TECHNOLOGY DEVELOPMENT TOWARDS INDUCTION WELDING OF A UD-PEKK TAIL SECTION WITH STIFFENERS

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ABSTRACT

Induction welding is one of several welding techniques suitable for joining thermoplastic composites nowadays. Currently, induction welding at an industrial level is used to weld secondary aircraft structures like tail movables, made from carbon fabric PPS. To further progress on the induction welding technique, one of the research topics in the European funded project "Light Innovative Flying Tiltrotor Tail (LIFTT)" is induction welding of primary aircraft structures made from carbon UD PEKK. One of the final demonstrators in the project is a tail section of the New Generation Civil Tilt Rotor (NGCTR). In this demonstrator, press formed carbon UD PEKK stiffeners are joined to a skin with variable thickness made from the same material by fibre placement combined with an autoclave process.
Multiple induction welding tests were conducted on flat plates to determine the basic process settings. Furthermore, as a next step towards the demonstrator, numerous L-shaped stiffeners were welded on flat skins with constant thickness. Cross-ply and a quasi-isotropic – for both the stiffeners and the skins – layup variants were welded and distinct differences in welding behavior were found. Significant deconsolidation occurred in the skin of the quasi-isotropic elements due to the influence of the layup on the generated eddy currents and the resulting heat affected zones. Additional cooling was used on these areas to prevent deconsolidation. C-scan and microscopic analyses of cross-sections showed a promising quality in the weld area for both variants.

1. INTRODUCTION

The driving forces behind the increased use of thermoplastic composite materials in fixed-wing aircraft, rotorcraft, UAV's and missile systems are their superior impact toughness, excellent thermal stability and – for most thermoplastic materials – their chemical resistance. Furthermore, despite the higher raw material costs compared to thermosets or metals, the costs of the finished component can be lower due to reduced handling, processing and assembly costs. The induction welding process, which can be exploited in assembly by eliminating fasteners or adhesives and reducing the assembly weight, is being studied as part of several research programs. Focus is more and more on welding of UD material, with its higher potential to being introduced for production of primary aircraft structures. In LIFTT the use of thermoplastic PEKK UD composites is being studied and the technology development towards the induction welding for the tail of the Next Generation Civil Tiltrotor (NGCTR) is described in this paper.

1.1 Induction welding background

Induction welding is a process where the heat required to weld is introduced by submitting the parts to an alternating electromagnetic field. The induced current in electrically conductive closed-loop (fibre) paths like weaves or cross plies are called eddy currents, and form a global loop in the workpiece in the form of the mirror image of the coil [1]. Several heating mechanisms take place during induction heating of carbon fibre reinforced thermoplastics. These are Joule losses in the fibres due to their resistance and two types of junction heating between crossing fibres in the layers, as schematically shown in Figure 1 on the left. The first is dielectric hysteresis heating where crossing fibres are separates by a thin layer of matrix material which, after exposure to the alternating electric field, generates a potential difference. The second junction heating mechanism is through contact between fibres in angled plies and is dependent on the contact resistance of the fibre junction and the voltage drop across it. The extent in which each mechanism contributes to the heating process depends on the process parameters that are applied and the material and layup that is being used [2].

The eddy current can freely form a closed loop when there is sufficient material around the coil position, however orientating the coil close to the edge will force the eddy current to choose a different path to still enable it to make a closed loop. This effect is illustrated in Figure 1 on the right. It shows the induction field of a pancake-shaped coil and its temperature profile. In the figure, it can be seen that reducing the width forces the outer current loops to run alongside the edge resulting in higher temperatures due to the increased current density. This is called the edge effect [3].

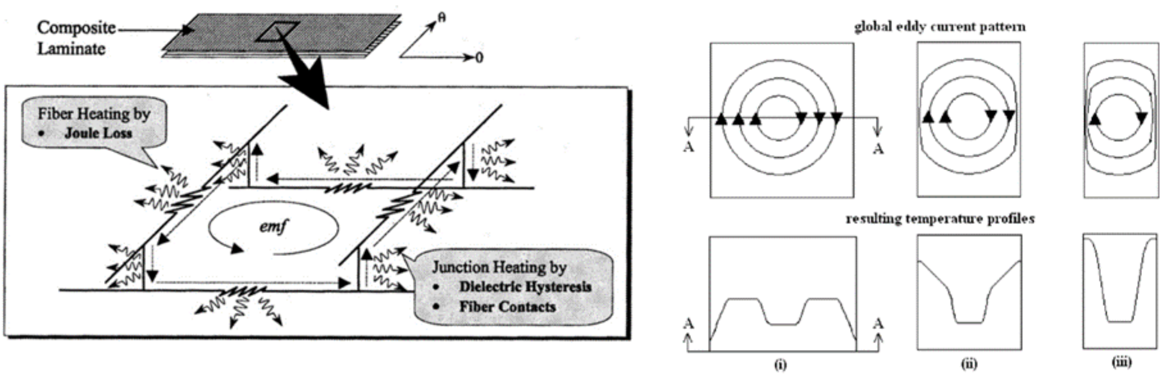


Figure 1 Left: Model of conductive loop [2], Right: edge effects resulting from changes in workpiece geometry [3]

1.1.1 Materials, layup and measurement method

For heating by induction in carbon fibre reinforced laminates, fibres at two different angles are needed for eddy currents to be generated as mentioned above. At NLR, extensive experience is gained with induction welding of PPS/T300 fabric, PEKK/AS4D UD and LM-PEAK/T700 and AS4D UD. For ease of comparison between induction welding behaviour of different materials NLR has standardized two different layups for conducting basic induction welding experiments. A 16 ply cross-ply laminate [(0/90)4]s and a 16 ply quasi-isotropic laminate [(0/-45/90/45)2]s are used for basic Single Lap Shear (SLS) and L-stringer pull off test specimens. Standard overlap of welded joint is decided to be 1 inch.

For temperature measurements during welding thermocouples are used in the weld interface. NLR selected type E thermocouples for all induction welding temperature measurements. For all experiments described in chapter 2, these thermocouples are placed at standard positions along the weld line (100, 200, 300, 400 and 500 mm) during welding experiments.

