INDUCTION WELDING OF THERMOPLASTIC COMPOSITES WITH LIGHTNING STRIKE PROTECTION

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ABSTRACT

Induction welding nowadays is one of several welding techniques suitable for joining thermoplastic composites. Currently, induction welding at an industrial level is used to weld secondary aircraft structures like tail movables and rudders. One of the challenges when progressing induction welding towards primary aircraft structures is more extensive use of lightning strike protection (LSP) in these parts.

In this work, tests were carried out on flat quasi-isotropic (QI) single lap shear specimens made by AFP from Toray Cetex® TC1225 T700/LM-PAEK unidirectional (UD) tapes. LSP material was applied single or double sided by hand in case of the continuous LSP. For the AFP LSP tape, slitted to a width of ¼", direct AFP placement onto the laminates was done in three different patterns being in 0°, 90° and a 0/90° orientation (gingham pattern). In the gingham pattern the LSP tapes are placed with a ¼" gap and overlap at certain sections. By optimising the welding parameters and the tooling it was possible to weld all types of LSP, in which the gingham pattern proved the best variant and the continuous LSP mesh the most difficult option to weld. Mechanical testing showed good performance of all the welds.

1. INTRODUCTION

In the Dutch RDM Mobility Fund programme "Thermoplastics for a sustainable aviation" one of the goals was to assess the feasibility of induction welding state-of-the-art LSP material and of beyond state-of-the-art LSP materials covering carbon fibre reinforced thermoplastic (CFRP) parts. Current state-of-the-art LSP material feature a continuous copper mesh which is added manually in the tool before consolidation. A new and automated approach is to slit the copper mesh into narrow tapes which can be processed by an automated fibre placement (AFP) machine directly onto the parts. It increases design freedom and opens up the possibility to optimise the placement of the LSP AFP tapes to aid the induction welding process.

To get a better understanding of the induction welding process with LSP materials a step-wise approach was chosen by first researching the heating behavior of substrates with LSP materials outside the weld setup with an infrared camera. Next, actual welding trials were performed and assessed on quality and mechanical properties. As reference, substrates without LSP materials were chosen. The results are presented in the next paragraphs and chapters.

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 carbon fibres are called eddy currents. They form a global loop in the material in the form of the mirror image of the coil [1]. Several heating mechanisms take place during induction heating of carbon fibre reinforced thermoplastics. The first is Joule losses in the fibres due to their resistance. The second 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 third 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 three mechanisms are schematically shown in Figure 1 on the left.

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].

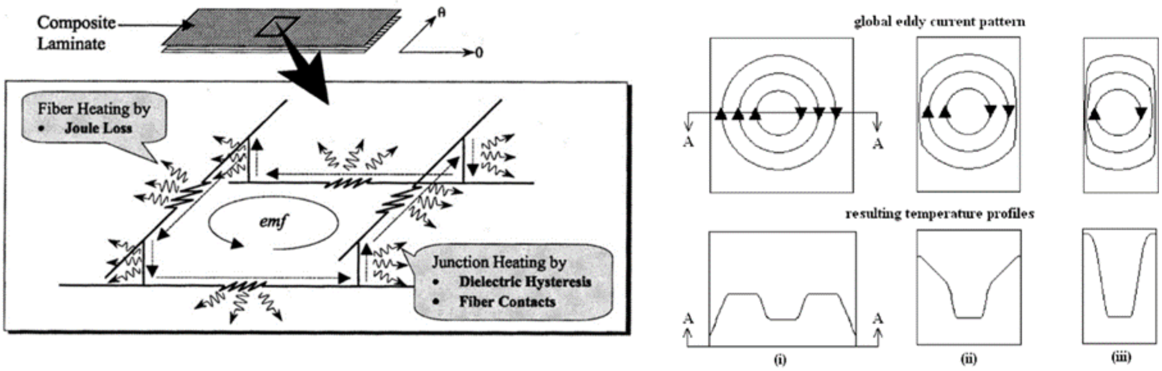


Figure 1 Left: Model of conductive loop [2], Right: edge effects resulting from changes in workpiece geometry [3]

1.2 Induction welding setup

Induction Welding (IW) research at NLR is done with a robotic setup featuring a 10kW Ambrell power supply and standardized KVE induction coil, see Figure 2. Single Lap Shear (SLS) joints of two flat substrates ranging up to 12 mm total thickness can be welded in a standardized weld tool at 1-inch overlap, 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 a 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.

Temperature measurements during welding are performed with Type E thermocouples in the weld interface placed at standard positions along the weld line (100, 200, 300, 400 and 500 mm) during welding experiments, see Figure 2.

