A New Testing Method for Implementing Diaphragm Pre-Tensioning in Double Diaphragm Forming

A. Tabatabaeian[1,2a], K. Ambuehl[1] and P. Harrison[1]

[1] James Watt School of Engineering, University of Glasgow, UK, [2] Department of Aeronautical and Automotive Engineering, Loughborough University, UK

[a] A.Tabatabaeian@lboro.ac.uk

Abstract. Double diaphragm forming (DDF) is a manufacturing process capable of shaping multi-layer blanks, with strong potential for low-cost, high-volume production applications. In this process, material layers are compressed between two flexible diaphragms and then deep drawn under hydrostatic or mechanical pressure to achieve the desired shape. However, forming multi-axial engineering fabric preforms and pre-consolidated thermoplastic blanks into complex geometries using DDF remains a significant challenge. This is primarily due to the occurrence of defects such as wrinkling, which compromise both the structural integrity and surface quality of the final components. This study introduces a novel DDF testing technique in which equi-biaxial strain is applied prior to the forming stage (referred to as pre-stretch). The proposed approach is shown to effectively eliminate wrinkling during forming. The technique is validated through both experimental investigations and numerical simulations.

Introduction

Wrinkling is a critical defect in fibre reinforced polymer (FRP) composites. Even moderate wrinkles can reduce compressive strength by 30% to 75%, initiate delamination, and reduce fatigue life by up to 50% [1]. Conventional matched-die forming and blank-holder systems can manage certain lay-ups, such as unidirectional or cross-ply configurations, but despite various methods to impart controlled tension in the forming sheet during forming (e.g. segmented blank holders or springs), these techniques often fail to suppress wrinkles when forming multi-axial lay-ups or complex geometries.
Double diaphragm forming (DDF) was originally proposed and developed in the 1980's to process advanced thermoplastic composites at high temperatures in autoclaves [2]. Lower forming rates, higher forming temperatures, smaller preform size and increased diaphragm stiffness and lower diaphragm compaction pressure have all been shown to alleviate wrinkling to some degree. Modification of **inter-ply friction** (using veils, powders and lubrication) and **diaphragm tensioning** have shown particular promise [3]. Typically, additional diaphragm tension is generated via the use of either a vacuum box or using risers, in both techniques diaphragm tension starts low and gradually increases during the forming process. For example, Chen et al. [4], introduced rigid blocks (risers) into a DDF process to modify the local diaphragm in-plane strain distribution. Their investigation used an optimised riser arrangement, demonstrably improving preform quality via reduction of out-of-plane wrinkles.

This study focuses on one of the two most promising techniques for mitigating wrinkling, diaphragm pre-tensioning [3]. First, a novel design for a traditional blank holder used in DDF, referred to as the no-tension blank holder (NT), is presented. Subsequently, a novel pre-tension (PT) blank holder is developed based on a simple analytical approach that relates its geometric dimensions to the imposed pre-strain. In a preliminary study, an initial PT blank-holder is designed and manufactured to explore the practical limits of diaphragm pre-stretch and its reliability. The results reveal that diaphragm stability is a critical factor in the design process. Consequently, numerical simulations are employed to develop a second (optimised) PT blank holder, which is then used in a fabric forming investigation involving deep-draw experiments on plain-woven glass fabric blanks. These experiments are conducted both with and without diaphragm pre-tension to assess the effects of diaphragm pre-tensioning on wrinkling and fabric cohesion.

Experimental and Numerical Methods and Results

All blank holders are manufactured from aluminium alloy with steel bolts. Silicon rubber O-rings used in the blank holders for clamping and sealing the diaphragms. General-purpose translucent/white silicone rubber sheets were used as diaphragms. Plain-woven glass fabric was used in forming tests. EL2 epoxy resin was used to lubricate the diaphragm/fabric interfaces, and a silicone lubricant spray was used to lubricate the diaphragm/tool interfaces. Fig. 1(a) shows all three manufactured blank holders. Fig. 1(b) shows the ideal diaphragm draw-in process with increasing vacuum within the PT blank holder cavity. Fig. 2 shows experimental stable and unstable vacuum draw-in behaviour when using the initial and the second PT blank holders, respectively. This suggests the importance of geometrical design considerations to avoid instability.

