INDUCTION WELDING TECHNOLOGY FOR THICK COMPOSITES

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ABSTRACT

Induction welding offers significant benefits for joining thermoplastic composites. Although it is commonplace to weld thin composites, welding thick composites remains a challenge due to the low magnetic field strength at the weld interface and overheating of the substrate closer to the coil. This study aims to develop an induction welding methodology based on KVE INDUCT® for thick composite substrates up to 8 mm thickness each, and demonstrate it for the first time. Quasi-isotropic C/LM-PAEK laminates were manufactured at thicknesses of approximately 4 mm and 8 mm. 4 mm + 8 mm and 8 mm + 8 mm substrates were welded from the thicker side. Several approaches were employed to weld the substrates: using a susceptor, adjusting the process parameters (weld speed & current), using additional heat sinks/constraints, and utilizing a magnetic flux concentrator. Welding thick composites required significantly lower speeds and higher currents compared to thin laminates. However, an innovative coil design involving a magnetic flux concentrator facilitated increasing the weld speed and lowering the current to values compared to standard thickness substrates (2.2 mm). Constraints placed along the edges of the substrates helped to constrain the flow by setting a physical boundary and extracting excess heat. Robust and high quality welds were realized with the innovative coil and additional heat sinks combined, demonstrated by C-scan analysis, without using a susceptor.

1. INTRODUCTION

The Dutch research project “Aviation in Transition” focuses on developing materials, production technologies, and construction concepts for large ultra-efficient aircrafts made of lightweight components. Thermoplastic composites play a significant role in this “transition” thanks to the advantages they offer, such as weldability, which enables lightweight, fast, and durable assemblies. One of the welding technologies that is being researched within this project is induction welding. Consortium composed of research institutes, companies, material and component manufacturers, among others, collaborate to increase the level of maturity of the induction welding technology for sustainable aviation and certify it. One of the main focus areas of the induction welding research is the welding of thick composites. From the application point of view, it is interesting to focus on thick composites since some aerostructures need to have high thicknesses due to strength and stiffness requirements. For instance, this is the case for the regions around the cut-outs such as windows, passenger or cargo doors, which need extra thickness to be able to endure stress concentrations. Researching induction welding of thick composites is interesting also because heat generation at the interface of the substrates becomes more challenging at higher thicknesses due to larger coil-interface distances.

During induction welding of thermoplastic composites, substrates to be welded are positioned in close vicinity of a coil through which an alternating current runs at high frequency, which generates an alternating magnetic field. This magnetic field induces “eddy currents” in the electrically conductive substrates, causing Joule heating due to the electrical resistance of the fibers and intra- and interlaminar fiber contacts [1], [2]. The applied magnetic field also causes dielectric heating in the thin layer of matrix separating the fibers at fiber-fiber junctions. These heating mechanisms depend on the magnitude of the magnetic field generated by the induction coil which decreases with increasing distance from the coil. This causes the parts of the substrate closer to the coil to heat more than the interface (skin effect), which is not desirable for welding. To focus the heat to the interface, typically a heat sink is used between the coil and the adjacent substrate in KVE Induct® technology, as mentioned in [3], and also illustrated later in Figure 3 of this paper as “standard heat sink”. This method successfully works for composite substrates of standard thickness (about 2 mm). Most previous work on induction welding involves welding of composites with this thickness [4], [5], [6]. However, as the thickness of the substrates increases, magnetic field close to the weld interface gets weaker. This poses multiple challenges for welding. Firstly, the temperature generated close to the interface decreases. Secondly, the warmest spot may not be at the interface anymore, but in the upper substrate, which causes issues such as squeeze out due to overheating. These issues necessitate additional measures about the welding method and tooling.

1.1. Aim

The aim of this work is to develop a methodology to weld carbon/LM-PAEK substrates up to 8 mm thickness each, having UD layers, in single lap shear (SLS) configuration. This thickness is based on the thickness of the fuselage skin around the cargo door of the MultiFunctional Fuselage Demonstrator (MFFD) developed within a Clean Aviation program.

1.2. Methodology

Approximately 8 mm + 4 mm and 8 mm + 8 mm substrates are welded such that the thicker substrate is closer to the coil. Several approaches were employed to weld the substrates: using a susceptor, adjusting the process parameters (weld speed & current), using additional heat sinks/constraints, and utilizing a magnetic flux concentrator. Mechanical strength of the welded panels are investigated by performing SLS tests. To serve as a reference for the weld strength, 16 mm thick laminate was consolidated in the autoclave in a single shot. Weld quality is further evaluated by microscopy analysis and non-destructive inspection (NDI).

2. THEORETICAL BACKGROUND

The reader is referred to the literature [1], [2], [4], [5] including our previous works for a more detailed explanation of the heating mechanisms. Herein, the influence of a magnetic flux concentrator on induction heating will briefly be covered since it helps to clarify the method utilized in this study.