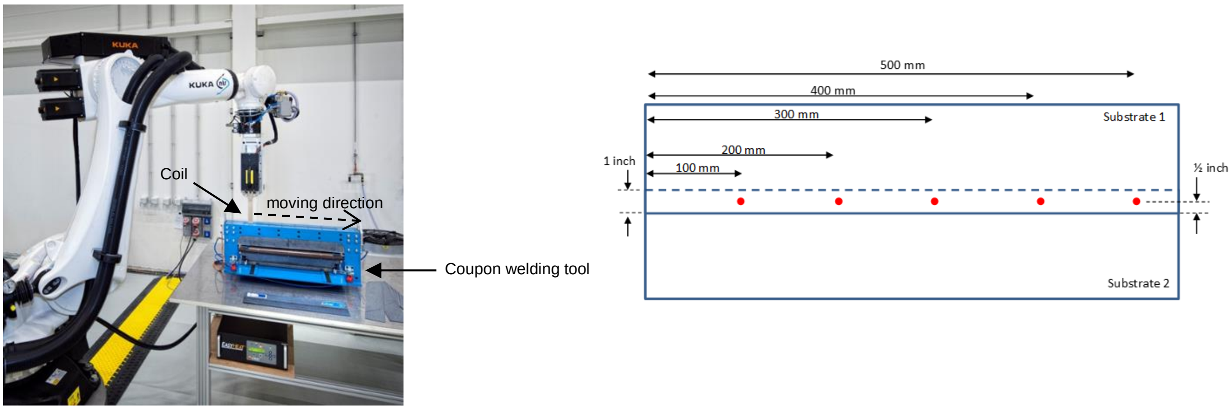


Figure 2: Standardized induction welding setup at NLR, Coupon welding of 2 substrates with 1" overlap (right)

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 weld interface and of other locations on the substrates and of pressure applied during welding.

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.

Research was performed according to the building block approach shown in Figure 3. In this paper the focus is on the coupon tests of Level 1 and the Level 2 element tests. The level 1 tests consist of static heating tests on laminates with LSP outside the weld tooling to determine the heating behavior on both sides of the laminate with infrared (IR) cameras. Continuous welding of single lap shear specimens consisting of two flat plates (one with LSP) is part of the level 2 experiments.

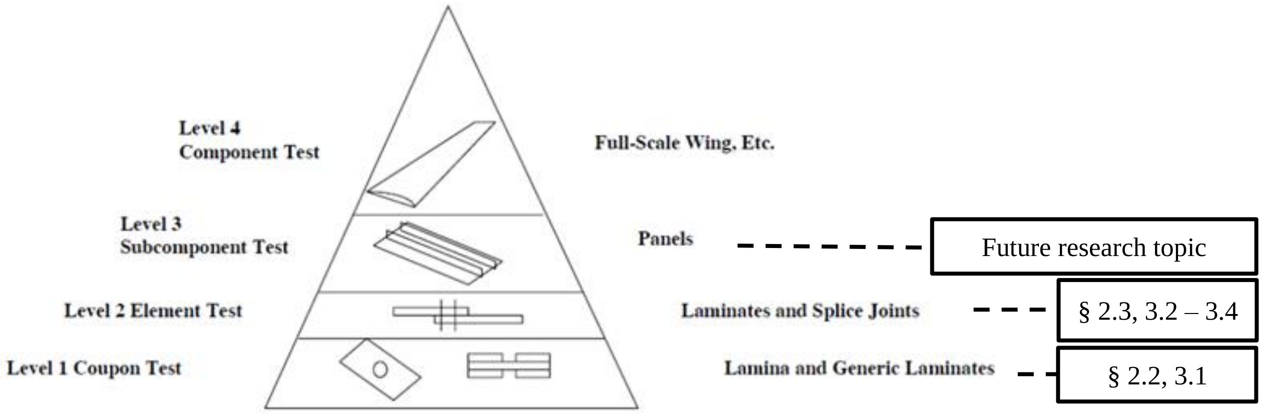


Figure 3: Example of the building block approach for testing purposes (ref. CMH-17 Vol. 3)

2.1 Thermoplastic material and LSP material types

Lightning Strike Protection (LSP) material on a CF composite structure is known to influence IW because the woven copper wire mesh mostly used for LSP material is highly susceptive to inductive heating, far more than carbon fibres. Two different types of LSP material supplied by Toray were tested. The first type is a 72 gram per square metre (gsm) woven copper mesh used for hand lay-up purposes and can be considered as industry standard. The second LSP material is a development grade 180 gsm woven copper mesh slit to ¼ inch tapes/tows which can be placed using an Automated Fiber placement (AFP) machine.

In total 4 different LSP configurations, single and double sided, were tested:

- Single continuous woven copper mesh ply (hand-layup)
- Slitted woven copper mesh (AFP) in 0° direction (=welding direction), butt-joint pattern
- Slitted woven copper mesh (AFP) in 90° direction (=perpendicular to welding direction), butt-joint pattern
- Slitted woven copper mesh (AFP) in 0/90° direction, “Gingham” checkerboard pattern

LSP configurations (single sided only) as also shown in Figure 4a, have been tested by Toray and exhibited all excellent damage scores (Zone 2A) based on damage calculations prescribed in the AGATE handbook. (Source Toray, from [11])

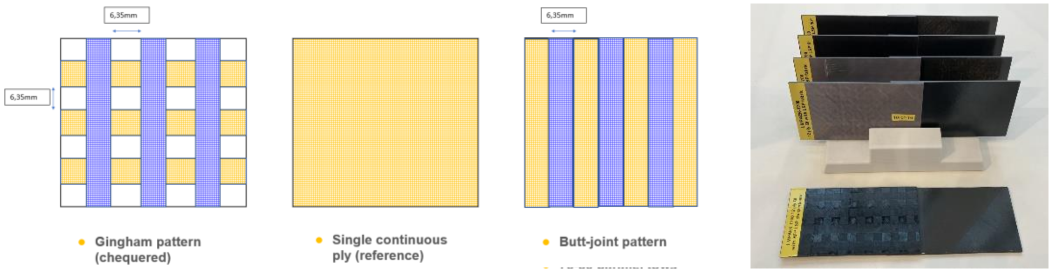


Figure 4 a) LSP configurations (Source: Prithul Narula, Toray), b) Examples of welded SLS coupons with LSP

The LSP materials were either placed manually or by robotic fibre placement on 12 ply quasi-isotropic laminates from UD Toray Cetex® TC1225 LMPAEK/T700.

