuned depending on environmental stability or material changes.

3.1.5 Transition Temperature Effects

After the laminates reach their set-point, they are not directly brought into contact with the filler. First they have to transition into the next section of the welding process during which the heat input from the hot gas may drop significantly. How much time is spent in this intermediate zone depends mainly on the welding speed and the size of this zone meant to measure the laminate temperature using a pyrometer. At higher speeds, the effect of the intermediate zone diminishes, but at lower speeds it may cause the laminate to cool down too much and affect the weld quality. The schematic drawing of the zone in Figure 21 helps to bring understanding to the phenomenons playing a role.

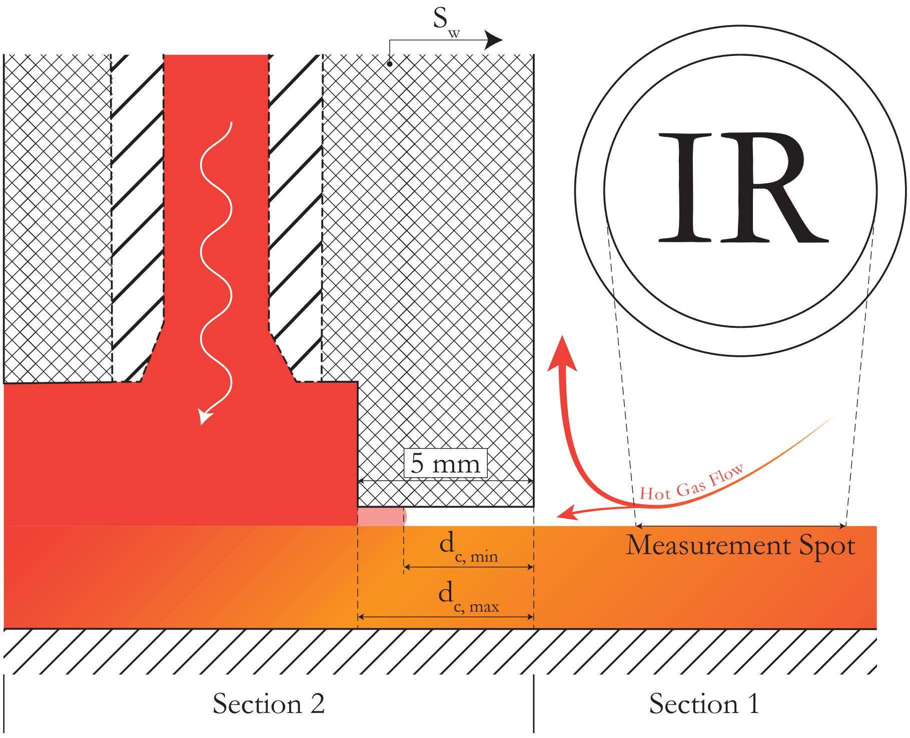


Figure 21: Transition from section one to section two.

The schematic uses the actual proportions of the machine and shows the stiffener laminate that is held in place while the welding head travels over it. The surface of the skin laminate is coincident with the page plane. It is the stiffener laminate that is checked for its temperature by the infrared ('IR') measurement. The measurement spot is positioned at about five millimeters from section two as positioning it closer would introduce radiative interference from the hot components of section two. After the measurement is conducted, the laminates enter a new heating transfer scenario where they are exposed to decreasing amounts of hot gas, increasing radiative heating from the filler heating section and at some point the conductive heating from the PPS melt that may flow under its own mold. This scenario is simpler when the filler heating section touches the laminates. In this case no gas or polymer would flow between the stages and the heat transfer is a pure conductive one. It is best to first quantify the effects of the transition zone and try to see if these become obsolete by increasing the welding speed. This will be done by inserting thermocouples under the stiffener laminate surface (chosen for accessibility). If a significant gas flow separation occurs or whether the radiative heat input has any significant effects will be investigated in these experiments. In any case, the transition zone has been made as small as possible to reduce these effects.

3.1.6 Laminate Heating Requirements

After the analysis that was conducted in the previous paragraph, the requirements put forward in sub-chapter "2.6 Process Parameters Overview" may be refined:

- Measure gas temperature gradient in the nozzle with two points.
- Distance between laminate temperature measurement and filler contact is 10 millimeter maximum.
- Actuation and laminate temperature measurement spot overlap.
- Use empirical gas temperature during start-up instead when there is no laminate temperature measurement.

- Have an adjustable measurement spot size for the laminate surface to facilitate different lay-ups.
- Measure the laminate temperature non-destructively.
- Measure the laminate temperature from 230-280ºC.
- Heat laminates up to 280ºC.
- Use gas flow of 70 LPM.

These requirements will guarantee processing temperatures of the laminates to be in the expected working range of PPS matrices. The points of measurement should ensure accurate data gathering about the material just before it comes into contact with the filler material.

3.2.1 Section Two: Applying the Filler

In this section of the welding head the filler is heated and brought into contact with the laminates. The process of adding the filler material to the laminates is very similar to injection molding processes where molten polymer flows into a new shape and is consolidated under pressure. After the filler is heated, it is forced into the weld volume. This is the space between the laminates and section two of the welding head. The weld volume acts as a mold and determines the geometry of the filler material that goes into the cooling section. Therefore, it suffices to say, that the skin-stiffener scenario is an injection molding problem where the molten polymer flow is supposed to weld together with parts of the mold.
The filler has a higher processing temperature range than the laminates because the material needs to be deformed into a stress alleviating shape. Where the laminates only need to have their surface temperature in a processing range, the complete filler material has to be in melt as it is injected in the weld volume. The filler processing range for injection molding is given by the manufacturer and gives rough boundaries for the process characteristics. The only downside of using this temperature range is that it might well be the case that lower filler temperatures work better due to a higher filler viscosity. This higher viscosity prevents leaking of the PPS flow and helps in building the pressure required to push out all voids in a short time. Therefore, the injection molding range of 310-330ºC is taken as a maximum temperature range requirement for the welding head, but true processing temperatures might fall under the range.
The time required for heating an insulating material through to its core asks for heating zones with considerable length. This length contributes directly to the possible welding speed range of the head. With the filler material, the option is available to place this heating zone perpendicular to the welding line in order to save on the footprint of the section and make it easier to adapt the design for cornering later on. As the filler will be brought into melt, the material flow will be able to bend into the welding line after being heated.
The filler should be heated through to its core to allow for deformation and bending into the welding line after heating. The full surface of the filler will be subjected to an axisymmetric heat input as this is the quickest way to heat the filler through to its core.

3.2.2 Filler heating: The Heater

The filler cannot be directly heated using an hot gas flow as it will have to be brought into a molten state. This would cause elongation or breaking of the filler wire. Only indirect gas heating is possible by heating a hollow conducting structure. The hollow cylindric geometry acts as a support for the material so it can be driven with stable flow rates towards and into the weld volume. As this support is vital for controlling the weld geometry, heating energy destined for the filler will always have to travel through this structure to reach its target. This supporting structure during heating of the filler is called the runner. It is part of the filler mold which also has to deform the filler material into its stress alleviating shape once it hits the laminates. The guiding structure will have to be continuous with the deforming mold to prevent the molten polymer from escaping while being pressurized. The support structure or runner can be heated with either convective, radiative or conductive heat sources.

Convective heat sources will give similar solutions as found in the laminate heating section. Hot gas flows will heat the runner, but uniform heating might prove hard to achieve. Radiative heating with either laser or infrared light sources suffer from the same problem of uniformity. Also, these light sources may have to be isolated from the infrared pyrometer in the laminate heating section to prevent interference. Conductive heating cartridges or spirals are very often found in industry as they are simple to use and powerful. They have to be fitted for a good thermal bond between heater and workpiece. Thermal paste can be used to fill the volume between the workpiece and the heater with conductive material, but can generally only go up to around 200 degrees Celsius. Therefore, correctly reaming the fitting hole is of great importance with higher processing temperatures.

For this machine, conductive heating has been chosen as the major heat source regarding filler heating. The main reason was simplicity in the mold temperature control and measurements and inherent uniformity in heating due to the diffusivity in the conducting material.

The runner is chosen to be a simple stainless steel tube with an inner diameter of three millimeters and an outer diameter of ten millimeters. This tubing is made easily replaceable with set screws so that in case of damage, stuck polymer or pollution, the machine can be repaired with little effort. The filler runner also lends itself well for conductive heating as it can be placed in cylindrical holes. A simple uniform heating solution is therefore found in conductive heating sources. Different form factors exist to allow for multiple ways of gaining contact with the target. In case of the filler runner, two options for conductive heating are available: spirals and cartridges. These options are depicted in Figure 22. The spirals are isolated resistive heating wire wound around the target. In most cases, such elements have to be wound on order which makes them expensive. Thermocouples are placed near the outer surface of the spiral to get an estimation of its inner temperature. When the spiral is wound using round wires, the contact between the runner and the heating element is a line contact. This limits the heat transfer between the two. Therefore, rectangular wire can be used for these elements which significantly increases the contact area between the runner and the heater. The wound wire consist out of a thinner CrNi-steel wire surrounded by electrically isolating, but thermally conductive powder. The powder is contained in a thin walled steel housing. The construction makes the spiral fragile and the heating element is therefore less applicable in a research oriented set-up which will inevitably require intensive maintenance after tests fail.

An alternative for the spiral is the use of standard heating cartridges. These heating elements are connected to the filler support tube through a steel solid block and are about a factor ten cheaper for the same power rating compared to the spiral wound alternative. The block diffuses the heat output of the cartridge before it reaches the filler tube. The heat input will therefore not be as uniform as with the spiral, but will still allow for simple, reasonably uniform heating which is above all easier to maintain. For now, the assumption of uniform heating is made as the thermal conductivity of the steel is two orders of a magnitude higher than the thermal conductivity of the PPS that is heated (Sietsma, 2020). Thermocouples are now mounted in the steel block around the runner. Although the sensors are close to the runner, the temperature of the frame will now be controlled.

To summarize, because the cartridges are standard solutions and the uniformity of the runner heating will probably be sufficient, heating cartridges are chosen as the heating source. The design is made to be adaptive to fit a heating spiral in case of lacking uniformity. The preference over standard heating cartridges is based on maintainability. The cartridges are less fragile and are easily replaced as they are standard parts with wide availability.

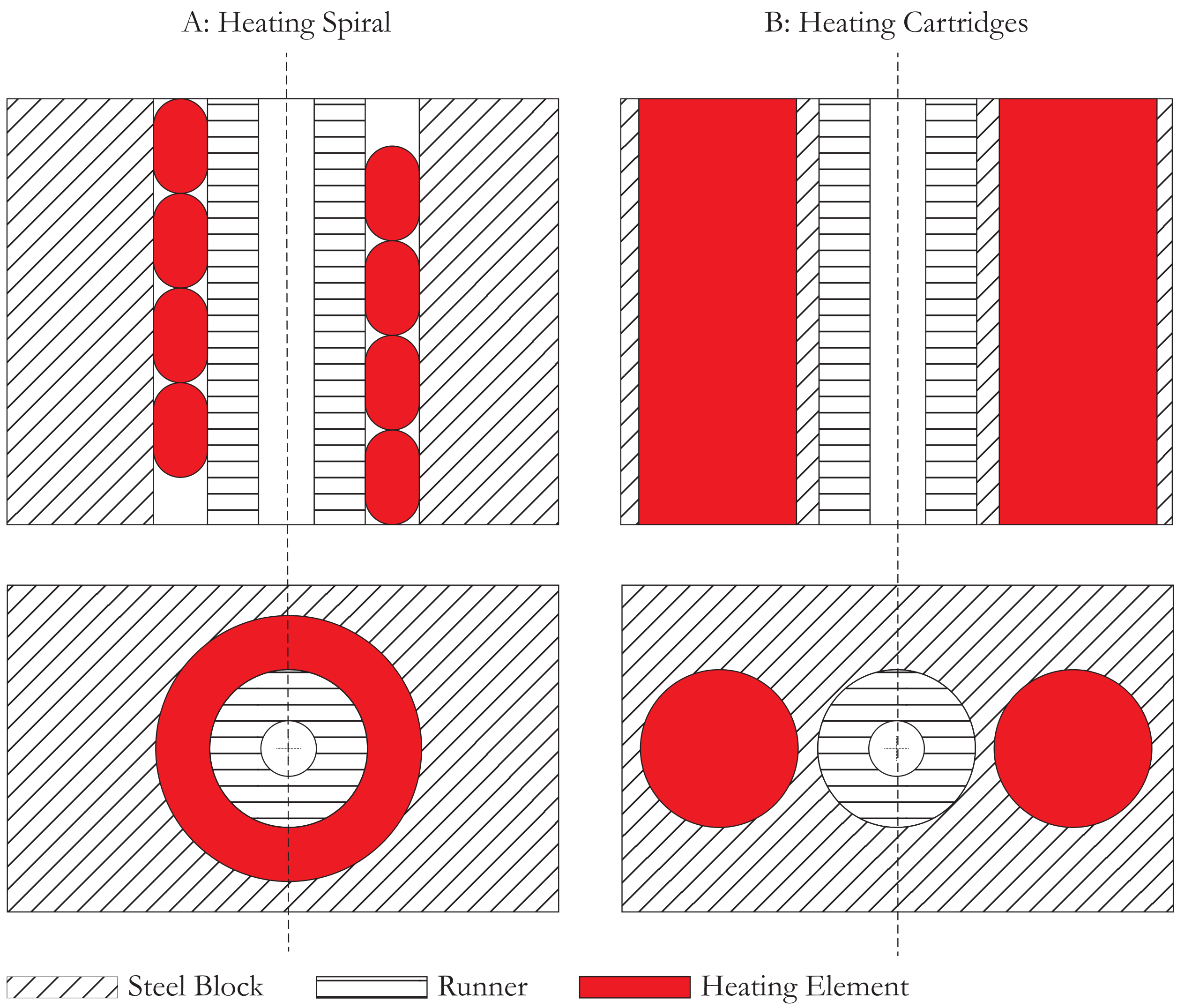


Figure 22: Two available heater concepts for the runner and filler.

The steel block is designed so that two heating cartridges are fitted symmetrically next to the runner. The heating cartridges do not reach completely down to the end of the runner which causes a temperature gradient over the length of the tube. This gradient has to be measured using multiple thermocouples as it provides an understanding about the filler heating and possible cooling in the runner. As the heating elements cannot go completely down with the runner, the lower region of the mold is intentionally subjected to the hot gas flow of the laminate heater. This will limit the cooling of the mold near the weld volume. A thermocouple will be placed at the lowest point of the block to make sure that the runner temperature is checked where the filler exits into the weld volume.

3.2.3 Filler Mold behavior

The filler rod is driven down into the heating section through a widened section of the runner. The widened section ends five millimeter deep into the heated steel block where the two heaters and the runner are housed. After the widened section, the inner diameter of the runner quickly closes in on the filler rod which starts heating through conduction. The inner diameter is lowered in the block to define a clear heating zone. Using Figure 23 to illustrate the problem, first consider scene A. Here the filler travels downwards over the dotted, vertical line as it reaches the smaller inner diameter. Once it is at frame height h_b, the surrounding runner is not at the block temperature. In scene B it is. This geometry just ensures that the runner has the same temperature as the block thermocouples. This helps in predicting the temperature of the filler once it exits the runner.

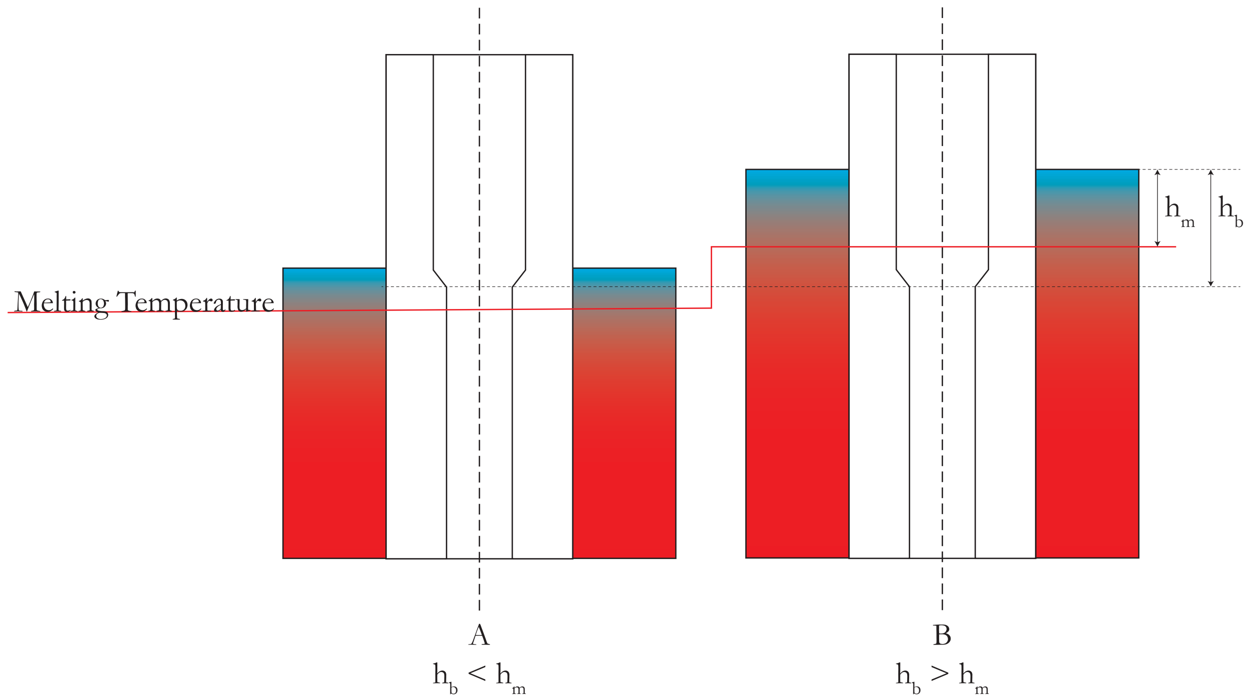


Figure 23: Placing the smallest inner diameter well within an environment which is above melt temperature (B).

The filler will exit the runner in a completely molten state and will fill the volume between the mold and the laminates, also known as the weld volume. The aim for this machine is to bring the complete filler material into its processing range with minimal thermal gradients. A uniform temperature of the filler will make more consistent welds as it does not matter which part of the filler makes contact with the laminates first. With a temperature gradient in the filler, hotter sections of the filler may thermally degrade while colder sections will lack the energy for interdiffusion at the interface. Because a single-sided welds cross-sectional area is larger than that of the filler rod, the filler feed velocity will be larger than that of the laminates. This velocity ratio between the materials has a quadratic relation with the chosen filler radius. Using a radius of 6 millimeters, which was also used in the autoclave T-joints of Fokker, the velocity of the filler into the heater will have to be about two-thirds higher than those of the laminates.

Sietsma (Sietsma, 2020) modeled the filler temperature gradient through the heated runner and experimentally validated his results. In his own research, a fifty millimeter long mold was used during experiments and proved incapable of reaching the processing temperature range at a feed rate of 10 millimeters per second. To increase the filler feed rate range, the heated zone length was extended to 117 millimeters in the actual welding head which would give the radial temperature profiles in Figure 24 of the exiting filler using the model of Sietsma.

In short, this model simulates the heating of the filler without taking the sticking of molten polymer onto the runner into account. The filler has an even flow front and thus travels uniformly through the complete heating zone. This means that the temperature gradient in Figure 24 is underestimated. The true temperature of the filler will probably be closer to the frame temperature on its outer surface.

In this simulation the runner temperature is set to be 330ºC over the full heating zone. This is the upper limit of the processing temperature supplied by the manufacturer (Celanese, 2019). Multiple welding speeds are simulated to see how the core of the filler will lack behind the outer walls. It seems that a filler feed rate between nine and ten millimeters per second causes a temperature difference of about 15-25ºC. This is the maximum expected feedrate for a welding speed of three millimeters per second and causes significant temperature deviations in the weld. The temperature deviations can, in turn, cause cooling rates in the weld to differ as well. The true nature of the effects of this non-isothermal scenario will have to further investigated with the real set-up.

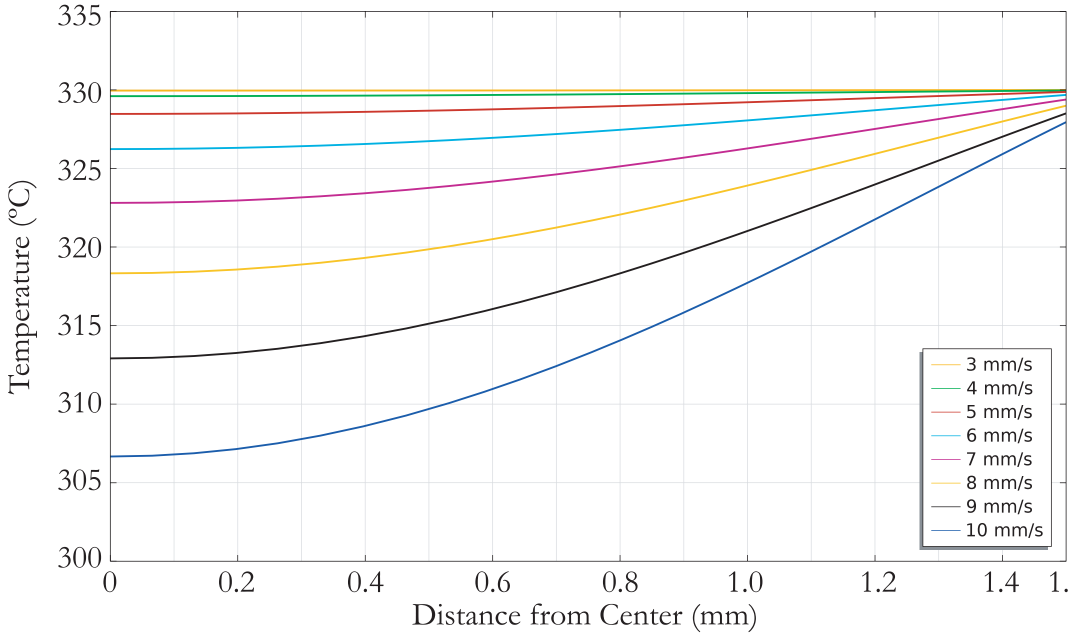


Figure 24: Temperature gradient of the filler from its core to its outer surface.

Increasing the mold temperature can help in bringing the filler core up to speed quicker. It will also introduce larger temperature gradients in the filler once it exits the runner. The aim of the heating system is to supply filler material in the correct temperature range with a minimal temperature gradient. All simulations have their outer surface heated to the same temperature as the runner. Therefore, the runner cannot deviate far from the intended processing temperature and the only option for heating the filler towards higher temperatures is by increasing the exposure time. This can be done by using slower filler feed rates or longer heating zones.

This heating behavior of the filler will be validated using experimental data further in the report. For now it is important to note that the control system can use this data to control the filler temperature as it is validated. The following paragraph will go into detail concerning the control system of the filler temperature.

3.2.4 Filler Heating: Measurement and Control

As the filler travels towards the laminates, it is desirable for the flow inside the mold to be unobstructed. Obstructions in the filler flow increase the chance of thermal degradation by extending exposure times to the elevated mold temperature. Filler material may get stuck in the heater and eventually find its way into the weld. Once a degraded piece is in the weld, it can be hidden from inspections while weakening the joint. To guarantee a consistent weld quality, no sensors should be placed in the filler flow itself to monitor its temperature as these sensors can be seen as obstructions to flow. Sensors can only be placed in the runner or in proximity to it as the sensor diameter is around the same as the inner diameter of the runner. Placing a sensor with such proportions in direct contact with the filler will always obstruct flow. This means that once the solidified filler rod enters the mold, no further direct measurements can be done to the material until after it appears from under the welding head. Any controller will thus have to be indirect and the closest possible control target is the runner temperature itself. Sietsma's thesis concerns the relation between runner temperature, filler feed rate and the resulting filler temperature gradient. An example of his model is presented in the paragraph "Filler Mold behavior". Using his validated findings, an indirect filler temperature control system can be developed that leaves the runner free from obstructions.

The basis of this control system is controlling the runner temperature. As a reminder, the runner is nothing more than a tube with an inner diameter just slightly larger (0.2 millimeter) than the cold filler diameter. This tube gets heated at its outer surface by a heated block and transfers the heat into the filler rod. Because non-isothermal welds require separate set-points for separate temperature controllers, a new heating source for the runner was added. This is simpler than controlling both the filler runner and the laminates with the same hot gas source and enables

the use of the better suited heating cartridges.
So the aim for the control system is to control not the filler itself, but the runner structure surrounding the flowing polymer. Three thermocouples will be placed near the runner to measure its temperature gradient over the heating zone. The thermocouples are placed behind the filler path, opposing the heated wall of the hot gas (Figure 25). This will give a more realistic view of the temperature gradient. Because only a single parameter, the input power into the heating cartridges, can be used to control the frame temperature, only a single input can act as the process variable. The filler control schematic is found in Figure 26. The process variable is chosen to be the middle thermocouple in the heating zone (Figure 25, thermocouple 2). The other two thermocouples are only there to analyze the temperature gradient of the block and thus the runner. This data helps improve the filler heating model predictions made by Sietsma.

