Focused Inductive Heat Generation in Weld Zones of Carbon Fibre Laminates by Magnetic Field Manipulation and Carbon Fibre Susceptors

N. Menke, M.C. Dhondt
German Aerospace Center (DLR) e.V., Stade, Germany

Abstract:
Research is done into alternative composite joining techniques, as contemporary methods require extensive work. The application of induction welding, one of the three most researched composite welding techniques, results in less labour and defects compared to mechanical fastening. The downside of induction welding is that the heating rate is reciprocal to the distance between carbon fibres and inductor and thus the weld zone cannot be heated exclusively. As a yielding surface leads to an imperfect weld, the aim of this research was identifying induction heating techniques to selectively heat the weld zone, such as manipulation techniques of the magnetic field and application of susceptors from carbon fibre reinforced thermoplastic. In addition, a verification for lightning strike protection (LSP) is performed.

Keywords: Induction Welding, Thermoplastics, Selective Heating, Magnetic Field Orientation, Susceptor

Introduction

For carbon fibre reinforced thermoplastics (CFRT), induction welding shows great potential for limiting the addition of mass and imposed defects while reducing the amount of labour that comes with joining parts by conventional riveting, thus resulting in lighter structures and lower production costs [1].
When welding by means of induction, a coil is put under high-frequency alternating current, thus creating a magnetic field around the coil. When a conducting material, such as carbon fibre, is placed within this magnetic field, eddy currents are generated. These currents heat up the material which can be used for welding. The schematics of a typical induction welding setup are depicted in Fig. 1.
A characteristic of induction welding is that the heating rate is reciprocal to the distance between inductor and laminate [2]. This can lead to a fully molten surface by the time the weld zone has reached melting temperature. A yielding surface leads to an imperfect weld due to loss of contact pressure required for proper consolidation and due to imprints. Accordingly, the aim of this research was to identify induction heating techniques to heat the weld zone of CFRT laminates while maintaining the solid state of the outer laminate surfaces.
To this end, three sub-questions were investigated:

1. Can specific plies in multidirectional CFRP laminates be heated by manipulation of the magnetic field?
2. Can a CFRP material be used as an insert in the weld zone in order to increase the temperature at the weld interface?
3. Is it possible to weld parts with lightning strike protection?

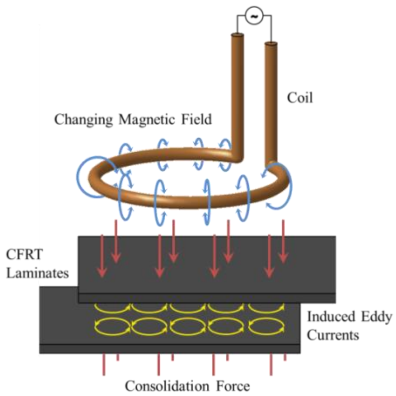

Fig. 1: *Schematics of induction welding setup*

State of research

This research focused on the heating of unidirectional (UD) reinforcement due to their higher mechanical properties and potential for automated manufacturing.
Both magnetic and electrically conductive materials can be heated via induction. As carbon fibres are inherently electrically conductive, CFRTs can be welded with or without a susceptor material. A susceptor material is an insert that converts electromagnetic energy to heat better than the laminate and is applied at the weld zone in order to melt the material locally while keeping the outer surfaces intact.
Susceptors made from third materials include metallic meshes from stainless or galvanized steel [3], and films with embedded particles or short fibres that form conductive networks [4]. As the

