Welding of Carbon Fibers Composite by Induction Heating

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***Abstract*—This paper presents works done by IREENA laboratory on induction heating of composite material. These works are based on characterisation of electrical properties and modelling of process.**

Keywords—Carbon Fibre Reinforced Polymer Composite, Characterisation, Modelling, Welding, Induction Heating

I. Introduction

Before composite material, the shape of a piece was designed according the mechanical strength of the material and mechanical solicitation. Composite material allows to design the material according the wanted shape and mechanical constraint. Composite material is pileup of several layers, in each layer carbon fibres are in the same direction and hold together by thermoplastic matrix. The relative orientation of each layers is defined according mechanical constraints. This configuration leads to a lighter weight for the same mechanical performance.

However, composite production is only 1% of metal production. To grow up this production, it is necessary to find new technological approach to improve the duration, the energetic consumption and the cost of assembly. For 20 years, IREENA laboratory works on solutions using induction heating. Indeed, it is possible to heat by induction composite material to weld composite or apply on composite thermal-induction NDT process.

It is very challenging to determine the induced current path due to the complex nature of composite material. IREENA laboratory works on two ways to develop a tool that assists to process optimization. First way, methods of identification and characterisation of electrical properties of composite and for the second way, a software of multi-physics modelling which takes into account the physical phenomena, and equipments.

II. Understanding of Induced Current Path

Identification of electrical properties of composite begins with experimental trials and micrographic observations.

A. Induction heating with U shaped inductor

The first experimentation done was to heat by induction two kind of composite material with a U-shaped inductor. The first kind of composite, called UD, is a composite with all layer in the same direction. The second one, called QI, the layers follow the sequence $[0, 45, 90, 135, 135, 90,45,0]_{2s.}$ Three trials was done with a frequency of 237 kHz and a current of 106A. First, UD plate was heated with fibres along the inductor-axis, an elevation of temperature of 12°C was observed. Second test, the UD plate was oriented in perpendicular direction, no elevation of temperature was detected. Third one, the QI plate was heated with an elevation of several hundred degrees in few seconds.

The first and second tests show the anisotropic behaviour of composite plates. The third one shows the strong impact of the layers' orientation on circulation of current.

B. Micrographic obervation

From micrographic observation [1], it is observed that fibres are random position in the layer, fibres are not straight but wavy which allow electrical contact between fibres in one layer and in interface between layers.

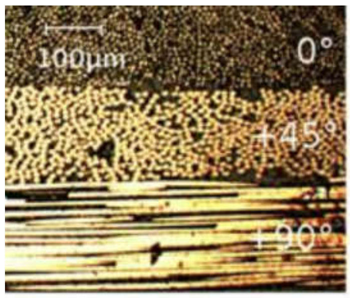

Fig. 1. Micrographic observation

C. Voltammetric trial

The last set of trial is voltammetric to determine the tensor of conductivity of one layer. It is not possible to work one a single layer due to problem of electrical contact. It is why, UD composite as used. Due to the random distribution of fibres, several samples was tested. Results are shown in Table 1.

The high anisotropic behaviour of composite is confirmed with the conductivity along fibres' orientation $\sigma_{\parallel}$ and in transverse direction. However, the conductivity in transverse $\sigma_{\perp}$ and thickness σ_t is not equal. Even if, analyse of microscopic shows uniform distribution of fibres in both directions. The measurement of conductivity along thickness for QI composite reveals specific phenomena in interface between layers and the effect of layers' orientation in global behaviour of composite.

	Conductivity (S.m^{-1})			
	UD $\sigma_{\parallel}$	***UD $\sigma_{\perp}$***	***UD σ_t***	***QI σ_t***
Measures	35062±872	7.29±0.52	1.46±0.21	2.56±0.42
Model	34724±0.37	7.27±0.06	1.28±0.08	3.07±0.26

TABLE I. CONDUCTIVITIES TENSOR

D. Homogenenisation procedure

Diameters of fibres are closed to 7µm, thickness of one layer is nearly 160-180µm and a composite piece can reach several meters. This scale factor leads the necessity of a homogenisation procedure to be able to simulate the magnetic and thermal behaviour of composite. To homogenise, the material is divided in Representative Elementary Volume REV. Voltammetric trial are performed on REV to estimate the conductivity along the three directions. Due to the random distribution of fibres, a statistical analysis is done to assure the results. In our procedure, a virtual material is generated to obtain REV of one layer or with interface between two layers[2], as shown Fig. 2. A comparison between our simulated results and experimental ones is shown Table 1. The good concordance between them show our capacity to simulate the good behaviour of current path in composite. Use generation virtual material allow to study impact of each parameters. More details of homogenisation procedure are given in paper [2].