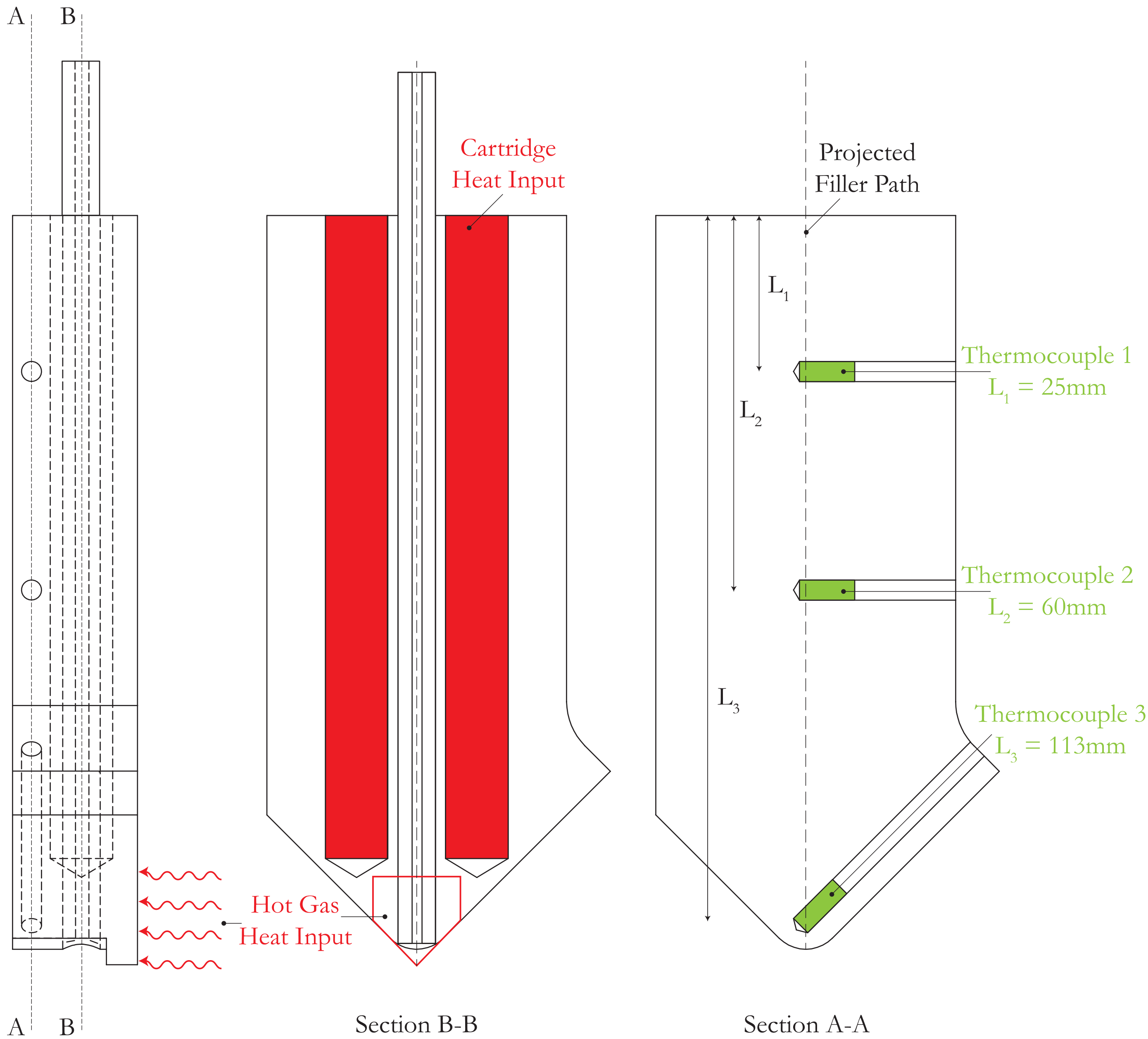


Figure 25: Measurements and actuation in the filler heating section.

The middle thermocouple was chosen as it is the best isolated sensor in the section. Because an open loop approach is taken in this controller design, the measurement input is chosen with the least disturbance. At the bottom of the heating zone, the mold is exposed to the flow of hot gas of the laminate control system. The gas

temperature will be fairly constant during straight welds with constant velocity, but will vary with welding speed. A change in gas temperature will mean a change in environmental temperatures of the filler control system. As the control system is open-loop, it will not be able to cope with these disturbances.
The third thermocouple provides the user with process data that is hard to predict due to its complexity. The heating cartridges are placed so that the overlap between the hot gas heating and the joule heating is minimal in the filler heater. This hopefully limits the temperature gradient in the filler heating zone.

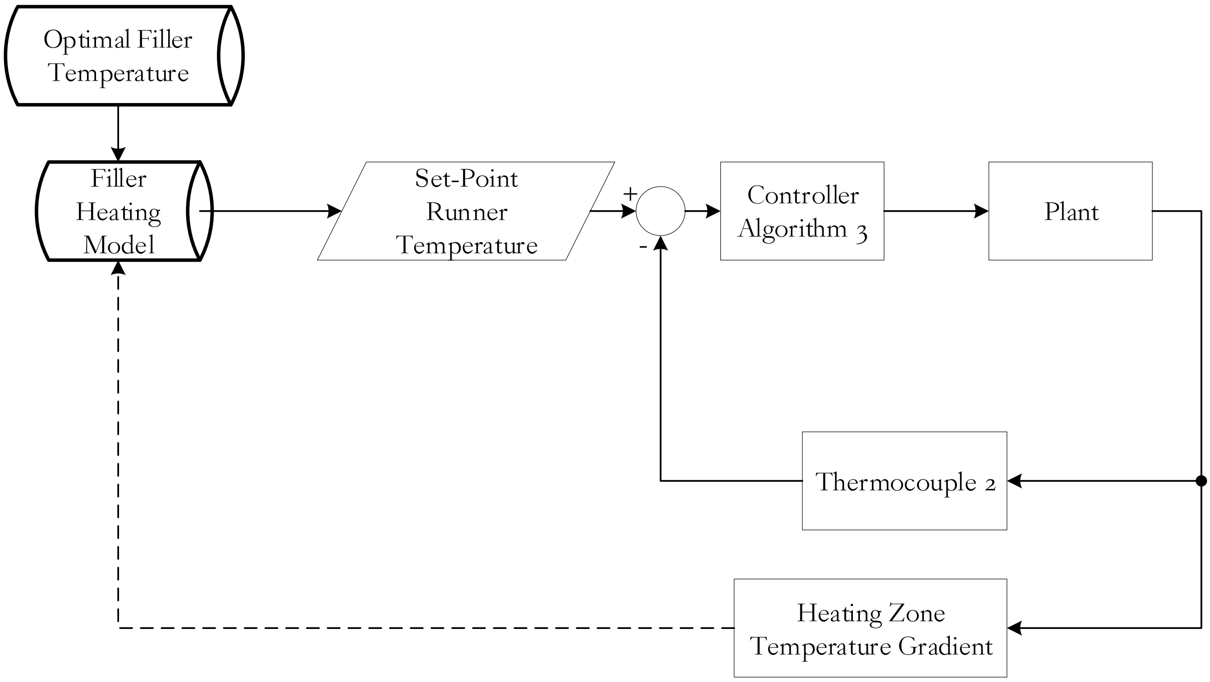


Figure 26: Open-loop filler controller.

3.2.5 Filler Deformation and Flow

After both the heated filler and the laminates are brought into contact, the filler is deformed into its stress alleviating shape. The molten filler material enters the weld volume and comes into contact with the laminates while both are in their processing temperature range. As the weld volume fills up with filler material, the pressure on the weld increases. This pressure forces out voids in the filler material and on the interface of the weld. This process is illustrated in Figure 27, from the moment the filler comes out of the heated runner to the moment the weld is performed.

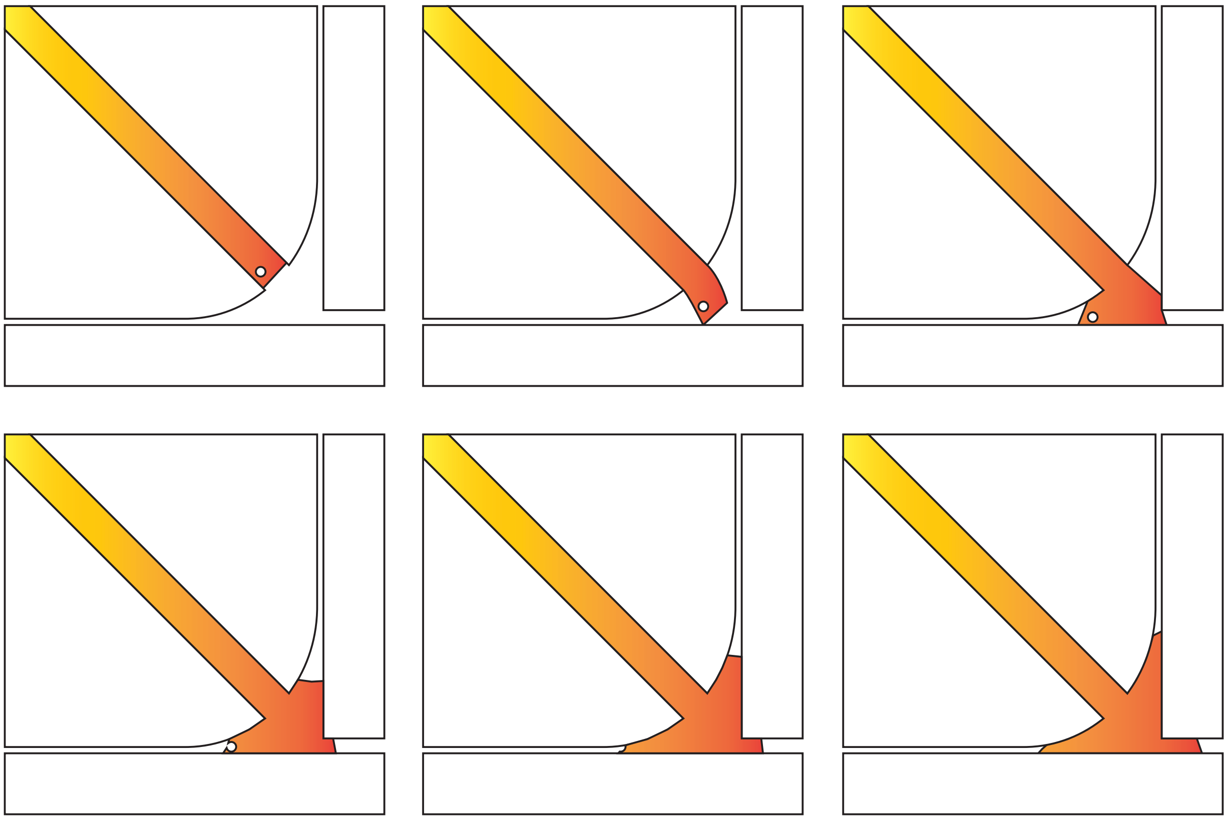


Figure 27: Filling of the weld volume by the filler.

Voids in the filler material induce stress concentrations under loading and can impact the weld strength. Voids on the interface also induce stress concentrations and limit the degree of contact between the filler and laminates. The pressure on the filler while flowing into the weld volume will have to be monitored as it is related to the amount of voids in the weld and the degree of intimate contact. Unfortunately, direct pressure measurement is not possible in such a hot and confined space as the weld volume with a radius of six millimeters. A much simpler approach is measuring the force on the welding head that is required to hold it in place as the filler is deformed under it. This is done by suspending the section on a load cell and a single degree of freedom linear guidance. The guidance ensures the load cell is loaded in a single direction. The measurement is ideally conducted as in Figure 28.

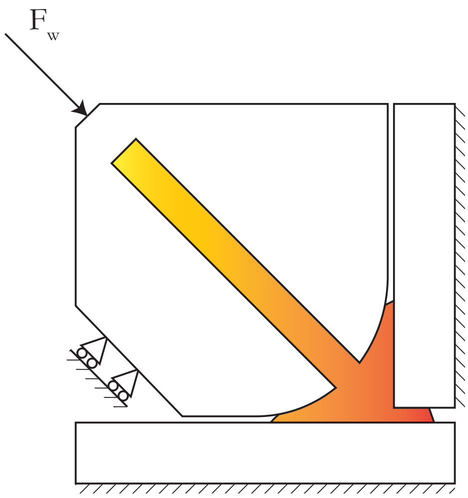


Figure 28: Welding force as an indicator for the pressure on the weld.

One of the few requirements for this set-up is to acquire a constant welding geometry. It is therefore required to stabilize the welding force without varying the welding geometry when the shoe is not in contact with the laminates. As temperatures are also required to remain constant, the only parameter left to control the welding

force is the ratio of filler feed rate and the welding speed.
Adding more filler material into a set weld volume would increase pressure on the joint, but the weld volume is not always set during single-sided welding. As can be seen in Figure 28, filler material can simply flow out from underneath the space between the laminates and the mold if the tool does not touch the laminates. The filler can solidify between stiffener and skin during single-sided welds if the laminate surfaces are cold enough or close enough to each other. This happened during test in revolution 3 of the T-CAT welding machine. The right image in Figure 29 shows the filler flowing only about one millimeter under the stiffener, probably because the laminates were too cold there and solidified the polymer flow. Not too much attention was given to this problem as it only arises due to a too small skin-stiffener distance (~0.2 millimeter) and the geometry of the stiffener.
The opening between the laminates is only part of the closed volume problem. There remain two possible exits for the filler material flow. These are between the welding head and either of the laminates. The welding head should therefore come into contact with the laminate as it would prevent leaking of the filler. It is unclear whether this is possible as the filler heating section might be too hot to place on the laminates. Heating the laminates above melt might damage them. Samples produced with previous set-ups showed that this distance does allow for the polymer to keep flowing in-between. This effect is also shown in Figure 29. The relation between the welding head-laminate gap, the welding force and the flowing behavior of the PPS will have to be characterized in the single-sided set-up by leaving no space between the two laminates. The flow underneath the stiffener is blocked by the opposing flow front during double-sided welding. Previous results show that the PPS has a low melt viscosity and thus flows easily. Therefore, to prevent leakage between the welding shoe and the laminate, the low viscosity is a disadvantage. PAEK polymers will have a higher viscosity which can help in limiting the flow distance. Also, short fiber reinforcements can bring the viscosity down.

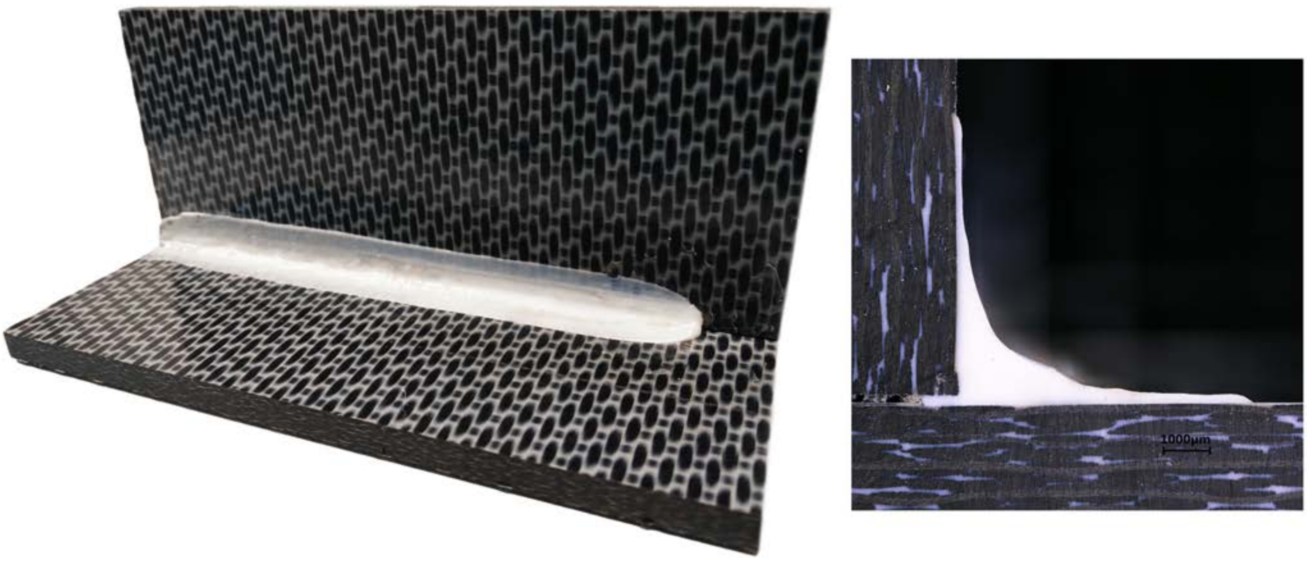


Figure 29: Sample welded with T-CAT REV3. Filler radius of 3 millimeter.

The impact of the weld force will be determined in the testing phase. Using this data, a minimum weld force boundary can be selected and the need for a control system can be assessed. It remains unclear if weld force control is required to keep the weld force above a minimum and weld strength consistent. As temperature, feed rates and weld volume are already held constant over the weld, the control system would only have to compensate for variations in the extruded rod such as diameter and voids. The control algorithm that is proposed here (Figure 30) is a simple closed-loop controller with output boundaries on the filler feed rate output.
In T-CAT revolution three the filler was gradually molded into its final geometry at the end of the filler heater (appendix B). In revolution four the whole underside of the welding head is parallel to the laminates which does not allow for gradual pressure increases. A small but steady decrease of the weld volume would help during shrinkage of the polymer in maintaining contact with the filler and creating a smooth weld surface. This tapered

design was not used because the filler might solidify too early and cause the welding head to get stuck. Once more is known about the cooling kinetics of the filler, a taper can be included in the filler heater section.

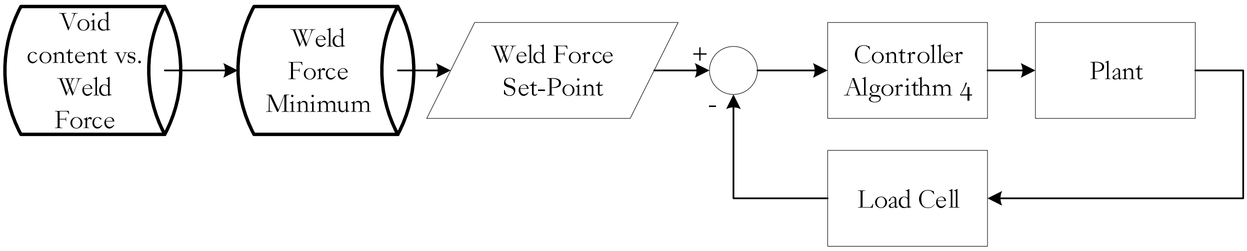


Figure 30: Weld force controller.

3.2.6 Filler Heating Requirements

After the analysis that was conducted in the previous paragraph, the requirements put forward in sub-chapter "2.6 Process Parameters Overview" may be refined. The requirements of the filler heating section are:

- Design for filler diameter of 2.85 millimeter (standard 3D printing size).
- Support the filler material to overcome buckling.
- Measure runner temperature at three points.
- Minimal length of the runner is 110 millimeters.
- Design clear start for filler heating section for simulation purposes.
- Filler temperature above 280ºC at feed rate of 10 mm/s.
- Filler heating path should be straight.
- Have a replaceable runner.
- Restrict filler flowing into the laminate temperature measurement spot.
- Filler geometry should have a 6 millimeter radius.
- Measure runner temperatures up to 330ºC.

These requirements will ensure a filler rod to be heated to at least its melting temperature at its maximal feed rate of 10 mm/s. The filler will be pressed into a stress alleviating shape by the welding head using a welding force. The requirements of the welding force are presented in the next paragraph. To make sure the filler heater will not get stuck, the filler path is set to be straight. This ensures that material can be pushed out the heater afterwards. If material still gets stuck in the runner, the whole device should not be damaged. The runner is easily taken out and replaced by a new piece of tubing.
The complete filler section is made to work with 3D-printable sized noodles with a diameter of 2.85 millimeters. This is because it is expected that PPS filaments will be become more widely available in the 3D-printing community in the future.
The heating length of the runner is determined by the model of Mante Sietsma. The simulation software requires a temperature gradient of the runner, the length of the runner and the speed of the filler rod to give a filler temperature profile. All these inputs are known when these requirements are taken into account.

3.2.7 Weld Force Requirements

After the analysis that was conducted in the previous paragraph, the requirements put forward in sub-chapter "2.6 Process Parameters Overview" may be refined. The requirements of the weld force system are:

- Let the load cell remain below 70ºC.
- Measurement range of 0-200 Newtons
- Provide 1 DOF guidance to load cell over full temperature range of the welding head.
- In case of linear bearing guidance use seals against contamination.
- Vary distance between welding head and laminates between 0 and 1 millimeter.

The weld force requirements focus on keeping the load cell within its given working temperature range. The measurement range is determined by experiments on the final set-up and was adjusted with hindsight. It is important to stress that the distance between the welding head and the laminates can be varied, but is expected to remain zero. In other words; the welding head should touch the laminates during welding to make sure that the filler has no way of leaking out of the weld volume. This can only be done when the bottom of filler heating zone is not above the melt point of the laminates as this would possibly damage the material. Ideally, the filler heating section touches the laminates while it has the same temperature as the set-point of the laminates.
At a last note, the filler heating section does not gradually push the filler into the stress-alleviating shape. The volume under the welding shoe is constant at all times. In future versions this might have to be adapted to make sure the filler is pressurized at all times as it is cooling down. Where the volume under the welding shoe should shrink is unclear. It will most likely be in the insulating section as it is here that the largest temperature gradient is present.

3.3.1 Section three: Cooling

After the materials are brought into contact and the interface is around or above melting temperature, only a fraction of a second is needed for interdiffusion at the interface. Once this intermolecular interdiffusion has taken place and the filler has filled the weld volume, the joint is ready to cool down. Because only small distances will be welded, the choice was made to design a passive cooling system which is the simplest cooling system in terms of maintenance. So after the polymer is driven onto the laminates, the welding head travels further over the joint with an isolation plate of ten millimeters thick and a passive cooling block. Thus, the cooling will be done partly through the laminate clamping system and partly through an aluminum cooling block placed on the filler material. As the filler is the hottest part of the weld, it makes sense to add a dedicated cooling apparatus here.
The aluminum block is suspended onto two press-fitted stainless steel shafts, meant for the linear bearings. Between the filler heater and cooler a ten millimeter thick ceramic sheet is clamped to isolate the two with an extremely small thermal conductivity of 0.3 W/mK.
The aim is to bring the complete joint temperature far enough under the melting point so that the structure co-consolidates. An estimate for the cooled target temperature was set at 200ºC. The bulk of the filler material is heated to a 330ºC maximum, so a maximum cooling temperature difference of around 130ºC is expected. With the fact that a cooling rate of 20ºC/s is the maximum while allowing the PPS to crystallize, a cooling trajectory of a minimum 6.5 seconds is required. With the maximum welding speed of three millimeter per second, this would give the cooling path a length of 20 millimeters to cool the joint at a constant rate while allowing it to crystallize. The cooling length was thus set at 40 millimeter (safety margin of factor two) under the assumption that the joint cools at a constant rate.
To cool the material, heat will have to transfer out of the material. Another assumption was made that the laminates will lose their energy through the clamps and the filler will loose most of their heat through the cooling block. As a six millimeter filler radius was chosen, the area of the filler cross section is about 10 mm^2. With the length of the cooling zone set at 40 millimeters, this gives a filler volume of roughly 400mm^3. Using a PPS density of 1350kg/m^3 this results in $5{,}4 \cdot 10^{-4}$ kg of PPS with a specific heat of 1516 J/kgK. For a temperature difference of 130ºC the cooling block of 40 millimeters long will thus have to continuously guide 106 Joule out of the filler. At the maximum welding speed, this energy will have to transfer within 6.5 seconds, thus giving a distributed heat input into the cooling block of maximum 16 watt.
A steady-state simulation was carried out in Solidworks to get a rough estimation of the temperature profile of section three. This is done to make sure that the load cell was not subjected to temperatures exceeding its operating

range of -10 to 70ºC. The results come from the FEM package of Solidworks and are displayed in Figure 31. A temperature boundary of 330ºC was set on the outer surface of the ceramic and the heads of the bolts into the aluminum. A convective temperature boundary of 15W/(m^2K) was used for the surfaces exposed to free flowing room temperature air and the upper face of the load cell was kept at 20ºC by its connection to the frame. The 16 watt heat input into the cooling block was only fed into the aluminum and not into the ceramic as this is where the filler can release the bulk its energy. In the steady state condition, the load cell does not exceed 60ºC. This is just within range, but it should be noted that the steady-state is only reached after about one hour.

The resulting temperature profile from the simulation (Figure 31) shows a steep temperature gradient in the ceramic which is expected from such an isolating material. This layer is required to keep the load cell within its operating temperature range, but may cause the filler to cool too rapidly once it comes into contact with the aluminum. This problem could be solved by controlling the temperature of the aluminum which is in direct contact with the filler. This will require further investigation.