1.2 Induction welding setup

For Induction Welding (IW) research at NLR a robotic setup featuring a 10kW power supply and standardized KVE induction coil is used, see Figure 2. An also standardized weld tool is used to easily manufacture Single Lap Shear (SLS) joints of two flat laminates ranging up to 12 mm thickness. Typically a 1 inch overlap of the joint area of the two laminates is realized, but other overlap areas are also possible. The tooling setup has a slot in the top through which the induction coil runs over the weld area and accommodates an heatsink material to control the temperature of the top laminate on the coil side of the welded area. As pressure is necessary during the weld process, the entire weld zone is pressurized. Additionally the standardized IW tool can be modified to weld an L-stiffener to a skin element by switching the SLS insert for an L-stiffener insert with a similar working principle. Welding of an L-stiffened test article is always done from the skin side in this setup. These L-stiffened test articles can be used for stringer pull-off tests to validate the strength of the welded joint.

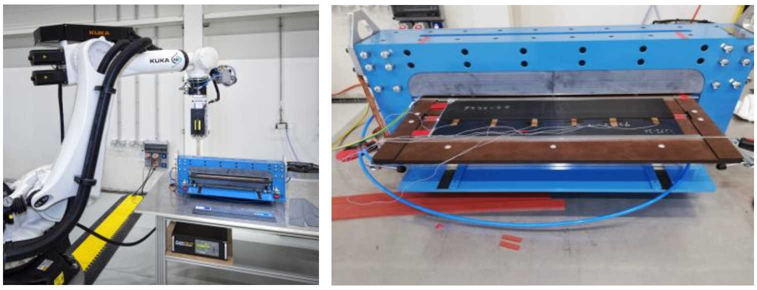


Figure 2:Robotic Induction Welding setup with standard SLS weld tool at NLR

The induction coil is mounted to the flange of a robot making it possible to manipulate and position the coil over the required welding interface at any defined speed. The weld power or weld current is directly controlled by the robot controller and can be varied over the weld path and linked to a variable welding speed. A digital twin of the induction welding cell is monitoring all the data streams provided, like robot speed and position, welding current and frequency, temperatures on the weldline interface and other locations on the laminates and pressure applied during welding. Based on this data and historical data of previous runs, suggestions to improve the welding process can be generated which is the next step to work towards a closed loop control of the induction welding process.

2. EXPERIMENTATION

All induction welding tests are carried out using a standardized test protocol. First, a so called power curve weld is performed in which five thermocouples are placed at the weld interface. During the power curve weld, multiple runs at increasing current are performed to determine the temperature at the settings. The welding speed is fixed. The final current needed to reach the target temperature is predicted based on an extrapolation of the test data and verified with an actual weld at this current. Next, at least two single weld tests are done on two separate specimens at the final setting determined from the power curve weld. In these tests only the two outer (as a temperature check) or no thermocouples at all are used to have a more realistic representation of an industrial induction welding setup for a UD tail section. If needed, the number of power curve tests and single weld tests are increased depending on the need for additional information.

The developments within LIFTT towards induction welding a UD-PEKK tail section with stiffeners is done according to the building block approach shown in Figure 3 and in this paper the focus is on the element tests of Level 2 and the Level 3 Subcomponent tests. The level 2 tests consists of welding single lap shear specimens consisting of two flat plates which are welded to each other. Welding of L-stiffeners on flat skins is part of the level 3 experiments. A short overview of these tests is given in the next paragraphs.

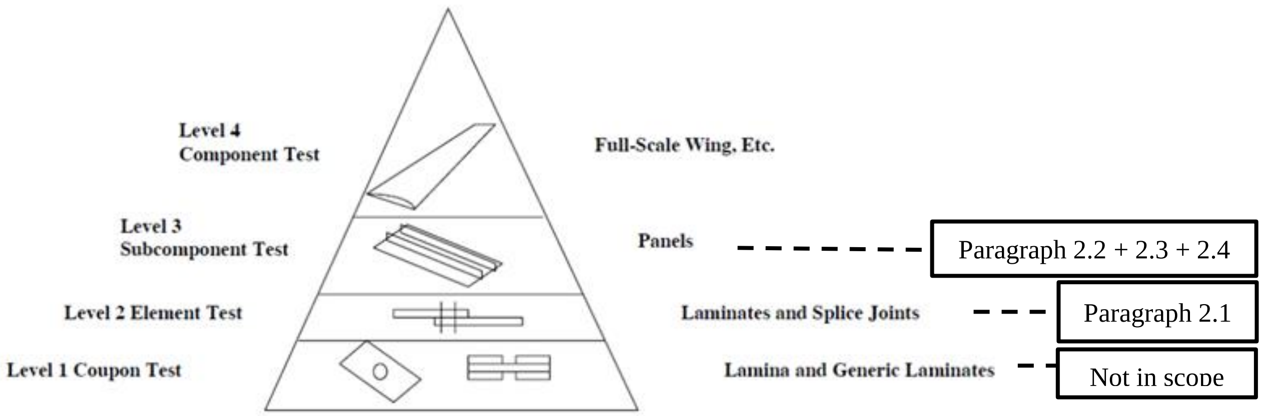


Figure 3: Example of the building block approach for testing purposes (ref. CMH-17 Vol. 3)

2.1 Welding of single lap shear specimens

Single Lap Shear (SLS) joints from PEKK/AS4D unidirectional tape were welded at NLR, before focus was shifted to the higher level L-type joints according to the building bock approach. Two flat plates with dimensions of 600 x 101.6 mm were welded at an overlap of 1 inch in the tooling described in paragraph 1.2. Both the cross-ply and quasi-isotropic layup mentioned in paragraph 1.1.1 were used. After welding at several parameters the quality of the welds are inspected by C-scan, microscopic analysis of cross-sections and lap shear tests. From these results the process settings for temperature and pressure are determined which will serve as the starting point for welding the L-stiffeners.

2.2 Welding of a L-stiffener on a flat skin

As a next step in the building block approach subcomponent tests (level 3) were done which consisted of welding a single L-stiffener onto a flat skin. The material used for the parts was AS4D/PEKK unidirectional tape from Solvay which was fibre placed into flat sheets after which the L-stiffeners were press formed and the skins were autoclave consolidated. The two layup configurations mentioned on paragraph 1.1.1 were used. Based on these layups the thickness is approximately 2.2 mm. The definition of the rosette and the dimensions of the parts are shown in Figure 4.