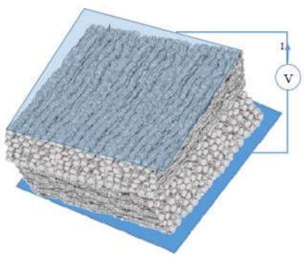

Fig. 2. Voltammentric trial on virtual material.

Inductance and capacitive effects are negligible compared to electrical contact for frequencies lower than 1GHz [1].

III. MULTI-PHYSICS MODDELING

After identify the tensor of conductivity of one layer and the interface phenomena between layers, modelling of induction heating of composite can be done using Finite Elements [3]. Solving electromagnetic EM problem allow to calculate EM power density which is the source term for thermal simulation. The modelling constraints are: 1. Anisotropic and layers' orientation which lead 3D model. 2. dependency of electrical conductivity at temperature which lead a coupling between electromagnetic and thermal phenomena. 3. Thin layer which lead use of hexahedron or degenerated element to avoid mesh deformation sensitivity [4]. 4. Reaction between load and inductor which lead to use surface impedance on inductor parts [5-6]. Moreover, surface's impedances allow to reduce time consumption. 5. Movement of inductor leads to use regular mesh to avoid interpolation. 6. To finish, to apply an optimization procedure, time consumption has to be reduced. Details to consider interface phenomena in model are given in paper [2].

IV. APPLICATIONS

Induction heating of composite can be used for welding airplane structure or NDT process. The welding of composite is briefly presented in this paper. To build the structure of airplane with composite, constructor affix omega reinforcement on large plate. To weld the two part, temperature in interface has to be reached 400°C during few seconds. Fig. 2 show the demonstrator of dynamic welding of composite. In recent development, chemicophysical model is added to magneto-thermal model to estimate the level of crystallisation of composite.

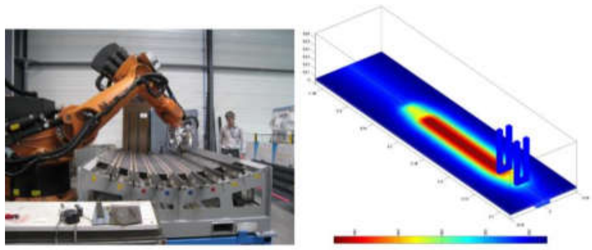

Fig. 3. Dynamic welding of composite

V. CONCLUSION

In this paper, an overview of IREENA's work on induction heating of carbon composite was done. The studies on identification and modelling allow to develop a tool of optimization of heating process. The future work will focus on application of model order reduction to improve time consumption and join works on welding and NDT to be able to ensure quality of the joint at the end of welding.

REFERENCES

[1] G. Wasselynck, D. Trichet, J. Fouladagar,"Determination of electrical conductivity tensor of CFRP using a 3D percolation model", IEEE Transactions on Magnetics, 49(5) : 1825-1828, may 2013.

[2] B. Kane, A. Pierquin, G. Wasselynck and D. Trichet, "Coupled Numerical and Experimental Identification of Geometrical Parameters for Predicting the Electrical Conductivity of CFRP Layers", IEEE Transactions on Magnetics 56 (2), January 2020

[3] O. Bíró, "Edge element formulations of eddy current problems," Computer Methods in Applied Mechanics and Engineering, vol. 169, no. 3–4, pp. 391–405*)*

[4] H.K. Bui, G. Wasselynck, D. Trichet, G. Berthiau, "Degenerated hexahedral Whitney elements for electromagnetic fields computation in multi-layer anisotropic thin regions", IEEE Transactions on Magnetics, 52(3), march 2016

[5] H.K. Bui, A. Ba, G. Berthiau, D. Trichet, "Fast 3D simulation of various applications of induction heating", IOP Conference Series: Materials Science and Engineering, vol. 424, no. 1, 2018..

[6] A. Desmoort, Z. De Grève, P. Dular, C. Geuzaine and O. Deblecker, "Surface Impedance Boundary Condition With Circuit Coupling for the 3-D Finite-Element Modeling of Wireless Power Transfer," IEEE Transactions on Magnetics, vol. 53, 2017.