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Press forming a 0/90 cross-ply advanced thermoplastic composite using the double-dome benchmark geometry

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ABSTRACT

A pre-consolidated thermoplastic advanced composite cross-ply sheet comprised of two uniaxial plies orientated at 0/90° has been thermoformed using tooling based on the double-dome bench-mark geometry. Mitigation of wrinkling was achieved using springs to apply tension to the forming sheet rather than using a friction-based blank-holder. The shear angle across the surface of the formed geometry has been measured and compared with data collected previously from experiments on woven engineering fabrics. The shear behaviour of the material has been characterised as a function of rate and temperature using the picture frame shear test technique. Multi-scale modelling predictions of the material's shear behaviour have been incorporated in finite element forming predictions; the latter are compared against the experimental results.

1. Introduction

Thermoforming of biaxial cross-ply laminates is potentially a fast and low-cost production technology for the manufacture of high quality advanced composite components. Above the matrix melt temperature, inter-ply sliding in these materials is restricted only by the limited adhesion provided by the molten matrix layer connecting the two plies. Thus, a priori, it might be assumed that the deformation modes of such a material would be less constrained than for woven or stitched fabrics. For the latter, inter-ply sliding has recently been shown to be a significant mode of deformation during the forming process [1]. This investigation therefore aims to answer the following questions regarding the thermoforming behaviour of biaxial cross-ply laminates when formed over doubly-curved geometries:

- Do they have enough integrity to hold together?
- Does their deformation conform closely to ideal trellis shear kinematics or is inter-ply slip significant?
- Can an existing rate-dependent constitutive model [2], originally developed for 2-D viscous textile composites, provide an accurate prediction of their thermoforming behaviour?

In addition to examining the thermoforming of cross-ply laminates, a further goal of this work is to explore the influence of a wrinkling-mitigation technique currently used in industry yet rarely used in experiments or modelled in the literature [3,4], namely, the use of springs, rather than a blank-holder to induce in-plane tension in the forming sheet.

The double-dome benchmark geometry [5] is a reasonably complex shape, of industrial origin, consisting of both doubly curved surfaces and also flat surfaces from which test coupons can be cut. Engineering fabrics, including shear rate-independent glass fabric at room temperature [7–9] and shear rate-dependent comingled fabric at high temperature [6,10] have already been formed using this geometry and the accuracy of several biaxial constitutive models in simulating these experiments has been evaluated [6–12]. Sensitivity studies by Willems [6,10,11] revealed that shear angle predictions are relatively insensitive to the form of the material's shear force versus shear angle curve, while tensile properties, friction and boundary conditions applied to the perimeter of the forming blank are more significant. Many of the mechanical models examined so far have provided good predictions for woven engineering fabrics formed over the double-dome geometry. An important goal of this study is to show how by changing material and boundary conditions in ways that are relevant to industrial manufacturing processes, the double dome benchmark geometry can be used to explore the influence of such changes and to evaluate the utility of current simulation techniques and models in accounting for them.

2. Material

Pre-consolidated uniaxial cross-ply sheet, approximately 0.7 mm thick, comprised of two layers of unidirectional glass-poly-

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propylene (PP) plies, with a 0/90 initial fibre orientation has been used. The composite consists of a PP homo-polymer matrix containing 60% volume fraction E-glass fibres (two consolidated layers of Polystrand ThermoPro Standard 60% 10 series, as supplied by the manufacturer, Polystrand® [13]).

3. Experimental set-up for high temperature press-forming of double-dome

The double-dome bench mark geometry has been manufactured at INEGI as a set of matched male and female steel tools (see Fig. 1). The experimental set-up used here is close to that of the benchmark set-up, though certain features have been changed to facilitate forming at high temperature. In particular, the blank-holder boundary conditions and the initial blank shape have been modified (see Section 3.3).

3.1. Manufacture of double dome tooling

The CAD models for the double-dome were downloaded from [5]. The models were exported from Solidworks to CAM software (PowerMILL, Delcam) and machining was performed on a 5-axis CNC machine (Fadal, VMC 4020). The tools were fitted with heating cartridges in top and bottom tools with cooling facility in just the bottom tool, though in this investigation room temperature tooling was used in all tests.