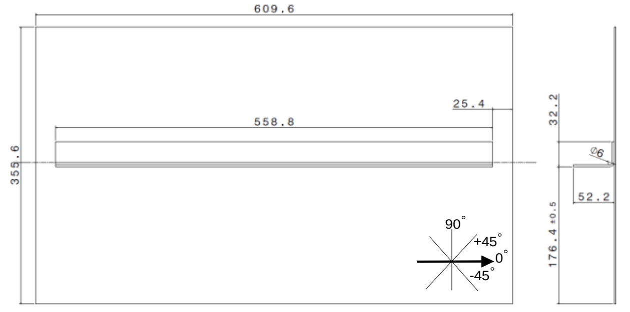


Figure 4: Rosette orientation and dimensions of single L-stiffener samples

Four sets of L-stiffeners and skins of both layups were available for induction welding tests. The baseline test scheme described at the beginning of this chapter was conducted to determine the needed current to reach the target welding temperature (380 °C). In case the maximum weld current of the generator is reached, the welding speed is lowered in order to increase the temperature. The settings of the fourth set (third single weld run) are based on the results from the first and second single weld runs to allow for final optimization of the process parameters.

To prevent edge effects and to maintain a constant temperature along the weld line as much as possible, a start/stop-zone with different process settings than in the mid-zone can be used. As a default for all SLS joints and also L-stiffeners, NLR does not use tailored start/stop-zones and only uniform settings along the complete weld line are applied. For comparison a weld using start/stop-zones for L-stiffeners and skins made from PPS fabric is shown to illustrate it is feasible to improve these zones.

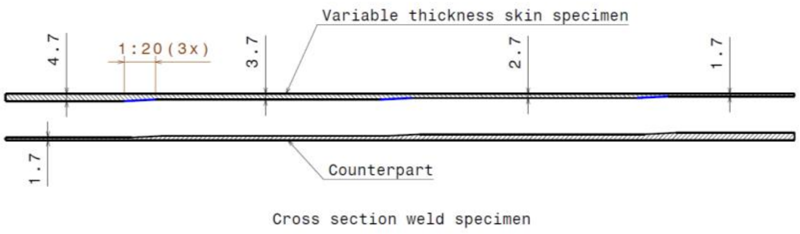
2.3 Welding of multiple L-stiffeners on a flat skin

As a next step towards welding a representative stiffened tail section an assembly of three L-stiffeners was welded onto a larger flat skin. The purpose of these tests is to determine if the induction welding process is influenced by the presence of multiple stiffeners and if edge effects play a role in welding L-stiffeners closer to the edge of the skin.

The materials, layup and test scheme are equal to the configurations used in the welding tests of the single L-stiffeners as described in paragraph 2.2. The size of the skin panel is different, being 610 x 650 mm (LxW), to accommodate 3 stiffeners at a pitch of 212.5 mm.

2.4 Welding of a skin laminate with variable thickness and changing weld depth interface

The typical tail structure targeted with the technology demonstrator within the LIFTT project has a stiffened skin with a variable thickness and some local reinforcements. From tip to root, the thickness of the skin of the technology demonstrator ranges from 1.7 mm up to 4.7 mm while the L-stiffener on the inner surface remains the same thickness. To identify the assembly approach using induction welding, different specimen with a variable thickness were manufactured using fiber placement followed by autoclave consolidation. The total specimen thickness simulating skin and stiffener is 6.4 mm and the welding depth changes from 1.7 – 4.7mm (thickness of welded skin), see Figure 5. The drop-off ratio used is 1:20. The laminates for the variable thickness specimen were milled to the desired thickness and ramp instead of laminating a variable thickness skin (Figure 5, right). When using the standard weld tool, the weld specimen needs to be parallel in order to be able to handle the part in this standard weld tool. This means the variable thickness specimen is welded to a similar counterpart for the initial trials to achieve a 6.4 mm thick parallel test specimen instead of the finally intended variable thickness skin and constant thickness stiffener.



Milled variable thickness weld specimen

Figure 5: Variable thickness welding specimen

3. RESULTS

3.1 Temperature development during welding

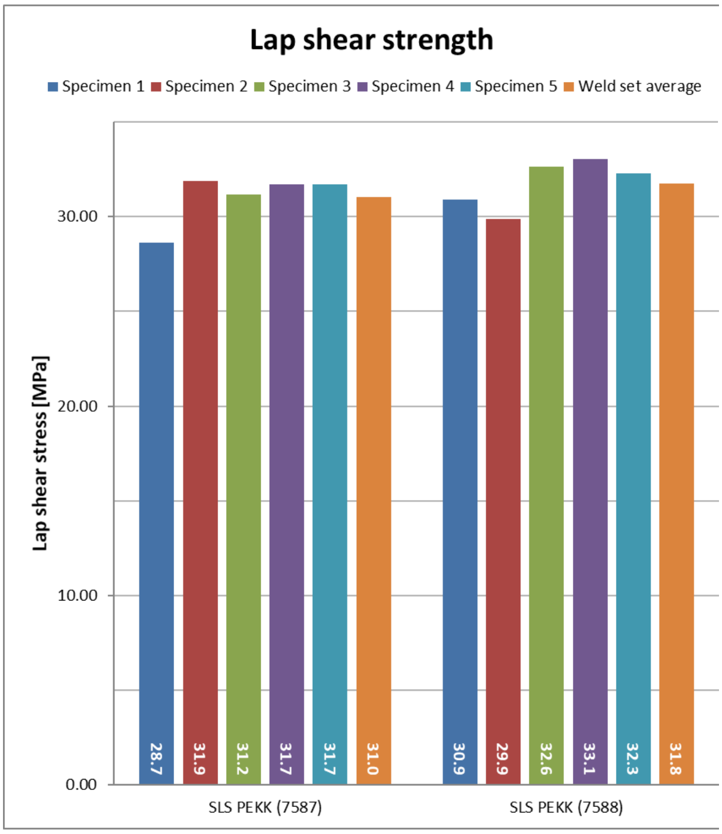
As the temperature during welding is one of the most important parameter multiple tests were done on SLS specimens and L-stiffeners welded on a flat skin to get a clear understanding of the temperature distribution across the weld interface. The results are described in the next paragraphs.

