Induction Heating of UD C/PAEK – What Thermography Can Teach Us about Eddy Currents

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Abstract:
Induction welding is an attractive technology for fusion bonding of carbon fibre reinforced thermoplastic composites. In this process, eddy currents are induced in the conductive carbon fibre network by an electromagnetic field, heating up the parts. In unidirectional (UD) ply-based composites, formation of eddy currents relies on the ply interfaces where changes in the fibre orientation facilitate closed-loop conductive paths. Improved control of the welding process therefore requires a deeper understanding how the fibrous architecture relates to the physical mechanisms governing heat generation, which is the focus of this work. It comprises induction heating experiments on thin laminates and a series of test performed on representative ply-scale specimens subjected to a strong electric current. Resultant heating has been monitored using an infrared camera. Combined, the recorded thermograms highlight that eddy currents are dominantly induced alongside the different fibre directions present in the lay-up and that the varying quality of fibre contacts at the ply interfaces affects the homogeneity of the current density within the plies.

Keywords: Induction Welding, Eddy Currents, Ply Interfaces, Thermography

Introduction

The development of fusion bonding technologies offers the aerospace industry more efficient assembly methods for thermoplastic composite (TPC) parts in terms of throughput time, cost, structural integrity and weight reduction when compared to traditional practice. Fusion bonding, or welding, involves local heat generation at the part interface to soften the matrix, consolidating the joint with application of pressure and time. Many welding technologies are nowadays available for TPCs, mainly varying in how pressure and heat is applied to the joint interface. However, when it comes to rapid manufacturing of large structures and volumes, induction welding is considered very attractive as heat is generated directly within the material and the process is highly automatable.

Induction welding relies on internal heat generation due to induced eddy currents in the electrically conductive network of carbon fibres, when exposed to an alternating electromagnetic field emitted by a coil (see Figure 1). Eddy currents generate heat when met with the inherent resistance of the carbon fibres (Joule heating) and the semi-dry contacts of fibre crossovers. Additionally, dielectric heating occurs at the junctions when fibres are separated by thin layers of polymer. [1]

It is challenging to generate eddy currents in unidirectional (UD) reinforced plies, because of their low transverse electrical conductivity [2]. Thus, in actual UD ply-based laminates, formation of eddy currents relies on the ply interfaces where changes in stacking orientation imply fibre crossovers, through which closed-loop conductive paths are present in the fibre network (see Fig. 1). This results in a high lay-up dependency of not only eddy current formation, but also the resulting heat generation, as the size and shape of conductive loops depends on the type of interlaminar fibre crossovers.

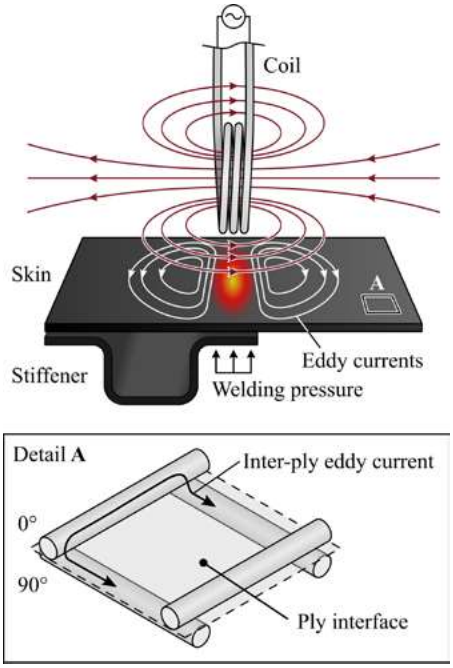

Fig. 1: *Schematic of induction heating of UD ply-based thermoplastic composites*

Currently, definition of the induction welding process windows for UD ply-based composites involves extensive and time consuming trial-and-error procedures, while at the same time the process shows to be sensitive to small variations in electrical material properties. For improved control of the process it is therefore required to gain a proper understanding about the fibrous architecture in relation to the physical mechanisms governing heat generation. This work explores the effect of the discussed fibrous architecture of UD ply-based composites in relation to the flow of eddy currents and the resulting heat affected zone (HAZ), through manipulation of the closed-loop conductive paths and monitoring the thermal response experimentally. First, thermograms of induction heating experiments on thin laminates will be discussed, which are then compared to validation experiments on representative ply-scale specimens to deepen the understanding of the preceding observations.