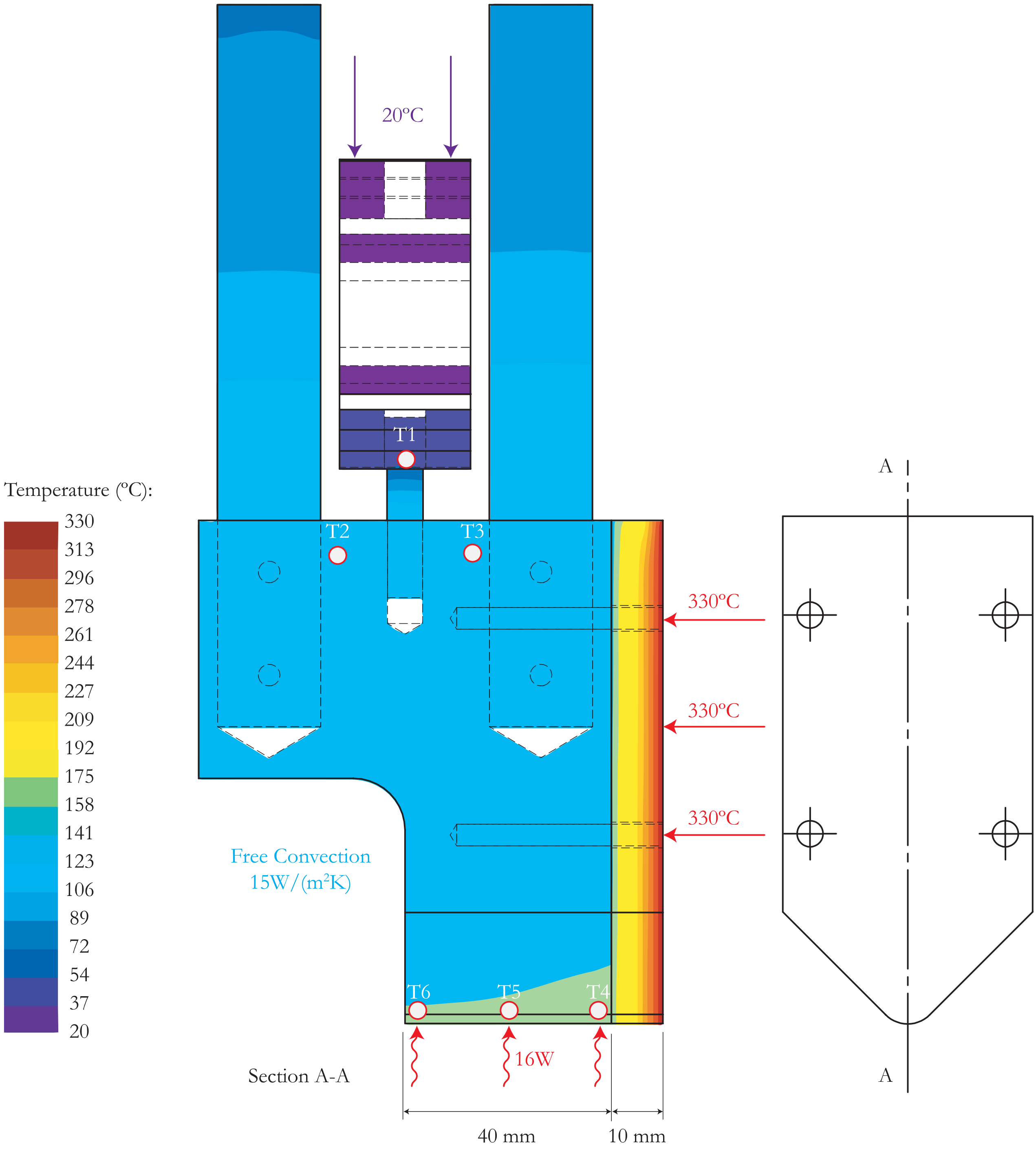


Figure 31: Steady-state temperature of section 3.

The cooling block is required to stay at least below 200°C during welding. As a weld will only take between one or two hundred seconds to complete, it is expected that the machine will only run for about five minutes at a time. This includes the transient cycle of heating both section one and two. As the steady-state of the cooling block is only reached after about one hour and the time required for the machine to be used is a factor lower, the transient behavior of section three was simulated as well. An initial material temperature of 20°C is used for the complete section except the 330°C outer surface of the ceramic plate. This simplifies the model by giving the filler heater its set-point temperature from the beginning. This will cause the model to over predict the temperatures in the section versus time, but that is not a problem for this rough estimation to see if the material stays cool enough. In Figure 31, six points are marked on the section plane whose temperatures are plotted in Figure 32. T1 shows the maximum load cell temperature laying well within range in the first five minutes. T2 and T3 are the temperatures of the two shafts. These shafts are placed in the cooling block with a 37.6 millimeter wall-to-wall distance. Using

a linear coefficient of thermal expansion for aluminum of $24*10^{-6}$ m/(m°C) the shafts will separate about 0.03 millimeter after five minutes. This expending distance is well within the tolerance of the linear bearing.
The temperatures close to the interface filler-cooling block T4, T5 and T6 stay below 200ºC in the simulation. In this simulation their respective temperatures lay close to each-other as the heat from the filler is evenly distributed over the bottom of the cooling block. In reality, the heat input distribution will shift to the beginning of the cooling zone where the temperature difference between the mold and the filler is the largest. This would induce a temperature difference over the cooling zone that is not visible here.
It seems that the cooling block has more than enough capacity to pump heat out of the joint during brief welds. In a production setting where the machine would have to be running continuously, passive cooling would not be acceptable, in a view to provide the design with consistent time-independent cooling. However, it shows that the primary function of cooling is fulfilled in a first instance. It prevents damaging the load cell and the linear guidance while providing cooling to the joint over a length that should allow it to crystallize. Whether the material indeed cools consistently over the full length of the weld will have to be further investigated.

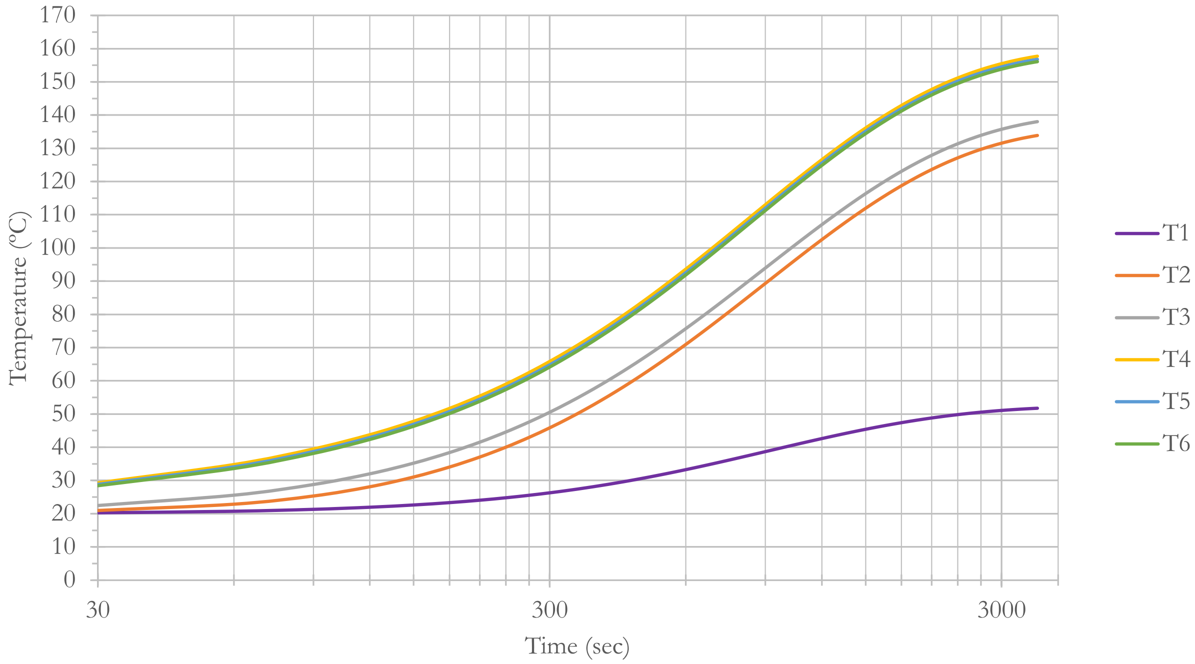


Figure 32: Transient temperatures probed in section 3.

A simple improvement to the cooling system would be to split the cooling into two isolated parts. One that is in contact with the joint and one that holds the shafts and load cell (Figure 58). The part in contact with the joint would be controlled to always be 150ºC to at least guarantee consistent cooling behavior.

3.3.2 Cooling Requirements

After the analysis that was conducted in the previous paragraph, the requirements put forward in sub-chapter "2.6 Process Parameters Overview" may be refined. Requirements for the cooling section are:

- Have a constant weld volume using a radius of 6 millimeter for the filler.
- Use Passive cooling to reduce complexity.
- Leave room for heating cartridge to bring the bottom of the element up to 200ºC.

This will be the first time that T-CAT is equipped with a cooling section. Not much is known about the cooling of the laminates, so it would be preferred if the cooling section is not too long. In the best case scenario, the cooling section is just long enough for the laminates to reach 200ºC. In that way, an IR-camera can be placed behind the cooling block to confirm this and the required length of passive cooling is found for a specific cooling block temperature. Luckily, the cooling block does not have to have the perfect length right away. Incorporation of the thermocouples in the laminates or on the interface can measure the cooling behavior locally as well.

It is most important to make sure that the cooling section does not get stuck on a solidifying filler. Therefore, the volume under the cooling section will have to remain constant.

There is a possibility that the cooling section will not prove to work consistently. When this happens a heating element may help to bring the cooling block up to a constant temperature. This will at least provide the weld with constant cooling over the length of the weld.

Chapter 4:
Process Control Performance

Without knowing clear requirements and details of the desired joint, there is no way to set detailed requirements for the controller. Where a structural part may require tight tolerances and cannot have an overshoot in process temperature, a non-structural part may allow for such deviations to take place. Therefore, the term controller validation really has no meaning unless weighed against set requirements. As the goal of the set-up is to produce controlled welds by controlling its process parameters, a controlled weld needs to be defined first by setting permissible errors in weld performance. This can only be done with the end product in mind.
Still, to get an idea of the potential of the developed process control and the set-up, feedback control regarding process temperatures is tested in this chapter. In this way, the impact of stabilizing process parameters on weld consistency can be inspected and improvements to the current set-up can be formulated.
Four welds are conducted in this chapter. These welds were proceeded by numerous welds to get a better understanding of the machine. Pictures of the set-up are presented in appendix D on page 81 to give the reader a better picture of how the set-up functions and how the welding head is moved over the clamped laminates.

4.1 Laminate Temperature Control

As argumented in “3.1.4 Hot Gas Heating: Measurement and Control”, the laminate temperature controller has a two-stage, cascaded design. First, the gas flow temperature is controlled to an experimentally determined set-point and the set-point of the hot gas is then adjusted by the pyrometer measurements to compensate for a drift in the laminate temperature. This reduces start-up effects and makes it easier to tune the control system heuristically.
An air flow of seventy liters per minute has a temperature step response as can be seen in Figure 33. Here the heater is fully powered at zero seconds and shows a response that can be estimated with a first order plus dead time (FOPDT)model. Using the FOPDT parameters and the heuristic tuning guidelines of Skogestad (Skogestad, 2001), the gas temperature is controlled using a simple feedback controller.

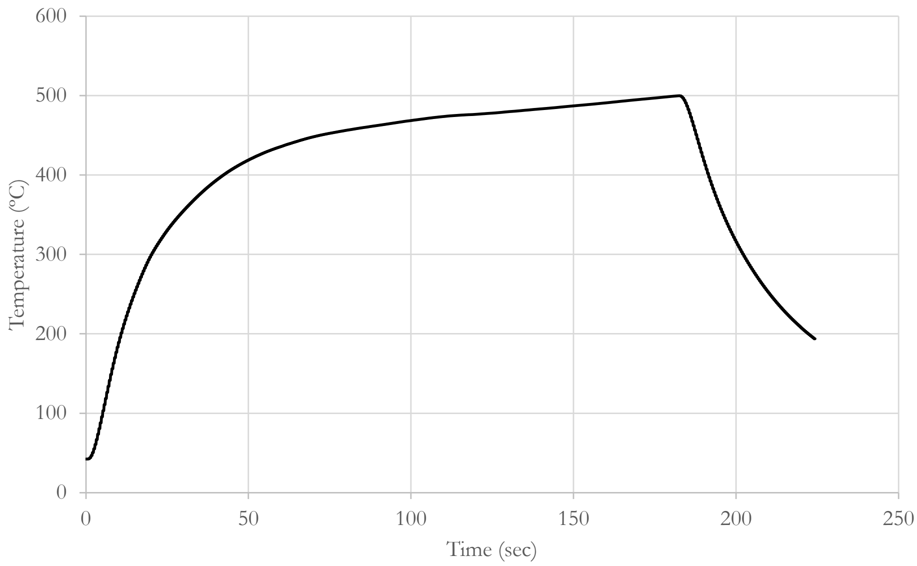


Figure 33: Step response of gas flow in the heater nozzle.

With a set gas flow rate of 70 LPM and set welding speed of 3 mm/s the hot gas flow was aimed at the laminates while being heated to different temperatures. Only a few data points are needed to find a rough linear relationship between gas and laminate temperatures at a given welding speed (plan from Table 2). This relation is enough to give the laminate temperature controller an offset where it can work around. In Figure 34, the case of woven carbon PPS plates of two millimeter thick is presented. This relation is only valid for a specific laminate on this specific machine (mainly dictated by the way of clamping the laminates). Data points are gathered around the expected temperature range of the laminates. Keep in mind, that only the stiffener laminate is measured with the pyrometer. The blue points refer to the experiments where a controlled gas flow temperature resulted in an average laminate temperature. The red points were later added to confirm that when the laminate is controlled to be at a certain temperature, the relation is still valid.

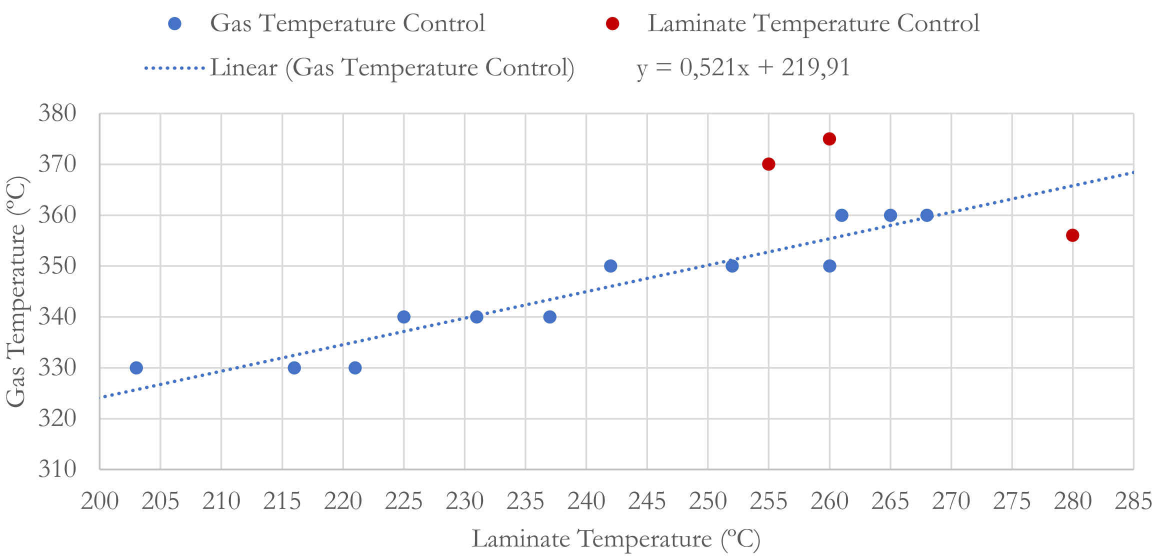


Figure 34: Relation between gas and laminate temperatures.

The need for feedback control of the laminate temperature rises mainly from the fact that during preheating of the welding head, parts of the laminates get exposed to the hot gas that escapes from the preheating station. This causes the laminates to be pre-heated at the start of the weld. This effect can be seen during a typical weld as shown in Figure 35.

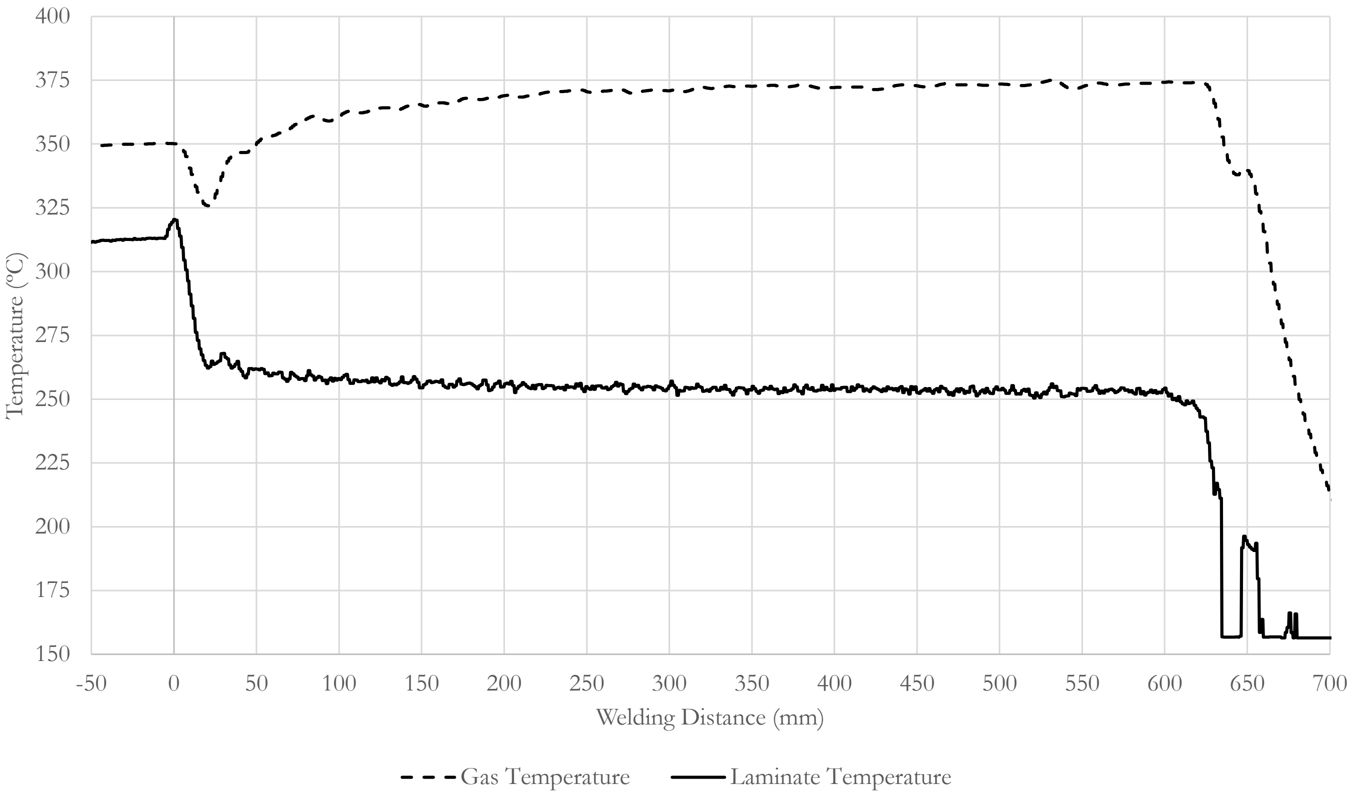


Figure 35: Automated control of laminate temperatures by changing the gas temperature.

The measurements in Figure 35 show the controller compensating for the laminate section that got pre-heated together with the welding head before the initiation of the weld. The cascaded controller is activated at the zero mark on the x-axis and limited to use gas temperatures of 355 ± 20ºC as it tries to bring the laminates up to 260ºC. The control action of adjusting the gas temperature to regulate the laminates has only got a proportional feedback loop. The lacking integral action explains why the set-point is never reached. For now, a stable laminate temperature proves the working principle of this controller design. With this simple cascaded controller design without an integral action the final temperatures after start-up (after 150mm in Figure 35) lay between 254 ± 3ºC. It is expected that with a properly tuned integral action the same error margins could be achieved around the set-point.

The error margins could be decreased further by increasing the pyrometer measurement spot. This would average out the small periodic peaks in the laminate temperature measurement that arise due to the weaving of the fibers. The controller does not have the resolution to compensate for these peaks and these may as well be filtered away by the measurement to present a realistic controller input. To give an idea of the measurement environment of the pyrometer, IR-images are taken of the laminates after heating. The results can be seen in Figure 36. The pyrometer spot size (red dotted circle) seems to take a reasonable average (but the diameter can be increased further) of the laminate surface and more importantly, the laminate does not cool down significantly once it leaves the heating stage. Just before the filler stage hits the laminates, it seems that the material is heated again. This conductive heating might help in evening out the periodic pattern too. The skin seems to be more cool than the stiffener. This effect is not part of the measurement scope of the IR-camera as the angle between the camera and the surface is too sharp.

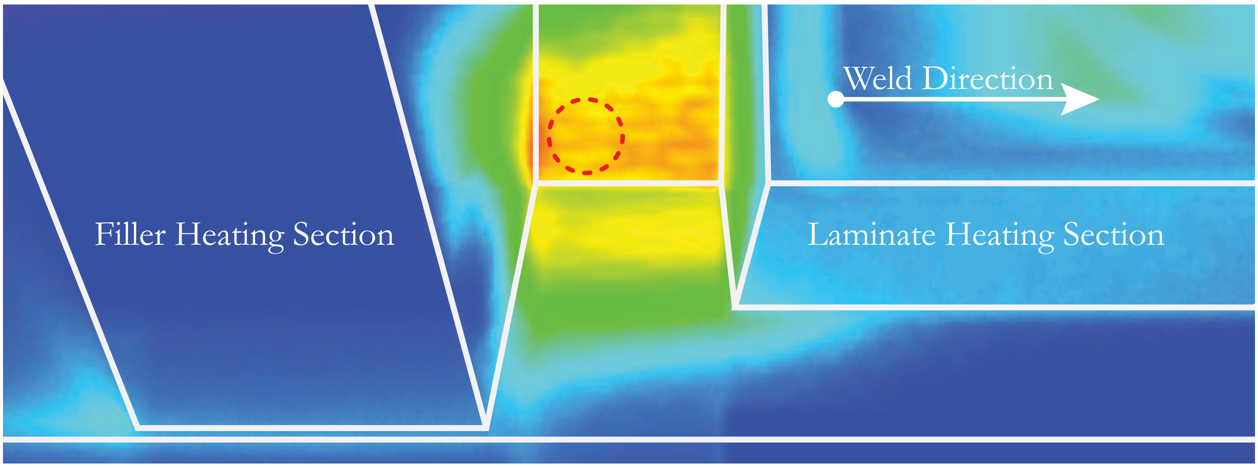


Figure 36: Heating pattern of the stiffener laminate after it leaves the hot gas nozzle. Pyrometer measurement is in the red, dotted circle.

It is worth adding at this point that it might still be a challenge to control a temperature difference between skin and stiffener. An uneven temperature distribution seems to be an inherent feature of the consecutive T-joint, where the stiffener is able to reach higher temperatures because it can only dissipate heat in one in-plane direction where the skin can do dissipate in two. When the flow of gas is aimed more towards the skin, this difference may be compensated for, but the amount of compensation may have to be adjusted with new temperature set-points or materials. Switching to separate actuators for both lamina might help, but first the effect should be properly investigated in a double-sided welding scenario. Welding the two sides of the T-joint simultaneously may cause the second dissipation direction in the skin laminate to be erased by the other opposing heater. In the single-sided welding machine presented in this work the effect is simply accepted but not investigated. The hot gas flow is moved about two millimeters out of center, but further design actions are not undertaken.

It is interesting to compare three welds side by side as it gives insight in the working of the machine and eventually proves the need for a controlled laminate temperature. The distance between the laminates will also be varied to study eventual effects of this adjustment. The temperature recordings of the three welds presented in Figure 37 show different ways of getting to a stable laminate temperature. The reader is referred to Figure 38 for positioning of the sensors. The information presented in the graph is summarized in Table 3 for analysis.

