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Determination of anisotropic geometrical parameters for the electrical characterization of carbon/epoxy composite during oven curing

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ABSTRACT

Cure monitoring is an important tool for ensuring manufacturing reliability and reproducibility of composite parts. Among a variety of techniques, electrical measurements are used. However, electrical values are affected by cure cycles and by the rheological and geometrical parameters during curing. All these parameters must be taken into account to establish electrical models. The present paper proposes to study the changes in the geometrical parameters of an oven-cured composite made of T700/M21 prepregs during curing. For this work, microstructural analyses (in the three orthotropic planes) were carried out using specific curing, i.e. by releasing the vacuum at characteristic points (time and temperature). The following parameters were measured (manual and automatic approaches): ply, inter-plies and global thicknesses; percolation parameters; and volume and surface ratios (fibres, matrix and voids). The parameters obtained will be used in future works to define an electrical model for real-time control of the cure process.

1. Introduction

Monitoring the manufacturing steps and implementing quality assurance are becoming increasingly significant factors when considering the whole fabrication of composite materials. The ultimate aim of our current study is to monitor the complete curing cycle of composite materials using electrical impedance measurements and thus to optimise their manufacture owing to an intelligent closed loop cure monitoring system. This optimisation of production should provide reductions in process and material costs, as well as bringing improvements in the properties of the composite structures obtained. In the aim to use the electrical impedancemetric response of carbon/polymeric laminates during curing, a very promising approach could be to find the electric current paths in the three orthotropic planes of composite material. In CFRP laminates, current flows mostly along the fibres in the longitudinal direction and via the percolation network in the transverse one. The higher the fibre volume ratio, V_f, is, the lower will be the electrical resistance values. In the transverse direction, the percolation network is defined by the fibre contact points, Nc, and the length of the fibre segments between contacts δec (Fig. 1). Furthermore, the volume ratios of the matrix, V_m, and the porosity (or voids), V_0, influence the inter-fibre capacitive transverse conduction. In the same way, as shown in Fig. 1, the established percolation-network through the global thickness, t_{glob}, of the laminate produces non-zero electrical conduction in the thicknesses of each ply, t_p, and inter-plies, t_{ip} (zones between plies).

To ensure real-time automatic control of the manufacturing, electrical modelling efforts at the ply and inter-plies scales are required to predict the value of the electrical impedance at each instant of cure. These models definitely should take account of the changes in the following geometrical parameters during the cure process: geometrical parameters (t_p,t_{ip}), volume ratios (V_f, V_m,V_0) and electrical percolation parameters (Nc,δec). Those parameters should be measured and correlated with each other both at local (plies and inter-plies) and global (laminate) scales taking into account anisotropy and rheological transitions. Thus one of the challenges of our current work is to settle a specific approach enabling the key geometrical parameters (t_p,t_{ip},V_f,V_m, V_0,Nc,δec) to be determined so that they can be used as inputs to an electrical impedance model of the composite. This latter should predict the electrical response of an U.D. laminate in the three orthotropic planes during curing that will be developed in future works. For this purpose this study was first performed with oven-cured laminates in order to settle an accurate methodology enabling the key parameters to be measured. The same approach is currently underway for comparison using autoclave curing.