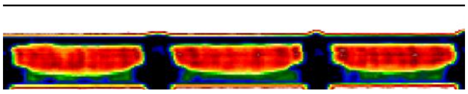
3.1.1 Single lap shear joints [(0/90)4]s

A concise overview of the temperatures measured during the SLS weld tests of a cross-ply set at the final weld settings is given in Table 1. At these settings the C-scan images, cross-sections and lap shear strength all showed good quality, see Figure 6. The lap shear strength according to ASTM D5868 was found to be above 30 Mpa with fibre tear failure at the weld interface based on a total of 10 samples from two different sets. Based on these results it was decided to set the baseline weld parameters for the L-stiffeners at a target temperature of 380 °C, 6 bar of weld pressure and 20 cm/min welding speed.

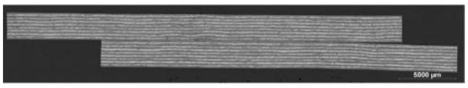
Table 1 Temperatures during welding of SLS specimen

Current [A]	TC1 [°C]	TC2 [°C]	TC3 [°C]	TC4 [°C]	TC5 [°C]	Average [°C]
Power curve set 1						
520.8	-	371.97	369.34	379.86	-	373.7

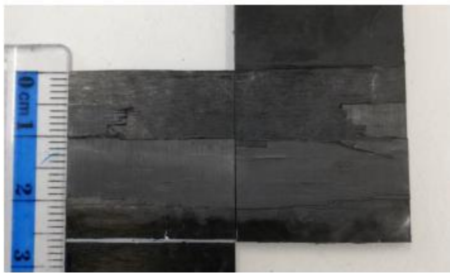




C-scan of section of SLS sample



Cross-section of SLS sample



Failure mode on SLS sample

Figure 6: UD PEKK lap shear strength and typical failure mode of SLS specimen

3.1.2 Single L-stiffener on flat skin [(0/90)4]s

The recorded temperatures during the runs at different currents are given in Table 2. All runs were done at a speed of 20 cm/min and 6 bar pressure. The target temperature was 380 °C as previously mentioned. As the position of the weld line was not a the correct position for the first set and because the achieved temperature was on average 20 °C above the target temperature, the second set was also used as a power curve run.

Table 2 Temperatures during welding of single L-stiffener on flat skin (cross-ply, power curve runs)

Current [A]	TC1 [°C]	TC2 [°C]	TC3 [°C]	TC4 [°C]	TC5 [°C]	Average [°C]
Power curve set 1						
302.4	180.9	186.1	185.9	190.7	194.2	187.6
403.2	269.5	265.9	266.3	270.3	275.3	269.5
451.5	298	298.3	297.1	307.8	330.1	306.3
533.4	386.3	388.5	396.9	405.5	423.4	400.1
Power curve set 2						
302.4	177.4	181.8	182.2	182.2	188.2	182.1
403.2	282.9	271.3	266.6	268.7	271.5	268.9
451.5	320.9	300.4	293.3	297.1	319.7	296.9
525.0	400.8	370.4	366.3	369.8	402.4	381.9

For power curve set 1 the difference between the five thermocouples is increasing at higher current. Especially the difference of the fourth and fifth, and to a lesser extend the third thermocouple compared to the first two thermocouples increase. The temperatures for set 2 in their turn show a different distribution compared to set 1. As the parts are identical between the sets a likely cause is the positioning of the thermocouples. From measurements taken across the width of the weld line it was found that the temperature can decrease with as much as 15 – 20 °C at 5 mm distance from the centerline of the weld. Furthermore, placing thermocouples between the parts creates a gap which can influence the induced heat and also the heat transfer from one part to the other during welding. This can be of influence on the achieved temperatures and weld quality of power curve runs and single weld runs.

The temperatures found during the single weld runs are given in Table 3. Two additional thermocouples were placed on the left and right side just next to the stiffener. For the second single weld run (set 4) only the two thermocouples next to the stiffener were used for validation so that there is no influence of the thermocouples on the weld interface.

Table 3 Temperatures during welding of single L-stiffener on flat skin (cross-ply, single weld runs)

Current [A]	TC1 [°C]	TC5 [°C]	TC_Left [°C]	TC_Right [°C]
Single weld run set 3				
302.4	170.8	184.9	122.9	128.5
533.4	428.6	407.2	293.3	269
Single weld run set 4				
302.4	-	-	117.9	125.1
533.4	-	-	291.1	271.3

Compared to the power curve runs, TC1 of single weld run set 3 is much higher at the final current of 533.4 A while it was lower during the control run at 302.4 A. As there was no apparent reason found, the measurement was considered as an outlier possibly due to damaged thermocouple shielding. The thermocouples just next to the L-stiffener are in good agreement between both sets which is according to expectation. It shows that the induction welding process has good repeatability and temperature differences during these tests can be accounted to thermocouple alignment issues and shielding damage.

3.1.3 Single L-stiffener on flat skin [(0/-45/90/45)2]s

A total of four sets were welded, presented in Table 4 are the results from two sets. As was explained at the beginning of the paper the temperature of a QI layup is lower than that of a cross-ply layup at the same current and weld speed. In general the difference is between 14 – 22% depending on the current. Inspection of one of the weld sets after welding at 577.5 A and 20 cm/min showed large deconsolidated areas in the skin next to the L-stiffener. The average temperature was 345 °C which is still below the target temperature of 380 °C.

To reach the target temperature of 380 °C the speed needed to be lowered from 20 cm/min to 12 cm/min in order not to exceed the maximum power of the generator. The deconsolidation issues were resolved by adding active air cooling to the welding setup directed at the affected areas. However, air cooling was only effective without thermocouples at the weld interface as the thermocouple wires block the airflow so these were removed for the fourth weld set. To still have a reference two thermocouples were placed next to the stiffener end (on the left and right). After multiple weld runs at increasing currents the final weld settings were determined at 527.1 A and a speed of 12 cm/min. These setting leave some room to increase the speed for future welding tests but this in turn can influence for example the weld width. Comparing the thermocouples next to the stiffener for both weld sets shows that these are in good agreement.