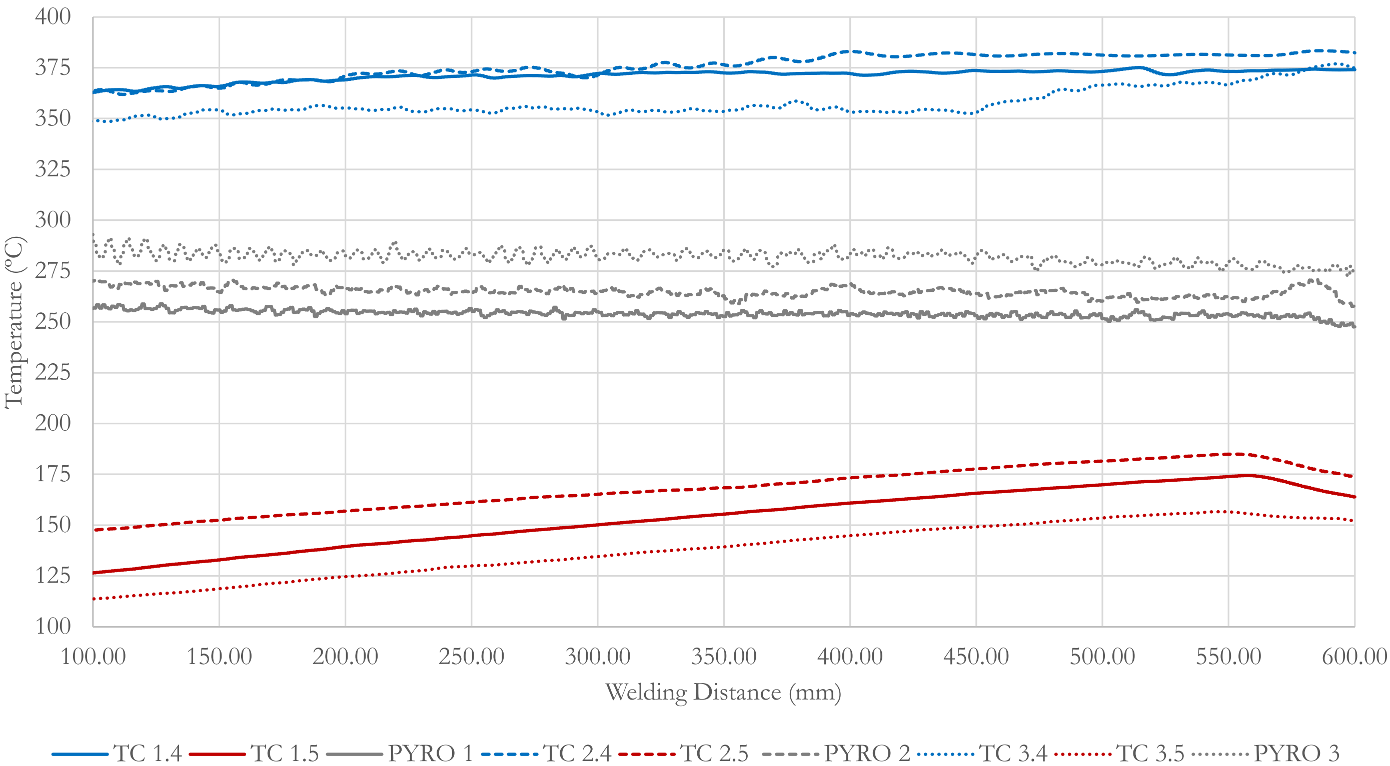


Figure 37: Three welds with PYRO X controlled.

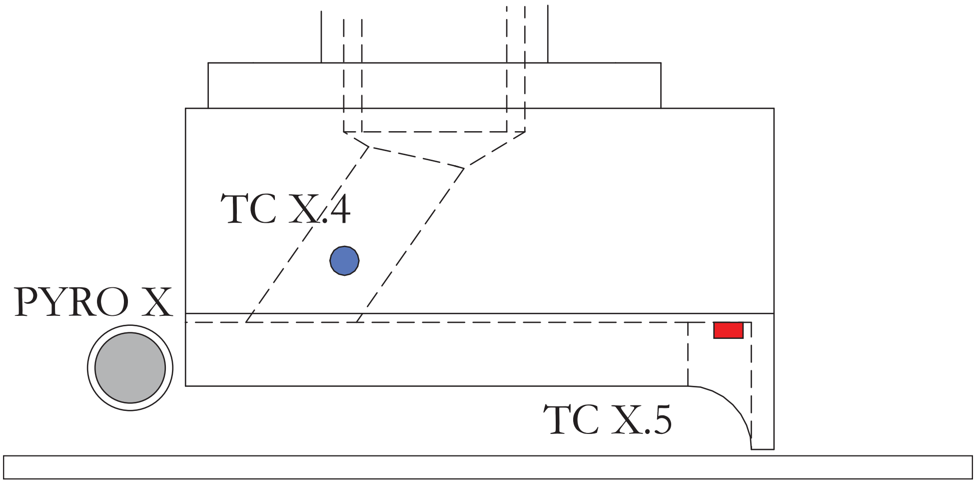


Figure 38: Sensor placement in the laminate heating section.

	Gas High			Gas Low			Stiffener Laminate		
	TC 1.4	TC 2.4	TC 3.4	TC 1.5	TC 2.5	TC 3.5	Pyro 1	Pyro 2	Pyro 3
Set-point (°C)	-	-	-	-	-	-	260	270	280
Average (°C)	368.1	372.0	355.7	148.3	164.0	133.5	254.1	264.9	281.9
Deviation (± °C)	42.3	43.0	21.2	33.9	26.2	28.4	6.5	8.9	9.4
Skin-Stif Distance (mm)	0	0	0.6	0	0	0.6	0	0	0.6

Table 3: Summary of data presented in Figure 37.

The laminate temperature controller works within ±10°C to control the stiffener laminate surface when start-up effects are included. It is interesting to see that for the highest laminate temperature, the lowest gas temperature could be used by leaving some space open between the skin and stiffener laminate. It is expected that the opening allows the hot gas to flow underneath the stiffener which expands the heating surface drastically.

4.2 Filler Temperature Control

As there is a single actuation point for the two heating cartridges, there is only one temperature probe that can be controlled. The filler guidance tube temperature is controlled in the center of the filler heating block (thermocouple 2 in Figure 26). Its step response is shown in Figure 39. This response is used to heuristically tune the controller. The center of the runner is chosen as it is the hottest point in the filler heating stage and is vital to limiting thermal degradation. There are two more thermocouples in the heating stage that enable the analysis of thermal gradients in simulations of the filler heating. These measurement points are simply left uncontrolled due to a lack of actuator inputs.

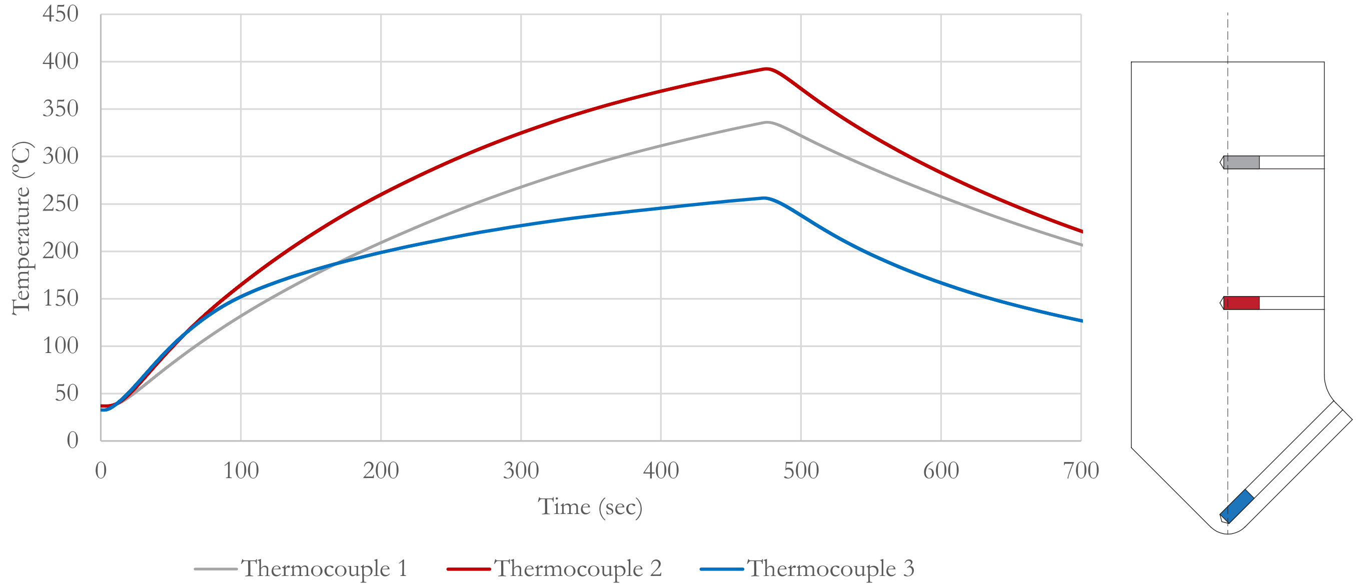


Figure 39: Step response of filler heater.

The lack of actuator inputs leaves the top and bottom of the filler heating section to settle at unspecified temperatures. During three welds, the middle of the filler heating section had the same exact set-point of 315ºC, but showed the behavior as shown in Figure 40.

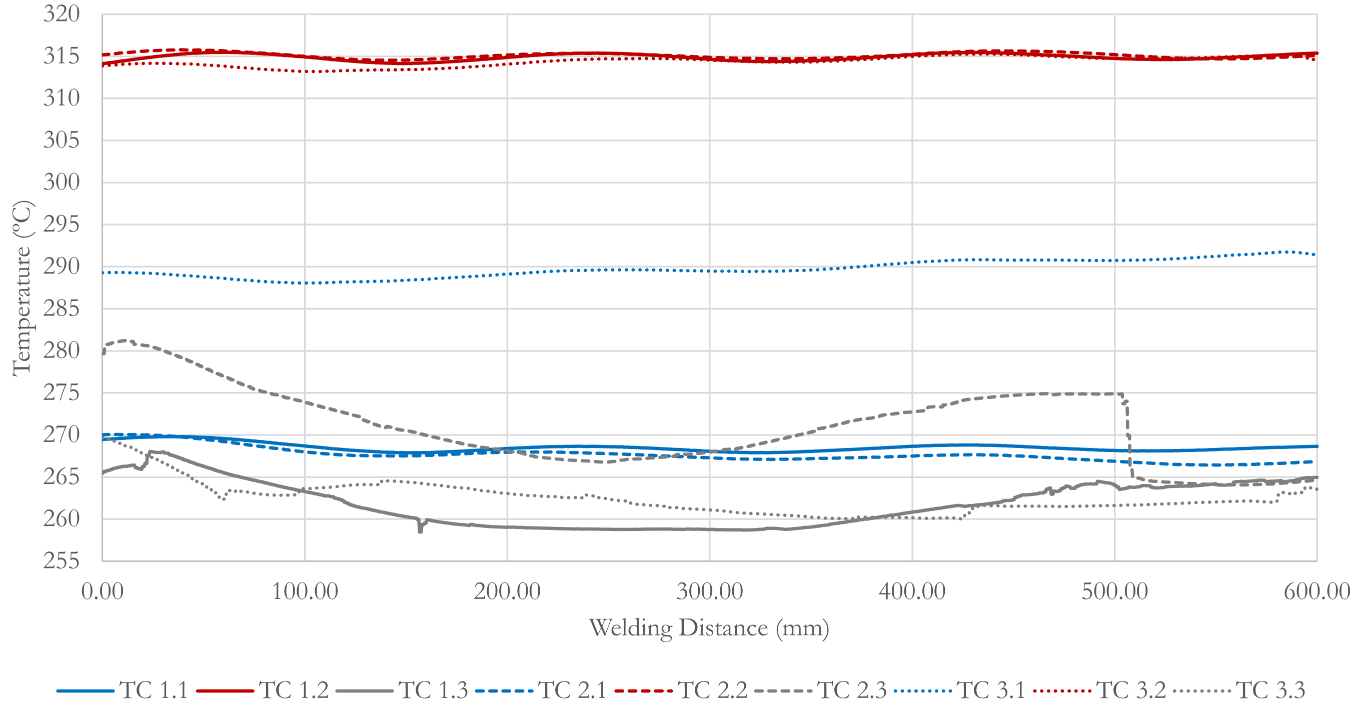


Figure 40: Three welds with TC X.2 controlled.

The data shows nicely controlled middle sections of the filler path, while the top (X.1) and bottom (X.3) are less stable in the temperatures they hold. The data in Figure 40 is summarized in Table 4.

	Top			Middle (controlled)			Bottom		
	TC 1.1	TC 2.1	TC 3.1	TC 1.2	TC 2.2	TC 3.2	TC 1.3	TC 2.3	TC 3.3
Set-point (°C)	-	-	-	315	315	315	-	-	-
Average (°C)	268.5	267.7	289.7	314.9	315.1	314.4	261.9	271.0	262.5
Deviation (± °C)	1.3	2.4	2.0	0.8	0.7	1.2	6.1	10.3	7.2
Laminate Temp. (°C)	254	265	282	254	265	282	254	265	282
Gas Temp. (°C)	368	372	356	368	372	356	368	372	356
Skin-Stif Distance (mm)	0	0	0.6	0	0	0.6	0	0	0.6

Table 4: Summery of the data presented in Figure 40.

It can be seen from the deviations that during welding, temperatures at the bottom of the filler path are more irregular compared to the ones found at the top. The top temperatures remain within ±2.4°C limits during welding, but can receive large offsets by changing the airflow by leaving space between the two laminates. The hypothesis is that with space between the laminates, gas is no longer forced to flow from the laminates up over the filler heater block. This limits convective heat loss of the filler heating section. Therefore, the top at TC 3.1 is hotter than TC 1.1 & 2.1 even though the gas temperature was colder. It seems that the distance between the two laminates has a larger impact than just the flow of the polymer. It also impacts the temperatures of the top of the filler heating section and the gas temperature required for bringing the laminates into the correct temperature range.
The bottom temperatures remain below the melting point of the PPS, which is useful when the head is pressed against the laminates, but the laminates cannot be brought into melt. So if the head makes contact with the laminates to have maximum control over the flow of the PPS, it will not melt the laminates and cause damage there. The exact effect the bottom has on the laminate temperature is unknown, so will have to be further investigated. The wall thickness of the filler heating system on the hot gas side ($d_{c, max}$ in Figure 21) could be reduced from five to about two millimeters if the effect is too large.
The model of Sietsma is used to simulate the radial temperature gradients in three fillers as they exit the runner. Using the averages of the temperatures during welding the data in Figure 41 is produced.

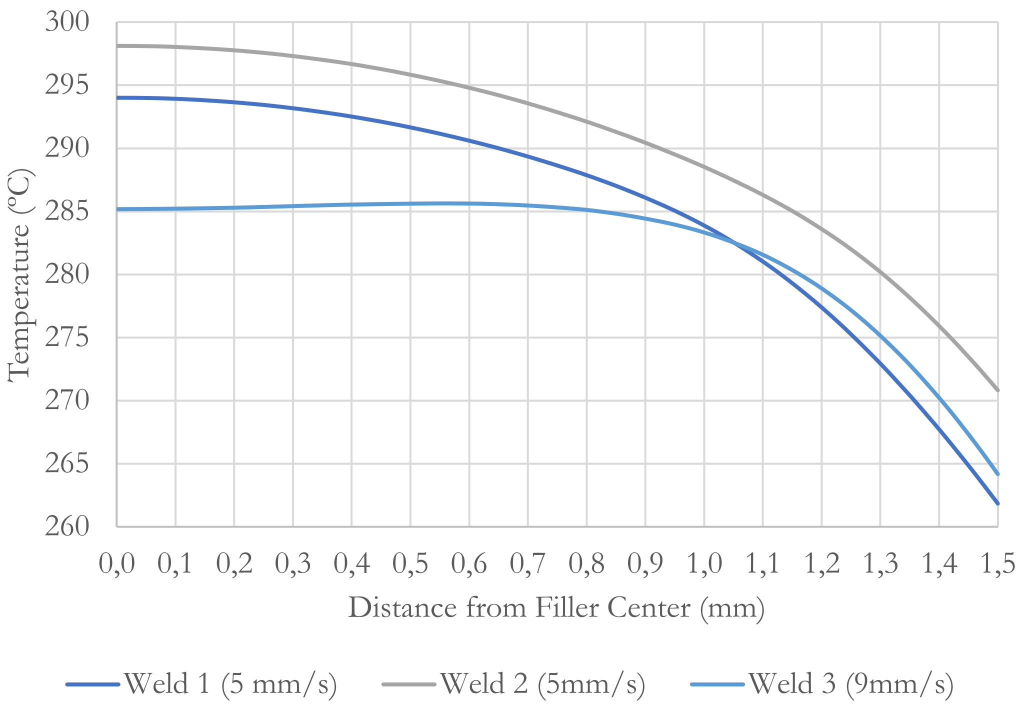


Figure 41: Temperature gradient in radial direction of the filler during welding of the welds in Table 4.

It is interesting to see that not only the height of the curve is adjustable, but also its shape. Due to high early temperatures of the runner in combination with increased filler feed rates, a temperature plateau is created in weld three. It is worth adding that the simulation predicts that the filler material is not fully molten, and that the simulation does not take into account sticking of the polymer to the runner walls. In the experiments conducted with the welding apparatus, the filler was always completely molten, so adding the sticking behavior to the simulation is probably necessary to no longer under-predict the filler temperatures.

4.3 Weld Force Behavior

The weld force is not actively controlled in this work. However, the weld geometry is held consistent in this set-up. Combined with constant feed rates and temperatures this should provide constant weld forces. It was expected that the weld force would increase as the filler driver started pushing material into the weld volume and then the parameter would reach a steady state value. A simple controller was proposed in the previous chapter to regulate this steady state value with the filler feed rate, but due to a lack of understanding of the weld force the controller could not be realized. It is expected that this controller (based on feedrate varying of the filler) is obsolete in the current set-up and that the weld force will stabilize naturally.

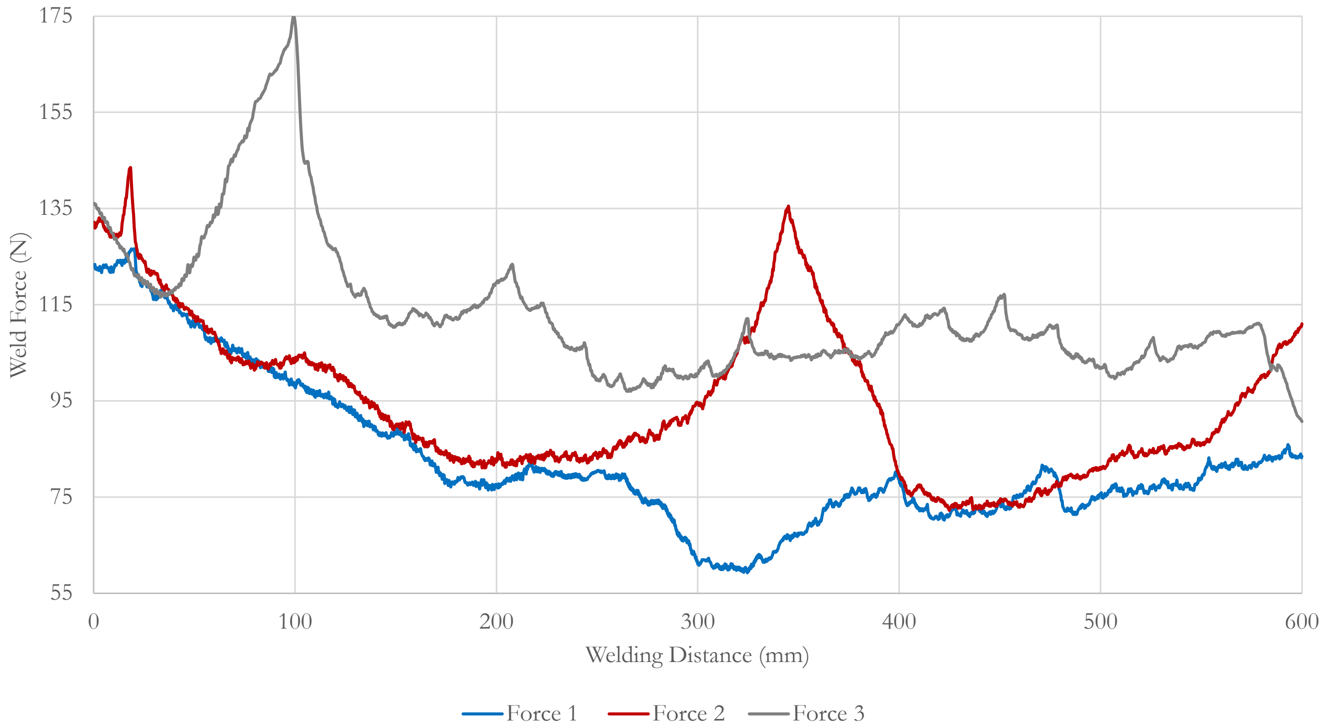


Figure 42: The welding force during the welds of Figure 37 and Figure 40.

The same three welds that were used in the paragraphs of this chapter had irregular weld forces (Figure 42). The weld forces do not seem to lay in the same range and show some large valleys or peaks occasionally. What causes these peaks is known however. In all welds, the peaks were caused by a broken connection between the load cell and the welding shoe. A ceramic bolt connecting the welding shoe to the load cell failed during welding. This allowed for a stick-slip effect as the bolt failure induced play in the welding head (Figure 43). Even when dried filler rods are used and temperatures are held constant some deviation is still present (weld number three used a dried filler rod).

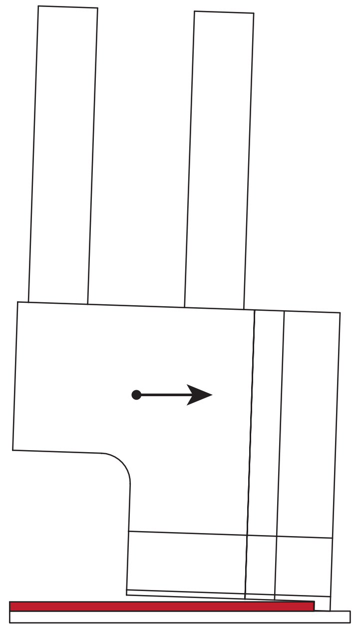


Figure 43: Stick-slip with laminates and loosing contact with the filler material.

However, it seems that the weld force is at least a rough indicator of weld quality as the large peaks in Figure 42 corresponded to excessive filler deposition and the valleys to a lack of filler material. Attaining a weld force that can be tuned or controlled to stay within qualitative limits seems to be a prerequisite for constant weld quality.
The presented measurements in Figure 42 suggest that the weld force can be increased by adding more filler material even though a distance is present between skin and stiffener laminate. The filler material was inserted at 9 mm/s instead of 5 mm/s during the third weld. This conclusion is drawn from the fact that the weld force of weld number three lays higher than the other welds most of the time.
As PPS has a low viscosity in melt compared to the PAEK family of polymers, the leaking of material with a little distance between the tool and laminates is a challenge inherent to the material. Increasing viscosity will allow for the use of higher welding pressures without varying the welding geometry.
To see if the weld force consistency would improve by a rigid connection between load cell and welding head the head was bolted to the sensor using steel fasteners. The play was taken out of the system which should prevent the stick-slip effect. The following results (Figure 44) come from a weld with 0.6mm distance between skin and stiffener and the welding shoe in direct contact with the laminates. The filler was driven with 6 mm/s so weld forces are substantially lower than weld force three in Figure 42.
What can be concluded from this experiment is that the initial peak is a feature of starting with the welding head on the laminates. Using an actuator like an air piston could help in overcoming this weld force peak by pushing the welding head onto the weld line at the start of a weld. With the current machine, the welding head is placed on the laminates when it is cold. As it is heated, the welding head expands together with the laminates which makes it impossible to travel onto the laminates anymore.
By fixing the welding head, the stick-slip was overcome. This resulted in a smoother filler that was consistent in geometry. A picture of the weld is shown in Figure 45. The filler has a constant radius and show no large blobs of additional filler material. So a consistent weld geometry is achieved.