Magnetic flux concentrators, which are widely used in induction heating applications, help to channel the magnetic flux in a well-defined area thanks to their high magnetic permeability, which facilitates a high magnetic flux density within it compared to air. As a result of this, in the case of a C-shaped magnetic flux concentrator as illustrated in Figure 1 [2], [7], the magnetic field is concentrated to the region right below the open end of the concentrator. This increases the current density in the lower surface of the coil, and the part of the substrate right below the coil.

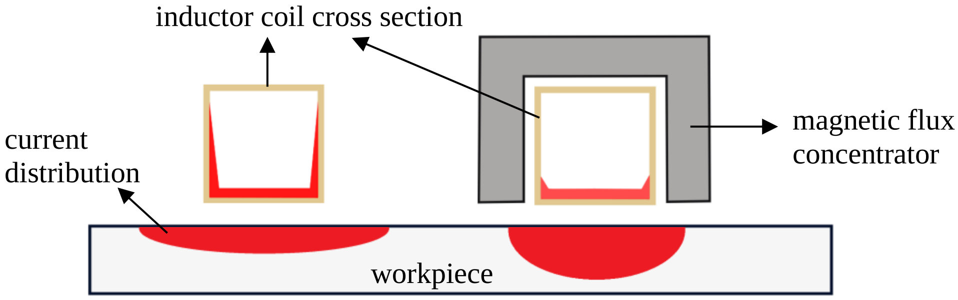


Figure 1: Effect of magnetic flux concentrator on the current distribution. Adapted from [2].

3. EXPERIMENTS

3.1 Materials and manufacturing

Substrates used for welding were manufactured using UD Toray Cetex® TC1225 LMPAEK/T700 tape. The aim was to weld two substrates having 8 mm thickness both. However, because of the limited space in the induction welding tool, 8 mm + 4 mm thick substrates were used in the initial weld runs by placing the 8 mm thick substrate at the top. This ensured that coil-interface spacing is the same as for 8 mm + 8 mm substrates. After upgrading the tool, both substrates in the weld sets had a thickness of 8 mm. The actual thicknesses of the laminates based on the nominal consolidated ply thickness provided by the material manufacturer are 7.74 mm and 4.42 mm, which are rounded to 8 and 4 mm while referring to them for the sake of convenience.

Substrates had quasi-isotropic layups of $[45/0/-45/90]_{7S}$ and $[45/0/-45/90]_{4S}$. They were manufactured by hand layup followed by autoclave consolidation. Autoclave consolidation cycle included a consolidation temperature of 365°C, a dwell time of 30 minutes at the consolidation temperature, a consolidation pressure of 7 bars, and a cooling rate of 5°C/min. After manufacturing, each blank was cut to a width of 101.6 mm and a length of 608 mm.

In two weld runs (weld sets 2 and 3 in Table 1), susceptors were used between the substrates. These susceptors are Toray Cetex® TC1225 LMPAEK/T300JB 5HS carbon fabric prepreg with 280 g/m^2 fiber areal weight co-consolidated on the surface of one of the substrates, and loose copper mesh reinforced LM-PAEK prepreg with copper areal weight of 72 g/m^2. For one of the weld runs (weld set 5 in Table 1), a layer of 100 µm thick neat LM-PAEK film was used from Victrex at the interface of the substrates.

Besides the substrates used for welding, a reference laminate with the layup $[[45/0/-45/90]_{7S}]_S$ was also manufactured to determine reference mechanical strength. Reference laminate had double the thickness of the 8 mm thick substrates. In the mid-plane of the 16 mm thick stack, 8 m thick upper and lower stacks were allowed to contact only in a 25.4 mm wide overlap region. To prevent the stacks from merging elsewhere, Upilex film was used adjacent to the overlap region, which separated the laminate into two in through-thickness direction. Similar to welded laminates, a part of the stack had neat LM-PAEK film placed between the sub-stacks to investigate the influence of neat film on the weld strength. Laminate was manufactured using the same processing parameters as for the substrates. After consolidation, reference laminate was trimmed such that SLS geometry was obtained.

3.2 Welding

Induction welding setup at NLR features a 10 kW Ambrell power supply, a KUKA robot on which induction coil is mounted, and KVE's standard coupon welding tool. Two different tools were used, one allowing a higher total thickness to be able to accommodate two substrates of 8 mm thickness each. A photo of one of the tools is provided in Figure 2, along with a schematic illustration of the SLS substrates and the location of thermocouples placed at the interface. As illustrated, substrates had an overlap of 1 inch (25.4 mm) and thermocouples (TC's) were positioned in the middle of the overlap. During welding, alternating current runs through the coil and the coil moves through the slot in the tool above the overlap.