Table 4 Temperatures during welding of single L-stiffener on flat skin (single weld runs, quasi-isotropic)

Current [A]	TC1 [°C]	TC2 [°C]	TC3 [°C]	TC4 [°C]	TC5 [°C]	TC_Left [°C]	TC_Right [°C]	Average [°C]
Power curve set 1								
501.9	328.1	324.8	325.3	327.6	325	179.8	228.2	326.2
527.1	378.5	369	372.6	380.3	376.8	230.2	270.2	375.4
Power curve set 2								
527.1	-	-	-	-	-	234.2	274.4	-

3.1.4 Multiple L-stiffeners on flat skin [(0/90)4]s

For welding the skin with three L-stiffeners two target temperatures were chosen, one at 380 °C and two stiffeners at 400 °C. During one of the welds at the higher target temperature the pressure was increased from 6 bar to 8 bar. The goal of these tests was to have a first indication of the effect of temperature and pressure on the weld quality of the L-stiffeners. The results are shown in Table 5. The measured temperatures of the five thermocouples do show some variation (coefficient of variation between 3 – 5 %) for which the exact reason is currently not known. This will be addressed in the remaining part of the LIFTT project. The average temperature reported in the table takes into account thermocouples TC1 – TC5 as none of the temperatures are classified as outliers.

Table 5 Temperatures during welding of single L-stiffener on flat skin (single weld runs, quasi-isotropic)

Current [A]	TC1 [°C]	TC2 [°C]	TC3 [°C]	TC4 [°C]	TC5 [°C]	TC_Left [°C]	TC_Right [°C]	Average [°C]
Power curve outer stiffener 1 @380 °C, 6 bar								
506.1	375	395.4	366.7	387.9	399.1	255.2	295.5	384.8
Power curve middle stiffener @400 °C, 6 bar								
527.1	374.1	403.7	393.5	398.4	418.3	269.7	310.1	397.6
Power curve outer stiffener 2 @400 °C, 8 bar								
529.2	392.3	-	396.1	435.6	410.1	265.3	316.5	408.5

On a second skin and set of stiffeners one power curve run with thermocouples and two single weld runs without thermocouples were welded to verify the quality in a realistic and more industrial process. During these welds no direct temperature measurements were done to prevent any influence on the induction welding process related to gaps caused by the thermocouples. The average temperature of the power curve run was comparable to the power curve outer stiffener 1 weld of the first set. The middle stiffener was welded at 527.1 A (same as for the first set) and the outer stiffener 2 was welded at a higher current (543.9 A) compared to the first set. As no temperatures at the weld interface were recorded the C-scan results in paragraph 3.2.1 must be used to get an indication of the quality.

3.1.5 Single L-stiffener on flat skin welded with start/stop zone

A set of two L-stiffeners and two skins were welded together – both made from PPS – for which a tailored start/stop zone with specific speed and power settings were used that differ from the settings as used in the mid-section. The measured temperatures showed a quite uniform temperature over the entire length of the weld. With help of the C-scan results, the resulting joint laminate quality can be studied and can be used to see the effect of the start/stop zone qualitatively, see paragraph 0.

3.1.6 Welding of a skin laminate with variable thickness and changing weld depth interface

Similar to a normal SLS specimen of constant thickness, the baseline welding parameters are starting point for the variable thickness specimen as well. This means the top and bottom laminate shown in Figure 5 have a 1 inch overlap in the welded area, target temperature in the weld interface (at all depth levels) is 380 °C and weld speed baseline is 20 cm/min. By implementing thermocouples on each different depth level and transition zone, the temperature distribution in the weld interface was measured. This initially started at lower temperature with a weld power of 450 A at a constant weld speed of 20 cm/min to prevent welding certain zones prematurely. Figure 7 clearly shows that with standard welding settings the temperature at the weld interface is not constant enough as can be expected as a result of the different weld depths. In order to realize more uniform heating, first the weld speed was adapted and made variable over the length of the weld. After some runs at 450 A ending at a variable weld speed ranging from 17.5 cm/min to 25 cm/min, also the weld current was made variable over the length of the weld. This improved the temperature distribution of the weld interface over the entire length within a window of approximately 5 °C in centre of the weldline. The settings were validated at a 470 A and 520 A, after which the majority of the thermocouples was removed. The two variable thickness specimens were welded together with a variable welding speed ranging from 17.5 – 25 cm/min combined with a variable welding current between 540 – 590 A over the length of the sample (see Figure 7). The results are shown in paragraph3.3.

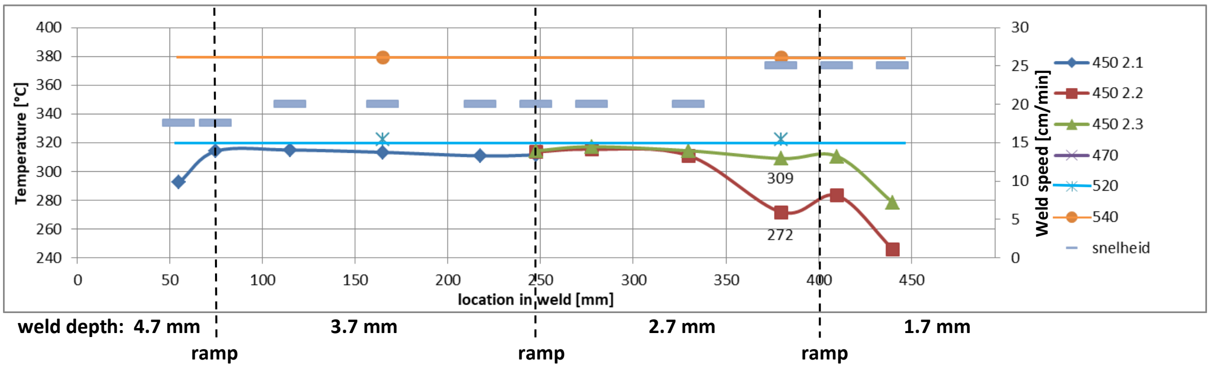
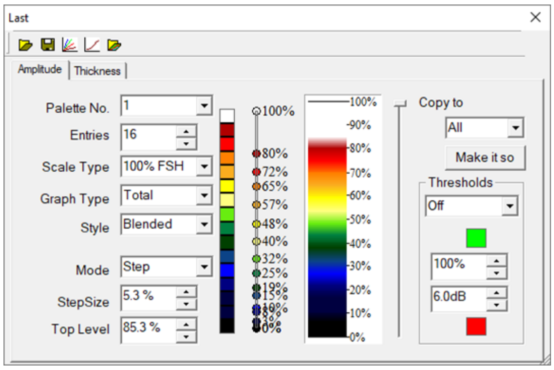