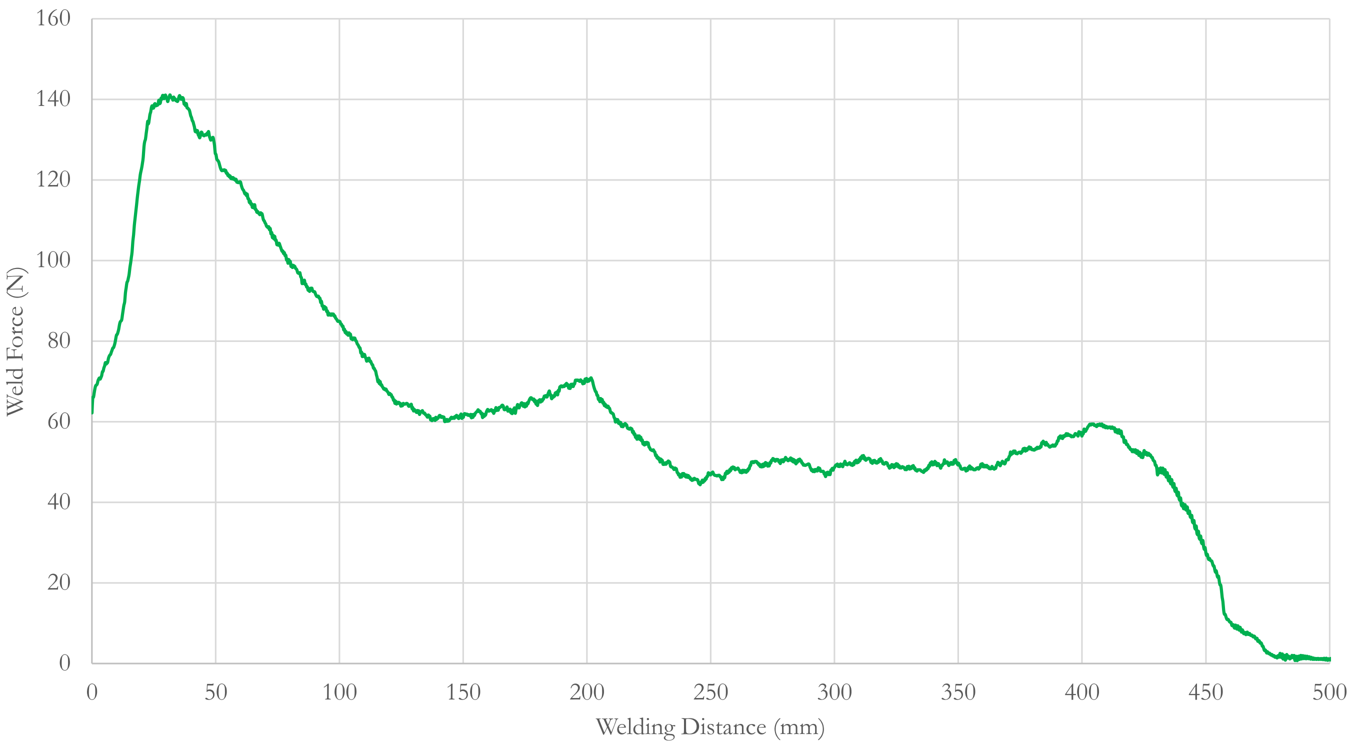
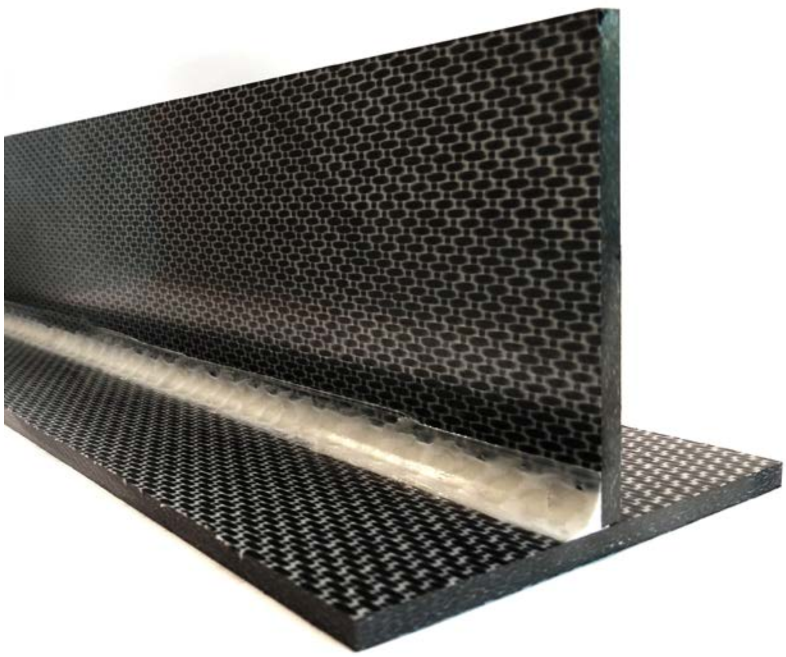


Figure 44: The weld force with all parameters controlled.



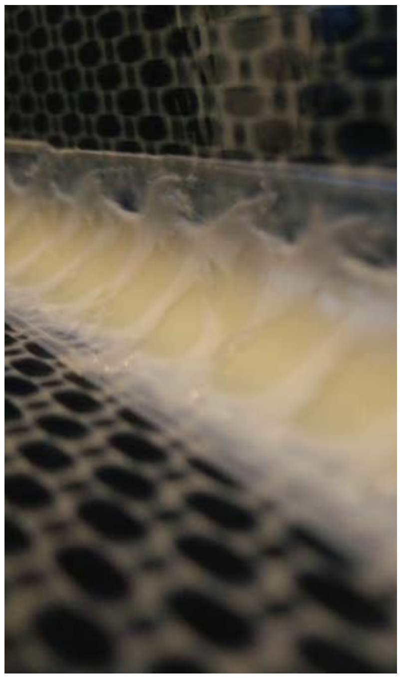


Figure 45: Weld with consistent geometry.

This weld still shows a regular pattern with change in color of the filler. This suggests a melt behavior linked to the filler folding in combination with inconsistent temperature behavior despite the temperature and geometry control. This is induced by the filler folding in combination with laminate temperature patterns and filler temperature gradients coming together to form different temperatures through the weld.

Chapter 5:

Weld Quality

In this chapter a few small, preliminary experiments with the set-up are performed. The insights gathered during these experiments are documented, but no true parameter analysis is conducted. Therefore, the T-joint is still left unoptimized and the true goal of T-CAT is left unfulfilled as planned.
First the strength consistency of welds with inconsistent geometries is tested. This experiment was conducted when the set-up still had play in the welding head caused by a broken connection (ceramic bolt). The chapter will conclude with a short experiment to gather insight in the cooling of the interface between the skin laminate and the filler.

5.1 Weld Consistency

To get an impression of the consistency of the weld quality, a single-sided weld is produced (weld number two of the previous chapter) and cut into 30 pieces, of which ten are mechanically tested (the samples were selected to be around the unstable section of the weld). The chosen weld is not visually consistent, but all temperatures were controlled using the set-up during welding. No space was left between the skin and stiffener so no polymer could flow between the two.
The 30 pieces of 15 millimeters wide are cut from the middle of the weld (75 millimeter was removed from both ends to remove start-up effects) so they could be individually tested. For the test, the specimen is clamped in the set-up displayed in Figure 46. The clamp is fixed in a tensile tester which pulls the weld apart. Because only the consistency is tested, the ultimate force is used directly and is not converted to any form of strength value. The results for the ten specimens extracted from weld number two are shown in Figure 47. All but one specimen show a linear relation between force and crosshead displacement before a brittle fracture. Besides, almost all specimens showed a clear interface fracture, indicating a poor interdiffusion of the filler polymer into that of the skin laminate (Figure 48). The two specimen that failed in the stiffener-filler interface, did so because there was almost no surface area between the two. These were also the weakest joints out of all the specimen.

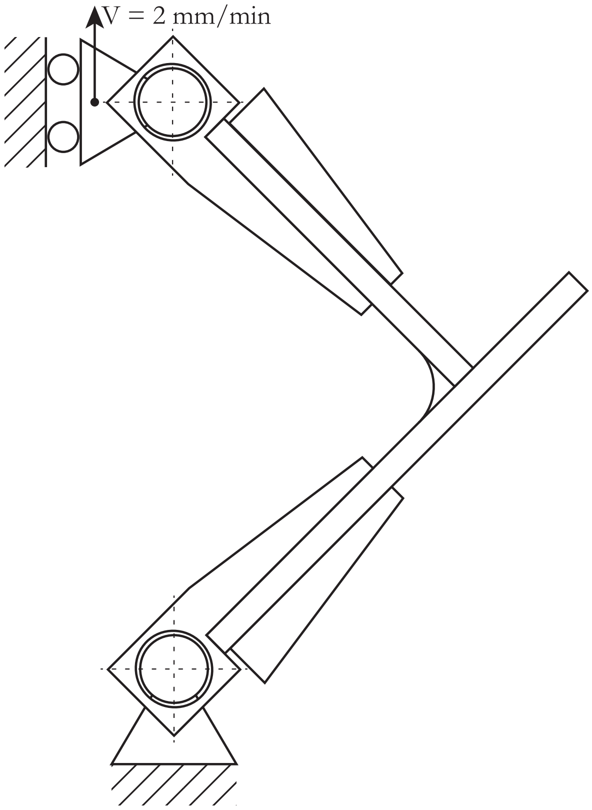



Figure 46: Tensile testing scenario.

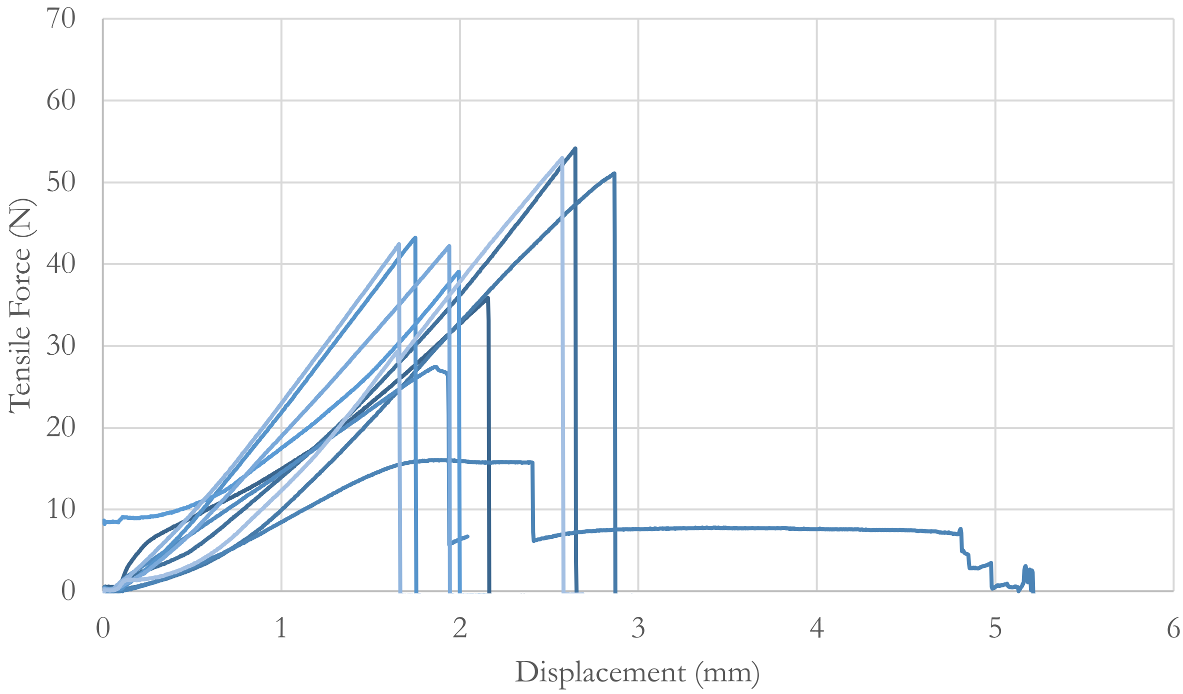


Figure 47: Ten slices tested.

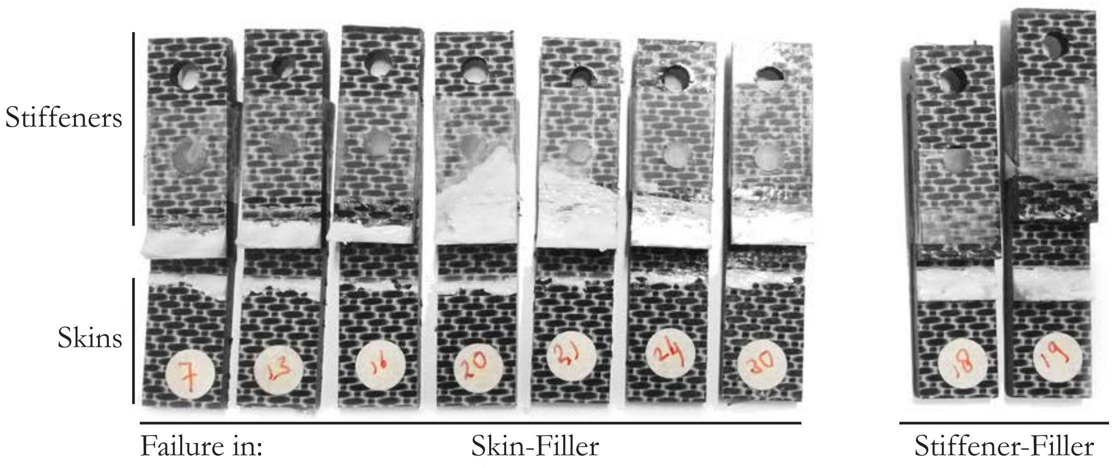


Figure 48: The destroyed samples of Figure 47.

These results allow for a weld strength indication along the weld line. To visualize this relation, the ultimate tensile force is plotted in Figure 49 as a circle against the position of the specimen in the weld. Figure 49 also shows the force measured during the welding. The welding force 'resembles' the geometry of the weld well (Figure 50); low values measured for specimens 18 and 19 are shown in Figure 50 to correspond with a small cross-section, indicating not enough filler was injected in the cavity.

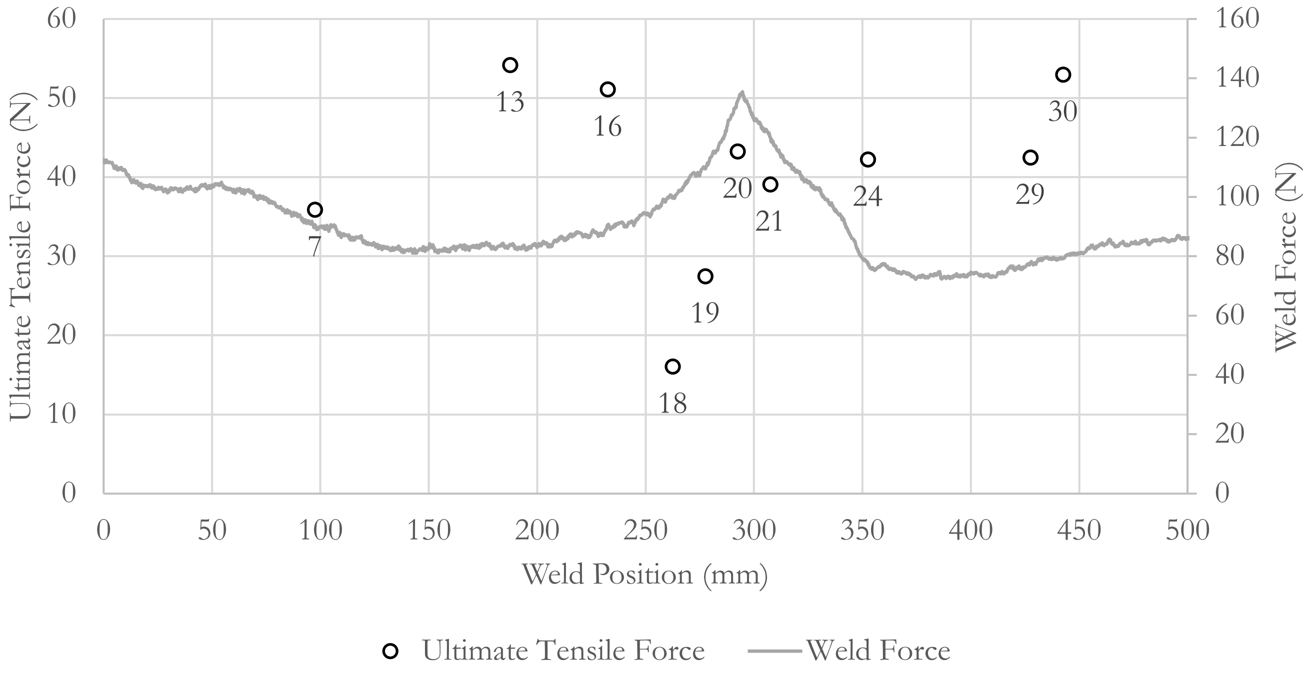


Figure 49: Ultimate tensile force along the weld line. Data labels correspond to slice number in Figure 50.

The weld force plotted in Figure 49 is shifted to make sure the testing position corresponds to the measured weld force value. Mostly samples around the weld force peak in the middle are investigated.

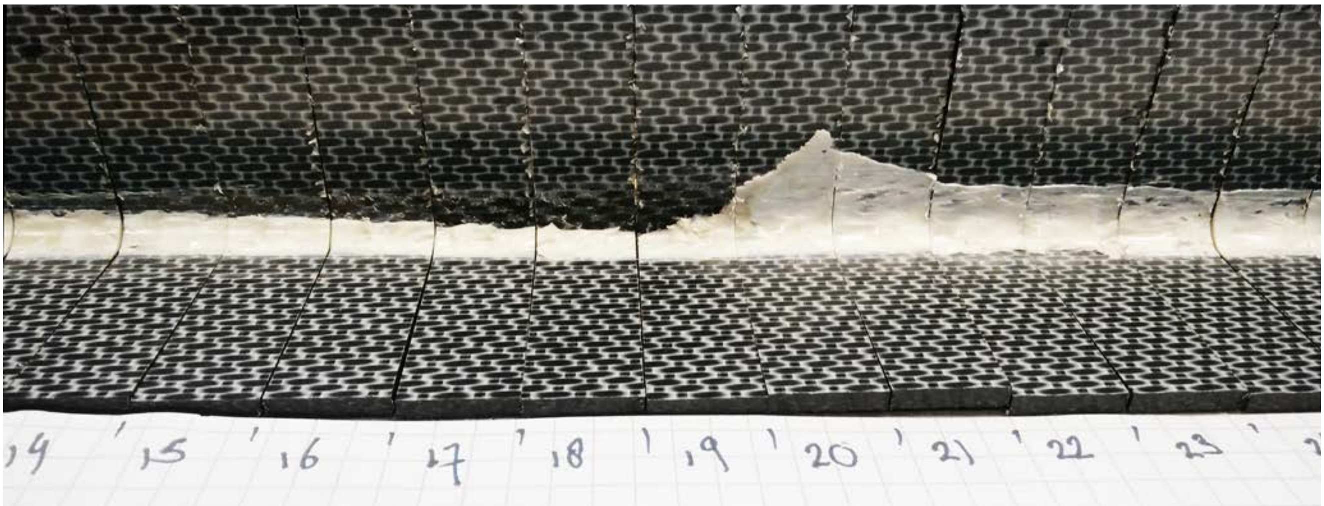


Figure 50: Photograph of the only deviation in the weld with the slice numbers written underneath.

Before slice 16 and after slice 21 the weld had consistent weld cross-sections. To give a better impression of the weld cross-section in the deviating section in Figure 50 microscope images are taken. A collage is given in Figure 51.

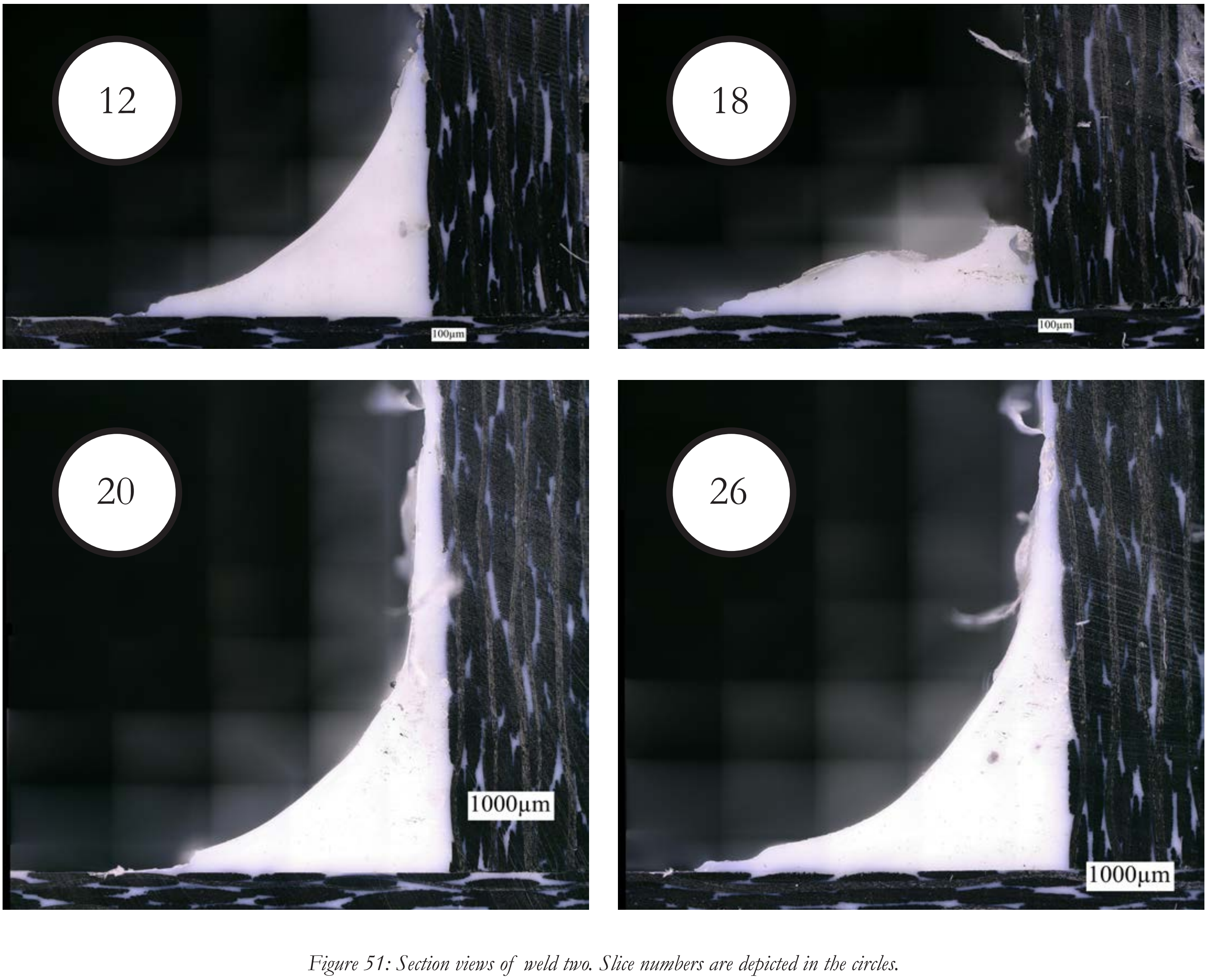


Figure 51: Section views of weld two. Slice numbers are depicted in the circles.

An exceptionally high or low weld force does give an indication about the change of quality of the weld due to geometric change in the filler. The data in Figure 49 together with the looks of the weld in Figure 50 suggest that the weld force rises due to excessive filler material feeding. The reason for the excessive filling is the stick-slip effect of the welding head and not an inconsistent filler feed rate.

5.2 Filler Feed Rate

Void formations were observed in some of the cross section of the weld. This rises the question on the potential influence of moisture in the filler, because weld forces were assumed to be sufficient. Weld one and two were made using undried filler noodles. After the production of the first two welds large voids in the filler flow in the filler heating section were found. The virgin filler material together with the heated dried and undried section view are captured in Figure 52.

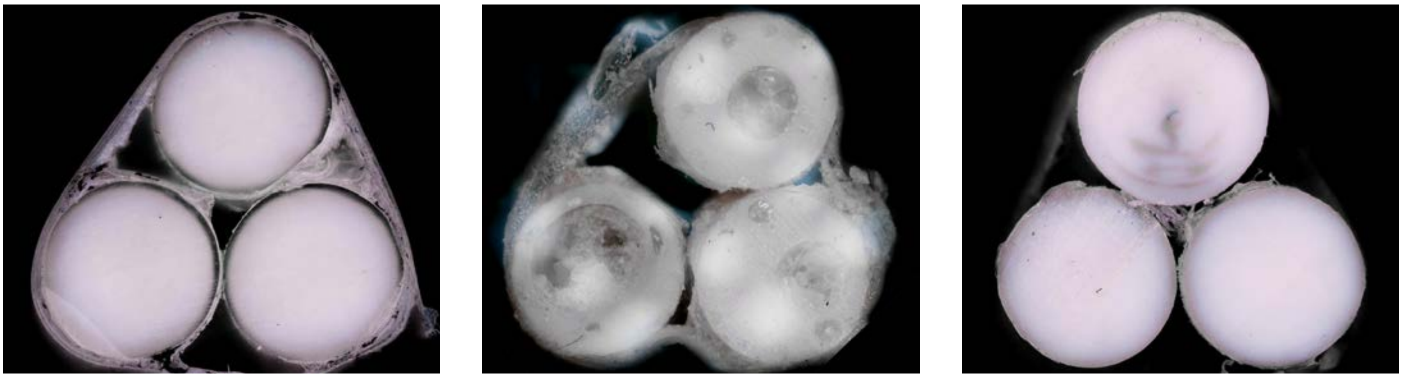


Figure 52: Virgin, processed undried and processed dried filler material cross-sections.

Drying the PPS (four days at 60ºC plus four hours at 110ºC) eliminates the voids in the filler supply. No extensive test are conducted using the dried filler material. Only weld three is made with the dried filler, but does still show peaks in the welding force (Figure 42) and an uneven weld geometry. A study on the presence of voids in the filler was not performed at this stage.

5.3 Laminate Temperature Sensitivity

The laminate temperature can fluctuate around its set-point by ±3ºC under steady state feedback control. If start-up effects are taken into account the deviation could get up to ±10ºC. This (±10ºC deviation) is a larger fluctuation than the filler material shows. This in combination with the results of "2.5 Non-Isothermal Welding Experiment", sparked the interest of the process sensitivity upon the laminate temperature. The relation between laminate temperatures and weld strength is not known (like all parameters), but a simple extra test at a different laminate setpoint will roughly illustrate the sensitivity of the process and underline the importance of further improving the controllers.
An extra weld was performed to evaluate the effect of certain parameters on the final result, without starting an extensive study. It was shown in "2.5 Non-Isothermal Welding Experiment" that the laminate temperature should have an influence on the interdifusion of polymer at the weld interface. Beside, the absence of a gap between skin and stiffener prevents the flow of polymer, thereby creating a stress concentration. In order to highlight these two effects, a third weld was performed with a higher laminate temperature (282ºC instead of 265ºC), a 0.6 mm gap between skin and stiffener and a dried filler.
The blue samples of Figure 47 came from weld number two were welded using 265ºC laminates. Weld three used 282ºC laminates for the weld. Its tensile force curves are added to the picture in Figure 53.

