Composites: Part A 68 (2015) 251–263

Contents lists available at ScienceDirect

Composites: Part A

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

Induced forming modes in a pre-consolidated woven polypropylene composite during stretch forming process at room temperature: I. Experimental studies

N.A. Zanjani *, A. Sexton, S. Kalyanasundaram

Research School of Engineering, ANU College of Engineering and Computer Science, Australian National University, 31 North Road, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 17 July 2014
Received in revised form 2 September 2014
Accepted 28 September 2014
Available online 13 October 2014

Keywords:
A. Fabrics/Textiles
A. Thermoplastic resin
B. Strength
E. Forming

ABSTRACT

In the current study, rectangular specimens of pre-consolidated woven Self-Reinforced Polypropylene (SRPP) possessing different fibre orientations and aspect ratios were stretch formed in an open die. Induced displacements were recorded by an in-situ 3D photogrammetric measurement system. Resultant principal strains were investigated to clarify the role of different deformation modes during stamp forming. The dependency of induced deformation modes to the specimens' geometries was studied. A novel path/deformation dependent failure criterion was established to distinguish between safe and failed regions of SRPP in a stamping process and to elucidate the dependency between failure and induced forming modes in a woven composite. The experimental results highlighted the suitability of consolidated SRPP to be formed into complex doubly curved geometries by the stamp forming process at room temperature. It was found that required forming depths could be achieved if a proper combination of specimen size, boundary condition, and fibre orientation was selected.

1. Introduction

In last few decades, shortage of fossil fuel resources, global warming and air pollution have raised worldwide concerns toward excessive energy consumption and its inevitable environmental impacts. According to statistics published by IEA (International Energy Agency) in 2012 [1], the transport industry is responsible for 22% of the total CO_2 emissions worldwide. To address this issue, European Union set mandatory regulations on car manufacturers to reduce CO_2 emissions of automobiles produced after 2015 [2] or they will be penalised for excess emissions. Results of analyses conducted by IFEU (Institute of Energy and Environmental Research) [3] revealed that every 100 kg reduction in the mass of automobiles results in a decrease of 2.2 t in CO_2 emission and 300–800 litre savings in fuel consumption over the lifespan of a vehicle. This provides sufficient incentives for car manufacturers to reduce the weight of their products to reach mandatory targets.

Woven Self-Reinforced Polypropylene (SRPP) composite, manufactured from polypropylene both as the matrix and reinforcements, offers a wide range of superior properties over monolithic materials and conventional fibrous composites. Thermoplastic polymers offer recyclability characteristics due to ability to be re-moulded and re-shaped after being initially consolidated. Polypropylene, as a typical thermoplastic polymer, offers low fabrications costs, environmental stability and ease of processing [4]. SRPP, constituted from highly drawn polypropylene fibres, benefits from a broad range of attractive properties including light weight, relatively high mechanical strength compared to plain polymers [5] and enhanced energy absorption characteristics. These properties make SRPP an attractive candidate to metals in applications where a combination of structural strength and reduced weight is necessitated. Woven SRPP possesses other attractive properties including higher modulus than polypropylene, internal integrity, balanced in-plane thermomechanical properties and enhanced resistance to crack propagation [6].

Currently, composites are manufactured via time-consuming, complex methods, such as hand lay-up and moulding techniques. High costs associated with these techniques and their incompatibility to current manufacturing procedures in major industries has hitherto restricted their applications to a few limited industries such as aerospace. Benefitting from composites in a broader range of applications is viable only if they are produced via a more effective technique capable of addressing high volume production rates. Stamp forming, as a rapid manufacturing technique, has been extensively applied and studied on prepreg woven composites [7–16]. The procedure includes forming of already impregnated woven fabrics into the desired geometry by a punch (draping)

* Corresponding author. Tel.: +61 (2)61258546.
E-mail address: nima.akhavan@anu.edu.au (N.A. Zanjani).

http://dx.doi.org/10.1016/j.compositesa.2014.09.023
1359-835X/

whilst sufficient pressure and temperature is applied. However, some issues can arise from excessive distortion and re-orientation of the material during forming due to the very low stiffness of the fabric. This can result in reduced mechanical properties of final products. Inefficiencies of current failure criteria in predicting safe deformation margins of a woven composite is another obstacle to be overcome if wide spread applicability of stamping on composites is desiderated.

To attain low manufacturing cycle times for components made of woven SRPP and to obtain cost-effective products, stamp forming of pre-consolidated composites seems propitious. Several studies have been previously conducted in this area [17–25]. The present study investigates the stretch forming behaviour of pre-consolidated sheets of woven SRPP at room temperature. The current research, inspired from sheet metal industry, aims at presenting a reliable measure to predict failure in woven composites during stamping procedure. This was accomplished by constructing a Forming Limit Curve (FLC), employed extensively in metal forming, based on induced strains in different specimens in the last stage of deformation. The novelty of this approach is demonstrated through predicting failure in composites by a combination of a history dependent failure criterion with induced deformation modes introduced by the ratio of two principal strains. This enabled us to establish an independent set of failure criterion for SRPP composite in particular regions of strain space each representing a different deformation mode. This methodology is analogous to employ an interactive failure criterion to predict failure in composites without imposing restrictions of a constant term on the right hand side of the equation.