Figure 7: Longitudinal temperature distribution at the weld interface of the 500 mm long variable thickness specimen on each weld depth level at different weld power settings and weld speeds

3.2 Non-destructive inspection of welded samples

C-scan inspection and microscopic analysis on cross-sectional samples were used to determine the weld quality. The attenuation scans presented in the next paragraphs can be interpreted with the 16 colored palette shown on the right. Settings were adjusted on the best area of the specimen (100%). No rejection or acceptance criteria are defined. Therefore the test results are relative.Single L-stiffeners on flat skin [(0/90)4]s and [(0/-45/90/45)2]s



In Figure 8 the attenuation C-scan results from two cross-ply and the final QI set are shown. All samples were scanned at identical settings. The thermocouple locations are clearly visible in the scans of the cross-ply samples. In the SW set 3 cross-ply scan there are some possible defects visible which are further analysed through microscopic analysis. A likely cause is that for a single weld run a higher current is required than the one determined during the power curve runs to create a good quality weld. During the power curve weld the interface is heated multiple times to a temperature close to or above the melt temperature of the material. This will inevitably have an effect on the final quality and in case only a single run is done at the target temperature the total time to ensure proper intimate contact and consolidation is lower which can lead to lower quality as well. Further investigation on this topic will be conducted within LIFTT and will focus, amongst others, on the optimum welding temperature and welding speed. The quality of the QI power curve weld run without TC's has uniform quality and width with only some minor indications of deconsolidation in the skin just next to the free edge of the stiffener feet. As can be seen from the welded PPS L-stiffener, using start/stop zones can clearly improve the quality of the weld at the edge of the stiffeners.

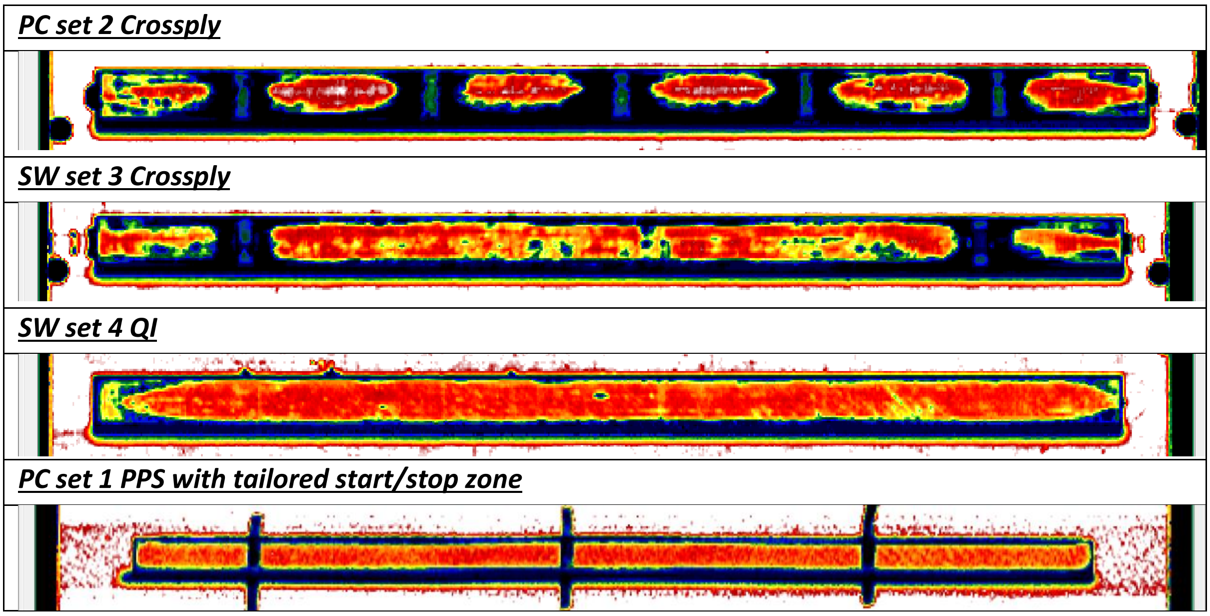


Figure 8: Attenuation scans of welded single L-stiffener samples

In the cross-sections of SW set 3 with cross-ply layup (Figure 9) the defects found in the C-scan can be traced to the L-stiffener where some areas with voids or delamination are found. After closer inspection of unwelded press-formed L-stiffeners it was found that similar defects are present in these parts to the ones found on the cross-section analyses of the welded samples. Further investigation will be carried out at a later stage to research this issue more in-depth. The weld interface of both the cross-ply and quasi-isotropic samples show no defects and are of high quality, see Figure 9.

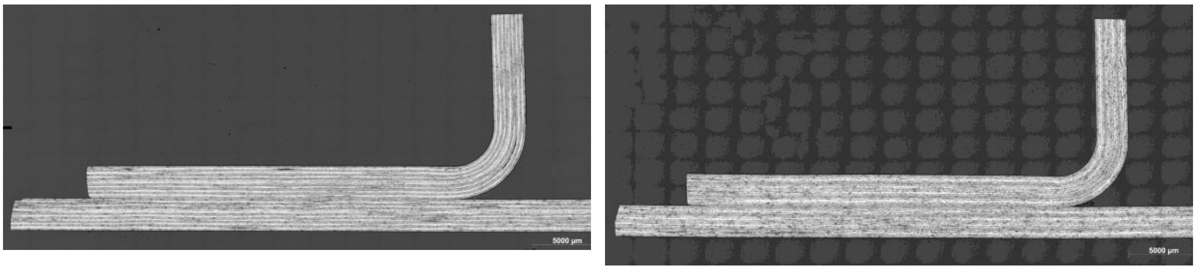


Figure 9: Cross-sections of welded samples (SW set 3 cross-ply left, SW set 4 QI right)

3.2.1 Multiple L-stiffeners on flat skin [(0/90)4]s

From the C-scan results shown in Figure 10 the difference between the different settings for temperature and pressure are relatively minor. The width of the weld at 400 °C is slightly larger, which is according to expectations. However, there is no clear difference between the welds at 6 and 8 bar visible on the C-scan. During a later stage in the LIFTT project microscopic analyses and pull-off tests will be conducted on these and newly welded L-stiffeners to further investigate the influence of weld temperature and pressure on the weld quality. This should also give a better indication whether the defects on some sections of the weld are related to the induction welding process or to the manufacturing process of the stiffeners itself.