Induction heating experiments

Unidirectional carbon fibre reinforced PEEK and PEKK from resp. Toray (Cetex TC1200) and Solvay (APC) was used in this study, with a fibre volume fraction of 59% and a consolidated ply thickness of 0.14 mm. The authors decided to elaborate on the PEEK material only in order to discuss the full scope of the work. Nevertheless, all observations apply equally to the PEKK prepreg in a qualitative sense.

A hot press was used to consolidate various 300×300 mm^2 4-ply laminates at a consolidation temperature, pressure and dwell time of respectively 385 °C, 20 bar and 20 minutes. The 4-ply lay-ups were symmetric and composed of two different orientations of fibre, i.e. $[\theta/\phi]_s$. This way, the inductive response for a single type of interlaminar fibre crossover was studied, representing an isolated equivalent section from a larger and typically more complex lay-up.

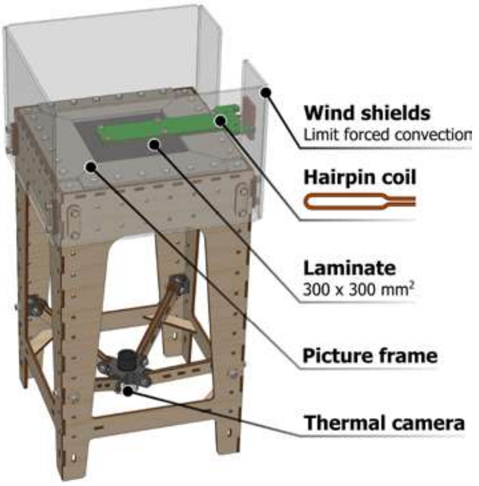

Fig. 2: Experimental set-up for induction heating thermography with a stationary harpin coil

An experimental test set-up (see Fig. 2) was developed for performing induction heating experiments with a stationary coil using the consolidated laminates. A FLIR A65 high resolution thermal camera was employed for temperature monitoring, calibrated by a thermocouple attached to but electrically isolated from the mounted laminate. Specimens were clamped in a picture frame, leaving an effective field of view (FOV) of 200×200 mm^2 for temperature monitoring with the infrared camera. Noteworthy, the mounting table is fully constructed out of electrically isolating materials and therefore transparent to the applied electromagnetic field. An air-core hairpin type coil was used for emitting a modulated electromagnetic field, generated by a 500 A (RMS) and approximately 350 kHz coil current. The stationary coil was centred above the target laminate separated by a coil-to-target coupling distance of 10 mm. These settings are deliberately chosen to result in very rapid heating, limiting heat dissipation and thus allowing heat losses to be observed close to the eddy currents concentrations.

Qualitative assessment of the thermograms

Fig. 3 shows the short time heat maps of the tested laminates and an AISI 430 stainless steel sheet (for reference), taken at the instant where the maximum temperature reached 50 °C. Note the rapidity of the test, as all frames are obtained within the first second of heating, and thus the eddy current distributions are assumed visually proportionate to the HAZ. Focussing on the stainless steel sheet first, it can be observed that for isotropic electrical conductors the eddy currents mimic the shape of the induction coil. This behaviour is dictated by Lenz's law, which states that the direction and shape of eddy currents induced in a conductor is such that the resulting electromagnetic field opposes the field that produced the currents in the first place. In other words, for a coil held parallel to a plate, eddy currents tend to copy the shape of the coil while running in opposite direction at every instant.

With this law in mind, the other thermograms in Fig. 3 can now be interpreted. First, it is worth explaining that the elongated shape of the hairpin coil is intentional. Compared to a circular coil, for which every fibre orientation would be equally susceptible, the hairpin coil 'favours' the presence of fibres in the longitudinal direction for efficient induction. This is reflected in the results presented in Fig. 3, where the shape of the eddy currents in the [0/90]s and [45/90]s laminates is not contrastingly different from the established isotropic response. The main difference is found in the curved sections of the coil, which now induce eddy currents with sharper transitions, in line with the fibre orientations present in the lay-up. More contrastingly, the thermograms of the $[45/0]_s$ and $[45/\text{-}45]_s$ laminates deviate substantially from the