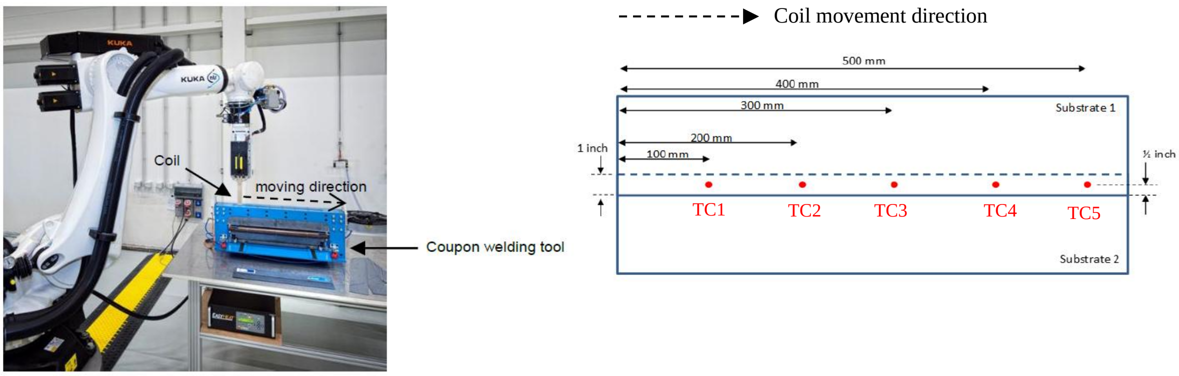


Figure 2: Induction welding setup and schematic illustration of the substrates and the position of thermocouples

Standard tooling also includes a heat sink placed between the upper substrate and the coil to prevent overheating, as illustrated in Figure 3. Pressure is applied via a pressure below the lower substrate.

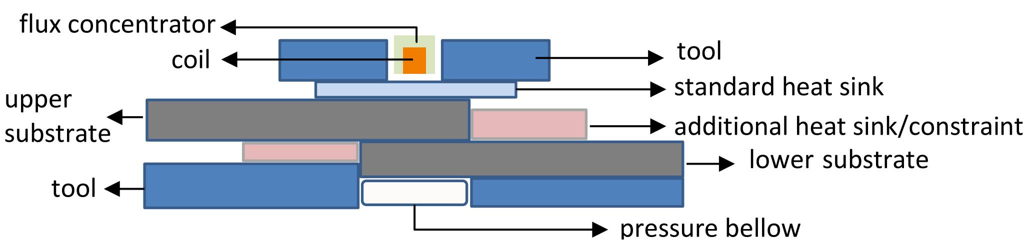


Figure 3: Schematic illustration of the cross-section of the induction welding tool including standard as well as additional components (such as flux concentrator and heat sinks at the sides of the substrates).

The illustration also includes the flux concentrator made of a Fluxtrol material suitable for the frequency of the induction field, and additional heat sinks/constraints, which are employed within this research besides the standard equipment and tooling used.

5 sets of substrates were welded. In different sets, influence of additional heat sinks, susceptors, and a magnetic flux concentrator were investigated on the weld quality and process parameters. An average interface temperature of minimum 360°C was aimed.

Process parameters, (constant current and speed), were determined to reach the target weld temperature for various weld runs which are listed in Table 1. In the table, the resulting average weld temperature is also shown, which will be explained in the "Results" section.

Table 1: Weld runs

Weld set	Thickness [mm]	Additional constraints	Flux concentrator	Susceptor / additional film	Speed [% standard speed]	Current [% max capacity]	Avg. weld temperature and standard deviation all TCs [°C]	Avg. weld temperature and standard deviation all TC2,3,4 [°C]
1	8+4	No	No	No	40	100	374.3±14.8	384.6±4.4
2	8+4	Yes	No	carbon fabric/LM-PAEK	40	100	353.8±9.1	358.3±1.6
3	8+4	Yes	No	copper mesh/LM-PAEK	40	100	355.9±9.4	361.1±0.5
4	8+8	Yes	Yes	No	60	75.6	358.7±4.3	360.0±0.3
5	8+8	Yes	Yes	LM-PAEK film	60	74.9	365.5±8.5	367.0±6.4

3.3 Mechanical tests, microscopic and non-destructive inspection of weld quality

After the laminates were manufactured, samples were machined for single lap shear (SLS) tests. Samples were extracted only from the weld sets 4 and 5, where both substrates were 8 mm thick, and also from the reference laminate.

Tests were carried out by using an Instron 100 kN universal testing machine. Overall dimensions of the specimens and tab length were based on ASTM D5868. Dimensions of the welded samples are shown in Figure 4a. Substrates have an overlap of 25.4 mm (1 inch) as illustrated in the figure. A loading speed of 1 mm/min was employed. Tabs having the same thickness as the substrates, and a length of 51.4 mm, were used as can be seen in Figure 4b.