2.2 Heating behavior of laminates with LSP material

To gain more insight in the effect of LSP material static heating tests were done outside the weld tool, see Figure 5. An Flir A70 IR camera was used to record the temperature on the upper and the lower side of the laminate. As no heatsink was used the maximum temperature during the experiments was limited to below the glass transition temperature T_g (145 °C). To gain more insight in the directional dependency of the LSP AFP material the induction coil was positioned in three different directions (0°, 45° & 90°). The panels were exposed to a constant current for 45 seconds, coil distance to laminate is 10 mm.

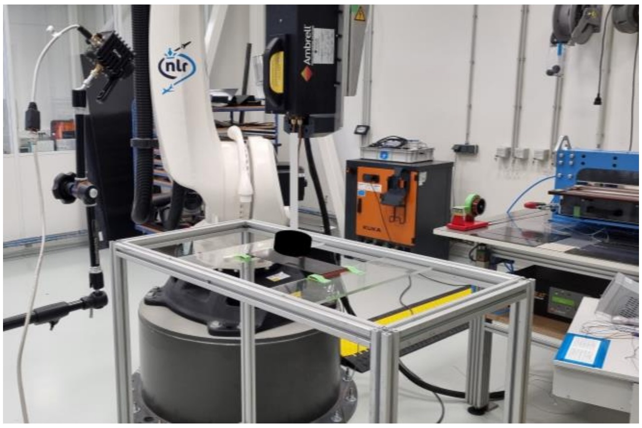


Figure 5: Test setup for heating behaviour experiments

2.3 Welding of single lap shear specimens with different LSP configurations

In the Single Lap Shear (SLS) welding experiments, two flat plates with dimensions of 608 x 101.6 mm were welded at an overlap of 1 inch in the tooling described in paragraph 1.2. The upper laminate included one of the four LSP types (single (facing IW coil) or double sided). As reference, a weld sample without LSP materials was included. After welding at several parameters, the quality of the welds was determined by C-scan, microscopic analysis of cross-sections and lap shear tests. The target temperature during welding was 360 °C and was monitored with thermocouples in the weld interface. In Chapter 3 the results are presented.

3. RESULTS

3.1 Temperature development of single laminates

As the temperature during welding is one of the most important parameters multiple tests were done to get a better understanding of the effect of LSP on the temperature distribution across the upper and lower side of a single laminate. Normally the lower side of the top laminate is at the weld interface. The goal of these tests is to determine if the weld interface can still be heated sufficiently despite the presence of the LSP material. For these experiments only single sided applied LSP is considered as this is the most relevant case.

All laminates were heated for 45 seconds with the same current in the setup shown in Figure 5. Pictures and the results of these tests can be found in the next paragraphs.

3.1.1 Reference samples without LSP

To get a better understanding of the effect of LSP material the first test was done on a single laminate without LSP, see Figure 6. For all three orientations the temperature between the bottom and top side are similar or slightly higher for the bottom side which is desirable for welding. Along the edges the edge effects are clearly visible. The most relevant case is the coil in 0° direction which shows a maximum temperature of 52.5 °C and 57.9°C for top and bottom respectively. The heat affected zone (HAZ) is long and narrow as expected due to the coil shape. In the 45° and 90° coil orientation the edge effect is dominant.

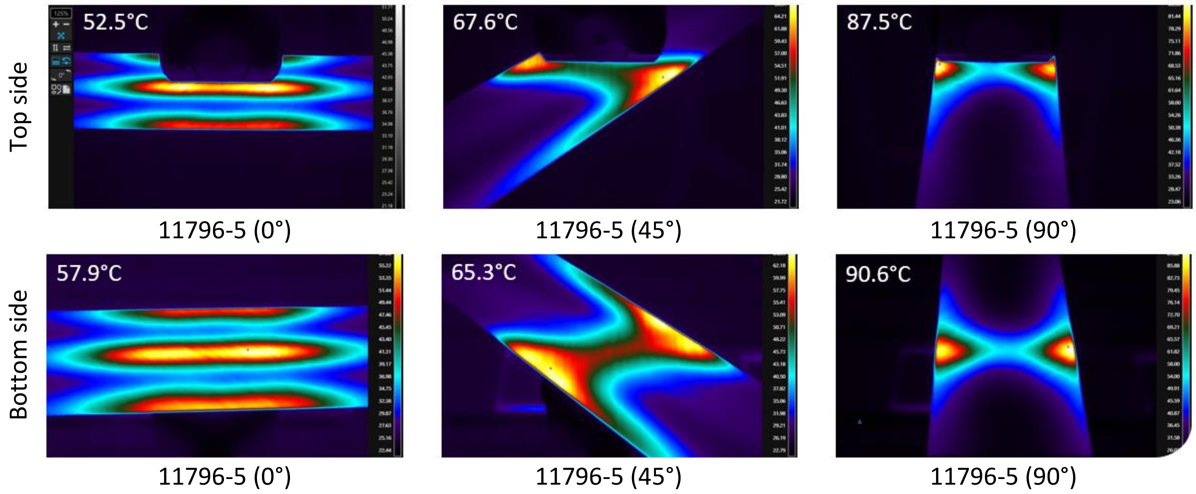


Figure 6: Heating behaviour of sample without LSP, 45 seconds after current has been switched on

3.1.2 Single continuous woven copper mesh ply (hand-layup)

The results for the single hand-layup LSP material are shown in Figure 7. In the left picture the top side of the laminate is shown. Only the edge effect on the front edge is visible due to the coil cover which blocks the view on the rear edge. Compared to the temperature on the lower side (right picture) it is clear that the top side of the laminate heats up more, approximately 24 °C or 21%. Furthermore, the HAZ is more concentrated, and has higher temperature gradients in the 0° direction, compared to the sample without LSP. Also, the maximum temperatures are much higher due to better inductive heating behavior of copper compared to carbon fibre.

