INDUCTION WELDING OF CARBON FIBER REINFORCED THERMOSET COMPOSITES VIA THERMOPLASTICS: OVERVIEW OF EXPERIMENTAL ANALYSIS OF INDUCTION WELDED SINGLE-LAP JOINTS.

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Abstract

Due to their high specific strength, fiber-reinforced polymers (FRP) offer high potential for lightweight structures in aerospace applications. The increasing use of FRP also intensifies the need for joining technologies suited for these materials. Novel joining methods could overcome the problems of traditional mechanical fastening methods, e.g. introduction of stress concentrations, possibility of galvanic corrosion and additional weight of fasteners. They can also offer considerable potential for applications in large-scale production.

In this paper, the potential of joining thermosetting materials via thermoplastic layers by induction welding is examined. To this end, sheets made from thermosetting composites with an outer layer of a thin thermoplastic film were manufactured, resulting in a bonding between thermoplastic polymer and thermoset resin during the resin curing process [1]. The thermoplastic film acts as welding layer for the induction welding process. In order to establish reference specimens with perfect bonding, single-shot specimens, i.e. without induction welding, were produced. The measured shear strength values were compared and the failure mechanisms were analyzed using SEM-EDX.

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1. Induction welding of thermosetting composites

A variety of solutions can be used for joining fiber-reinforced polymers (Figure 1). Adhesive bonding and welding form an alternative to mechanical fastening methods. Due to the high potential for automatization and repeatability, welding has been identified as a promising solution for joining thermoplastic composites [1-4].

Among the different welding techniques, induction welding promises to be a clean and fast process [2] and can be applied in a continuous process. It has been proven to be highly capable for heating of

FRPs [5] and to allow the manufacturing of joints with lap shear strengths comparable or superior to traditional joining techniques [6].
To analyze the potential of this technique, a welding process has been developed that allows joining thermoset composites using thermoplastic layers. The thermoplastic layers are heated by electromagnetic heating and then consolidated under pressure.

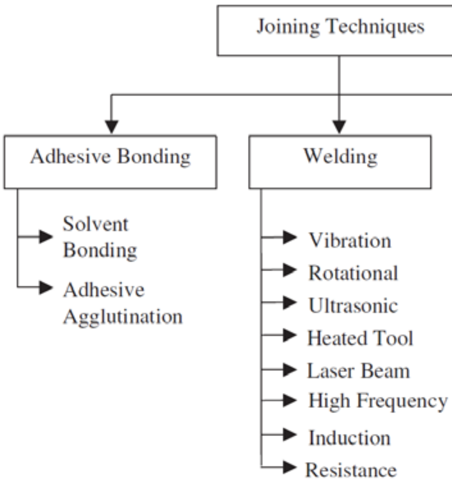

Figure 1. Joining techniques [2]

2. Induction welding and “perfect” welding as a benchmark

In order to assess the performance of the induction welding process presented here, the produced joints were tested mechanically. Several authors have commented on the deficiencies of traditional shear test methods in obtaining realistic shear strength values [7, 8], therefore comparative tests between benchmark specimens (“perfectly” bonded) and induction welded specimens were performed.
The sheets to be joined consisted of 8 plies of prepreg Cycom 977-2-35-12K HTS-268-300 with a stacking sequence of $[0/90]_{2s}$. In order to join the sheets by induction welding, a thermoplastic (TP) layer from polyethersulfone (PES) was cocured in the autoclave with the thermosetting (TS) sheets. In this way, the bonding forces between TP and TS polymers were realized via an semi-interpenetrating networks (semi-IPNs) structure. After curing, the two sheets were brought into contact with the thermoplastic layers on their surface for welding. During welding, the thermoplastic layers are joined and form a connecting layer. The process is illustrated in Figure 2, schematically it can be represented as a TS/TP-TP/TS type joint.
In order to optimize the joining process, the influencing variables regarding materials (composition and thickness of the thermoplastic and thermosetting layers), joint geometry (overlap width, joint configuration), welding process (inductor geometry, distance between welding head and laminates) were varied in several sample series and the resulting joint properties were analyzed.