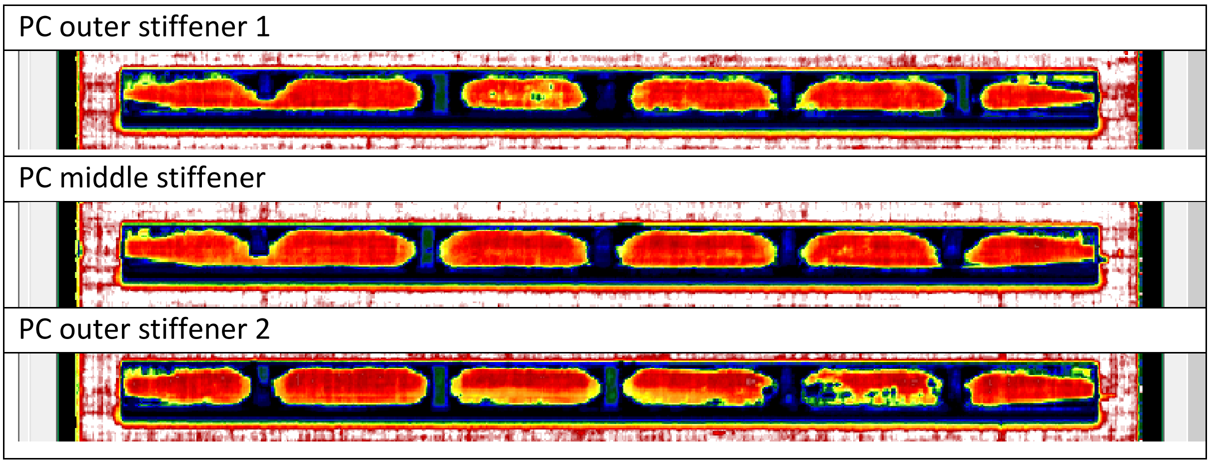


Figure 10: Attenuation scans of welded multiple L-stiffener samples

On the C-scan of the single weld of the middle stiffener a mixed quality is found (see Figure 11) in which approximately half of the weld line shows good quality and the other half shows higher attenuation values indicating some type of defects. In the area encircled a thermocouple was placed underneath the samples to get an indication of the temperature. This is partly responsible for the disturbed quality but microscopic analysis will be carried out to get a clearer picture of the nature and location of the possible defects. The C-scan of outer stiffener 2 which was welded at a theoretical temperature of 420 °C shows a much more uniform quality along the entire length and width. This supports the theory mentioned in paragraph 0that a single weld run needs a higher target temperature to reach sufficient quality.

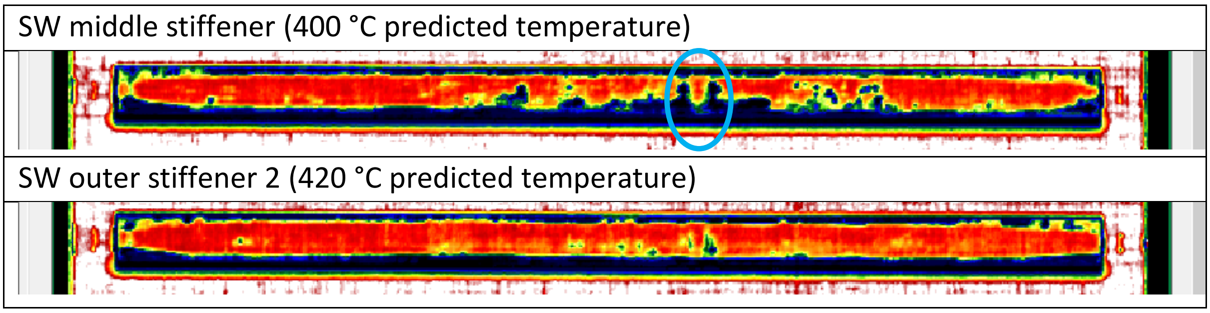


Figure 11: Attenuation scans of welded multiple L-stiffener samples

3.3 Variable thickness

The C-scan result of the variable thickness weld specimen simulating a skin and stiffener with a total thickness of 6.4 mm with welding depth ranging from 1.7 – 4.7mm (thickness of welded skin) and drop-off ratio 1:20 is shown in Figure 12. In general it shows a promising result regarding the weldline quality at different weld depths including the 1:20 transition zones. The black areas in the middle are due to thermocouples in the weld interface used to validate the temperature of this specimen. The start and stop zone on the left and right of the specimen are not optimized for this test and should be fine-tuned to improve the quality in this region. Especially on the right side were the top laminate is only 1.7mm thick (see Figure 5) and heavily influenced by the non-tailored heatsink material used on top.