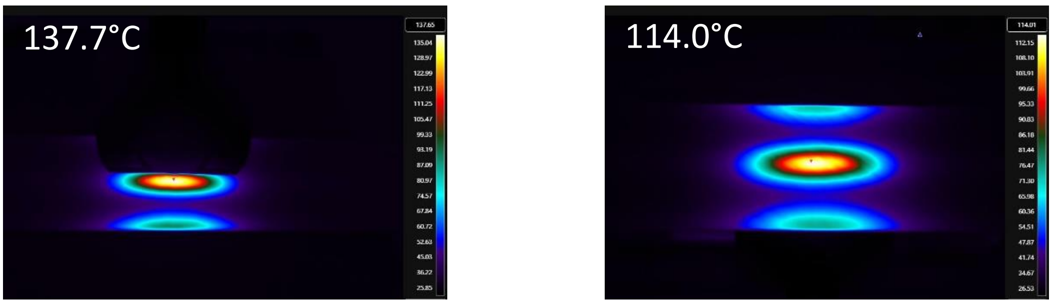


Figure 7: Heating behaviour of single layer of continuous woven copper mesh. Top side with LSP (left), bottom side no LSP (right), 45 seconds after current has been switched on

3.1.3 Slitted woven copper mesh (AFP) in 90° direction (=perpendicular to welding direction), butt-joint pattern

From the pictures in Figure 8 it can be seen that for the slitted LSP in 90° direction the temperatures achieved are between the reference sample and the fabric LSP sample. The difference between top and bottom temperature is approximately 11 °C or 13%. Due to the discontinuous nature of the LSP tape the HAZ is also more irregular, especially in the edge effects of the rotated coil directions.

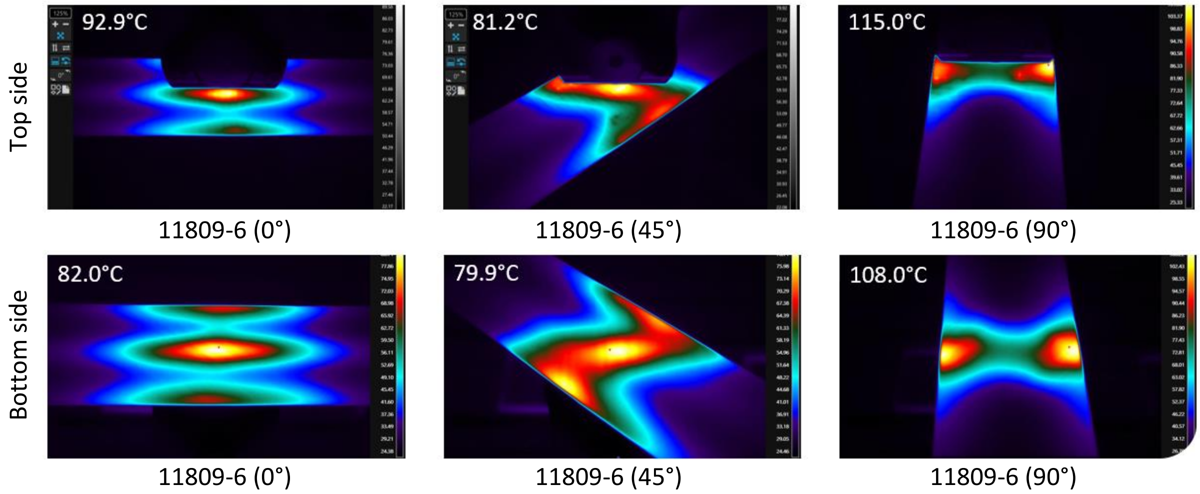


Figure 8: Heating behaviour of single layer of LSP AFP tape in 90° direction, 45 seconds after current has been switched on

3.1.4 Slitted woven copper mesh (AFP) in 0° direction (=welding direction), butt-joint pattern

With a coil direction of 0° the temperature is close to the reference sample without LSP with the difference that the highest maximum temperature is now on the top side with LSP. Compared to the lower side the top of the sample is approximately 7.5 °C warmer (13%). Less edge effects are visible on the samples with rotated coil which could be caused due to some local hotspots below the coil. A possible cause for the local hotspots is edge heating within the LSP AFP tapes. Future research is planned to determine the exact cause.

