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Analysis of the thermomechanical shear behaviour of woven-reinforced thermoplastic-matrix composites during forming

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ABSTRACT

Shear behaviour of a glass fibre/polypropylene composite is characterized over a wide range of strain rates and forming temperatures using the bias extension test. A temperature- and rate-dependent material model is here introduced to describe the observed behaviour. The model is based on a continuous approach and formulated considering a stress objective derivative based on the warp and weft yarns rotation. The effects of temperature and strain rate on the shear behaviour are analysed via bias extension test simulations. Temperature change in the sheet during forming was measured. This data is used to model cooling during forming. Isothermal and transient forming simulations were performed in order to show the effects of temperature and forming speed on the obtained shear angle distribution. It was found that at low forming speeds the assumption of isothermal forming is not valid anymore since the cooling of the sheet affects the shear behaviour.

1. Introduction

Interest in woven-reinforced thermoplastic-matrix composites has grown over the last years due to their faster, and hence cost effective and function integrated, processing possibilities in comparison with traditional thermoset-matrix composites [1]. Textiles pre-impregnated with thermoplastic resins can be heated above the matrix melting point in a matter of seconds using infrared heaters and formed into a three-dimensional (3D) component, involving significantly shorter cycle times than autoclave processing or resin transfer moulding techniques [2,3]. Advanced manufacturing techniques such as local reinforcement via tape placement [4,5] are also facilitated due to the presence of the thermoplastic matrix. Enhanced performance, shorter cycle times and low density are some characteristics which made woven thermoplastic composites attractive to aerospace and automotive industries [6].

Accompanying the industrial development of specific thermoforming processes, numerical efforts started to be made in order to accurately simulate the stamping/forming of these materials. Kinematic approaches were firstly proposed but they proved to be limited when evaluating complex unsymmetrical geometries and/or different holder systems since no forces are taken into account [7]. Mesoscopic approaches to model the behaviour of the reinforcement during forming have been also explored [6,8,9]. However, continuous approaches constitute unequivocally what has been the most explored field [7,10–15]. In this kind of models, the composite is considered as a continuous medium and is modelled using standard shell or membrane (if bending stiffness is neglected) finite elements.

Mechanical behaviour of woven composite sheets is in principle dictated by its biaxial tensile [1,16], bending [17,18], and in-plane shear [19–26] properties. Tensile strains in fibre direction are usually very low due to the high stiffness of the fibres [10,27,28]. Bending behaviour becomes relevant if the size and shape of potential wrinkles is of interest [29–31]. Nevertheless, the onset of wrinkling is related to achieving a critical shear angle [32]. In this way, in-plane shear behaviour is probably the most relevant deformation mode due to the large rotations experimented by the warp and weft yarns during forming. Fibre reorientation during forming determines the final mechanical properties of the component and is therefore very important information for design engineers.

The principal objective of this article is to characterize the shear behaviour of a glass fibre/polypropylene composite and its dependence with the strain rate and temperature. Due to the viscous nat-

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ure of the thermoplastic matrix, stresses in the material depend on the loading rate [33] and an accurate constitutive description should take this fact into account. Additionally, temperature dependence started lately to be considered [3,34,35] because the temperature might not be uniform in the component when forming takes place. Another fact which evidences the need for temperature-dependent models is that very low forming speeds can lead to a transient thermal state, modifying in consequence the material mechanical response. Many authors neglect this [7,30,34] since forming stage is usually short although significant drops in temperature during forming have been already reported [30]. Material manufacturers recommend press speeds of approximately 50 mm/s which should be reduced to 5 mm/s during the last part (approximately 10 mm) of the forming [36]. Depending on the particular forming conditions, the isothermal forming assumption might not be valid.

This paper starts with a mechanical characterization of the in-plane shear behaviour of a roving glass fibre/polypropylene composite covering a wide range of forming temperature from 180 °C (453 K) to 220 °C (493 K) and three different crosshead speeds. In the subsequent section, the phenomenological rate-dependent model proposed in [33] is extended introducing temperature dependence. Following this, a series of bias extension test simulations is presented to clarify the effect of strain rate and temperature on the shear behaviour. Temperature evolution during forming is then evaluated and real convection and conduction conditions are quantified. Finally, the implemented thermomechanical model is used to perform isothermal and transient simulation in order to show how the forming speed affects the shear behaviour of the composite not only due to its inherent rate dependent behaviour but also due to temperature changes in the forming blank.