weld strength and reliability can be reduced by the introduction of third materials due to problems with bonding, thermal stresses, stress concentrations and corrosion [5-7], CFRTs themselves offer the possibility to be applied as a susceptor.
To effectively heat carbon fibre reinforced plastics by induction, closed conductive loops need to be formed to allow for the formation of eddy currents. Therefore, only fabrics and cross plies will heat up when placed in an alternating magnetic field, while stacks of unidirectional (UD) plies in a single direction will hardly heat up.
Thus, a ply of woven fabric-reinforced CFRT shows great potential for being used as a CF-susceptor. In a weave, fibres have perpendicular orientation and are in contact, thus forming closed loops. Depending on weave pattern, fibre volume content, titer and thread count, fabrics from carbon fibre display different heating rates when heated by induction. Using this effect, laminates have already been tailored from fabric-reinforced CFRTs that would produce more heat near the weld interface and less heat close to the coil [8]. Plies of fabric-reinforced CFRT displaying a high heating rate could also be used as susceptor materials in welding applications for layups consisting of unidirectional plies. Given that the rest of the laminate displays limited heating rates, the most heat is generated by the CF susceptor at the weld interface. This method leaves no foreign material in the weld.
The second aforementioned approach to inductively welding CFRTs is the susceptorless approach. As discussed, the closed loops required for the formation of eddy currents in CFRT are created when fibres in different directions either touch each other or are very close to each other, as is not only the case for woven reinforcements but also in multidirectional layups with high fibre volume contents [8]. Therefore, CFRTs can be welded without a susceptor, but without further manipulation the resulting temperature profile has its maximum slightly below the upper surface [9].
Approaches to shift the point of highest temperature in the direction of the weld zone that have been shown in research include active cooling and avoidance of the formation of closed loops by insulation of differently-oriented plies [9, 10].
Additional methods to improve upon the induction welding process for CFRTs from multidirectional layups that have not been shown in research include but are not limited to:

- Influence of magnetic field direction and frequency on the heating behaviour of differently-oriented plies
- Application of susceptors made of carbon fibre (CF) for multidirectional layups
- Application of thin-ply or highly conductive CFRP to improve the temperature profile
- Welding with lightning strike protection

Experimental investigations

All induction heating was performed using a 12 kW *i-class* induction generator with attached 170 mm single-coil vertical hairpin inductor by COBES GmbH, both water-cooled by an *ers SC 2.5 VS* system cooler. The inductor, as depicted in Fig. 2, was pressed onto the laminates by means of a pneumatic cylinder, exerting a force of 2.5 kN which corresponds to a pressure of 5.25 bar below the inductor. In this setup, the three requirements for effective welding are fulfilled simultaneously, as the inductor heats up the parts, cools the top surface, and provides pressure for consolidation.

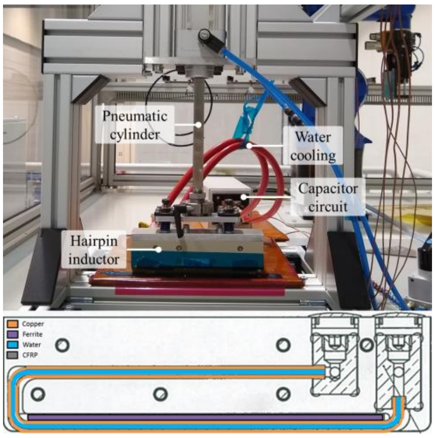

Fig. 2: *Induction welding setup and inductor layout*

The oscillation frequency of the magnetic field generated by the induction setup resulted to 422 kHz. The two installed capacitors with an individual capacitance of 0.17 µF could not be changed at the time of this research and as a result the effect of different frequencies on heating of CFRTs was not investigated.
To investigate the influence of magnetic field orientation and power, four different laminates with integrated thermocouples (TC) were fabricated from CF-PEKK UD tape (Teijin HTS45 194gsm). Thickness and width of the material were 0.2 mm and 300 mm, respectively. The tape had 34 weight % of matrix material which corresponds to 58 volume % of carbon fibres. All parts were fabricated by hand and consolidated in an autoclave. The investigated laminates were:

A. $[45, 0, -45, 0, 90, 0]_s$
B. $[45, 0, 90, 0, -45, 0]_s$
C. $[45, 90, -45, 0, 0, 0]_s$
D. $[45, -45, 90, 0, 0, 0]_s$

The chosen lay-ups were alterations based on the parent laminate A, a common aerospace laminate. Changes were made in order to investigate possible differences in heating behavior between 0°/90° and 0°/45° interfaces, as well as the influence of the number and position of interfaces to plies in different orientations, i.e. closed loops of CF. Isolated type E thermocouples of diameter Ø 0.13 mm were positioned through the whole thickness of the laminate. Another four laminates with the same layup as the ones with thermocouples were built.