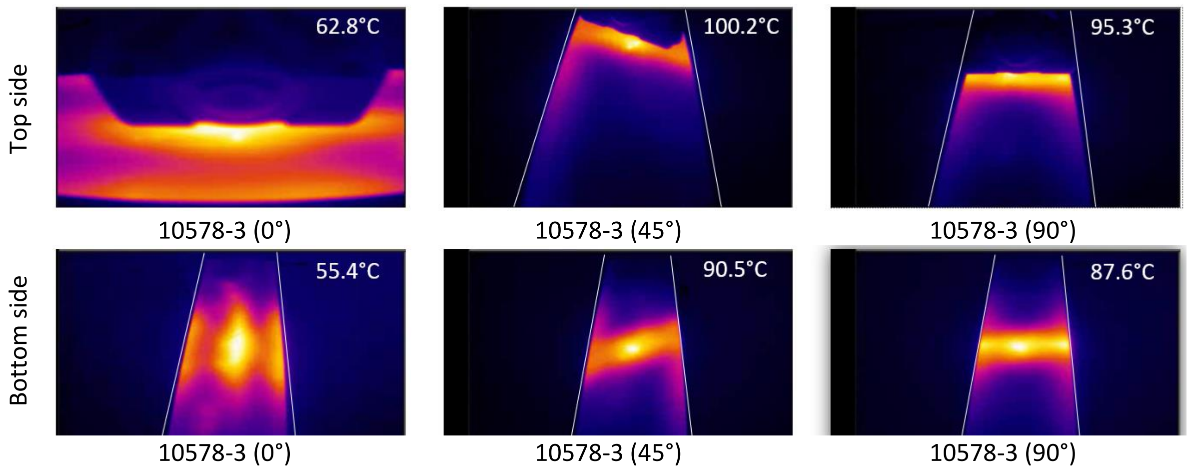


Figure 9: Heating behaviour of single layer of LSP AFP tape in 0° direction,45 seconds after current has been switched on

3.1.5 Slitted woven copper mesh (AFP) in 0/90° direction, "Gingham" checkerboard pattern

The results of the heating trials for the gingham pattern are shown in Figure 10. Temperatures on the top and bottom side are in the range of the fabric LSP layer. The difference between the two sides is approximately 29 °C or 27%. Also, for the gingham pattern the HAZ is more concentrated below the coil. This is the case for the coil at 45° and 90° orientation as well, edge effects are less pronounced. In the picture of the coil oriented at 45° the gingham pattern is clearly visible and shows that the copper LSP tapes develop more heat than the carbon fibres.

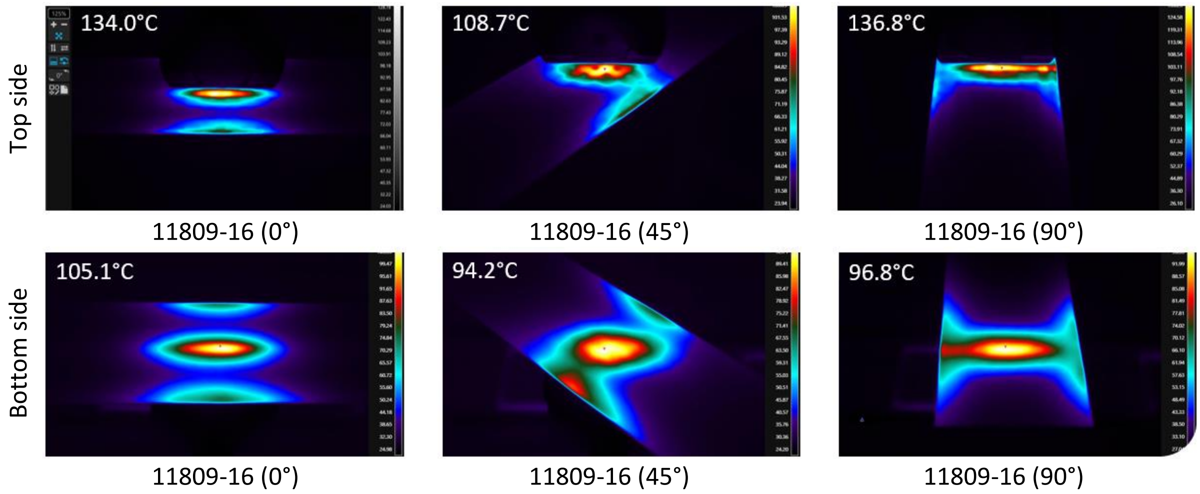


Figure 10: Heating behaviour of single layer of LSP AFP tape in 0/90° direction (gingham),45 seconds after current has been switched on

3.1.6 Discussion

From the results presented in the paragraphs above it is clear that samples with LSP material reach higher temperatures on both sides of the sample at the same current and time compared to the reference sample without LSP. This might lead to the false conclusion that laminates with LSP are easier to join by induction welding that laminates without LSP. All tests were done at relative low current. From additional testing at higher currents it was found that the temperature in the LSP layer increases exponentially instead of a linear increase for samples without LSP. Therefore, it was needed to weld the LSP specimens with lower current and speed (see next paragraph) to avoid unwanted edge effects and have a more stable and reliable process.

3.2 Lap shear specimen welding behavior

Single lap shear substrates (608 x 101.6 mm) were placed in the coupon welding tool with 1 inch overlap as described in paragraph 1.2 and shown in Figure 2. Top substrate 1 has LSP material on the outside, facing upward, and IW is done from the LSP side of the assembly. The inductive heating behavior and heating response was indeed to be found heavily influenced by the LSP material as expected. Especially the single continuous woven ply is found challenging for IW of the SLS substrates. After fine-tuning of the process parameters, it was shown possible to induction weld all configurations. An overview of the weld temperatures and weld speed of the substrates is shown in Table 1.