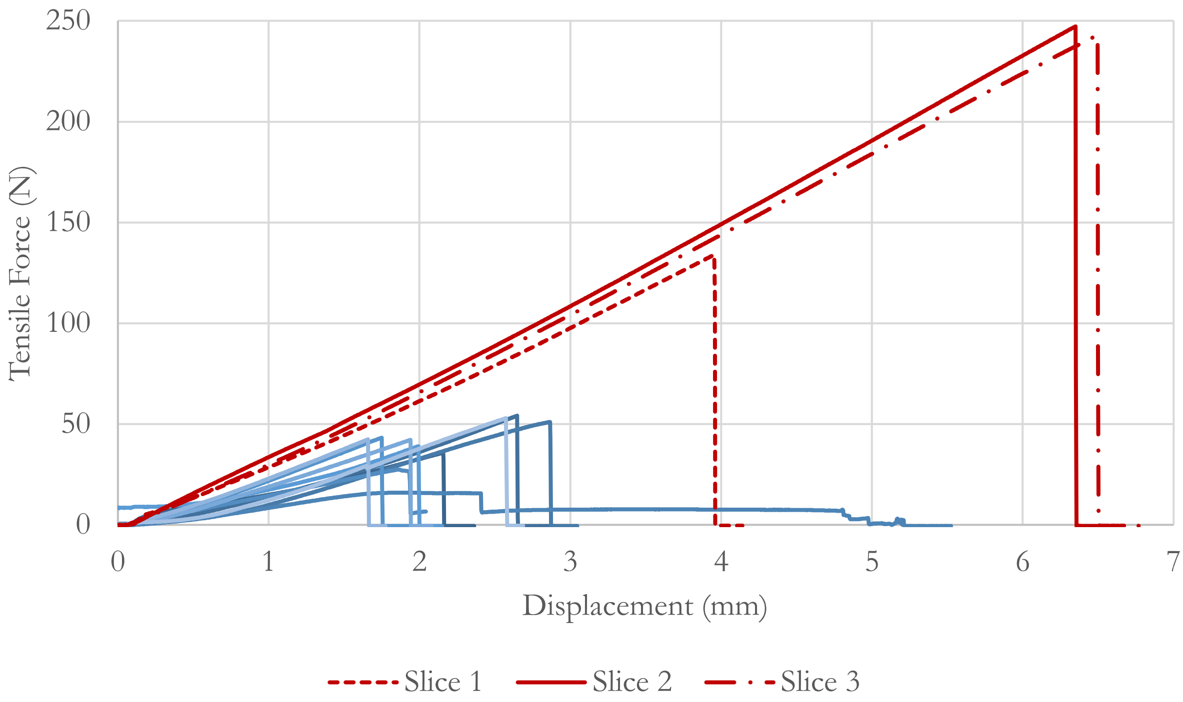


Figure 53: Weld two in blue, weld three in red. There is a significant improvement in strength.

There is a significant improvement in the strength test performance of the joint due to the increased laminate temperature. The reason for this strength increase is probably the improved interdiffusion between skin and filler. Samples had increased joint strength as the weld no longer failed at the filler-skin interface, but broke in the weld itself. Of the three slices that were tested of weld three, two of them (slice two and three) failed in the filler material. Slice 1 still failed in the skin-filler interface, but only after deflecting about a third further than the slices of weld two. A photograph of the three slices of weld three can be found in Figure 54.

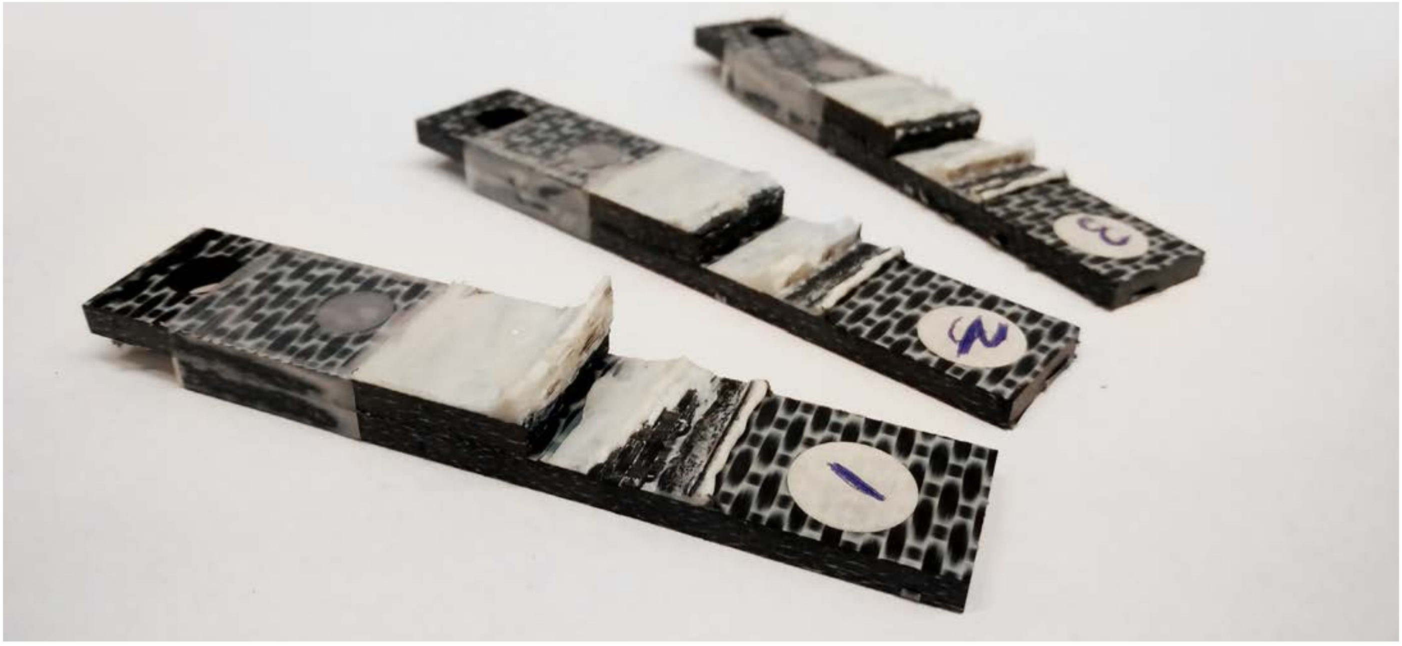


Figure 54: The slices of weld three. Slice number correspond to the stickers on the samples in the pictures.

The increase in laminate temperature did not solely increase the joint strength. The other factor was the distance between the laminates during welding. The filler was allowed to flow between the laminates and increase the interface surface available during the weld.

The conclusion from this short experiment is that the process is very sensitive to a combinations of temperature and skin-stiffener laminate distance changes. Increasing the temperature of the laminates by 17°C together with 0.6 millimeters between the laminates results in increasing tensile performance by about a factor of five.

5.4 Cooling Rates and Crystallinity

An important factor in weld quality is the degree of crystallinity of the weld. This is determined by the cooling rate of the weld. To get an insight into this rate a test-run was conducted where three thermocouples were embedded in cut-outs in the stiffener laminate. The placement of the thermocouples had an interval of around 160 millimeters and can be seen in Figure 55. The data measured during this weld is presented in Figure 56 and Table 5.

Figure 55: Thermocouple placement in a gap under the stiffener laminate.

The three thermocouples did not have close contact with the laminates before they were hit with the filler material. The measured temperature before the contact with the filler is made is therefore determined by the gas temperature of 317°C (in the nozzle). The thermocouples therefore show a first peak when being brought to their hottest point by the hot air. A typical response as shown in Figure 56 then shows a drop of about 20-40°C before the filler-thermocouple contact. The filler temperature should between 260°C and 300°C according to the model of Sietsma. The moment the filler touches a thermocouple, a second, smaller peak is found in the data of Figure 56.

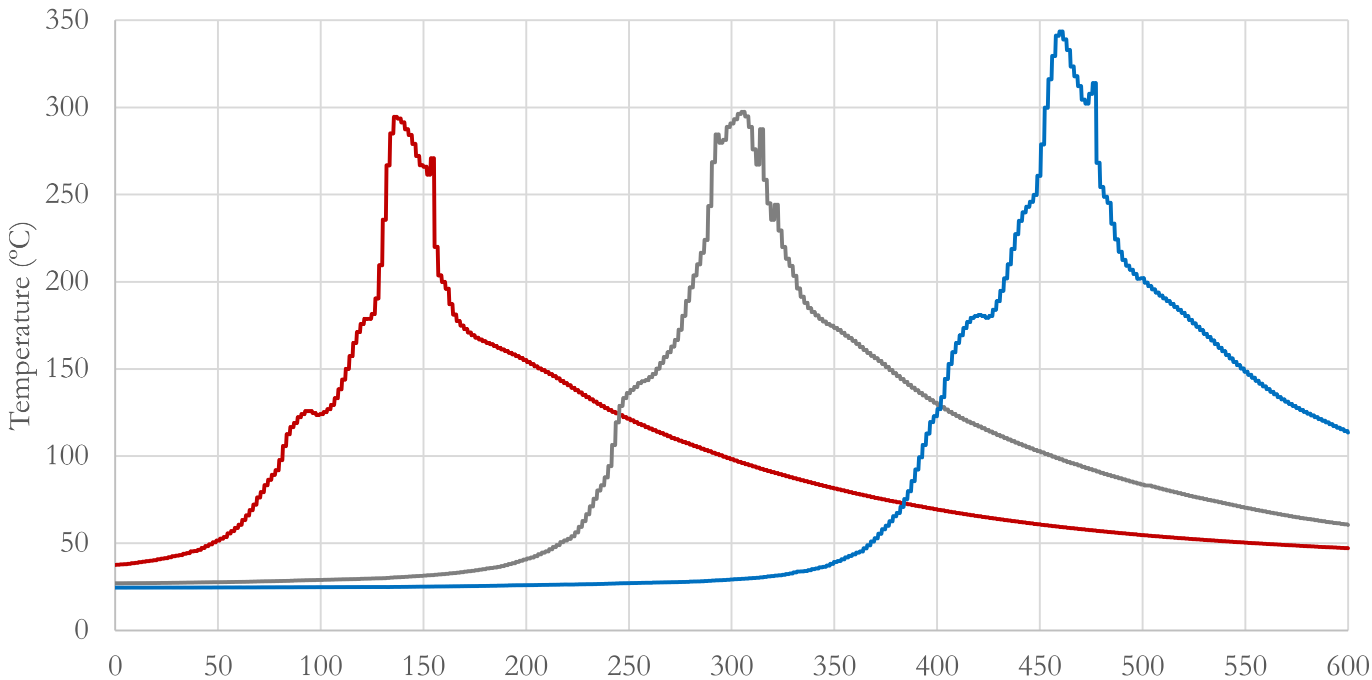


Figure 56: The readings of the thermocouples during the weld.

Laminate Temperature (ºC)	257
Gas Temperature (ºC)	317
Filler Heater: TC 1 (ºC)	263
Filler Heater: TC 2 (ºC)	314
Filler Heater: TC 3 (ºC)	259
Welding Speed (mm/s)	3
Filler Speed (mm/s)	5
Skin-Stiffener Distance (mm)	0

Table 5: Set-up parameters during the weld of Figure 56.

From the second peak onwards, the thermocouple measures the interface temperature. For the three cases the cooling rate down to 200ºC is shown in Table 6.

Interface 1 Rate (ºC/s)	35
Interface 2 Rate (ºC/s)	15
Interface 3 Rate (ºC/s)	15

Table 6: Cooling rate of each thermocouple.

From these cooling rates, it is hard to say anything about the degree of crystallinity in the final weld. At some points the interface might have formed some crystals, but what is proven is that more control is needed regarding more gradual cooling. Whether the controlled cooling could take place in-line is completely determined by the welding speed requirements and the welding trajectory. Lower welding speeds and straight trajectories allow for slower cooling rates. To control the cooling, the cooling section should remain close to or in contact with the weld. The interface of the weld might cool quicker as the filler comes into contact with colder laminates, so the cooling rate might also limit the non-isothermal welding range.

What is known is that the filler folding and its thermal gradient and the laminate temperature pattern play a role in the initial temperature before cooling and the cooling rate locally in the joint.

Chapter 6:
Conclusion & Recommendations

6.1 Conclusion

Welding of fiber reinforced plastics is proving to be a valuable addition to a designers toolbox when it comes to the assembly of thermoplastic components. Hot gas welding of thermoplastics has reached maturity in the non-reinforced plastics industry and shows potential to do the same in the composite world. Hot gas welding for reinforced thermoplastics is proposed in this project. This technique is used to directly weld a T-joint by addition of a filler material connecting a laminate skin to a laminate stiffener. Locally heating the laminates with addition of molten filler material allows for placing the welding head on any actuation system that is able to follow the weld path. This makes the process more adaptive than autoclave techniques. The question remains if locally heating the laminates can come close to the quality of an autoclaved T-joint (or flanged alternative). Until now, no comparisons have been made, but the set-up designed during this project will enable researchers to do just that.
An, at this point single sided, welding head was developed around the T-joint welding parameters that relate to the general physical welding parameters 'temperature', 'pressure' and 'time'. These parameters are shown in Figure 57 together with the welding and control parameters for testing the T-joint and controlling welding parameters with T-CAT REV4 specifically. The diagram in Figure 57 shows all parameters that are relevant for this project. The future might prove some parameters to be missing or obsolete.
The proposed design is made of the following sections: a laminate heating section, a filler heating section, a welding shoe with cooling block and a support system for both skin and stiffener laminates. When it comes to the laminate heating system based on hot gas, the current technology of T-CAT REV4 controls the laminate temperature by adjusting the temperature of the hot gas based on pyrometer measurements of the stiffener laminate. The filler heating section uses a heated steel pipe where a polymer rod is fed through. The feedrate of the polymer is set and the temperature in the middle of the tubes length is controlled using a thermocouple measurement. The full temperature gradient of the tube is measured with additional thermocouples. The welding shoe brings both the heated laminates and filler together and deforms the filler into its stress alleviating shape. The welding shoe also cools the joint afterwards.
The current technology of T-CAT REV4 allows for the stiffener temperature to be controlled within ±3ºC excluding start-up effects. This is promising, but the implications on measurement accuracy in relation to the point of filler contact remain unknown. In any case, the stiffener surface temperature will be influenced by the filler

heating section. The magnitude of the temperature change caused here is expected to lay within a few degrees. The temperature of the skin laminate and possible deviations from the stiffener will have to be further investigated in the simultaneous double-sided welding scenario.
The filler temperature is controlled indirectly by heating a support structure called the runner. The runner is a tube that comes into contact with the filler rod for a known distance. The temperature gradient of the runner is measured, but not controlled. Only a point halfway up the runner is controlled for its temperature, the top and bottom of runner have floating temperatures. The top temperature of the runner seems influenced by the air flow through the skin-stiffener gap. Leaving room between the laminates allows the top of the filler heating section to get about 20ºC hotter. Still, the temperatures of the top and middle filler section remain stable during welding. The bottom of the runner can show ±10ºC deviations during welding. It is estimated that this affects the average filler temperature with about ±4º. This is thus the estimation for the controller precision. A thermal model is used to estimate the scale of this effect, but may need to be improved to include the sticking of the filler to the inner walls of the runner at increased temperatures.

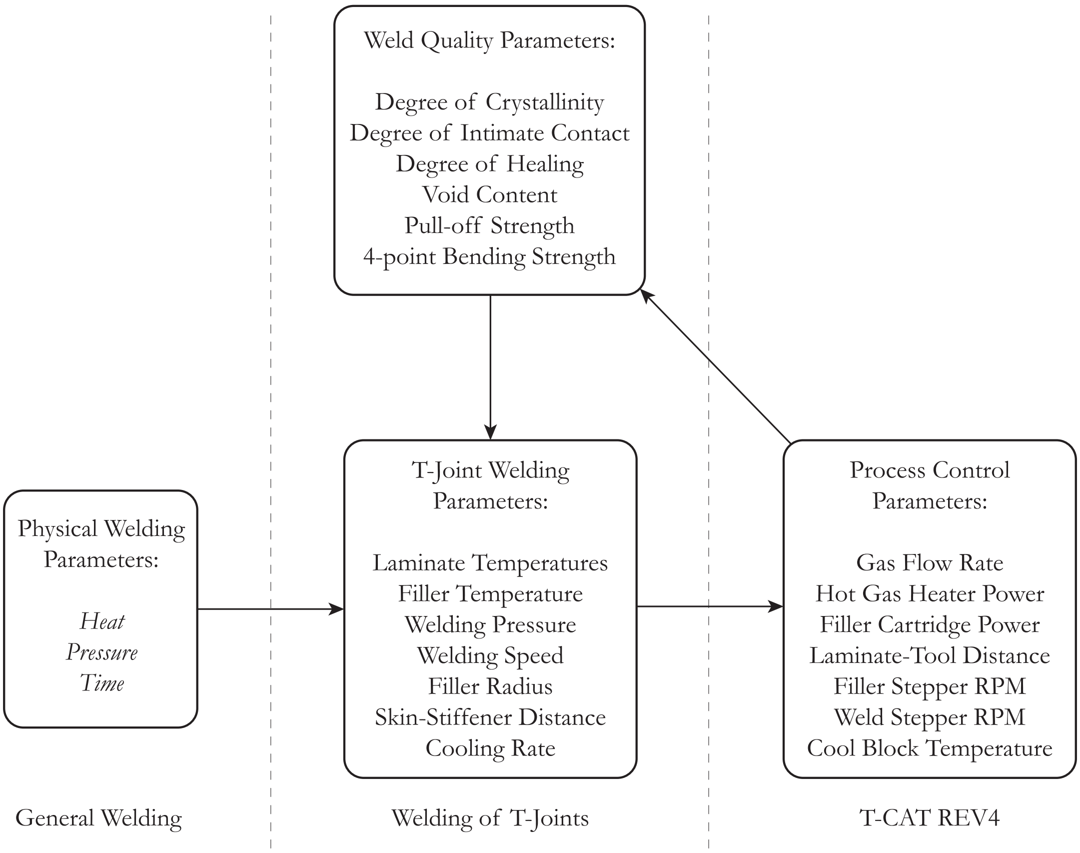


Figure 57: Relevant parameters during welding development.

As far as the welding shoe is concerned, the welding pressure remains unknown as only the weld force is measured and not enough data is available on the contact area between the injected filler and welding head. Valid ranges for the welding force can be found using T-CAT REV4.
An extra function belonging to the welding shoe section is passive cooling. Active cooling rate control is currently not available. Local variations in the hue or whiteness of the weld indicate that variations in maximum filler temperatures and/ or cooling rates and thus crystallinity are present. Cooling rates did indeed vary greatly in thermocouple measurements at the weld interface.
T-CAT REV4 is able to lay welds on PPS composite plates. Preliminary tests have shown that optically consistent welds can be produced. It also showed that the welding quality, for example the welding strength can be significantly improved by varying welding parameters. This opens the way to use the setup to perform research relating welding parameters to the welding qaulity.

The current parameters that are used in this PDEng for controlling and testing T-joints deliver welds are produced using controlled heat inputs that do not degrade laminates nor filler. The accuracy of the measurements needs to be further investigated. The welds cooling and pressure behavior is still inconsistent, but can improve in future set-ups. No mechanical test have been performed on the constant geometry welds produced at the end of this PDEng. They should perform better on weld strength consistency than the welds that were tested. Future areas of focus will be presented in the following paragraph.

6.2 Recommendations

Without moving immediately into the double-sided welding scenario necessary to weld a T-joint in one shot, further developments can be made with the current single-sided machine. Divided into the three welding sections of laminates heating, filler heating and pressurizing and cooling, the following points have been gathered.

In the laminate heating section, the control system should be adapted to include integral control to the laminate temperature with the possible expansion of a skin temperature measurement next to that of the stiffener. In any case, if the move is made to double-sided welding, the heat flow through skin and stiffener should be characterized after which the hot gas flow may be redirected to compensate for an eventual temperature difference between the two laminate surfaces. Modeling of the heat flow in laminates will help in understanding the cooling of the laminate once it travels under the filler heating section and is no longer exposed to the flow of hot gas. To make the impact of the laminate cooling as small as possible, the laminates should be brought into contact with the filler as quick as possible after measurement. This can be done by shortening the obstruction wall of the filler heating section that prevents the polymer flow from flowing upward into the laminate heating section. This flow preventive barrier is five millimeters long in the current design. This could be reduced by about three millimeters. Sietsma did do grounding work concerning heat dissipation in the laminates, but experimental data can easily be gathered using T-CAT REV4 in the true welding set-up. The main question that needs to answered is how the temperature changes after the pyrometer measurement as both laminates are brought into contact with hot steel (somewhere between 250-280ºC) for two to five millimeters (the filler flow barriers length). All in all, the temperature measurements with the pyrometer will need some correction to give the laminate temperature at the point of contact. What this adjustment is, will have to be investigated.

The same goes for the filler material temperature measurement which is more indirect than the laminate measurements as the polymer itself is never measured. The filler material in the runner will stick to the inner walls of the runner. This behavior is not modeled yet, which causes the model to underestimate filler temperatures. Adding the stick scenario will increase the accuracy of the temperature controller. Also, the assumption that the runner has the same temperature as the thermocouple in the heating block will have to be tested.

The dimensions of the welding head determine the maximum welding speed that can be achieved as larger welding heads can contain longer heating zones. It is expected that larger welding heads will be the most likely direction of future development as they can produce fast welds in straight lines (or slight curvatures). Smaller, slower welding heads might prove themselves for more detailed work, but they get in the working arena of autoclave processes.

Another point of improvement is the lack of insulation in the set-up. This was done to keep everything easily accessible, but when insulated, the power necessary to heat up the filler will be lower (the nozzle of the hot gas might also benefit here). This will decrease rise times of the system and will make the uncontrolled sections of the runner more stable in temperature as the gas flow impact is reduced. If inceased control is needed on the runner temperature gradient, the more expensive spiral heaters can be made to fit in the current welding head. This spiral can run deeper towards the bottom of the runner, which will keep the runner temperature gradient small. As the spiral heater is smaller in size, the leftover space can be used to mount insulation to the heating section without increasing the footprint of the welding head.

After the filler is brought into the weld volume, it should be deformed into the correct shape. Right now, the filler wire has to be driven into the weld volume at increased speeds compared to the welding head movement. The filler wire folds over itself once it enters the weld volume. This creates weld lines inside of the final filler which might cause the weld to fail in the end. This is something to investigate in the future of this project.

For now, the filler could be reinforced with short fibers to make its thermal expansion coefficient and its elasticity modulus lay closer to that of the laminates. This will decrease thermal stresses in the joint after welding and increase the viscosity of the filler during welding. The effect of the increase in viscosity on the complex flow behavior of the filler is unknown, but it will be easier to contain the filler in the weld volume. The molten PPS will not leak as easily. This might also prevent it from flowing under the stiffener laminate which is undesirable. The added fibers will also decrease the thermal gradient in the filler material compared to the non-reinforced PPS used now.

A larger load cell should be used than the one in the current set-up with the new filler material. For now, 500 newton seems a more suitable range as using the non-reinforced, low viscosity PPS filler already produced peaks in the weld force of 200 newton.

The load-cell should no longer be placed directly onto the cooling section. The frame block can be placed closer to the welding head by repositioning the load-cell on top of the frame instead of beneath it. The linear guides will then come up from the welding head through the linear bearings in the frame before they are mounted to the load-cell (Figure 58).

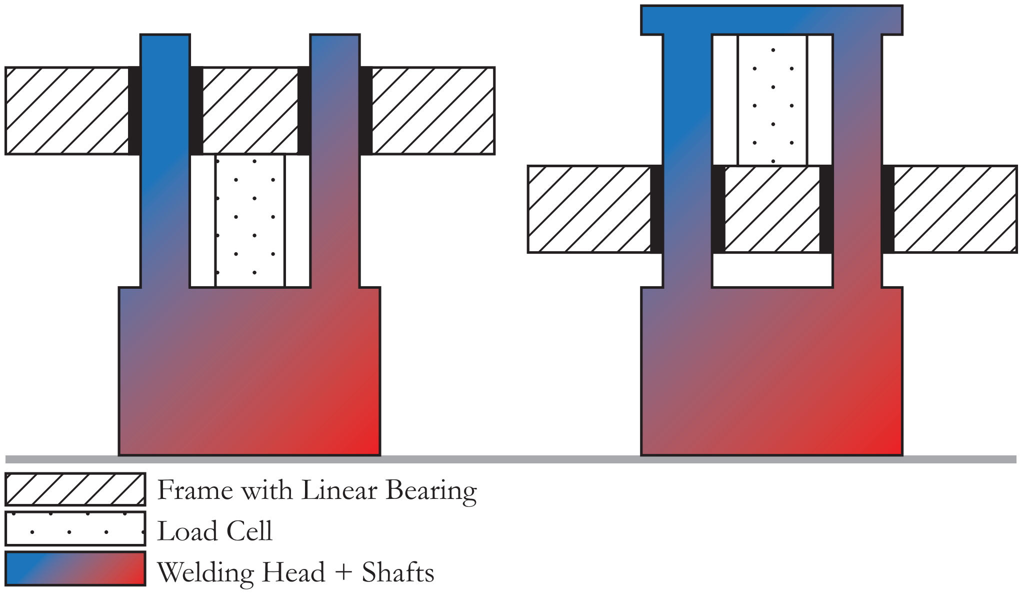


Figure 58: Positioning the loadcell on top of the frame gives a cooler mounting point on the welding head.