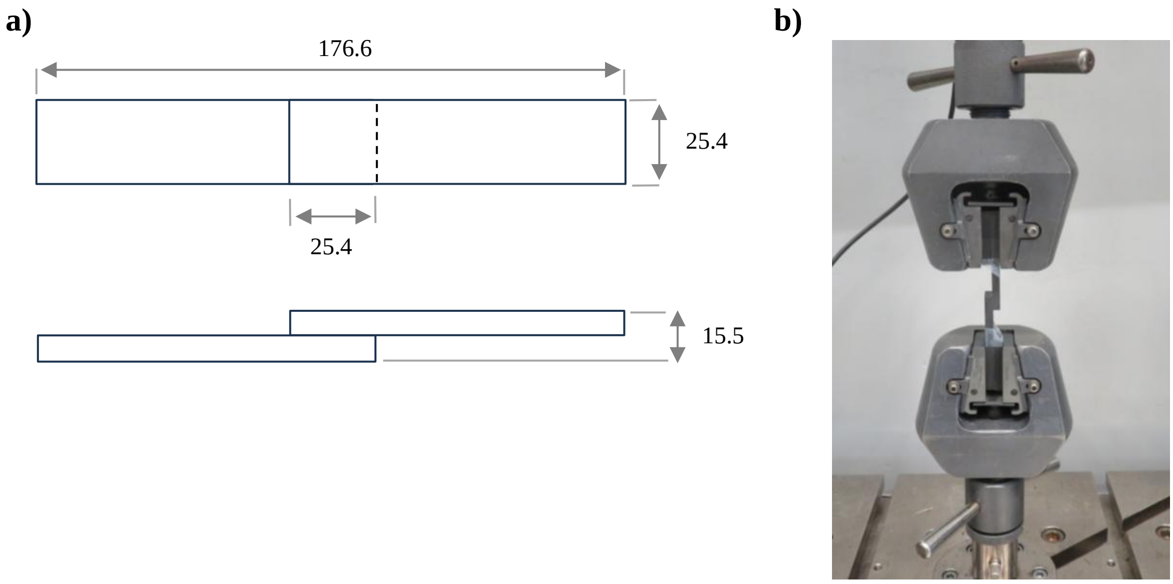


Figure 4: Dimensions of the welded SLS samples in millimeters (a) and a photo of a SLS specimen during test (b).

Two panels welded with the coil featuring a flux concentrator, panels 4 and 5, were ultrasonic C-scanned. Both the weld overlap and the parts of the substrates outside the overlap area were separately scanned. A 16-colour palette shown in Figure 5 is used to display the scan results, where the red color indicates 80% signal amplitude of the reference case, indicating good quality.

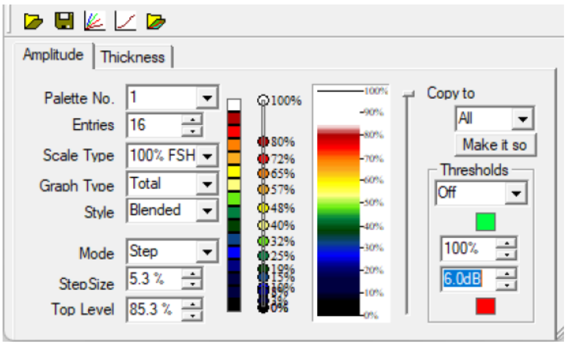


Figure 5: 16 colour palette for C-scan results

4. RESULTS

4.1 Weld temperature, visual appearance

Table 1 shows the average temperatures and standard deviations, both for all thermocouples (TC’s), and for the thermocouples 2, 3, and 4 to exclude the start and stop zones where TC1 and TC5 lie. Although there is a considerable standard deviation when all TC’s are considered, it decreases significantly once the start-stop zones are excluded. This is because temperature measured by TC1 is typically lower than other TC’s. The region in the weld overlap to the left of TC1 is at room temperature before the heating starts, which is different from the situation for the other TC's. Temperature uniformity in start/stop zones can be improved by applying variable process parameters as the coil travels, as demonstrated in [6], but this method is not employed in this research as it is not within the scope.

Welding speeds and currents in this study are indicated with respect to the standard welding speed and maximum power of the power supply, see Table 1. Standard welding speed is the speed used to weld laminates with a thickness of about 2 mm. In the weld sets 1, 2, and 3 in this study, which were welded with the standard coil, the speed needed to be decreased to 40% of the standard speed to weld the thick laminates to attain weld temperature with the maximum current the power supply could apply, as listed in Table 1. In weld set 1, where no additional heat sinks/constraints were used, an average weld temperature of 374.3°C was attained, which was above the target value. Upper substrate experienced a significant level of squeeze out (up to 4-5 mm), as shown in Figure 6a. This showed that the heat is not concentrated at the interface by utilizing only the standard heat sink above the upper substrate, and the heat affected zone in