All test laminates were tested with an inductor rotation of -45°, 0°, 45° and 90° around the laminate's surface normal. The inductor voltage was ramped to 40% voltage in 1 second and maintained for additional 2 seconds. Parts were let to cool down to below 40 °C between the measurements. Always two laminates of the same layup were put below the inductor to simulate welding configuration, the part with thermocouples as the top part. Every TC was targeted separately with the middle of the inductor in order for them to receive the same magnetic field. All laminates were tested twice; once from the pressure piece side and once from the mould side. The influence of inductor power was tested by increasing the supply voltage from 35-55% in 5% increments and measuring the profile of temperature increase in laminate C. All tests were performed below melting temperature such that the specimen could be tested with different magnetic field characteristics without fabricating new specimen.

Three fabric susceptors were built, two from a 2x2 twill fabric (200 gsm) and one from plain weave fabric (400 gsm). Embedding in different amounts of PAEK foil resulted in fibre volume contents of 57%, 42%, and 57%, respectively. The difference in matrix material was expected to only have negligible influence on the heating rate of the susceptor, as the product of loss tangent and dielectric constant – which influences dielectric heating – is similar for PEKK, PEEK and PAEK.

Additionally, two thin-ply susceptors were fabricated from PEEK UD tapes of 0.04 mm thickness and 1 inch in width. The fibres were T800SC fibres from Toray Industries Inc., Tokyo, Japan and had a volume fraction of 60%. The susceptors had five layers in different directions such that their thickness was approximately the same as that of one ply of regular material while having a higher number of crossing points. The combined fibre areal weight of the thin-ply susceptors was 200 gsm. The layups $[90, 0, \overline{90}]_s$ and $[90, 45, \overline{0}]_s$ were chosen to investigate the difference between gradual and maximum change between ply angles.

The different susceptors were put between two laminates and heated at inductor angles of 45° and 90°. The temperature increase of the last ply of the top plate was measured five times for each susceptor. Laminate C was used for these tests.

Finally, to test how added lightning strike protection (LSP) influences the temperature profile, a separate mesh that was not consolidated with the test laminates was clamped below the bottom laminate. This setup was chosen to reuse the same test parts as before. The LSP used was 3CU7-100FA from Dexmet Corporation, Wallingford, CT, USA.

Results

For all performed testing, the increase in temperature was considered, rather than the absolute maximum temperature reached.

A general trend could be observed that higher temperatures were measured around plies in the same orientation as the inductor, suggesting that currents were induced in fibres parallel to the hairpin inductor. This is backed by Lenz's law, according to which induced currents create a magnetic fields to oppose the change in magnetic field that generated them.

For all tested laminates, most heat was generated for an inductor orientation of 0° which matches the aforementioned assumption. In case of laminates A and B, the majority of plies were oriented in the 0° direction while simultaneously having the maximum amount of interfaces to plies with different orientations. Thus, a maximum amount of closed loops was available for currents induced in 0° layers. Laminates C and D did not share the property of having the maximum number of interfaces for 0° layers, but still showed the highest temperature increase for an inductor orientation of 0°. The following hypothesis was postulated for this phenomenon: Electrical contact was also formed between plies in the same orientation such that closed loops with differently oriented plies could be formed over a distance of more than two plies. The contact between plies in the same orientation could also be increased by undulations or marginal deviations during hand lay-up that allowed for formation of closed loops in UD-material.

For inductor orientations other than 0°, small increases in temperature could be found at the interfaces of plies with which the inductor aligned, however, for those measurements errors could not be ruled out.

Examining the average temperature increase for different laminates for an inductor orientation of 0°, it was noted that laminate D was heated more than laminate C, by roughly 20 K. The only difference between these laminates was the angular increment between adjacent plies, suggesting that a 0°/90° interface is heated more than a 0°/45° interface. Furthermore, comparing the average temperature increase for laminate A and B for an inductor orientation of 0°, a similar observation was made. Laminate A was heated more than B, as the presumably more efficient 0°/90° interfaces were located closer to the core. Hence, the surface cooling of the laminate was less effective and less heat was transferred from laminate A. This resulted in a higher average temperature increase for laminate A in comparison to laminate B which had better heat generation close to the surface. This, however, does not imply a better temperature profile.

For increased inductor voltage, no change in the shape of the temperature profile could be identified.

Fig. 3 displays the measured temperature increase for all tested carbon-fibre susceptors. In comparison to the susceptorless setup, all susceptors had a positive influence on the temperature at the weld zone. The fabric susceptors showed a higher temperature increase for increasing fibre volume content (fabric 1 > fabric 2) and increasing thickness or higher fibre weight (fabric 3 > fabric 1). It should be noted that all susceptors had a similar fibre areal weight as one ply of the UD material used to build the test laminates. This excludes fabric 3 (400 gsm).