The cooling section should be made more consistent. Heaters can be added to make sure the cooling section is always at the same temperature, but also active air cooling might be an option depending on the required temperature for the cooling block. Another improvement to the weld force consistency is to press the welding head against the laminates instead of clamping it in a fixed position. An air piston can press the welding head against the laminates once it is above them. Such an actuator will thus also be helpful for weld start and end issues. The piston should overcome the largest welding forces so that the welding head is unable to come loose from the laminates.

As a last point the welding head can be adapted to have a tapered design that slowly reduces the weld volume to compress the filler onto the laminates. Right now, there is no taper, but further research can show where this taper should be placed and how quickly it should decrease the weld volume. What is important however, is that the cooling section remains in contact with the joint. The cooling rate is still varying too much in the current set-up. This is due to the non-isothermal nature of the materials in use. The laminates show thermal patterns due to their lay-ups and the filler has a thermal gradient due to the runner temperature gradient. Next to these effects, the filler is also folded over itself to create a highly non-isothemal weld. The laminates may benefit from the contact with the hot steel of the filler heating section which may even out the thermal gradient by conductive heating.

So in conclusion, multiple new improvements present themselves. What is important is to take note of the current machines capabilities and make a lot of welds to characterize. Small tweaks to the controller set-points or measurements can have large effects on the weld performance, but which parameters will have the biggest impact remains unknown. T-CAT REV4 allows for a better understanding of the process than ever before and can give the best answers to its own improvements.

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Appendix A: Non-Isothermal Welding

A.1 Joint Characteristics

This research aims to map temperature process parameters for a specific matrix polymer; polyphenylene sulphide (PPS) during T-joint welding. T-joints are a type of joint that form a square angled connection between two plates. The two plates are interconnected by a pure polymer section called the filler which is deformed from a rod into tangent shapes to alleviate stress concentrations (paragraph Figure 2 on page 3).
The first T-joints for thermoplastic composites were produced using injection molded filler inserts combined with two laminates in an autoclave molding cycle (Offringa, 2012). This was done to place stiffener ribs onto a structural beam. This process proved the strength of the joint type to be at least equal to its competing, flanged joint counterparts while reducing manufacturing costs. Still the joints molding process was highly inflexible and expensive and could be improved by moving from global to local heating technologies. This is where this research found its place. Local heating solutions will only heat the nearby welding interface which preserves the rest of the laminates from thermal degradation or deformation. The process is also applicable to a wide variety of products which can drive down manufacturing costs by its flexibility.
Faster joining processes can potentially be created using non-isothermal joining scenarios, as heating and cooling time can be reduced on the component. Welding a T-joint requires the filler material to deform before it can gain full intimate contact. The deformation of the filler wire requires heating above the melt temperature through the thickness of the cylindrical rod to make sure that enough material is able to flow into the new filler shape. To save time and energy, the higher filler surface temperature can be used to melt the surface of the laminates and create a molten interface. This scenario is non-isothermal in nature, as the two surfaces will have two different surface temperatures before contact is gained.

A.2 Experimental Test Plan

During welding, three temperatures are regarded as important for the final joint strength. These temperatures are the filler and laminate temperatures. The filler will be heated to a set processing temperature which lays in a range defined by the manufacturer. It is assumed that the laminates will both have the same temperature, but this temperature needs to be optimized with an experimental analysis. A custom set-up was built for this experiment as there was no machine that could heat the samples, measure the surface temperature before contact was gained and pressurize the joint while cooling. Photographs of the used set-up can be found below in the photograph series in Figure 59.
Using a side-view of the machine the working principle is explained in the drawings in Figure 60. An hinged construction allows heating both 10*60*4mm filler and laminate samples while recording their temperature using a IR-camera just before contact is made. Both material specimens are heated simultaneously using infrared heating elements via a proportional feedback loop between phase cut 250VAC power outputs and thermocouple data. Each specimen is featured with two thermocouples placed inside on locations shown in Figure 60. The data from the sensors is averaged to form the sample temperature which is controlled. So each test had four thermocouples, two for the laminate sample and two for the pure polymer. The controller is built in the LabVIEW®programming language and the IR-camera in use is the Xenics GOBI-1520.

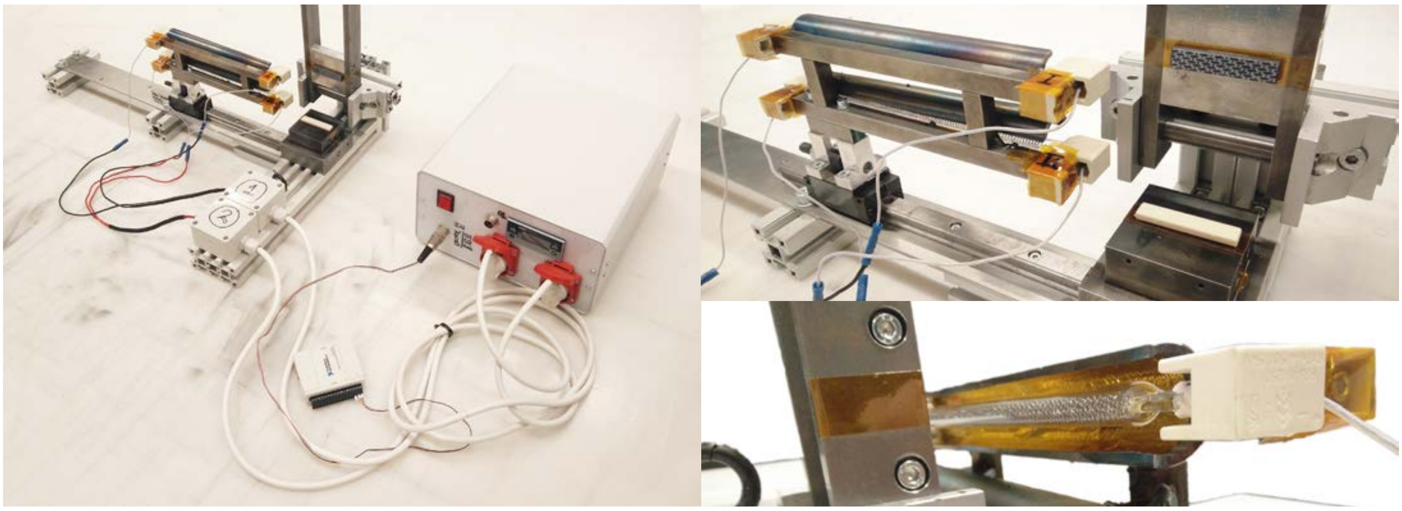
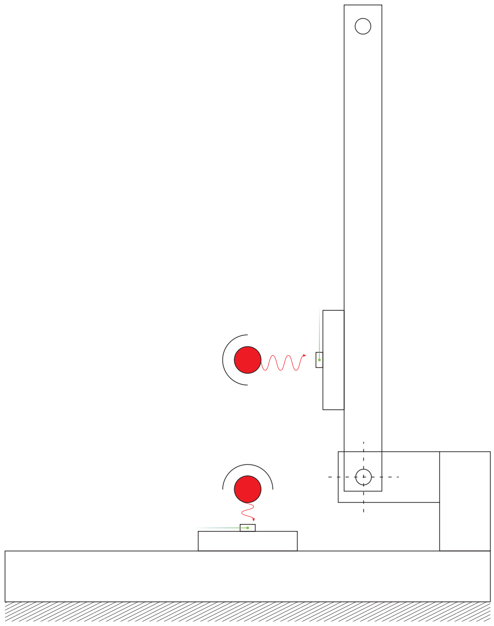


Figure 59: The experimental set-up made for this chapter.

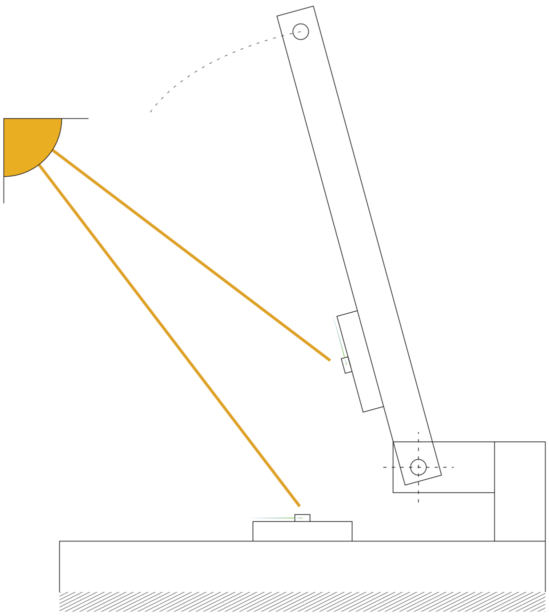
The setup is made to reach both of the temperature set points before pressurizing every joint similarly using a set weight on top of the sample. The pressure on the joint remained a low 40kPa (estimation) as this did not cause the filler to deform greatly. As the samples were not clamped from the side, filler polymer could flow outward underneath the laminate sample when pressure increased. A next iteration of this machine should surround the samples so greater pressures can be used. This trade-off caused the pressure to be a factor lower than for instance tape placement processes, which gave rise to voids in the specimen.
The used PSS granulate is Fortron214 from Celanese. This polymer is used for both the filler material and the matrix material of the laminate. Polyphenylene sulphide (PPS) is a semi-crystalline engineering thermoplastic that has excellent mechanical and thermal properties combined with a relatively low melting point of 280°C. Next to its high flame and chemical resistance it possesses a very low melt viscosity. Details of the polymer relevant temperatures can be found below (Celanese Database, 2019):

Melting Temperature	280 ^{o}C
Glass Transition Temperature	90 ^{o}C
Processing Melt Temperature	310 - 330 ^{o}C

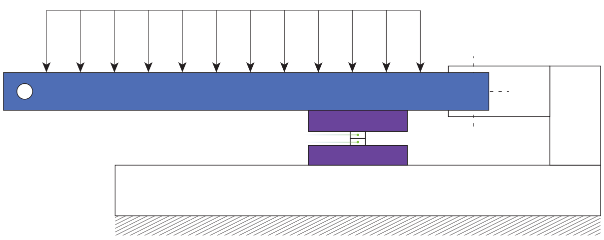
The manufacturer specified that the polymer should be injection molded between 310 to 330^{o}C. One can expect the polymer to have good flowing behaviour at this temperature, but exposed to open air, oxidization can impact its mechanical performance. This experiment does not use injection (over)molding to produce the joints, but presses two heated specimen against each other in the open air. To limit thermal degradation and extreme deformation of the specimen during welding, the temperatures used should be limited.
The set-up uses thermocouple data to heat the samples. The average temperature of the sensors was used as a control input. When the thermocouple average had reached a stable value, the thermal camera started recording and the materials were pressed together. The thermal camera data was post-evaluated to find the actual surface temperatures.
The set-up lacks the power to reach high filler temperatures. Surface temperatures of the filler can be controlled to lay within the range of 285^{o}C to 295^{o}C (IR-camera surface temperatures). This is still above the melting temperature of the polymer.
The laminate temperature testing range is chosen to be between 180^{o}C and 265^{o}C (IR-camera surface temperatures). This should give data points with average interface temperatures up to 280^{o}C. It is expected that in exceeding this interface temperature range, excess energy may degrade or deform the weld. This assumption may be tested with the final welding in production for the PDEng.
Recorded surface temperatures show gradients caused by the insufficient distance between the heating elements and the samples. The working principle of the machine only allows to make a test matrix of the controller set-points and not the true surface temperatures measured with the IR-camera. The set-point of the filler was always



Infrared heating of the samples using thermocouple measurements below the sample surface.



Surface temperature measurement with an infrared camera.



Constant pressure with weight of the set-up arm. Passive cooling with metal blocks.

Figure 60: Welding procedure. Components are color coded corresponding to colored words in the text boxes.

300°C to enhance the changes of the surface temperature falling in the processing range of the polymer. This set-point was experimentally tested in earlier tests. The laminate temperature set-point will be increasing from 200°C to 285°C in twelve steps.
The welded samples were tested on their strength using the short beam shear method. This method gives a performance indicator of the welds shear dominated behaviour and is popular in the composite industry. One could look into mixed mode fracture testing, but the ratio between mode one and mode two loading cases in a specific T-joint loading scenario should be known. This research also uses short beam shear experiments as they are quickly conducted and are still relevant to the loading of a T-joint. The drawing in Figure 61 shows how specimens are loaded in short beam shear testing. In total twelve test were undertaken. Reproducibility was not tested in these samples.

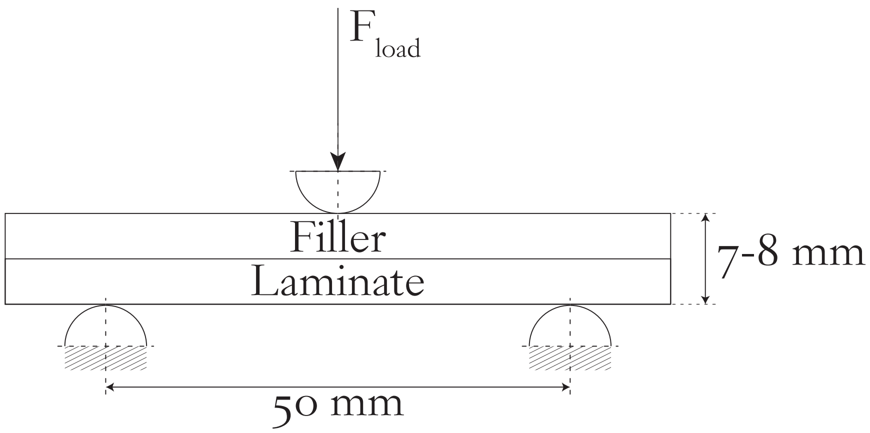


Figure 61: Short beam shear principle. Pure PPS at the top and laminate at the bottom.

A.3 Results

Twelve specimen were welded and tested. The IR-camera provided surface temperature data of the samples just before contact. This raw data showed the gradients in the temperatures. The effect of these gradients in unknown. The laminate specimens are the one on the top that show gradients from left to right. The laminates are varied in temperature and thus show large differences between their temperatures and gradients. The hotter specimen showed substantial temperature gradient caused by uneven heating of 250-300ºC. The colder laminates had no gradient.
The bottom samples are the pure polymers which were controlled to lay within a tighter temperature range. The samples are similar to each other and only vary slightly. The specimen did show more extreme, radial thermal gradients of about 250-350ºC (hot in the middle). The surface data of each sample was averaged into a single value. This can be seen in Figure 62. There was always an error between the average thermocouple data and the average surface temperatures measured by the infrared camera. This error never exceeded eleven degrees Celsius.

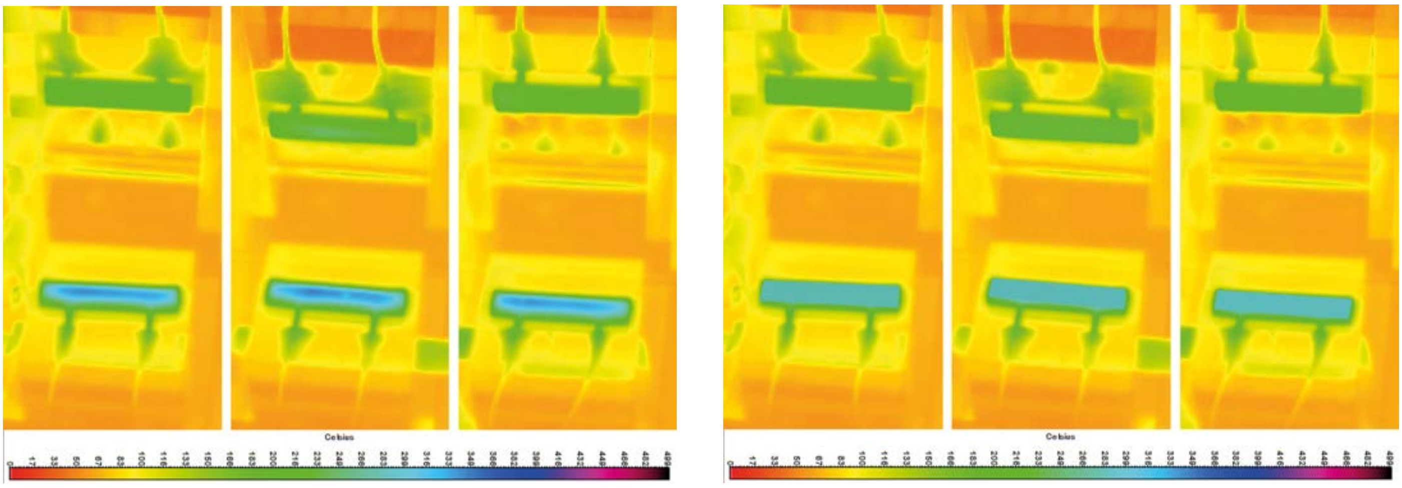


Figure 62: Samples 103, 104 and 111 before and after taking the average over the sample surface.

All filler surfaces turned brown due to oxidization (Figure 63) as they were exposed to air above melting temperatures for two to three minutes during heating. The setup could be improved by limiting the oxygen around the filler material by an inert gas flow or quicker heating times. The heating and cooling cycle of a typical filler specimen can be seen in Figure 64.

Figure 63: The browning of PPS in sample 111.

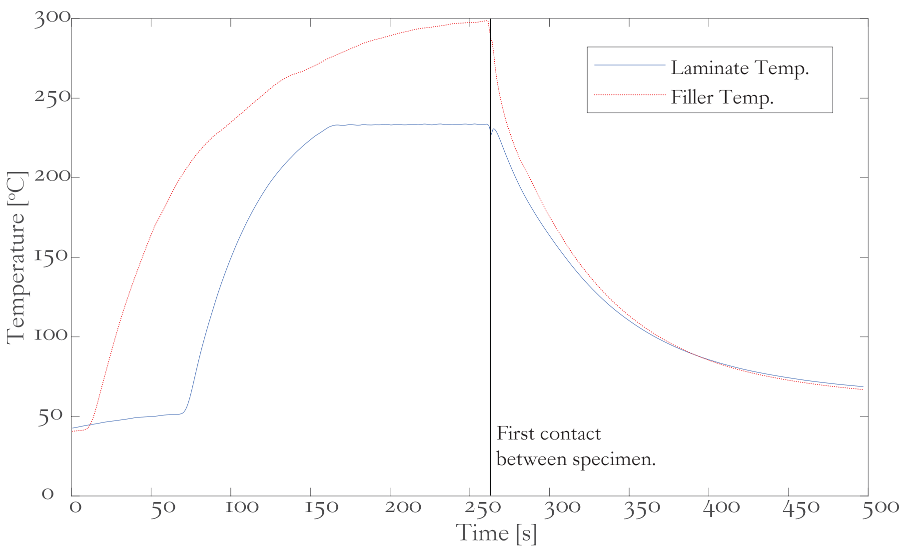


Figure 64: Heating cycle of a sample.

The filler thermocouples show the cooling rate of the polymer. As soon as the heat source is removed, the sample temperature drops around 30 degrees in 6 seconds. This would indicate a maximum cooling rate of 5ºC/s, which would enable the PPS to crystallize. Cooling was passive through the aluminium and steel clamps of the set-up. After the twelve welds were tested, the ultimate loading of the specimens are plotted against interface temperatures. The interface temperature was the average of two averages and is thus not representative to the large gradients. Two distinct groups can be identified in the plot of the data (Figure 65). The first group consists of samples that were welded at too low temperatures. The second group is formed by samples that are welded above a minimal interface temperature of about 260ºC. The temperature boundary of 260ºC seems to give better performance with less variation under the joint strength.

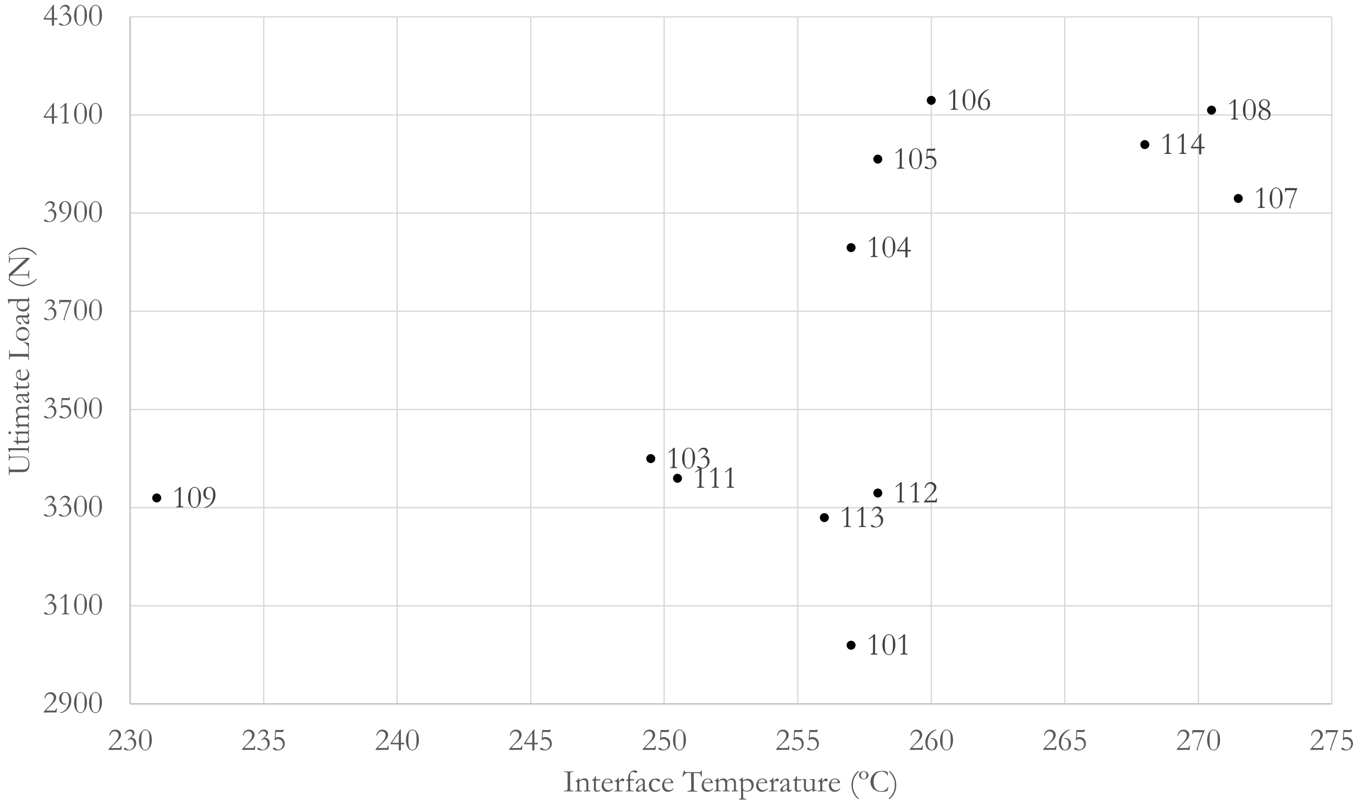


Figure 65: Ultimate loading versus interface temperature.

In order to analyse the effect of interface temperatures on the location of the weld failure in the sample, a visual inspection was carried out to categorize failures. Three fracture scenarios are observed: from full delamination at the interface to full fracture of the welded sample, via partly delamination and fracture of the polymer or the laminate. The data in Table 7 shows that the green group of samples has predictable failure in the laminate.

T_{lam}	T_{filler}	T_{inter}	Weld #	Ultimate Load	Failure Filler	Failure Interface	Failure Laminate
181	281	231	109	3320	X	Full Separation	Middle Fracture
231	283	257	101	3020	Transverse Fracture	Halfway Separation	X
230	282	256	113	3280	Transverse Fracture	Full Separation	X
216	283	250	103	3400	Transverse Fracture	Full Separation	Middle Fracture
216	285	250	111	3360	Transverse Fracture	Halfway Separation	X
231	283	257	104	3830	Transverse Fracture	X	Middle Fracture
233	283	258	112	3330	Transverse Fracture	Halfway Separation	Middle Fracture
233	283	258	105	4010	X	X	Middle Fracture
235	285	260	106	4130	X	X	Middle Fracture
256	285	271	108	4110	X	X	Middle Fracture
251	285	268	114	4040	X	X	Middle Fracture
258	285	272	107	3930	X	X	Middle Fracture

Table 7: Table with the corresponding welding temperatures.

A few samples showed imprints of a resin rich zone of the laminate onto the polymer part. Specimen 109 showed by far the biggest spot of approximately 2-3mm^2. SEM-microscopy images were made of both sides of the broken weld interface (Figure 66).

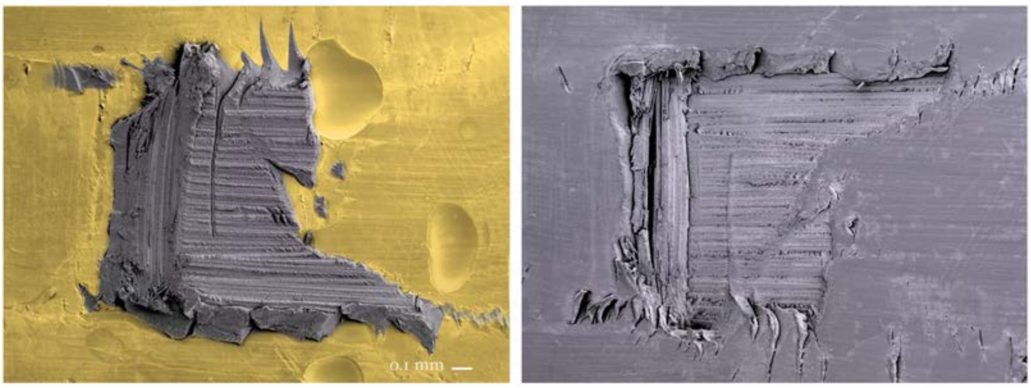


Figure 66: On the left a piece of fiber reinforced PPS on top of a pure PPS plate. The right image is the original substrate. Images were colored by hand to identify regions.