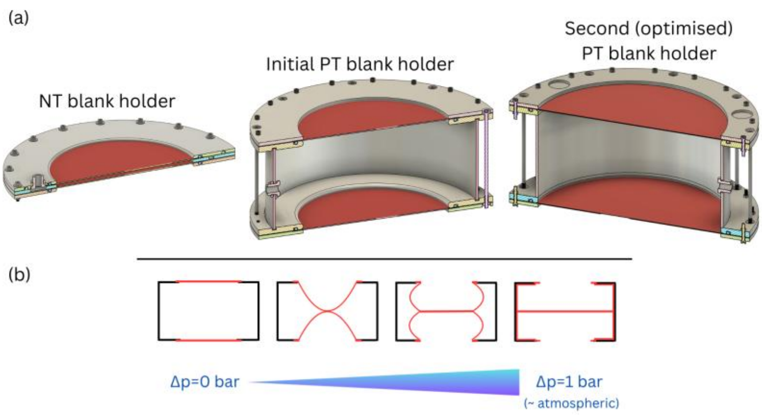

Figure 1: a) The manufactured blank holders, b) the anticipated ideal diaphragm draw-in process with increasing vacuum within the PT blank holder

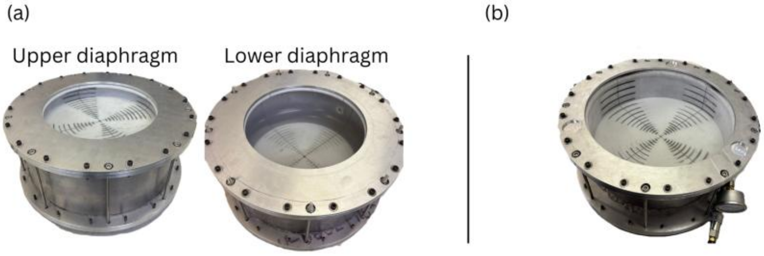

Figure 2: Vacuum draw-in behaviour: a) unstable (initial PT design), b) stable (optimised PT design)

Abaqus/Explicit was used to simulate the vacuum draw-in processes for PT blank holders. The blank holder was modelled as a three-dimensional discrete rigid body and meshed with R3D4 elements. The rubber diaphragms were modelled using reduced-integration shell elements (S4R) with enhanced hourglass control. Each simulation consisted of two steps: gravity and vacuum draw-in. Vacuum pressure was applied by linearly increasing the pressure on the surfaces of the diaphragms over 1s, from 0 to 100 kPa (1 Bar). Contact properties were adopted from the literature. The predicted true strain (LE11) was extracted, converted to engineering strain, and compared with the experimentally measured engineering strain at corresponding points. The numerical simulation confirmed experimental observations; an unstable and a stable draw-in response when using the initial and the optimised PT blank holders, respectively. The optimised PT blank holder and the NT blank holder were then used in a deep draw forming test setup to assess the influence of pre-tensioning on fabric wrinkling. As shown in Fig. 3, the PT blank holder completely eliminated wrinkling.

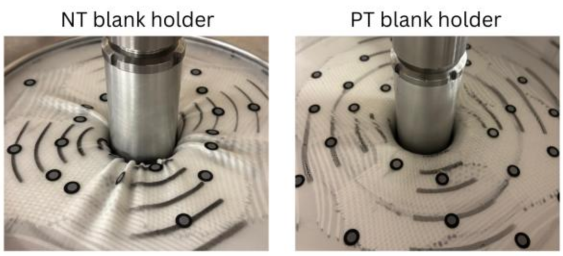

Figure 3: Successful wrinkle mitigation using the optimised PT blank holder

Acknowledgements

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