3.2. Heating and transfer system

In order to form the pre-consolidated uniaxial cross-ply sheet the polymer matrix had to be heated to above its melt-temperature and quickly transferred to the press for forming. An open-sided radiant heater oven (see Fig. 2) was designed together with a compressed-air driven shuttle system, to enable fast transfer from oven to press. The heater contained eight 1 kW radiant heating lamps (Elstein, FSR 1000–230 V), situated inside the top and bottom of the oven (Fig. 2a) and the blank sheet was automatically positioned between the two heaters using a blank-holder frame and shuttle rails (see Fig. 2b).

After various experiments, the most controllable method of heating the sheet was found to involve pre-heating the oven to a set temperature with a metal partition sheet separating the top and bottom halves of the oven. Equilibrium was achieved in both regions after approximately 5–10 min. The heaters were switched off before removing the metal partition sheet and the composite blank was inserted. A 260 °C pre-heat temperature produced the heating profile within the blank shown in Fig. 3a (measured using a specially designed temperature probe involving a thermocouple sandwiched inside 2 uniaxial consolidated sheets). The blank was removed from the oven after 100 s, when the rate of change of temperature of the blank was lowest (see Fig. 3a). This enabled better control of the blank temperature prior to forming. The subsequent cooling rate (see Fig. 3b) of the blank when removed from the oven was measured as approximately linear at $-2.96 \pm 0.31\ ^{\circ}C\ s^{-1}$ (error indicated using standard deviation). The average shuttle transfer time was measured at 0.73 ± 0.06 s. The average press closure time was measured at $2.68s \pm 0.19$ s. Thus, the total time from removing the sheet from the oven to press closure was about 3.4 ± 0.25 s corresponding to an approximate temperature decrease of about 10 °C. Four experiments were conducted using an oven temperature set to 260 °C, this provided an initial blank temperature of around 200–225 °C before leaving the oven (see Fig. 3a) and an estimated blank forming temperature of between 190 and 215 °C. One further experiment was conducted using an oven temperature set to 270 °C and an estimated blank forming temperature of between 200 and 225 °C. The oven temperature and fibre orientation for these experiments is given in Cases 1–5 of Table 1.

3.3. Blank-holder system, blank shape and spring stiffness

The original set-up for the bench-mark experiment involves an arrangement in which the blank is constrained using a normal pressure applied to its surface using a segmented blank holder, as described in [6,7]. The set-up is difficult to use at high temperatures due to the need to heat the entire pre-consolidated thermoplastic blank prior to forming [6]. Also as the tribology of molten advanced composite laminates is complex, accurately modelling the friction condition within the blank-holder is not straightforward. The slip behaviour involves both static and dynamic frictions both of which are rate, temperature and pressure dependent [14,15]. These practical problems and complexity of the friction condition can be avoided, at least under the blank-holder, using an alternative technique; applying tension via springs and clips, see Fig. 4a. This technique is of further interest as it is currently employed in industry due to its simplicity and flexibility. Following preliminary forming trials (see, for example, Fig. 4a), the blank shape had to be modified from the bench-mark prescribed geometry of 270 × 470 mm [e.g. 7] for two reasons: (i) During forming of the sheet, clips attached to the blank are drawn towards the tool-

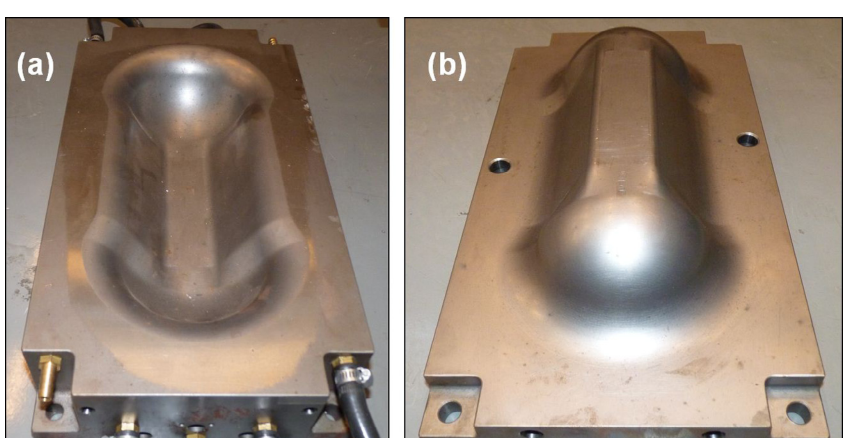

Fig. 1. Tooling based on CAD model from [5]: (a) female die, (b) male punch.