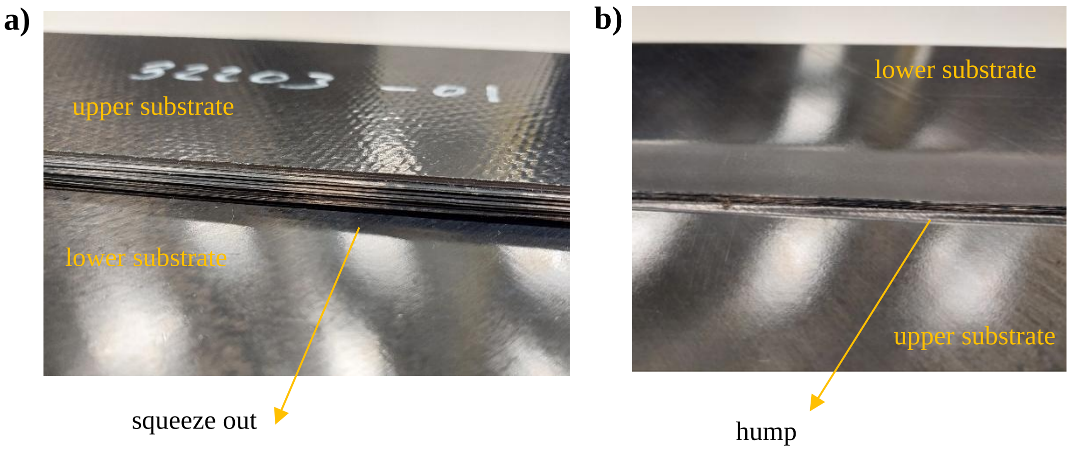


Figure 6: Appearance of welded panel 1. a) Regular orientation, b) welded panel flipped.

the mid-thickness of the upper substrate is larger than the width of the overlap. Squeeze out was also visible on the other side of the upper substrate by formation of a "hump", as shown in Figure 6b. Overheating and a lack of pressure there are also thought to contribute to the formation of the hump. Because of these problems, additional heat sinks/constraints were employed as illustrated in Figure 3 in the next weld runs to constrain the flow of matrix and extract excess heat.

Welding of sets 2 and 3 involved utilization of side constraints/heat sinks and susceptors. At the same current level as weld set 1, lower weld temperatures were obtained, which is linked to the cooling effect of the constraints/additional heat sinks. It was also seen that the use of a susceptor did not help to decrease the current regardless of the type of the susceptor used. This is thought to result from a low strength of the magnetic field at the interface. Hence, as the next step, an innovative coil equipped with a magnetic flux concentrator was used in weld sets 4 and 5 in order to concentrate the magnetic field. As shown in Table 1, it was possible to reach the desired weld temperature at 60% of the standard speed, an increase of 50% with respect to

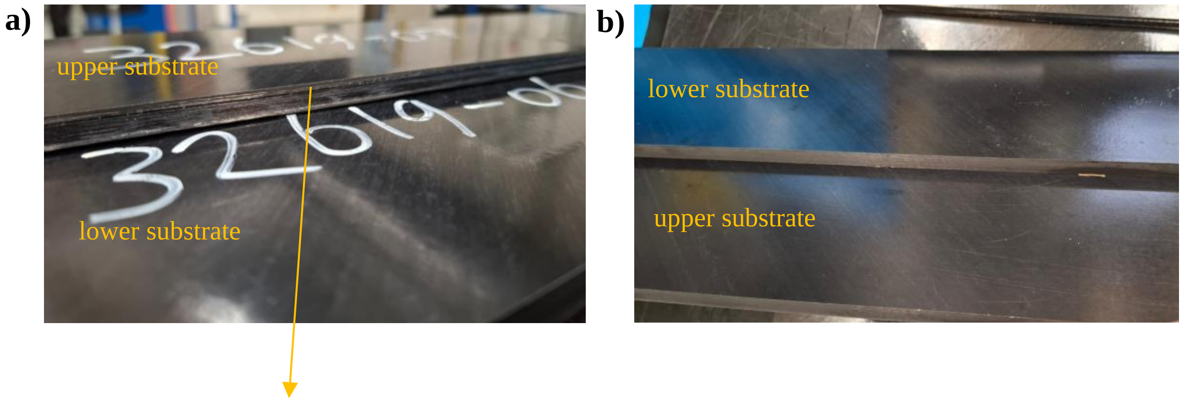
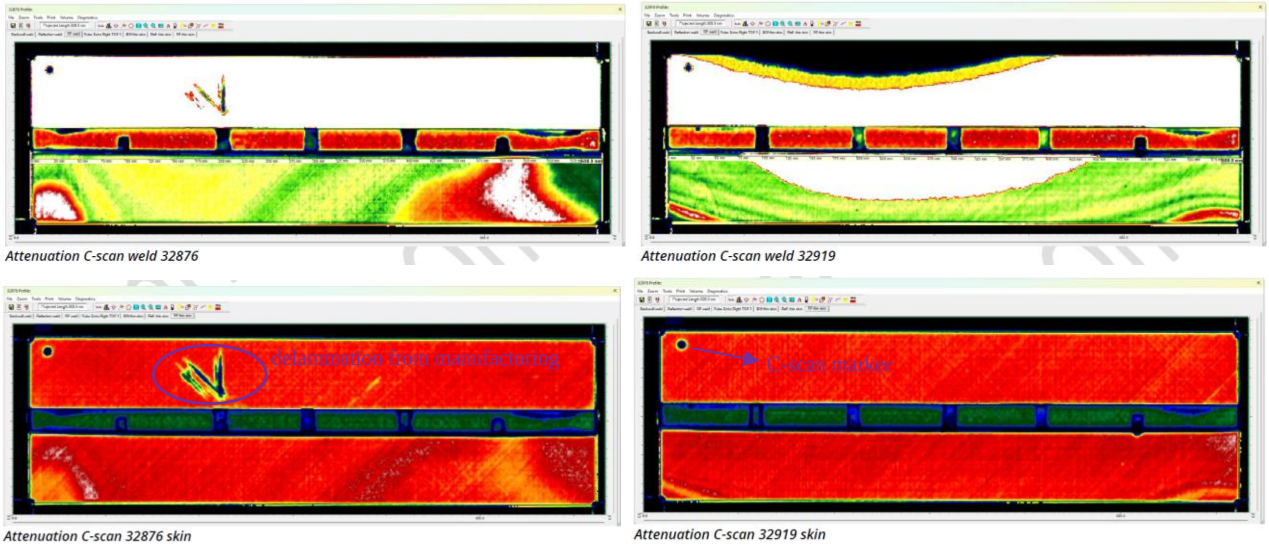