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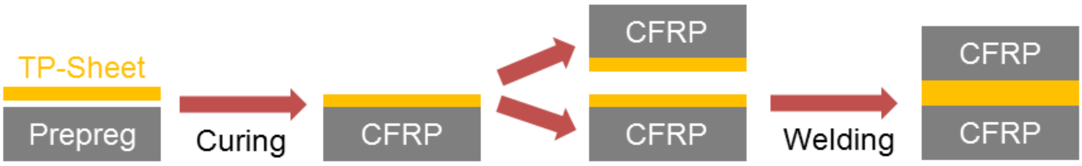

Figure 2. Induction welding process of thermosets via TS/TP semi-IPNs formation (schematic), TS/TP-TP/TS type joint

A jointed-arm robot with a welding head designed at IVW was used for induction welding (shown in Figure 3). Influential welding parameters, e.g. distance between inductor and specimen, temperature of the consolidation roller, pressure for air cooling and consolidation pressure were monitored during welding. The utilization of a jointed-arm robot allows for an automization of the welding process and thus makes a continuous and reproducible bonding process of parts with complex geometries possible.

Figure 3. Jointed-arm Robot with welding head.

To produce benchmark specimens with the best achievable joint properties, the two laminates were cured together with one thermoplastic layer. In this way, a thermoplastic layer without a TS/TS interface is bonded with the laminates via the semi-IPNs structure. This kind of bonding is called “perfect” welding hereafter and can be compared with the induction welded specimens. This type of joint can be represented as TS/TP/TS and is schematically given in Figure 4.

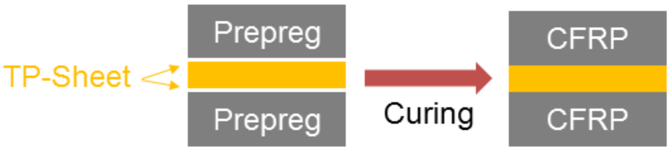

Figure 4. “Perfect” welding process (schematic), TS/TP/TS type joint.

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Following both processes, sheets of thermoset laminates joined via thermoplastic layers were obtained. After manufacturing, specimens for mechanical testing were prepared as described in the following chapter.

3. Mechanical testing

After welding, the sheets were cut to length and specimens were cut from the sheets using a water cooled saw with a diamond blade (see Figure 5 for specimen geometry).

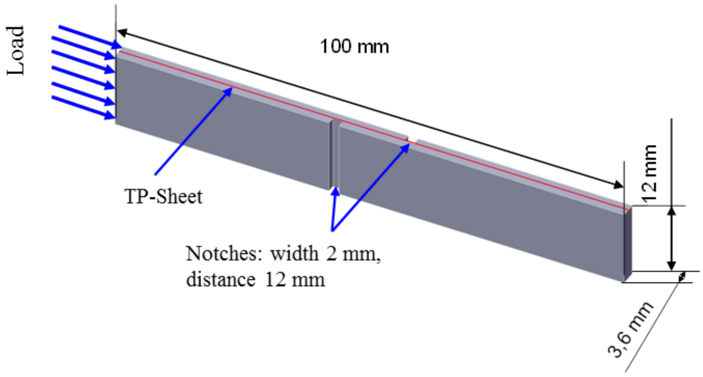

Figure 5. Specimen geometry.

The notches were milled into the specimens using a high speed drill. The depth of the notches was inspected optically using a microscope to ensure that the thermosetting laminate was separated completely and shear could only be transferred via the thermoplastic layer. Figure 6 shows the milling process and fixture.