Table 1 Overview of welded substrates

LSP configuration	Temperature [°C]	Current [A]	Speed [cm/min]
Double[1] fabric	343	609	15
Single[2] fabric	342	519	8
Single fabric	376	584	10
Single fabric	370	605	12
Double AFP 90°	365	475	12
Single AFP 90°	365	466	12
Double AFP 0°	368	577	12
Single AFP 0°	344	529	12
Gingham pattern	370	542	8
Gingham pattern	362	521	8
Reference (no LSP)	350	529	20

1) Double sided LSP
2) Single sided LSP, faced towards induction coil

Additional heatsinks or cooling was needed to prevent overheating in some sections of the substrates, mainly on the edges due to the before described edge effects which is more significant compared to SLS substrates without LSP. Compared to the LSP AFP tape in 0° and 90° more current and/or lower weld speeds were needed to achieve the weld temperature of 360 °C for the single LSP fabric samples. The gingham pattern is slightly easier to weld than the fabric LSP type.

Welding of the fabric LSP can be improved by having the LSP layer also at the weld interface which acts as a susceptor during welding. Lower current and higher weld speeds are possible. The effect of adding LSP layers on both sides of the substrates is less pronounced for the AFP LSP types. Compared to welding without LSP material the speed needs to be decreased by 25 – 60 % depending on the LSP configuration.

A typical weld temperature development of the five thermocouples during welding of the gingham pattern LSP type and of the reference sample without LSP can be found in Figure 11. It can be seen that for both configurations the temperature of the last four thermocouples shows low variation. The fist thermocouple shows a slightly lower temperature due to the nearby edge. Therefore, it can be concluded that sufficient temperature control during induction welding of LSP laminates is possible by adjusting the speed and current in combination with cooling and use of heatsinks.

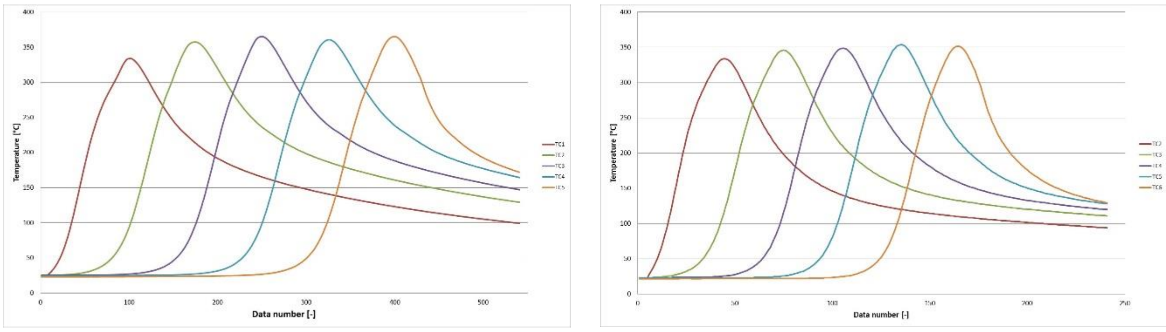
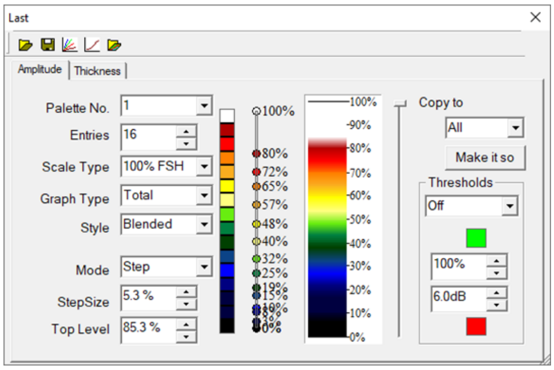


Figure 11: Typical weld temperature development across the weld length for gingham LSP (left) and the reference sample without LSP (right)

3.3 Quality inspection of welded samples



After welding, quality was checked through ultrasonic C-scanning and microscopic analyses of cross-sections. C-scan results of the four single sided LSP configurations are shown in Figure 12. The scans are done both of the welded area as of the surrounding laminate to evaluate the weld line and absence of de-consolidation inside or outside the weld area. Different gain settings were needed for the different LSP types. With the 16 colored rainbow palette on the right the 80% level (red coloured) is defined at the point of sound material. Therefore, red colour indicates good quality. The attenuation scan of the weld area (located in the centre of the substrate) is showing good quality for all substrates. Also, the direction of the AFP LSP tape is visible (90°, 0° or gingham pattern) on the laminates next to the weld interface. In case of the gingham pattern the copper mesh on the top side of the panels gives a disturbance of the ultrasonic signals. The black/dark blue narrow vertical indications in the weld line are caused by the thermocouples which were removed after welding.