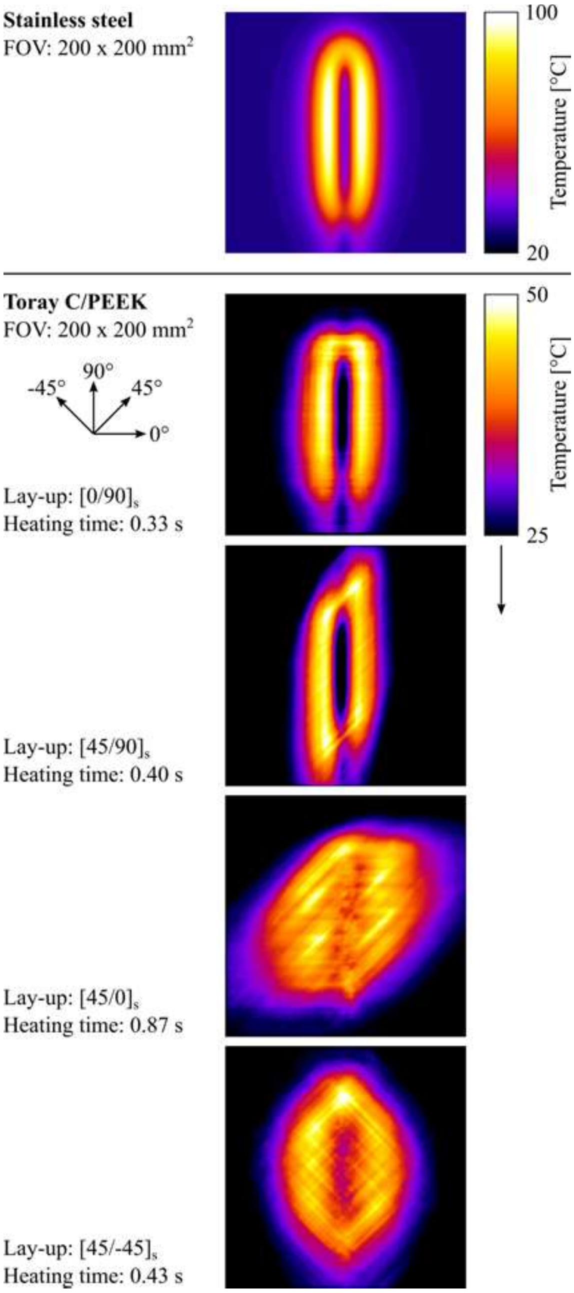

Fig. 3: *Thermograms of 4-ply laminates and a stainless steel sheet heated with the hairpin coil*

others. In absence of 90 degree plies combined with the poor transverse conductive properties of the UD reinforcement, numerous interfacial junctions are required to form a closed-loop current using the available fibre orientations. These inefficient loops, featuring a relatively high resistance, can decrease the heating rate strongly, as indicated by the time stamp of the $[45/0]_s$ thermogram. Despite these results being exaggerated by the coil shape and simplistic and thin lay-ups, it highlights that the HAZ is governed by both the type(s) of crossover(s) present in a lay-up and the orientation with respect to the coil.

Lastly, the thermograms of the $[45/0]_s$ and $[45/\text{-}45]_s$ laminates unveil significant inhomogeneity in the distribution of the eddy currents, i.e. a lack of a smooth transition between the HAZ and its surroundings. An understanding of this behaviour is explored in representative ply-scale experiments discussed in the remainder of this work.

A ply-scale study on fibre crossovers

The role of interfacial behaviour on the distribution of eddy currents is investigated by manufacturing cross-shaped specimens as displayed in Fig. 4. The specimens consists out of two orthogonally placed 300×50 mm^2 prepreg strips, consolidated at their crossover, with a smaller square ply added on top of the crossover area for local symmetry. An autoclave was used to consolidate the specimens at a consolidation temperature, pressure and dwell time of respectively 385 °C, 8 bar and 30 minutes. Filler material was used underneath the specimens to support the thickness step between the bottom and mid-ply, thereby avoiding fibres to break upon application of pressure.