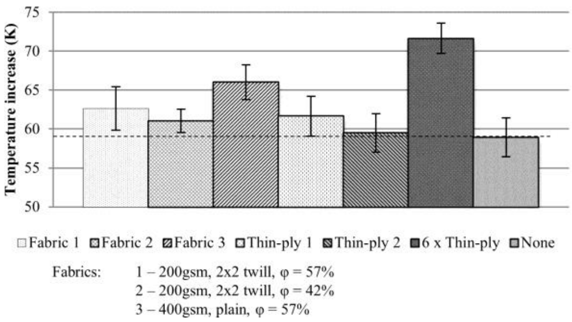

Fig. 3: *Weld zone temperature increase for carbon-fiber-susceptors*

The thin-ply susceptors performed within the same range of the fabric susceptors, with the version with angular increments of 90° displaying better heating behaviour than its counterpart with increments of 45°. In order to rule out inaccuracies in the measurement of temperature increase for the thin-ply susceptors, six layers of thin-ply were stacked. This resulted in the highest temperature increase of all susceptors, thus showing that each individual layer contributed to increasing the temperature at the weld interface.

As LSP was added to the welding setups, both the temperature increase in the top laminate and weld zone, and the temperature gradient in the bottom laminate decreased. The former was due to the magnetic field containing a given amount of energy. Since eddy currents can flow through the copper LSP more easily than through the CFRP, the copper absorbs a lot of this energy and thus less energy is left to heat the CFRP. The second observation likely resulted from heat conduction from the LSP into the bottom laminate.

Conclusion

It could be shown that the orientation of the magnetic field has an influence on the heating of the laminate and that fibres parallel to the hairpin inductor show a tendency to be heated more, as long as closed loops can be formed. Adjacent plies with a difference in orientation of 90° heat up better than adjacent plies with a difference in orientation of 45° and their respective positioning has an influence.

All CF-susceptors resulted in a higher temperature at the weld interface. More research is needed to optimize layup and dimensions of susceptors to achieve considerable improvement of the temperature profile. The addition of LSP resulted in a total decrease in heating of the laminates. At the side of the LSP no peak temperature was measured.

References

[1] Arnt R. Offringa. Thermoplastic composites – rapid processing applications. *Composites Part A: Applied Science and Manufacturing*, 27(4): 329–336, 1996. 4th International Conference on Automated Composites.

[2] Stephan Becker, D Maurer, Miro Duhovic, and P Mitschang, Quality-controlled continuous induction welding of cfrp composites. JEC Composites Magazine, 52: 40–43, 2015.

[3] E. Rodriguez-Senín, I. Villegas. Effect of mesh configuration on the induction welding process of thermoplastic composites. *16th European Conference on Composite Materials*, 2014.

[4] M. Muddassir. Development of nano/micro hybrid susceptor sheet for induction heating applications. PhD thesis, Technische Universität Kaiserslautern, 2016.

[5] C. Ageorges, L. Ye, and M. Hou. Advances in fusion bonding techniques for joining thermoplastic matrix composites: a review. *Composites Part A: Applied Science and Manufacturing*, 32(6): 839–857, 2001.

[6] L. Moser. Experimental Analysis and Modeling of Susceptorless Induction Welding of High Performance Thermoplastic Polymer Composites. PhD thesis, Technische Universität Kaiserslautern, 2012.

[7] T.J. Ahmed, D. Stavrov, H. Bersee, and A. Beukers. Induction welding of thermoplastic composites - an overview. *Composites Part A: Applied Science and Manufacturing*, 37: 1638–1651, 2006.

[8] S. Becker, P. Mitschang. Influences of textile parameters on the induction heating behavior of CFRPC. In *21st International Conference on Composite Materials*, 2017.

[9] O. Schieler, U. Beier, and P. Mitschang. Control of the through-thickness temperature distribution in carbon composite aerospace parts during induction welding, *Journal of Thermoplastic Composite* Materials, 31(12): 1587–1608, 2017.

[10] C.M. Worrall, R.J. Wise. Novel induction heating technique for joining of carbon fibre composites. *16th European Conference on Composite Materials*, 2014.