INDUCTION WELDING OF PPS-CARBON COMPOSITES: MODELING AND EXPERIMENTAL RESULTS

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Summary

An experimental study accompanied by numerical finite element (FE) analysis of induction welding of PPS-carbon composites is reported. In order to develop a robust process devoted to welding of advanced composites for aeronautical applications, the influence of the fundamental process parameters such as generator power, distance between induction coil and laminate, coil geometry and laminate lay-up on the heating rate and the heat distribution were analyzed using FE simulations carried out with Comsol Multiphysics software. The model was validated through the comparison of experimental and model results obtained in stationary and dynamic experiments. Infrared thermography was used to obtain full field temperature measurements of the heated surface. A prototype panel was obtained by welding “L” shaped stringers on a flat laminate was performed using optimized parameters. The strength of welded joints was measured either by single lap shear measurements either by peeling of the mentioned stringers.

1 Introduction

Thermoplastic matrices for composites are characterized by several advantages compared to thermosetting ones. Among other, the possibility of welding parts is considered one of the most relevant. Different techniques have been proposed and tested at lab scale and in some case the production scale [1-6]. Indeed aeronautic structures have been joined by resistance welding. When glass fibers reinforced composites must be welded metal wire net is needed. On the other hand, when carbon fiber composites are used their electrical conductivity can be exploited to generate heat in the welding region.

Induction welding is also a well assessed technique for metal parts joining. It has been successfully applied to carbon fibers reinforced composites for the last 15-20 years. The studies carried out on continuous induction welding of thermoplastic matrix/carbon fiber composites indicated that high performances joints can be obtained [1-4,
The attainment of proper welding procedures leading to repeatable strength of welded joints is a critical issue still not fully achieved, but necessary to better exploit the potential of thermoplastic composites in different industrial applications, and mainly in the aerospace sector [3-5, 8]. While resistance welding requires the preparation of the joining interface with proper conductive materials followed by an electrical heating along the overall welding line, induction welding requires minimum preparation, even if the welding is performed moving the heated area along the welding line at constant velocity. Resistance welding is characterized by lower heating and cooling rates compared to induction welding [6]. The main disadvantage of the induction welding, beside the required full knowledge of the multi-physical phenomena at the basis of this technique, are the lack of available industrial equipments specifically developed for composites. For this reason a new induction welding machine was developed for continuous welding of advanced thermoplastic composites. This apparatus, in which some new features were introduced to ensure a proper temperature distribution across the thickness of the joint, was designed thanks to a huge work comprising numerical and experimental activities.

The initial fundamental step for the development of the new induction welding machine was the study of a numerical model to support the analysis of the different parameters involved with the induction welding principle. The numerical simulation of the electromagnetic field generated by an inductive coil and the related eddy currents within the conductive material to be welded, were modeled together with the heat exchange phenomena due to the Joule effect. The numerical results were validated thanks to the comparison with experimental data, i.e. temperature measurements by means of thermocouples and IR thermography (field temperature measurements).

The good matching between experimental and numerical data indicated that a reliable numerical tool, for the definition of optimized welding parameters support was developed. The effectiveness of the optimized parameters was proved by the high values of mechanical performances found for the welded joints. Finally, thanks to the experimental and numerical work carried out, useful guidelines and procedures the application of for induction welding of composites in the aeronautic sector were gathered.

2 Materials and Methods

The study of the processing parameters was carried out on carbon-fibre fabric reinforced polyphenylensulfide(CF-PPS), the CETEX ® composite provided by TENCATE (5-harness satin; fibre volume fraction: 50%; thickness: from 1.2 to 2.48 mm).

The experiments were performed with a 600 kHz, 220 V induction generator, designed and developed in cooperation with SINERGO (see Fig. 1). While the tension and frequency are kept constant, the power, ranging between 0.5 kWh and 3.5 kWh, can be tuned for each particular coil and weld geometry investigated. The other parameters that can be changed during the welding are listed below:

- Coil distance;
- Consolidation pressure (applied by means of a cooled cylinder);
- Feed velocity (velocity of the welding head, from 1 m/min up to 50 m/min);
- Cooling rate of the upper surface of the joining.
During induction welding experiments, heat is produced within the conductive carbon fiber reinforced composite, and the temperature in the welding region must increase above the melting temperature of PPS matrix, i.e. 340 °C. On the other hand while the temperature of the lower and upper surface of the welding region is kept below 220 °C. In particular the surface closer to the inductive coil was continuously controlled through an optical pyrometer (see Fig. 2). Consolidation pressure was applied during welding of “L” shaped stringers on a flat laminate thanks to a cooled cylinder capable to reduce the temperature of the molten material below its crystallization temperature.