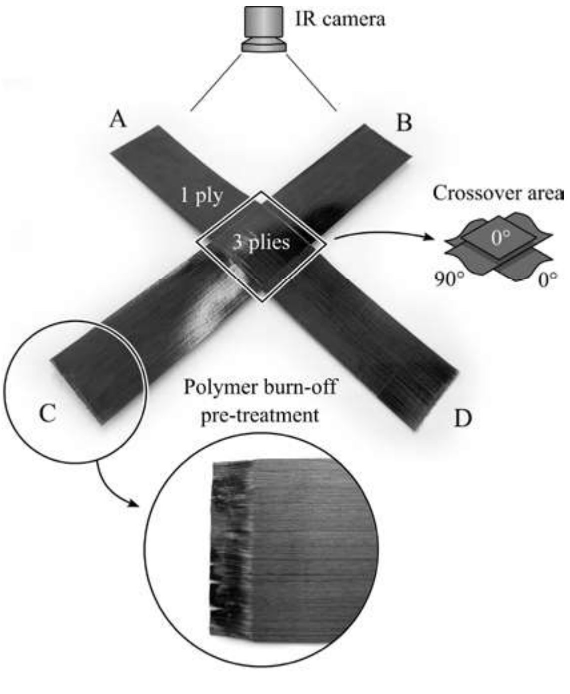

Fig. 4: *Photograph of an as-consolidated specimen used for characterisation of interfacial behaviour*

The cross-shaped specimens are representative for a single junction between two subsequent plies, as present in the 4-ply laminates subjected to the induction heating experiments. A Tenma 72-13360 DC power supply was used to impose a strong current of 10 A by connecting two of the four ends of the specimen to the supply using pressurised copper probes that spanned the width of the tape ends. Prior to testing, all four ends of the specimen were subjected to a local polymer burn-off pre-treatment using a gas torch to homogenise the electrical contact with the copper probes (see Fig. 4). During each experiment, the Joule heating behaviour was monitored using a thermal camera as electric current was passed either through a single tape (A to D), or forced through the ply interface (A to C). Comparing both responses will help further interpreter the induction heating observations.

Figure 5 shows thermograms for the initial heating response of both circuit configurations. When connecting both ends of the same tape, lateral distribution of the direct current is surprisingly uniform. This indicates there is little variation in the electrically conductive properties among (intralaminar clusters of) the embedded carbon fibres. Contrastingly, similar heating behaviour is absent in the electrically charged tape sections leading into and out of the crossover region when current traverses the ply interface. This is partly a geometric implication, as the current density scales with the unequal length of the fibre paths present from A to C. The thermogram, however, features irregular heat-up of certain clusters of fibres that cannot be explained by this geometric effect. This observation shows that it is rather an uneven amount and quality of electrical contact between adjacent plies that causes distorted introduction of electrical current in otherwise homogenous behaving plies. Hence, the interface morphology plays a crucial role in the local distribution of the eddy current density.

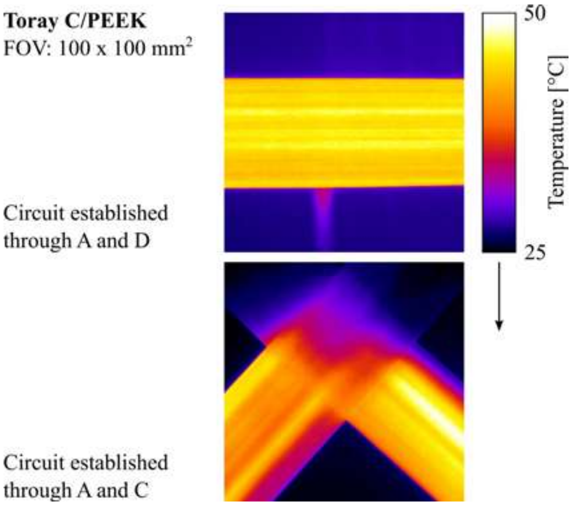

Fig. 5: Thermograms of the same cross-shaped specimen in case the direct current was passed either through a single tape (top), or traversed the ply interface (bottom)

Conclusions

Induction heating experiments are performed on thin UD ply-based laminates to observe the role of the fibrous architecture on the HAZ. It was shown that eddy currents and resultant heat are dominantly generated alongside the fibre orientations present in the lay-up and that the orientation and the type of ply interfaces can drastically affect the current distribution. A series of test performed on representative ply-scale specimens subjected to a strong electric current showed that the varying quality of fibre contacts at the ply interfaces distorts the homogeneity of the current density within the plies. Together, these qualitative results provide an insightful basis for further studying the underlying mechanisms governing heat generation during induction heating of UD ply-based TPCs.

References

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[2] W.J.B. Grouve, E.J. Vruggink, E. Sacchetti, R. Akkerman. Induction heating of UD C/PEKK cross-ply laminates. Procedia manufacturing, 47:29-35, 2020.