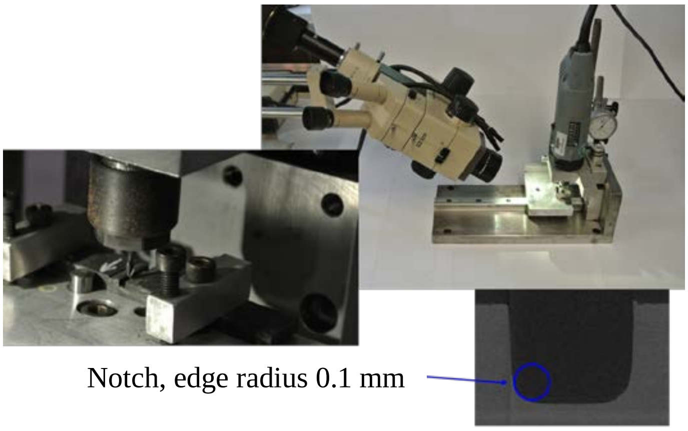

Figure 6. Milling of the notches in the specimens.

The testing procedure was based on the regulations of ASTM D3846, though modifications in specimen geometry had to be implemented due to the manufacturing process. In order to avoid stability problems, a buckling support was used during testing. The compressive load was introduced edgewise as indicated in Figure 5. To minimize the influence of the buckling support, the bolt force

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was recorded via sleeves equipped with strain gauges. The specimens were tested until failure and the maximum compressive load was recorded. The maximum load is divided by the shear area to obtain the shear strength. In reality, the shear stress distribution in the shear area is not homogenuous [9]. In this case, the test method was used for comparative testing of benchmark specimens (“perfect” welding) and specimens produced by induction welding, rather than trying to obtain absolute values for the shear strength of the joint.

4. Results

Table 1 summarizes the results of the shear tests. The induction welded specimens were manufactured using the optimum configuration of the influencing factors described above. The shear strength of the induction welded specimens is 80 % of that of the “perfectly” welded specimens, thus both methods produce functional bonds. Analysis of a cross-section of the joints showed some imperfectness of the welded PES/PES interface which could contribute to the lower bonding forces.

Table 1. Results of the compression shear test.

Specimen Group	Shear strength	
	Mean (MPa)	Standard deviation (MPa)
“Perfect” welding	54	5
Induction welding	41	7

Five “perfectly” welded and six induction welded specimens were tested. The failure mechanism of both types of welding was subsequently analysed by scanning electrone microscopy supported with element mapping (SEM–EDX). It was found that the induction welded specimens exhibit similar failure mechanisms to the specimens produced by “perfect” welding. Based on these results it was concluded that the welded joints are subjected to the mixed cohesive-adhesive failure, the failure front starts in the thermoplastic layer and passes throught the laminate followed by a delamination on the EP/fiber interface, thus an interaction between PES and EP in semi-IPNs structure is stronger than a cohesive strength within the laminate. The proposed failure mechanism is schematically represented in Figure 7. Moreover, these results also confirm the accuracy of the chosen compression test configuration.

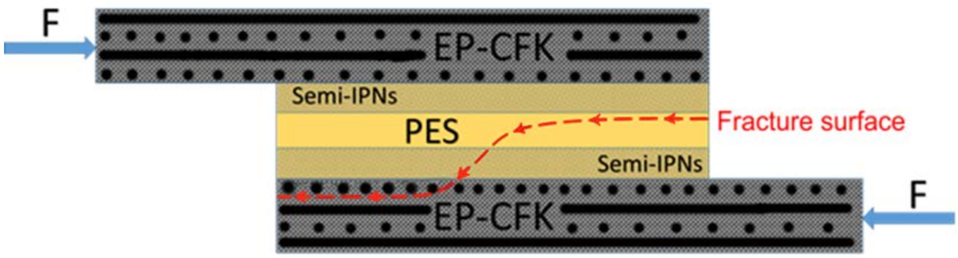

Figure 7. Proposed fracture mechanism of the welded joints.

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5. Conclusions

The results of the research show that induction welding via thermoplastic layers is a promising technique for bonding thermosetting laminates. The possibility of automatization qualifies this process for application in efficient processes and for complex parts. Though the shear strength is 20% lower than that of "perfectly" bonded specimens, analysis of the fracture surface shows that the failure mechanism is similar.

Acknowledgments

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