Continuous welding is obtained through the coil motion at constant velocity. A commercial microbolometric FLIR Infrared thermocamera with 320x256 Focal Plane Array with a standard 24° lens was used for field temperature measurements. The mechanical properties of the welded joints were evaluated by single lap tests according to ASTM D5868 and by peeling tests on “L” shaped stringer welded on a flat laminate (width = 23 mm).

3 Finite Element Model

Finite element simulations using Comsol Multiphysics 4.2 finite element (FE) software were carried out coupling electromagnetic and energy balance differential equations in order to calculate the temperature distribution and to optimize the coil geometry.
Figure 3: picture of the coil used in the first FE simulations (top) and FE calculated temperature profiles (bottom).

In order to simulate the heat generation caused by the magnetic field, generated by an alternate current which flows in the coil, a study in the frequency domain was done with the Comsol Magnetic Fields module. The current in the coil was modeled by means of the Lumped Port tool, in which tension and characteristic impedance of the welding machine were introduced. At last heat generation due to the eddy currents (Joule effect) flowing in the carbon fabric, under proper initial and boundary conditions, was modeled with the Comsol Heat Transfer in Solids module.

4 Results and Discussion

Simulations at different power and distance between the sample and the coil were initially carried out adopting a simplified geometry (Fig. 3) of the induction coil. In these simulations the coil was not moved and the time required to reach a temperature of 260 °C (533 K in fig. 3) at a point of the sample surface below the coil (surface temperature) were determined and then compared with experimental data.

These simulations were obtained setting proper values of the key physical parameters for simulations, i.e. magnetic
permeability, magnetic permittivity, electrical conductivity.

Figure 5: comparison of the temperature distributions obtained with a circular coil (top) and the “Double-D” coil (bottom)

Then more complex welding configurations as well as coil geometries, leading to a more uniform temperature distribution within the welded joints, were modeled and compared. In particular the two coil geometries, shown in Figs 4a and 4b, were considered.

The results of FE simulations obtained adopting a circular coil and a Double-D coil are shown in Figure 5a and 5b. The temperature calculated at the interface between the two components to be welded were compared with that measured by a thermocouple. In this case the coil was not moved and after 60 s the power was turned off. This comparison is shown in Figure 6, where the numerical and experimental temperatures are plotted as a function of the heating time for the circular coil. A very good agreement between numerical and experimental results is obtained. A similar agreement between FE model results and experimental data was also obtained comparing the results of the finite element simulation with the results of infrared thermography and using the “Double-D” shape coil.

Figure 6: comparison of the numerical and experimental temperatures during heating and cooling.

The validated FE model was then applied to optimize the process parameters and the coil dimensions for two different geometry. A static FE analysis was also performed changing the distance between the composite surface and coil (Figure 7b). The temperature evolution at the welding interface obtained with different values of power (Figure 7a). The horizontal lines in these figures represent two limits: the upper curve is placed at the matrix degradation onset while the lower matrix melting point. These plots indicates that optimized conditions can be found combining these two process parameters.
Figure 7: Temperature evolution after 45 s at the welding interface as a function of the position across the coil center. The composite-coil distance is changed (top), keeping the power at 40% of the maximum value of 2.1 kW and the power (bottom) as the percentage of its maximum value, keeping the coil-composite distance = 2 mm.

Welding of two flat laminates was performed as preliminary activity in order to fabricate specimens for single lap shear tests. The results of these experiments indicate that very high performances of the welded joints, up to 26 MPa, in good agreement with the values reported in the literature [2], can be obtained.

A typical plot reporting the shear stress as a function of the crosshead displacement obtained in a single lap shear test is reported in Figure 8, together with a picture of the fracture surface of the single lap specimen. The average value of resistance obtained with the single lap shear test is reported in Table 1:

<table>
<thead>
<tr>
<th>Test</th>
<th>Maximum shear stress (MPa)</th>
<th>Peel strength (N/mm)</th>
</tr>
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<tbody>
<tr>
<td>Single Lap Shear</td>
<td>26.27±2.91</td>
<td>9.60±0.68</td>
</tr>
<tr>
<td>Peel test</td>
<td></td>
<td></td>
</tr>
</tbody>
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Table 1: Results of single lap shear test and of peel test on L shaped stringer welded on a flat laminate.

The results of peel tests performed on specimens obtained welding with L-stringer
on a flat laminate are also reported in Table 1. A picture of the break surface, occurring at the joint between the “L” shaped stringer and the composite laminate, is shown in Figure 9.

Figure 9: Break surface of peel test at the joint interface.

5 Conclusions

A prototype panel stiffened with four “L” shaped stringers was fabricated as shown in Figure 10. The developed numerical model is currently used to optimize the induction welding of more complex geometries, such as composite laminates stiffened with stringers of different shapes. Moreover induction welding will be applied to other thermoplastic matrix composites, such as PEEK and PEKK matrix composites.

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7 References