Figure 7: Appearance of the welded panel 4. a) Regular orientation, b) welded panel flipped.

the standard coil. Furthermore, required current level decreased to around 75% of the maximum capacity of the power supply, allowing processing parameters to be tuned further if necessary for a future welding scenario. Visual appearance of the welded panel (set 4) is shown in Figure 7a. It is seen that the additional heat sinks/constraints help to constrain the flow of the flow of matrix in the upper substrate. Squeeze out can still be noticed by eye, especially in the regions not covered by the constraints: the height of the constraints was 6 mm, which is thinner than the substrate. In the next weld runs, it is suggested to increase the height of the constraints. Furthermore, minor squeeze out can be noticed also next to the top surface of the lower substrate, which is due to the thermocouples that run over the top surface of the lower substrate preventing contact of the constraint with the edge. Therefore, it is suggested also to optimize the placement of the thermocouples for the next runs. Flipping the welded panel, in Figure 7b, it is seen that the no delamination occurred at the lower surface of the bottom substrate. Edge of the lower substrate showed no squeeze out. Apart from the additional constraints/heat sinks, the presence of magnetic flux concentrator is also thought to help alleviate squeeze out effects by decreasing the size of the heat affected zone, which was demonstrated in [8].

4.2 C-scan, microscopy, and mechanical tests



Panel 4 Panel 5

Figure 8: Attenuation C-scan results of the panels 4 and 5. Upper images are from the weld area, lower ones are from the substrates.

Attenuation C-scan results of the panels 4 and 5 are shown in Figure 8, where the upper images are from the weld area only, and the lower images are from the substrates except the weld overlap area. In the scan results of the weld area, thermocouple locations are visible with blue color. Dominant weld color at the overlap indicates high weld quality. There are under-welded regions at the start and end zones of the welds, which is common for this weld technology and can be improved by adjusting process parameters such as by employing variable speed and current [6], which the innovative coil allows. Weld width is expected to be about 24 mm based on the width of the red colored zone in the overlap, which is another sign of good weld quality. The lower images also show good post-weld quality in the substrates outside the weld zone. However, panel 4 has minor delamination in one of the substrates, which was present in the substrate before welding and was caused because of embedding several thermocouples in the laminate the substrate was cut from.

Next, results of the microscopy analysis is discussed to assess the weld quality. Micrographs of weld sets 4 and 5 in Figure 9 show that the whole overlap is welded and no voids exist in the weldline; both being signs of good weld quality. Substrates are also predominantly void-free (except one minor void in the upper substrate of weld set 4). Mid-portion of the upper substrates experienced a squeeze out of about 1.4 mm despite the constraints, which is much smaller compared to weld set 1, nevertheless still undesirable to have. It is thought that this squeeze out was caused by non-optimum contact between the constraint and the edge of the laminate and non-optimum clamping of the constraint which might have led it to displace.

