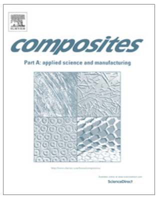
Composites: Part A 78 (2015) 211–222

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa



Thermomechanical analysis, modelling and simulation of the forming of pre-impregnated thermoplastics composites

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ARTICLE INFO

Article history:
Received 24 January 2015
Received in revised form 9 July 2015
Accepted 15 August 2015
Available online 22 August 2015

Keywords:
B. Thermomechanical
C. Computational modelling
D. Mechanical testing
E. Forming

ABSTRACT

In this paper, the viscoelastic behaviours of pre-impregnated (prepreg) thermoplastic composites are analysed using the bias-extension test. A new constitutive model is proposed in order to simulate the forming of thermoplastic composite prepregs at the macroscopic scale. The model is based on a continuous approach. Hyperelastic behaviours are associated with dry reinforcements. Four principal deformation modes, all considered independent, define the hyperelastic potential: the elongation in warp direction, the elongation in weft direction, the in-plane shear strain and the bending contribution. Experience shows that viscoelastic behaviour is mainly associated with the in-plane shear deformation. A non-linear visco-hyperelastic model based on the generalisation of Maxwell rheological model is considered for this type of deformation mode. The finite element simulation of a stamping case using this model is introduced. The influence of temperature on the forming stage and the performance of the model are evaluated.

1. Introduction

Pre-impregnated thermoplastic and thermoset composites are widely used in the aerospace industry for their excellent mechanical properties, impact resistance and fatigue strength all at lower density than other common materials. However, thermoplastic composites have several advantages over thermosets; they have shorter thermoforming cycles during manufacturing than autoclave composites, higher ductility and impact resistance, as well as the capacity to be recycled. These differences make pre-impregnated thermoplastic composites an ideal material for mass production of high quality structures.

In recent years, the automotive industry has shown increasing interest in the manufacturing processes of thermoplastic–matrix composites materials [1–3], especially, in thermoforming and thermoforming-stamping techniques for their rapid cycle times and the possible use of pre-existing equipment. Both techniques can be easily automated and are based on the same technology as metal sheet shaping.

An important step in the prediction of the mechanical properties and technical feasibility of parts with complex geometry is the use of modelling and numerical simulations of these forming processes which can also be capitalised to optimise manufacturing practices [4–7]. Different families of modelling approaches have been developed to describe the forming of pre-impregnated composite materials and can be classified as: kinematical, discrete and continuous approaches. The kinematical approaches [8,9] are mapping algorithms where the lengths of the yarn stay constant and the rotation between the warp and weft directions is free at each intersection. The mechanical properties of the material were omitted in the calculations resulting in efficient numerical methods in terms of computational time but giving purely geometric results depending on the manufacturing tools. Discrete approaches generally consider the scale of the yarns in order to maintain a reasonable computing time. Tows are usually modelled by elastic bars and the non-linear shear behaviour can be done by addition of diagonal elastic–viscoelastic truss elements [10] or by membrane elements [11].

In continuous models, the prepreg is considered as a homogenised continuous material and can be discretized by shell or membrane elements. These are by far the most widely studied approaches. One of the first continuum models for a prepreg's forming was proposed by Rogers [12] based on Spencer's work on anisotropic materials [13,14] and subsequently extended by Johnson [15]. In this model, the unidirectional, or bidirectional, fibres are assumed inextensible and the prepreg is considered as an idealised fibre-reinforced model. It has been the subject of several works [16–21]. However, the inextensibility constraint of

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http://dx.doi.org/10.1016/j.compositesa.2015.08.017
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this model can lead to numerical difficulties when implementing in a FE code [22]. In recent years, several models based on the modification of this theory have been proposed avoiding its shortcomings and implementing more sophisticated methods by considering the microstructure of the composites like homogenisation [23–25] and energy summation techniques [26,27].

This work offers a different approach to the simulation of thermoplastic prepreg composites forming based on the finite strain viscoelastic model initially proposed by Simo [28]. The proposed model is based on convolution integrals [29,30] defined under the principles of irreversible thermodynamics and within a hyperelastic framework. It is based on physical invariants that represents the major deformation modes of shells made of composite prepreg: the elongation in the warp and weft directions, the in-plane shear strain and the bending deformation. Consequently the corresponding strain energy potentials which are assumed to be uncoupled can be identified by classical tests on textile composite shells (such as tension, in plane-shear and bending tests). The viscoelasticity is introduced exclusively for the shearing mode. Tensile deformation mainly concerns the fibres that are not viscous and bending viscosity stiffness is assumed to be of secondary importance.