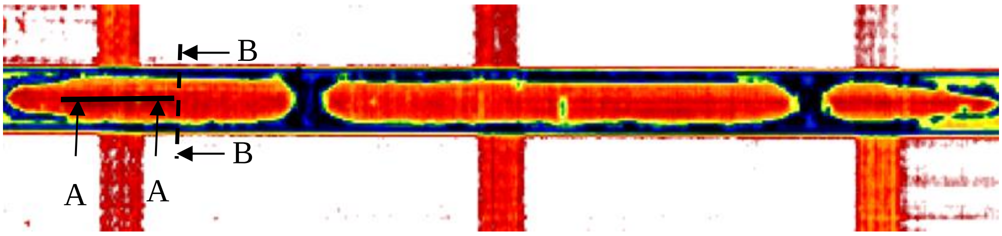
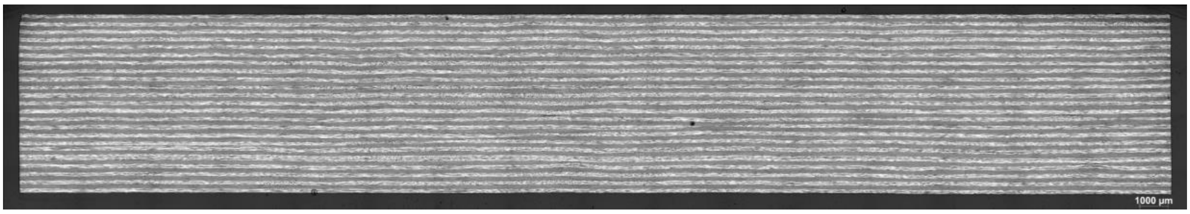


Figure 12: C-scan result of the variable thickness weld specimen

Cross section A-A shown in Figure 13 is taken over the two deepest levels and the 1:20 transition zone in between. Cross section B-B (Figure 14) is taken immediately at the end of section A-A showing the width of the weldzone at the weld plateau at 3.7mm deep.



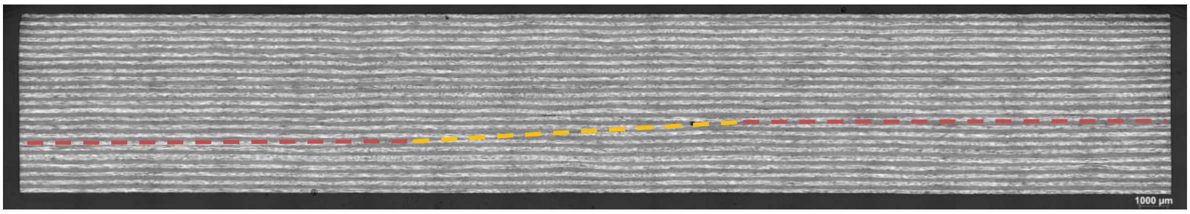


Figure 13: Top; Cross-section A-A: Location of weld interface not visible (top laminate 4.7 mm, bottom 1.7mm, including ramp) Bottom; Same cross-section indicating location of weld interface.

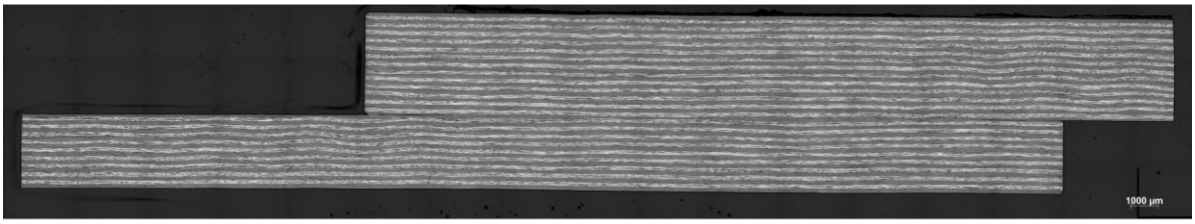


Figure 14: Cross-Section B-B: Weldline width correspond with C-scan (top laminate 3.7 mm, bottom 2.7mm)

These sections confirm the C-scan image and weld width at those welded locations. It confirms the quality of the weld interface at the different depth levels and over the transition zone. As the specimen were milled to the desired variable thickness, there is no inaccuracy or undulation of fibres visible at the 1:20 transition ramp between different depth levels. As a result the interface at section A-A is barely visible after welding and can only be identified after very high magnification of the cross section.

4. CONCLUSIONS

In the development towards induction welding of a stiffened tail section within EU project LIFTT a building block approach was used and focused on welding of single lap shear specimens and on welding of single and multiple L-stiffeners on flat skins.

Before welding of L-stiffeners was started an investigation on welding of the SLS specimens was performed to determine the process settings. From welding trails on AS4D/PEKK plates with cross-ply layup the settings were determined at 380 °C, 6 bar weld pressure and a welding speed of 20 cm/min. C-scan and cross-section information showed promising quality and the lap shear strengths found were around 31 MPa.

During the weld tests of the single L-stiffeners a distinct difference in welding behavior was found between the cross-ply and quasi-isotropic specimens. The cross-ply samples could be welded at lower power and higher speed (20 cm/min) and the weld quality from the C-scans and cross-sections showed the heat could be concentrated at the interface. For the quasi-isotropic samples on the other hand more power was needed and the welding speed had to be decreased to 12 cm/min. Due to this combination deconsolidation of the skin next to the L-stiffener occurred. On additional samples deconsolidation could be prevent by cooling the affected areas through forced air cooling. Another possible solution would be to increase the pressurized area but this was not possible with the current tooling.

From the tests on welding multiple L-stiffeners on a larger skin (both cross-ply layup) a comparable behavior to the single L-stiffeners was found. Also tests at target temperatures of 400 °C and 420 °C were done as well as a test with 8 bar welding pressure. Compared to the welds at 380 °C the width of the weld at 400 °C visible on the C-scan images was slightly larger. There was no visible difference between the weld done at 6 and 8 bar pressure. Differences were found between power curve welds and single welds. On the C-scan images the quality of the power curve weld was higher. This is caused by the fact that during these welds the interface is heated multiple times at or above the melting temperature. This increases the quality as there is more time for intimate contact and consolidation. Welding at higher temperature (420 °C) showed that the quality of the single welds can be improved.

Welding a variable thickness skin means that it should be possible to weld at different weld depths including drop-off transition zones. By using both variable weld speeds and weld currents it is shown possible to achieve a high quality weld line. C-scan results match with cross-section information and underline this conclusion. Further fine tuning of either tooling or weld strategy is necessary to improve control in all regions, but initial results are very promising.

- **<u>Acknowledgement</u>**

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 945521. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

- **<u>Disclaimer</u>**

The results, opinions, conclusions, etc. presented in this work are those of the author(s) only and do not necessarily represent the position of the JU; the JU is not responsible for any use made of the information contained herein.

5. REFERENCES

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