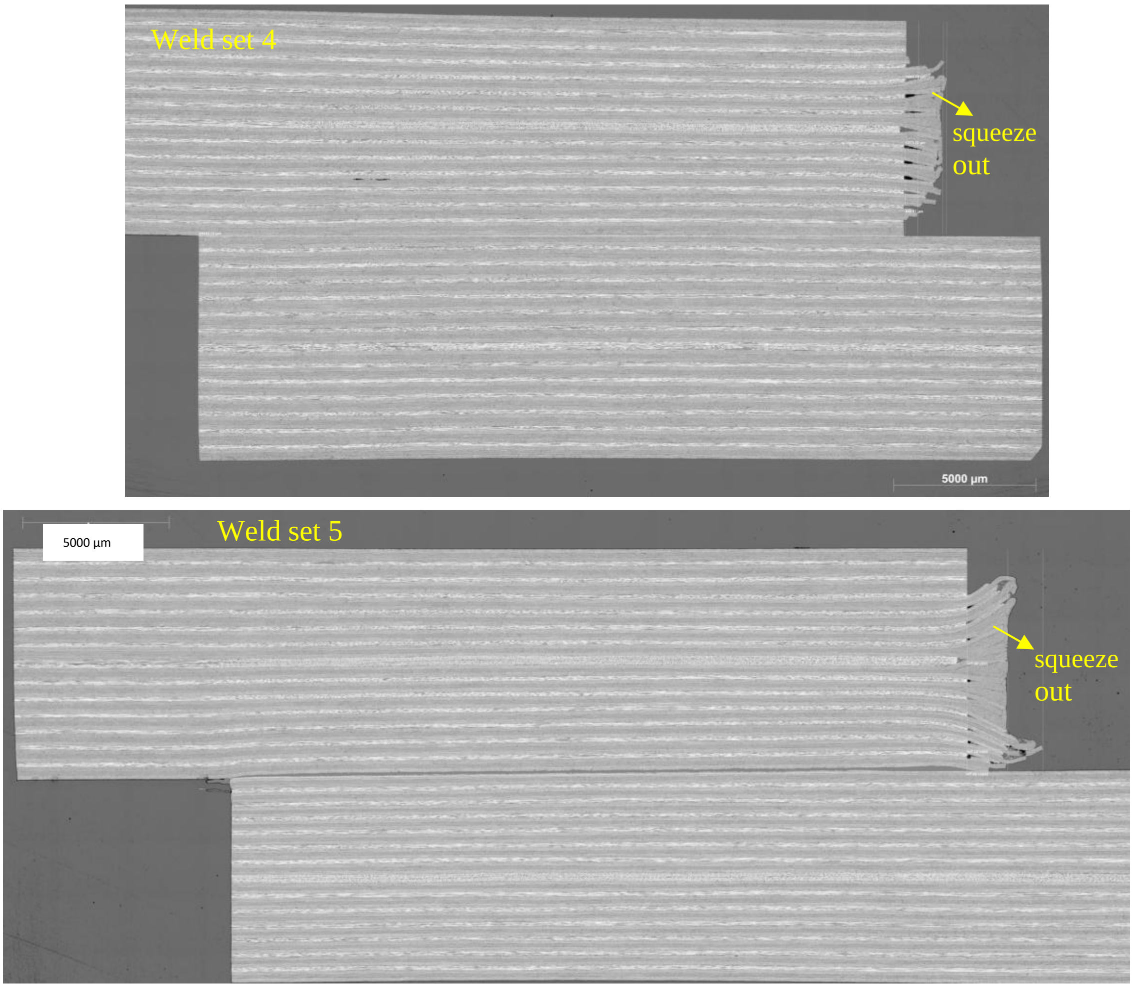


Figure 9: Micrographs of weld set 4 and 5

Weld set 5 experienced a higher volume of material squeezed out, which is thought to be linked to higher average weld temperature shown in Table 1. The positioning and clamping of the constraints will be improved for future weld runs to further decrease the squeeze out.

Lastly, SLS test results are discussed. SLS strength is displayed in Figure 10, and the fracture surfaces of the welded and reference samples are shown in Figure 11 and Figure 12. Note that the SLS strength of the welded samples is calculated based on the actual weld area measured on the fracture surfaces shown in Figure 11. Welded samples without film (weld set 4) and with film (weld set 5) had SLS strengths of 36.2±1.1 MPa, and 48.1±1.7 MPa, respectively, as displayed in Figure 10. Low scatter obtained in both weld cases indicates uniform weld quality. Weld strengths are higher compared to thin laminates [5]. Less bending during SLS testing due to higher stiffness of the thick laminates is thought to play a role in this. Addition of a neat polymer film boosts the weld performance by improving wetting at the interface, similar to observations of Kruijk et al. [5]. The significant difference in the weld strength with and without film is linked to the failure behavior: while the failure is mostly interfacial when no additional film is used, substrate failure is dominant when a film is added, as shown in Figure 11. Reference samples with and without film had a strength of 37.4±0.3 MPa and 42.0±0.7 MPa, respectively, which means weld strength is either very close to or higher than that of the reference (in the case with film). Higher weld strength might have been facilitated by the edge sealing caused by squeeze out of the substrate and added film. Failure behavior of the reference samples, shown in Figure 12, is similar to that of welded samples.