Large voids can be found on top of the yellow coloured pure PPS due to the low processing pressure. These induce stress concentrations to create weak links in the interface. Another fibre spot was found on the PPS substrate of weld 112 (Figure 67). This image shows that specimen 112 was fractured halfway in the filler material. The sample in Figure 63 showed the same type of failure. The pictures are taken at the middle of the broken specimen and show the fibers that stuck to the other specimen. Again, voids surround the area, but now a fracture can be seen in the laminate too. It seems as a complete fiber bundle has shifted due to the fracture.

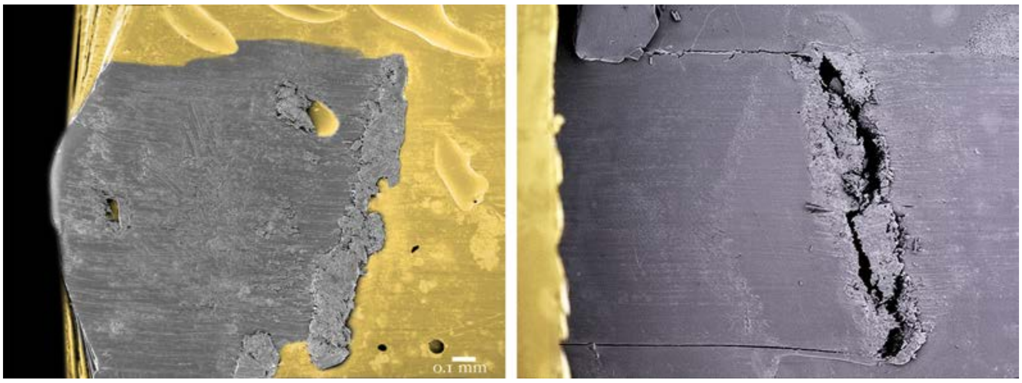


Figure 67: On the left a piece of fiber reinforced PPS on top of a pure PPS plate. The right image is the original substrate where now a fracture around the fiber bundle can be seen.

A.4 Conclusion

With the filler sample surface within the temperature range of 285°C to 295°C, the strongest bonds form when the interface temperature is over 269°C. Creating a secure bond, requires the polymer chains at the surface to melt and interdiffuse and thus it is expected that weld strength will increase with interface temperatures up to around 280°C. What happens after this point is unclear. Thermal degradation is limited by the set filler temperature, but raising the interface temperature by heating the laminate further might lead to deconsolidation of the laminate before welding. This could mean that with further increasing temperatures, the weld strength will decrease. Filler temperature does not lay within the processing range defined by the manufacturer. These temperatures should be increased, but thermal degradation may cause damage to the weld. In the welding head under development, the filler should be heated between 310 and 330°C, while exposure to oxygen should be limited. Quick heating and cooling cycles can also be of importance here to reduce the effect of thermal degradation by limiting exposure times.

Using the limited testing results of this research, an automated welding head will have to be able to achieve interface temperatures of at least 269°C to have better and more predictable performance under short beam shear loading. Higher interface temperatures of up to 280°C will most likely allow for stronger welds. The slow experimental passive cooling allowed the PPS to crystallize. Increased cooling rates will make the joint tougher and thus less brittle which can be beneficial in dynamic loading cases.

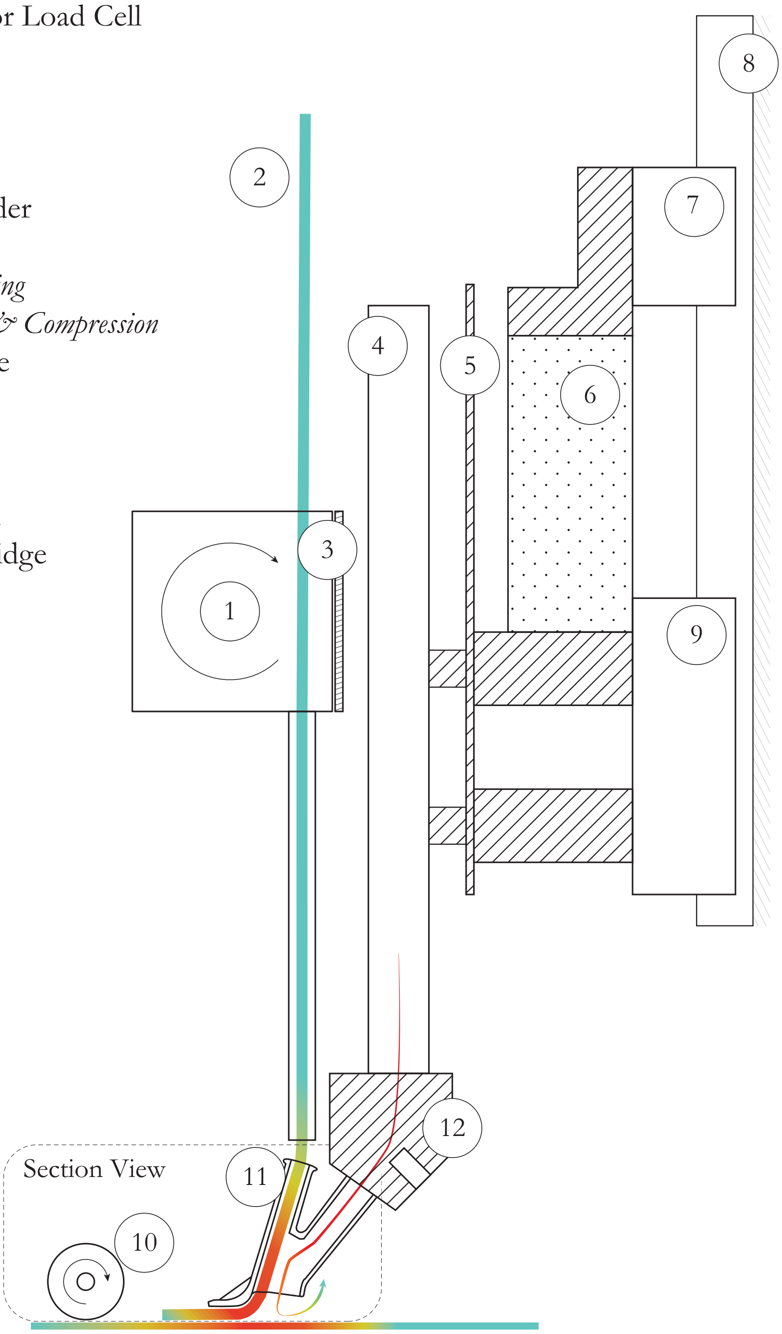
The non-uniform heating of the samples was revealed by the infrared camera. Moving away the infrared heaters from the samples may give more uniform heating, but this was impossible as the set-up was already at maximum power for these experiments. It seems that hot gas or laser light are better candidates to bring the PPS up to processing temperatures. These sources enable higher heat transfers between source and sample and have improved uniformity in heating.

As a last remark, pressures were lacking in this design. Attention is required in regulating the flow of the filler while pressurized. Because there was no mold completely surrounding the filler material in this design, pressures were limited to a low 40 kPa. This left voids at the interface in the samples welded at lower interface temperatures which could be seen after they had failed at the interface. The stronger samples were not inspected on their voids as they did not fail at their interface.

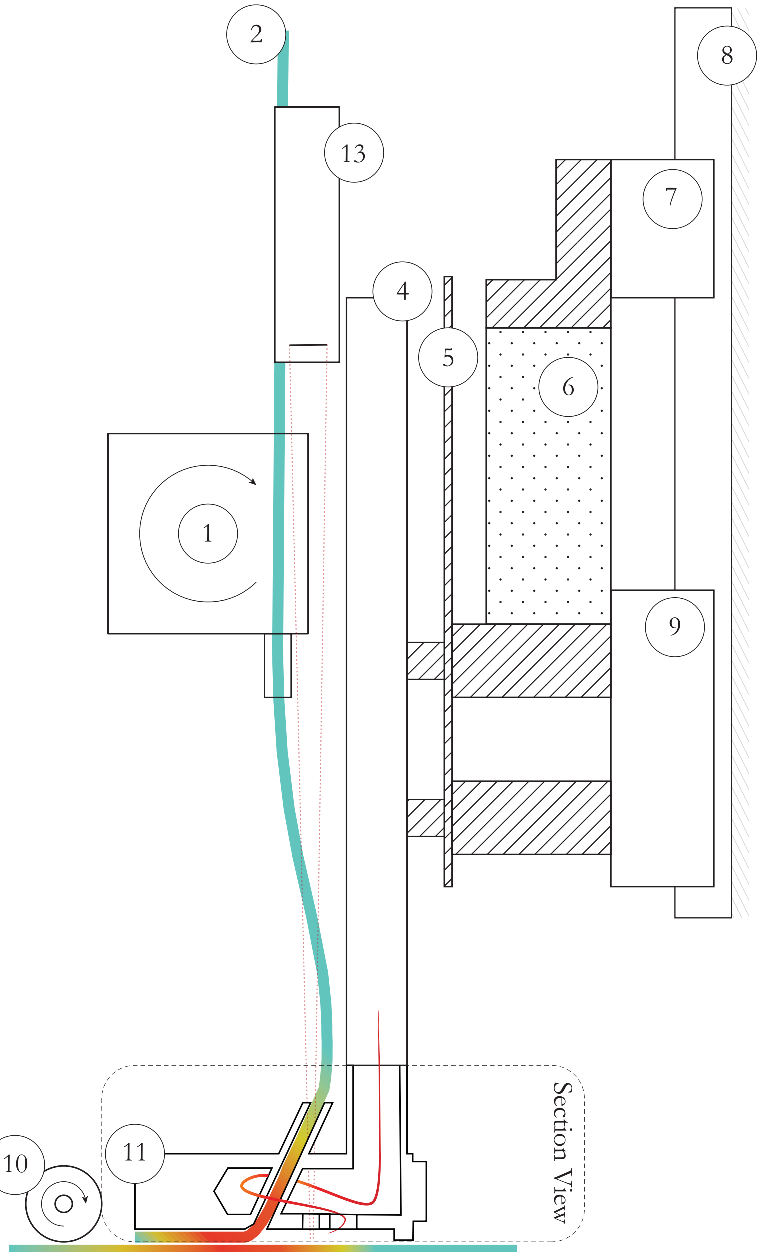
Appendix B: T-CAT drawings

Component List:

1. Filler Wire Feeder
2. Filler Wire
3. Wire Feeder Heat Shield
4. Hot Gas Gun
5. Heat Shield for Load Cell
6. Load Cell
7. Rail Clamp
8. Rail
9. Rail Wagon
10. Laminate Feeder
11. Welding Shoe
    a. *Laminate Heating*
    b. *Filler Heating & Compression*
12. Thermocouple
13. Pyrometer
14. Heatsink
15. Linear Guide
16. Heating Spiral
17. Heating Cartridge



T-CAT REV1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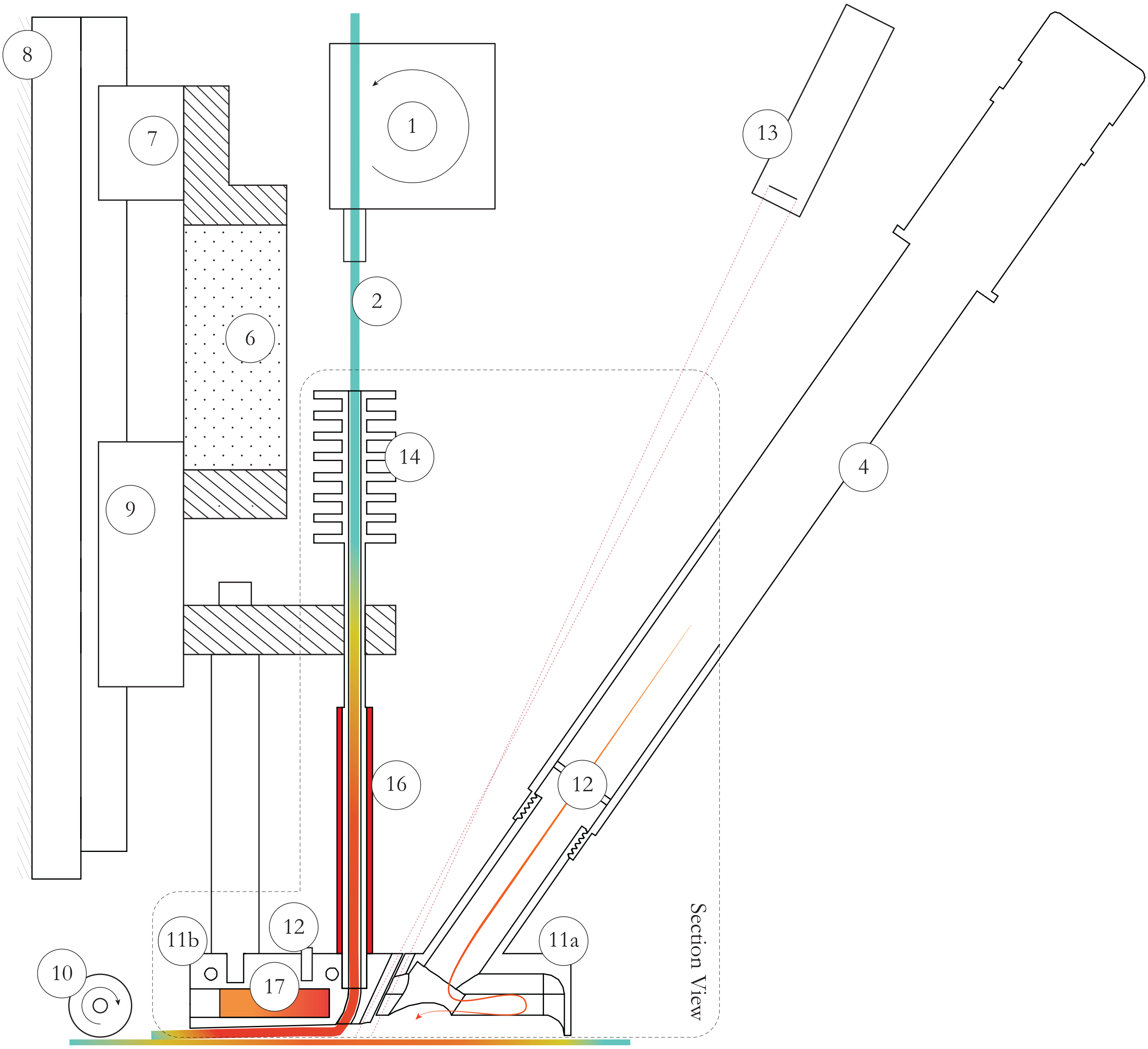
Section View



T-CAT REV3

Appendix C: Complete Requirement Overview

Hot Gas Laminate Heating:
- Measure gas temperature gradient in the nozzle with two points.
- Distance between laminate temperature measurement and filler contact has a 10 millimeter maximum.
- Actuation and laminate temperature measurement spot overlap.
- Use empirical gas temperature during start-up instead when there is no laminate temperature measurement.
- Have an adjustable measurement spot size for the laminate surface to facilitate different lay-ups.
- Measure the laminate temperature non-destructively.
- Measure the laminate temperature from 230-280ºC.
- Heat laminates up to 280ºC.
- Use gas flow of 70 LPM.

Conductive Runner Filler Heating:
- Design for filler diameter of 2.85 millimeter (standard 3D printing size).
- Support the filler material to overcome buckling.
- Measure runner temperature at three points.
- Minimal length of the runner is 110 millimeters.
- Design clear start for filler heating section for simulation purposes.
- Filler temperature above 280ºC at feed rate of 10 mm/s.
- Filler heating path should be straight.
- Have a replaceable runner.
- Restrict filler flowing into the laminate temperature measurement spot.
- Filler geometry should have a 6 millimeter radius.
- Measure runner temperatures up to 330ºC.

Weld Force:
- Let the load cell remain below 70ºC.
- Measurement range of 0-200 Newtons
- Provide 1 DOF guidance to load cell over full temperature range of the welding head.
- In case of linear bearing guidance use seals against contamination.
- Vary distance between welding head and laminates between 0 and 1 millimeter.

Cooling Section:
- Have a constant weld volume using a radius of 6 millimeter for the filler.
- Use Passive cooling to reduce complexity.
- Leave room for heating cartridge to bring the bottom of the element up to 200ºC.

Drive:
- Drive the welding head over the laminates at 1-3 mm/s.
- Feed the filler with a rate of 1-10mm/s
- Home the welding head automatically.
- Set start and end limits to the welding trajectory.
- Maximum moment around the driving direction is 80 Nm.

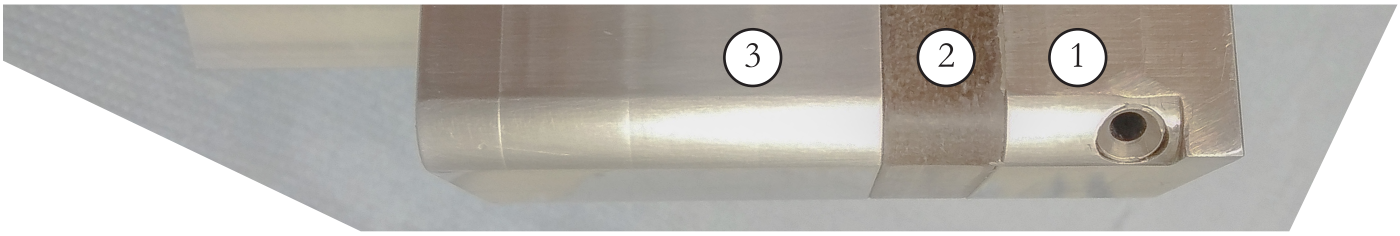
General Electronics:
- Vary power output of the heaters continuously between 0-100%.
- Shield sensing equipment from power equipment.
- Provide a warning light on the welding head to indicate temperatures above 80ºC.
- Input of additional 3 thermocouples next to laminate and filler heater sections.

- Prevent ground loops.
- Include optional failsafe for load cell temperature.

Software:
- Measurement and control loop takes 1 seconds maximally.
- Provide separate drive and data I/O dashboards.
- Allow user to adjust controller parameter inputs.

Appendix D: Gallery of T-CAT REV4.

The welding head moves over clamped laminates to produce the weld. The pictures in this appendix enlighten on the use of the machine and how its supported by other components.
The picture at the top of the next page shows the underside of the welding head consisting out of a steel filler heating section (1) followed by a mica insulator (2). The cooling block (3) is made out of aluminum. The radius of all parts is the same so that the weld volume remains constant and the welding head cannot get stuck on solidified filler material.
The second picture from the top shows the complete welding head on its rails. The hot gas produced by the heater (4) and the filler heating section can raise the temperature off the load cell over its given operating temperature. Therefore, air cooling is added to the load cell using the fan (5).
On the outer edge of the wagon the pyrometer (6) is positioned. The pyrometer measures the laminate temperature between the hot gas and the filler heating section. To warn the user if the a component of the machine is over 80ºC, a warning light (7) is added in the support frame.
To make single-sided welds, a clamping system was made (8) that is connected to the rail. The wagon is driven by a stepper motor (9) through a belt drive.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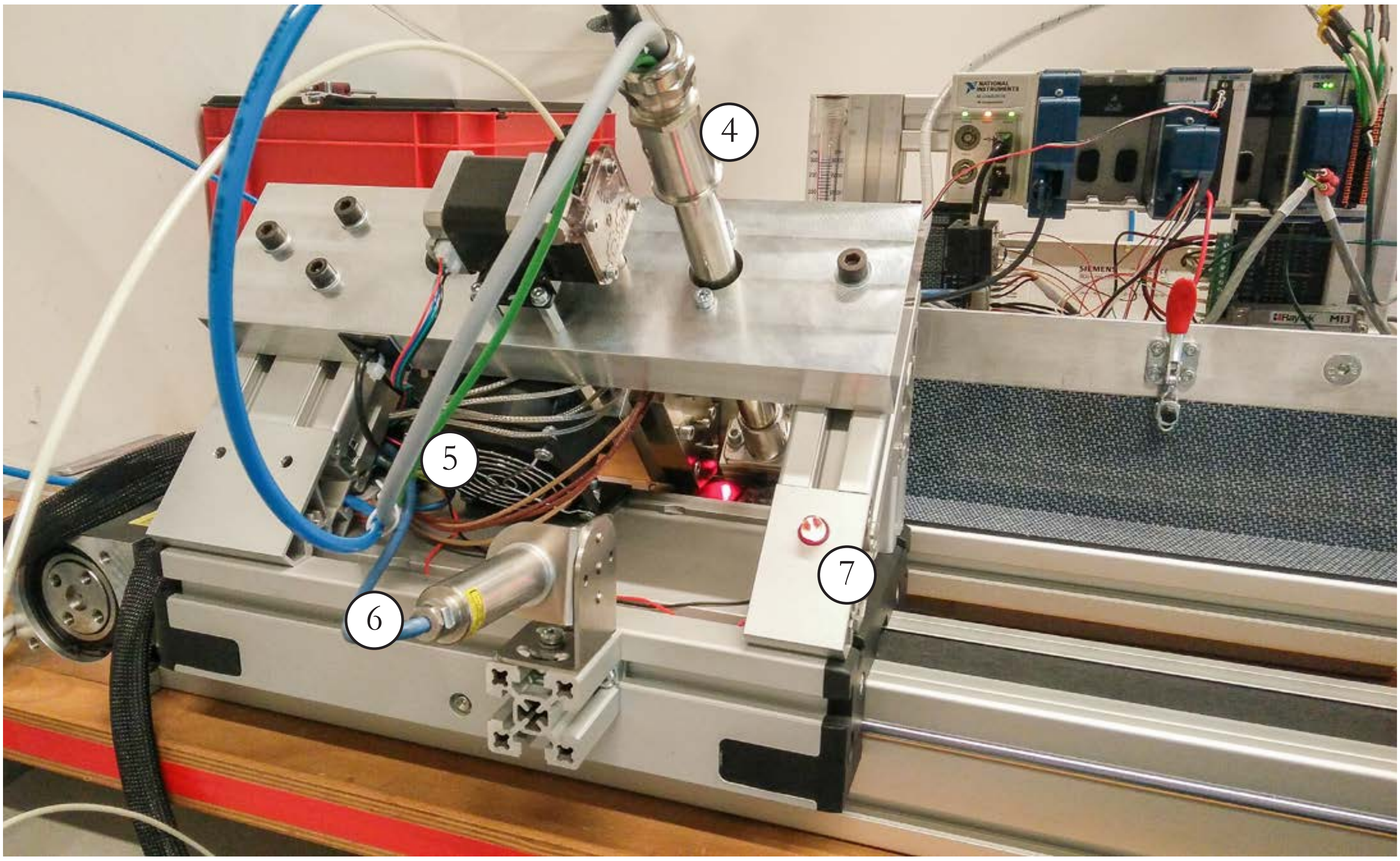
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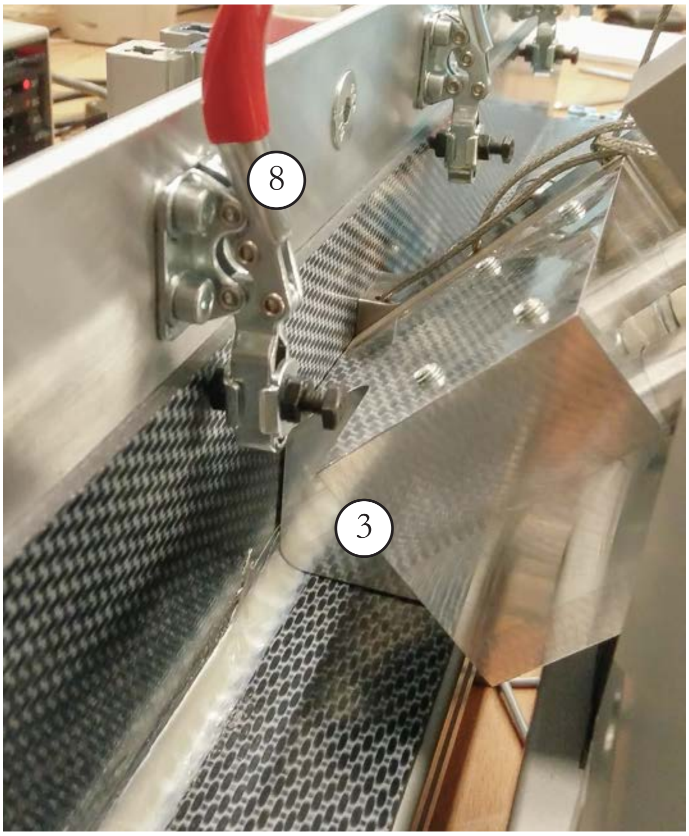
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T-CAT
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Appendix D: Digital User Interface T-CAT REV4