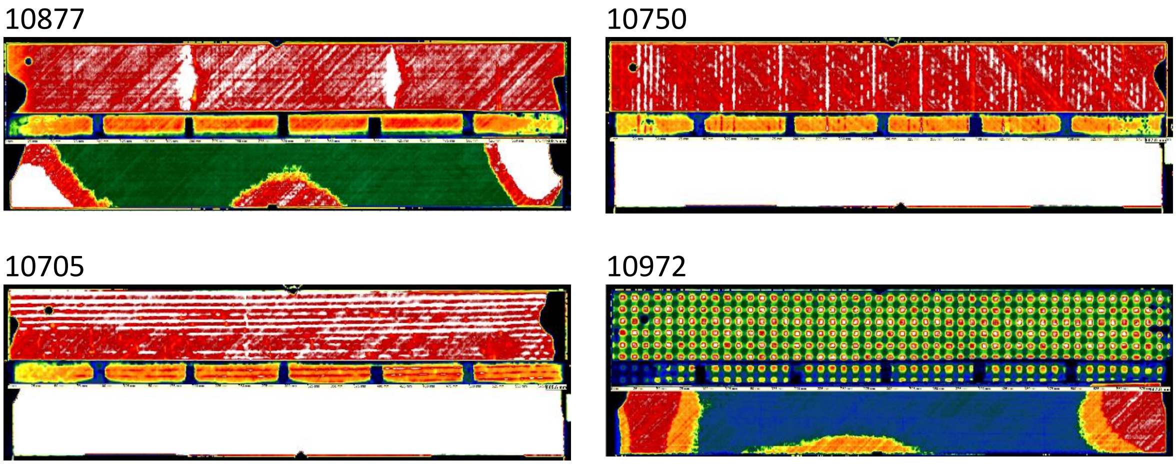


Figure 12 Attenuation scans of substrates with single sided LSP. Top left: hand layup fabric, top right: 90° AFP, bottom left: 0° AFP, bottom right: gingham pattern

When scanning the SLS substrate with the gingham pattern from the other side and checking the backwall scan a clearer result is obtained for the quality of the weld, see Figure 13.

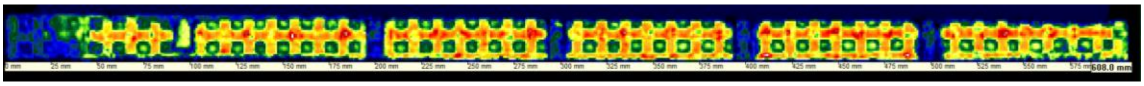


Figure 13 C-scan results from side without LSP

Analysis of the cross-sections confirm that the quality of the welds is good. No delaminations or voids are found in the laminates. Two cross-sections of the single sided hand layup fabric and the gingham pattern LSP type are shown in Figure 14. On the top side of the upper substrate the copper wires of the LSP material are visible.

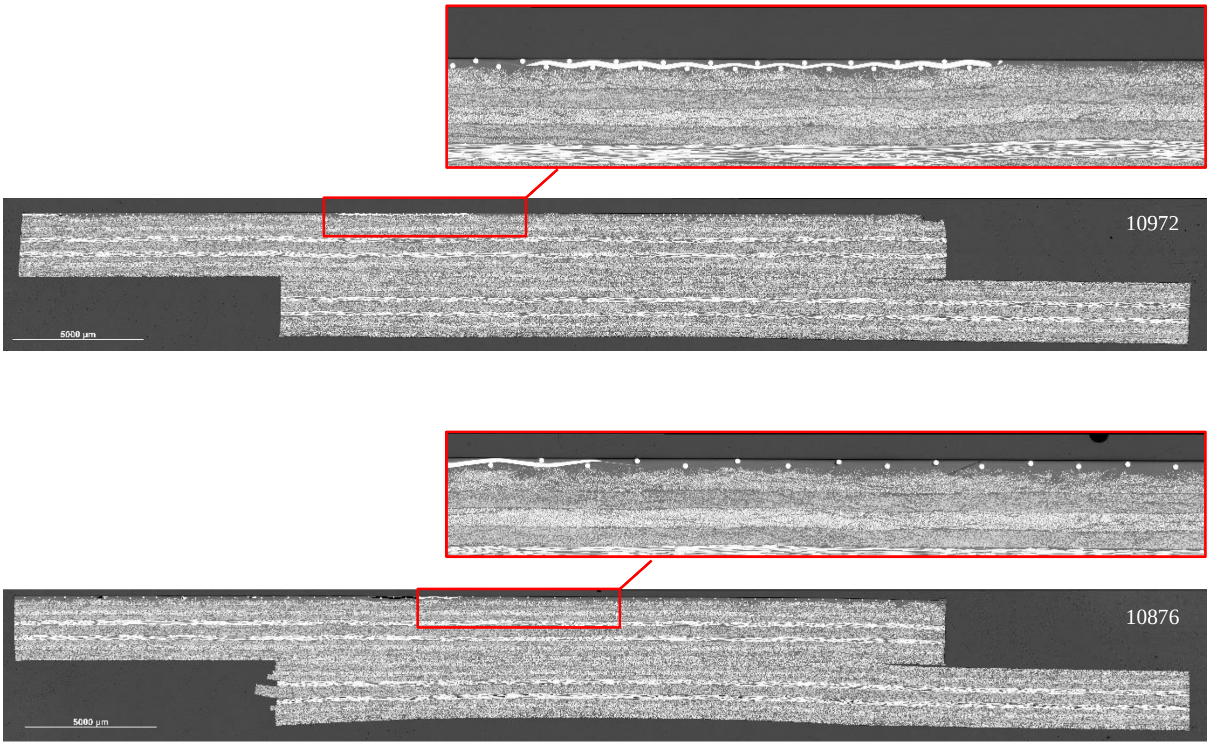
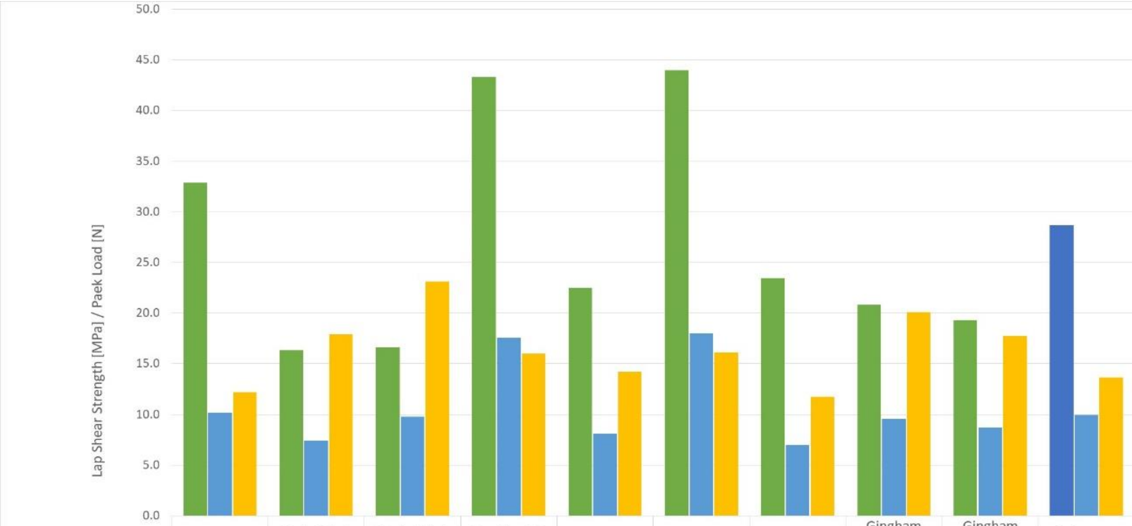