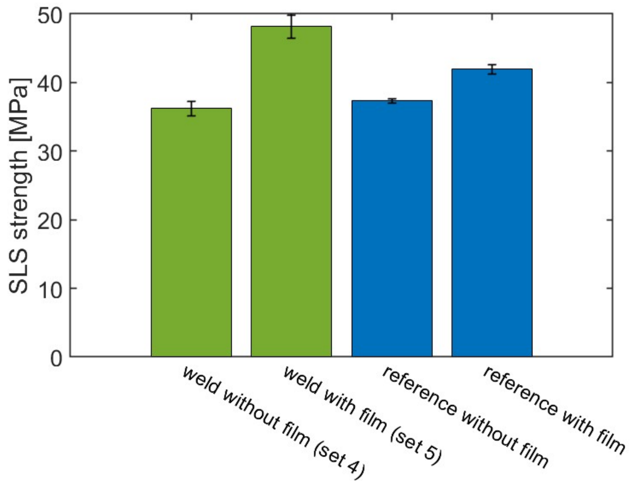
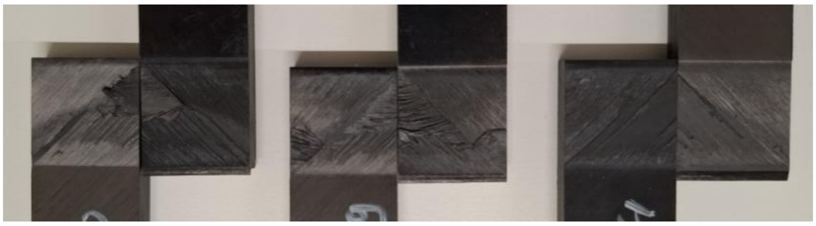


Figure 10: Single lap shear strength of reference and welded samples

Weld set 4 (without film):



Weld set 5 (with film):

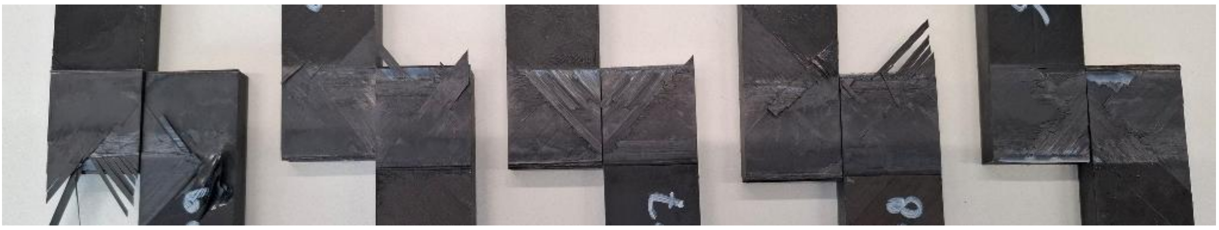
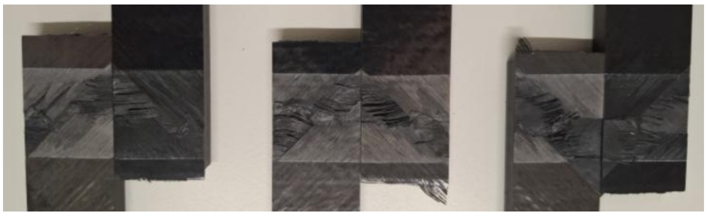


Figure 11: Fracture surfaces of the welded samples

Reference (without film):



Reference (with film):

Figure 12: Fracture surfaces of the reference samples

5. CONCLUSIONS AND FUTURE WORK

In this work, a methodology was presented to weld thick composites. This work showed that adapting the coil design and tooling was necessary to enable the welding of thick composites. The use of a magnetic flux concentrator decreased the power consumption and increased the welding speed considerably. Furthermore, the use of constraints along the edges of the substrates limited the squeeze out by setting a physical boundary and facilitating heat conduction, eventually improving weld quality. Lap shear strengths comparable to reference case was achieved, demonstrating high weld quality.

Future work in coupon-level will involve additional mechanical characterization tests such as interlaminar shear and fracture toughness tests, and an investigation of the influence of crystallinity on the mechanical performance. Later, following the building block approach, more-complex welds will be performed, such as welding thick L-stiffeners to flat or curved thick skins, eventually aiming to develop an induction welded door surround structure demonstrator. In the meantime, simulation model demonstrated in NLR's previous papers [5], [9], [10] will be extended to the welding of thick composites.

6. ACKNOWLEDGEMENTS

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