This approach offers both simplicity of using an independent failure criterion and precision of considering strain history in the current mechanical state of the composite. Furthermore, the accuracy of predicting failure in a woven SRPP composite, during a typical forming exercise, increases considerably. This is due to the fact that the current failure criterion is established based on the outcomes of an extensive forming practice on the composite rather than simple uniaxial and biaxial characterization tests. Furthermore, outcomes of the current study highlighted substantial differences between stamp forming behaviour of metals and pre-consolidated woven SRPP at room temperature. The current study is the very first of its kind to investigate stretch forming of a pre-consolidated SRPP and to predict failure in a woven composite through an evolving Forming Limit Diagram (FLD).

2. Experimental procedures

2.1. Material

Specimens were made of balanced multilayered 2/2 twill weave SRPP having 0.9 g cm-3 volumetric density manufactured by Propex Fabrics GmbH (Germany) (Fig. 1). The material was produced via a hot compaction technique, originally developed at Leeds University. The fibre volume fraction of SRPP was 55% according to manufacturer's datasheet [26]. Some basic mechanical properties of SRPP composite are provided in Table 2.

2.2. Specimens geometry

The specimens were consisted of rectangular cut-outs from a 200 mm diameter circle. The width of the samples varied from 12.5 mm to 200 mm (Table 1). In Table 1, **Re** indicates Rectangular shape of the specimen, as opposed to the specimen possessing an hour-glass geometry commonly used in stretch forming of metallic samples. The number after **Re** indicates the sequence by which the specimen was used in stamp forming experiment and **W** indicates the width of the specimen. Thickness of all samples was 1 mm. To elucidate different forming behaviour in stretch forming, each specimen was employed with two different fibre orientations. Specimens possessing [0°, 90°] fibre orientation were used to reveal forming behaviour ranging from uniaxial extension to biaxial stretch. To reveal intra-ply shear behaviour of SRPP, samples possessing [45°, 45°] fibre orientations were stretch formed. To investigate failure in SRPP, two concepts extensively employed in metal fabrication was applied: The Forming Limit Diagram and the Forming Limit Curve. The Forming Limit Diagram (FLD) is a graphical representation of strain state at different material points determined by induced minor and major strains. The FLD could be constructed at any single deformation stage and therefore it demonstrates an evolving behaviour due to the evolution of the material's strain state during a forming process. The FLD is used to investigate induced deformation modes in different regions of specimens and to evaluate the contribution of different strain states in a typical deformation practice. To determine safe and failed deformation margins of SRPP, a Forming Limit Curve (FLC) was employed. A FLC is a curve tangent to the FLD at the last stage of deformation and is obtained via forming specimens beyond their failure limits. This curve distinguishes between failed and safe deformation margins of a typical material during any forming practice.

Incorporated failure modes in a forming exercise are depicted by a strain ratio parameter (SR or β = minor strain/major strain). Each deformation mode is characterised by a constant value

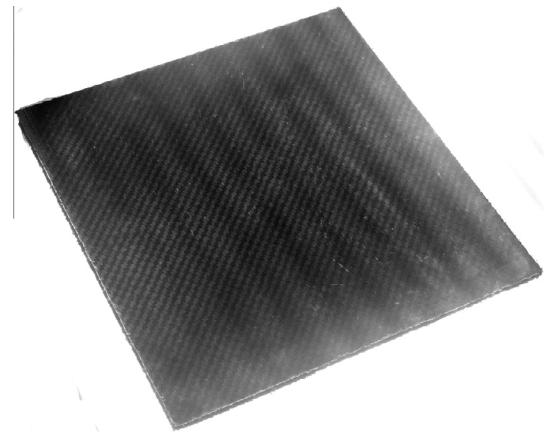

Fig. 1. A sheet of SRPP composite.

Table 1
Specimens employed in the study.

Sample	W (mm)	Sample	W (mm)
Re1W12.5	12.5	Re5W100	100
Re2W25	25	Re6W125	125
Re3W50	50	Re7W150	150
Re4W75	75	Re8W200	200

Table 2
Mechanical properties of SRPP composite.

Technical properties	Test method	Value	Unit
Density	ISO 1183	0.92	g/cm^3
Initial tensile modulus	DIN EN ISO 527	4200	N/mm^2
Tensile strength	DIN EN ISO 527	120	N/mm^2
Tensile strain to failure	DIN EN ISO 527	20	%
Flexural modulus	DIN EN ISO 178	3500	N/mm^2
Compression strength	EN ISO 604	300	Mpa
Tensile impact strength	EN ISO 8256	1000	kJ/m^2