Figure 14 Microscopy of SLS coupon with Gingham pattern (top) and fabric LSP (bottom) on upper laminate

3.4 Lap shear strength of specimens

After quality inspection SLS samples were extracted from the substrates and tested according to ASTM D 5868-01 Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic Bonding. In Figure 15 the average lap shear strength, average peak load and the weld width for the LSP configurations and reference sample are shown.



	Double fabric	Single fabric (342 °C)	Single fabric (376 °C)	Double AFP 90°	Single AFP 90°	Double AFP 0°	Single AFP 0°	Gingham pattern (370 °C)	Gingham pattern (362 °)	Reference (no LSP)
Av. SLS Strength [Mpa]	32.9	16.4	16.6	43.3	22.5	44.0	23.5	20.8	19.3	28.7
Av. Peak load [N]	10.2	7.4	9.8	17.6	8.1	18.0	7.0	9.6	8.7	10.0
Weld width	12.2	17.9	23.1	16.0	14.2	16.1	11.8	20.1	17.8	13.7

Figure 15: Test results on SLS specimens with LSP and reference specimens without LSP

Compared to the reference SLS test result (no LSP) the samples with single sided LSP configurations show a decrease in single lap shear strength. On the other hand, the double sided SLS samples show a significant increase in SLS strength up to 153 % compared to the reference samples. It is known from previous research that adding resin film at the weld interface can improve the SLS strength up to 148 % [4]. As the LSP mesh is embedded in a resin layer it has a similar effect on the SLS strength.

Peak loads found for the single fabric and both gingham pattern LSP samples are comparable with the reference despite the lower SLS strength. This is caused by a wider weld width of these samples. As most of the load is introduced as peak loads at the edges of the weld interface the middle section of the weld is not critical for strength. Increasing the width increases only the middle section which in turn causes a decrease of the SLS strength. Further optimisation of the induction welding process with LSP is ongoing and will be presented in future papers and on conferences by the authors.

4. CONCLUSIONS

Based on the results from C-scan, microscopy and lap shear tests, it can be concluded that induction welding of QI 12 ply UD Toray Cetex® TC1225 LMPAEK/T700 laminates with different lightning strike protection configurations is possible by adjusting the process parameters and using additional cooling or heatsinks to prevent overheating or deconsolidation issues. It is found feasible to re-melt the interface between the laminates only locally using inductive heating, without a negative effect on the remaining laminate outside the weld area. While more challenging for the Gingham pattern LSP, the work also shows that C-scan is a possible non-destructive inspection method to evaluate weld quality of welded parts.

Furthermore, it was found that the AFP type of the LSP material had some advantages regarding the inductive response of the LSP layer when exposed to a magnetic field. Due to the slitted nature necessary for AFP lay-up, the area of the LSP material influenced by inductive heating is more localized and better to control compared to the continues woven copper mesh used for hand layup. An advantage of the slitted LSP material is also that the direction of the slitted LSP "tapes" in relation to the direction of the weld line can be influenced for improved welding.

During induction welding the LSP layer facing towards the coil heated up more than the interface. The higher the current, the bigger the difference between the temperature of the weld interface and the LSP layer. It is therefore recommended to use a high-temperature resistant heatsink on the LSP layer and to weld with lower current and speed compared to induction welding without LSP.

Single lap shear tests showed that samples with the single fabric LSP layer and the Gingham pattern LSP layer can sustain similar peak loads as the reference samples without LSP. The SLS strength of these LSP types is lower due to a wider weld interface. When applying the LSP layers double sided welding improves and higher peak load (+80%) and SLS strength (+53%) is achieved. Overall it can be concluded that induction welding of SLS samples with LSP layers underlines the potential for future application of induction welding of primary aircraft structures with lightning strike protection.

- Acknowledgement

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- Miscellaneous

Patent pending.

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