2. Shear characterization using bias extension test

The bias extension test [3,24,25,35,37] has become a very popular technique to characterize shear behaviour of dry woven and woven composites. It basically consists of applying an axial displacement on a specimen with a ±45° fibre orientation with respect to the load direction and aspect ratio larger than two. Due to the woven nature of these composites, three regions with different deformation can be identified; indicated as A, B, and C in Fig. 1. The main objective of the test is to obtain a pure shear state on region C.

2.1. Material

The material studied in this work was a roving glass fibre/polypropylene (PP) consolidated composite, commercially identified as Tepex® dynalite 104-RG600(1) 47%. Table 1 summarizes its main characteristics. A single ply was analysed in order to avoid inter-ply effects.

A simple thermal characterization was performed via DSC analysis at 10 °C/min. Melting temperature of PP was registered at 165 °C as shown in Fig. 2. Crystallization temperature, also shown in Fig. 2 as the peak of the cooling curve, is 124 °C. Melting and crystallization temperatures strongly depend on the heating/cooling rate [38], amongst many other factors. An increase of the shear stiffness while the material cools and its temperature approaches the crystallization temperature is expected. In order to consider such effect bias extension test between 180 °C and 220 °C were carried out. Recommended forming temperatures [36] and test temperatures are also indicated in Fig. 2.

Specimens were cut out of plates employing a StepFour Xpert 1800P CNC milling machine. Specimens dimension were $h = 250$ mm and $w = 100$ mm, where h and w are width and height as shown in Fig. 1.

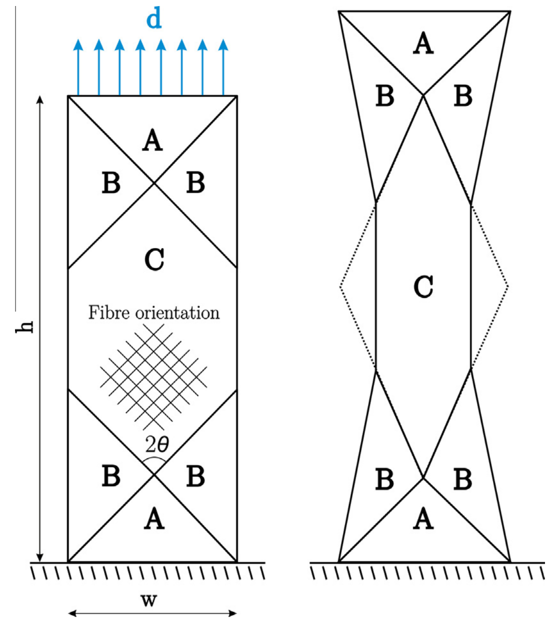

Fig. 1. Initial (left) and deformed (right) specimen in a bias extension test.

Table 1
Material properties of studied prepreg.

Reinforcement	Fibre	Roving glass
	Fabric	Twill 2/2
	Area weight (g/m^2)	600
	Yarn (tex)	1200
Matrix	Polymer	Polypropylene (PP)
Laminate	Density (g/cm^3)	1.68
	Fibre content (vol%)	47
	Thickness per layer (mm)	0.5

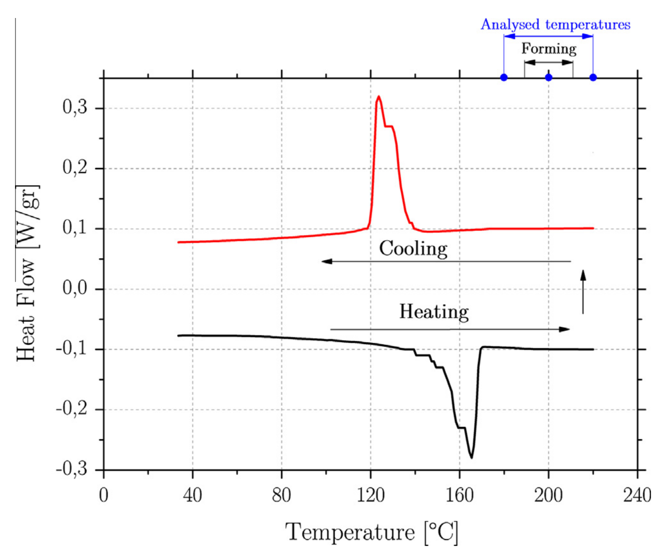

Fig. 2. Differential scanning calorimetry of studied composite. Heating rate: 10 K/min.

2.2. Experimental set-up and conditions

A servo-hydraulic MTS 852 Damper Test System (MTS, Minneapolis, USA) was employed to perform the bias extension tests.