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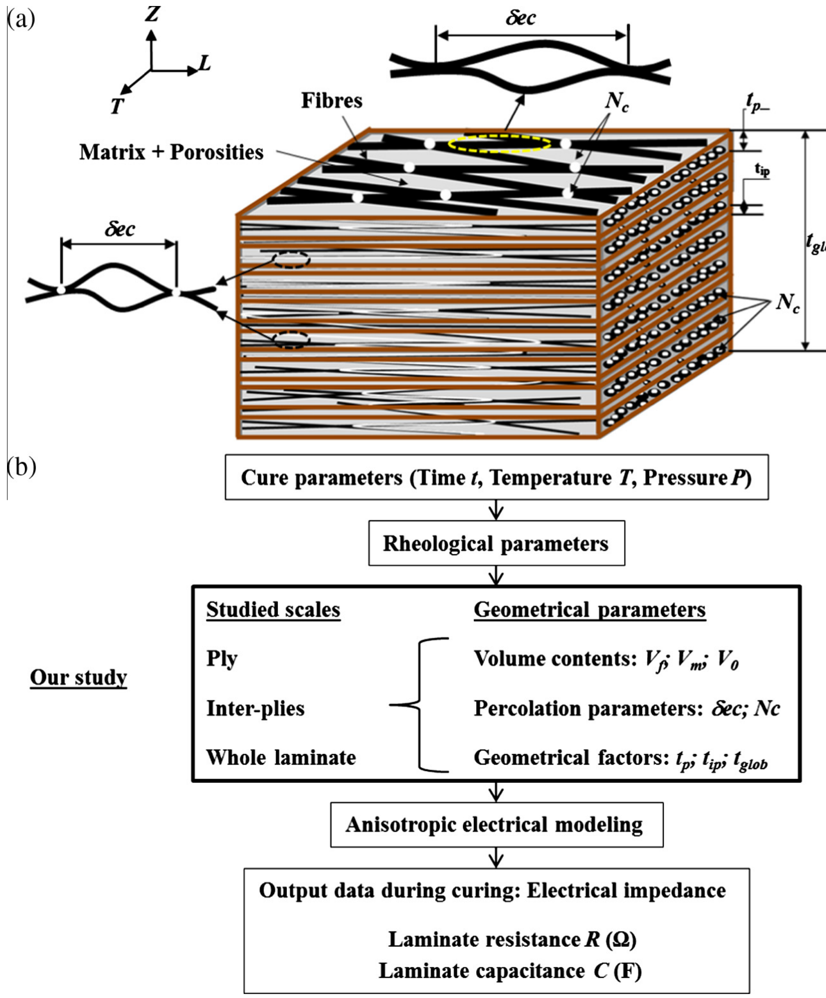

Fig. 1. Schematic model of carbon percolation-network due to fibre contacts in the transverse and the thickness directions of UD laminate (a) electrical modelling diagram during curing (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The present work is the starting point of an out-of-autoclave (OOA) curing wider study carried out in our laboratory with various aims not necessarily devoted to electrical ends.

This paper is organized as follows. In Section 2, a state of the art is proposed to highlight the originality of our work. The experimental approach developed to define the geometrical parameters is exposed in Section 3. Then, two kinds of microstructural analyses are described (with automatic and manual approaches). In Section 4, a final analysis is proposed not only to link the results obtained to the different curing steps, but also to highlight potential laws that will be used in a future electrical model during curing. In Section 5, main results are summarized, some conclusions are drawn and some perspectives given.

2. State of the art

The purpose of our work is to link the changes in laminates geometry and physical characteristics (such as fibre volume fraction and void content) during their curing to their electrical behaviour and to understand the relationships between geometry, physical parameters and electrical current pathways.

Consequently our bibliographical study focused onto two distinct topics: (i) electrical behaviour of carbon/polymeric laminates, (ii) changes in carbon/polymeric laminates (obtained from prepregs) geometry and physical characteristics as functions of curing parameters. A quick overview is also given about in-situ cure monitoring methods.

The well-documented literature shows that impressive efforts have been made to propose in situ cure monitoring methods such as: dielectric measurements (essentially applied to GFRP) [1,2], ultrasonic methods [3,4], measurements of composite electrical resistivity [5,6] and use of optical fibres Bragg gratings (FBG) [7,8]. Concerning modelling of electrical behaviour of CFRP composites and the determination of current pathways through the laminates, main Refs. [9–11] have shown that authors never tried to link the parameters of their modelling to the manufacturing conditions. Furthermore even if published works concern carbon/epoxy laminates manufactured from U.D. prepreg plies, none of them has studied the case of laminates with unreinforced matrix interlayers. It is clear – in carbon/epoxy laminates – that electrical current is conducted by carbon fibres and that unreinforced polymeric interlayers will behave as electrically insulating plies. This is why it is important to pay attention to potential changes in the geometry of these interlayers while laminates are cured.

Several experimental and/or theoretical studies were carried-out upon the changes undergone by the fibre volume fraction, the thickness (laminate, plies), the void content and the permeability of composite parts made from prepreg plies during curing. Numerous methods and modelling efforts were made to propose analytical solutions enabling changes in volume ratios of the composite during curing to be predicted. Gutowski and Morigaki [12]