In the first part, an experimental campaign was carried out in order to investigate the in-plane shear behaviour of fibre-glass/polyamide-6.6 prepregs. Secondly, an anisotropic visco-hyperelastic model for thermoplastic prepregs is suggested below. Third, this model is subsequently introduced into a finite element code and certain thermoforming simulations are performed and presented to evaluate the physical mechanisms involved in the process.

2. Experimental procedure

2.1. Material

The material used in the presented paper is a commercially available pre-consolidated plate provided by Solvay. The plate is made up of five 8-Harness Satin glass/PA66 thermoplastic prepregs as shown in the microtomography picture (Fig. 1). The main characteristics of the composite are listed in Table 1.

Thermal proprieties measurements of the polymeric matrix (PA66) were preformed and are provided in Fig. 2. Classic DMA analysis measures the mechanical proprieties of materials below the melting temperature, as is shown in the DSC analysis, the melting temperature of PA66 is 262 °C (Fig. 2a). The model proposed herein describes de mechanical behaviour of prepreg composites in molten state.

2.2. In-plane shear behaviour

In-plane shear is the most important mechanism of deformation of a reinforcement [31]. Indeed, due to its low shear stiffness compared to its high rigidity in the fibre's direction, the reinforcement can sustain large deformations and take-on complex shapes around non-developable surfaces. The study and characterisation of this deformation mode is therefore essential to develop a constitutive model.

Table 1
Main material properties.

Fabric ID	Evolite®
Matrix	PA66
Fibres	Glass
Fabric wave	8-Harness Satin
Fibre volume (%)	48
Void content (%)	<0.2
Areal density ($g\,m^{-2}$)	546
Thickness (mm)	2

The experimental analysis of in-plane shear behaviour in thermoplastic prepreg is based on bias-extension tests over a range of processing temperatures.

2.3. Bias extension test

The bias-extension test [32–34] is performed on a rectangular specimen where the fibres in warp and weft directions are initially oriented at ±45° from the load direction (Fig. 3a). When the specimen is stretched, the fibrous and woven nature of the specimen leads to zones with three different deformed states: A, B and C (Fig. 3b): In zone A there is no deformation ($\gamma = 0$), in zone C the stretching leads to a pure shear deformation ($\gamma = \pi - \alpha$) and in zone B the stretching of the specimen leads to a semi-shear deformation, the angle in this zone is assumed to be half that in region C ($\gamma/2$).

Assuming the non-sliding at crossovers and the inextensibility of the fibres, the theoretical shear angle γ as a function of fabric size and the current displacement d is given by:

$$\gamma = \frac{\pi}{2} - 2 \cdot \cos^{-1}\left(\frac{D+d}{\sqrt{2} \cdot D}\right) \tag{1}$$

where $D = L - l$, L and l are the initial height and width of the specimen, respectively. In order for the three different deformation states can exist, the height of the material specimen must be at least twice its width. This theoretical behaviour is verified as long as the deformation mechanisms, such as intra-ply slip, are insignificant compared with the shear mode deformation [27].

The clamping force F can be related to the shear force F_{sh} by assuming that the power made through the external force is dissipated in two zones, zone B and zone C. Eq. (2) gives its analytical expression for a given shear angle [33,35]

$$F_{sh}(\gamma) = \frac{1}{(2D-l)\cos(\gamma)}\left(\frac{FD}{l}\left(\cos\left(\frac{\gamma}{2}\right) - \sin\left(\frac{\gamma}{2}\right)\right) - l\cos\left(\frac{\gamma}{2}\right)F_{sh}\left(\frac{\gamma}{2}\right)\right) \tag{2}$$

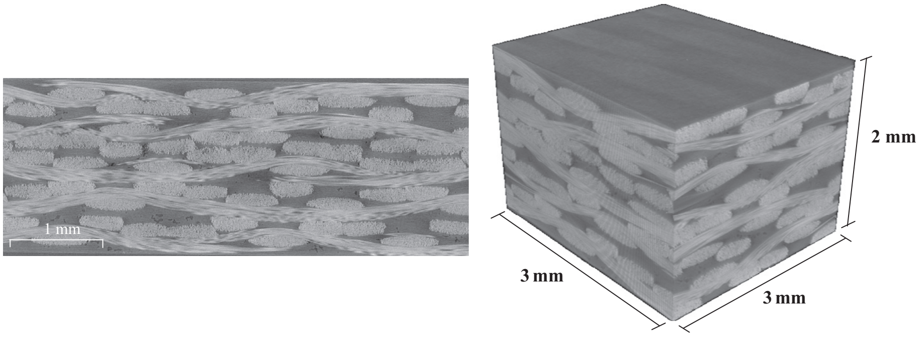

Fig. 1. Micro computed tomography (µCT) of the pre-consolidated material (8-Harness satin weave fibre-glass/PA66) at the initial state.