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High-resolution computed tomography in resin infused woven carbon fibre composites with voids

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Tomographic imaging using both microfocus radiation and synchrotron radiation was performed to assess the void defects in resin transfer moulded woven carbon fibre composites. The focus of this study is on characterising the void homology (e.g. local void size and spatial distribution) in relation to weave orientation, infusion direction and potential effects on damage formation in tensile loading. As the orientation angle between the fibre direction of unidirectional layer in the laminate and the direction of the global resin flow increases, from parallel to perpendicular, larger voids and a greater volume fraction of voids were observed, which led to increased damage formation upon loading. Significant accumulation of voids around both the layer interfaces and yarn fibres were also observed. With regard to yarn design, it is recommended to balance the benefits (e.g. fabric handling, structural integrity of preform) and drawbacks (e.g. lower fibre content, more voids) of the supporting yarn. Also, sensible placement of resin inlets and outlets could reduce the amount of deleterious voids, i.e. by promoting resin flow along the fibre direction in the most defect-sensitive off-axis layers.

1. Introduction

The composites industry has traditionally made high performance primary structural components out of pre-impregnated reinforcements cured in an autoclave oven. The high pressures involved in such processes and the unidirectional fibres in the constituent layers result in high fibre content and minimal void formation. Non-autoclave composite manufacturing processes such as resin transfer moulding (RTM) have lower cycle times, reduced operating costs and require less capital investment. However, RTM results in more voids in the laminate due to entrapment of air bubbles during filling [1,2]. Voids are known to be detrimental to the mechanical performance of the material [3–10]. A deeper understanding of the formation of voids, and their effect on damage and mechanical performance is desirable in the context of improving the performance of RTM and other non-autoclave manufactured components.

The practical importance of voids has prompted research into the mechanisms behind void formation in RTM (see e.g. the review article by Park and Woo [2]). The study of the mechanical entrapment of voids in composites consisting of fibre bundles, such as woven fabrics, usually relates to the formation of intrabundle micro-voids and interbundle macro-voids due to the relative flow velocities of the infusion resin inside and outside the fibre bundles [11]. Higher applied pressures result in faster macro-flow in between the fibre bundles, outpacing the capillary wicking flow into the tightly packed fibre bundles, thus creating entrapment of intrabundle bubbles [12]. The majority of these bubbles remain trapped at the location of formation due to the densely packed fibre architecture [13,14] and eventually diffuse into solution (i.e. Henry's law) as the local pressure rises with the advancing flow [15]. The opposite case occurs with a low applied pressure. As the fluid flow velocity is decreased, the macroscale interbundle primary flow is outpaced eventually by the intrabundle capillary flows. The secondary intrabundle flow seeps into the interbundle gaps at various places ahead of the macro interbundle flow front, thus entrapping relatively large interbundle bubbles [1,16]. These interbundle

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bubbles often escape the laminate by travelling quickly between the bundles to the flow front and bursting into the vacuum at the vent [17]. The chance of these larger bubbles escaping depends on the interbundle gap width, the applied pressure, and the bubble size. As the resin pressure increases with the advancing flow front, the driving pressure behind the bubbles increases, and the size of the bubbles decreases according to both the Ideal Gas Law and Henry's Law until a critical bubble size is reached, allowing escape [15,18,19].

Current attempts are being made to couple void formation and void movement models to be able to predict the final distribution [20,21]. These models would assist in RTM process optimisation for high-performance composites, however, they are limited by (i) the difficulty of measuring *in situ* void formation [22,23], and (ii) the complexity of fluid dynamics modelling for the various flow paths and fibre architectures in industrial RTM processes. Recent work has analysed in-plane flow through fibre bundles arranged at 45° and 90° with respect to the flow [20], and experimental void formation has been reported for biaxial weaves [16,24], although the majority of the relevant literature has considered only unidirectional (UD) fibres parallel to the flow direction. The present study undertakes experimental void characterisation to assist in understanding the flow paths and subsequent void formation in a more complex fabric; a quasi-isotropic layup woven plies.

Previous work has investigated the influence of voids on mechanical properties [3–10], most having focused on prepreg materials. As the microstructure and constituents in composites manufactured with resin infusion processes are usually different from those in autoclave-cured prepregs, the effects of defects on mechanical properties must still be established in RTM composites to pave the way for determining design allowables for the void contents.

Failure mechanisms associated with voids in loading modes such as transverse tensile [8] and multi-axial fatigue, both flexural [4] and in tension [9], have been investigated. The aim of understanding such mechanisms is to allow strategies to suppress damage growth and increase the mechanical performance. Potentially, mechanism-based models could be used to decrease the amount of required testing. Such simulation tools will require an understanding of the effects of void size, shape, location, clustering, and concentration [10,25]. Traditional approaches to quantifying voids are typically limited to the average void volume fraction throughout the entire part. This is a single parameter, which is of limited use in determining local microstructural effects. Unlike prepreg processing [3–7], void concentrations are not homogeneous in resin infusion processes such as RTM due to the pressure gradient resulting from infusion and the often more heterogeneous microstructure of the fibre preforms. The voids are also not homogeneous in size and shape due to the variety of bubble entrapment mechanisms governing void formation [11]. These complications for RTM composites imply a need for characterising the voids at a local level, i.e. allowing for spatial variation.

Conventional measurement techniques are not well-suited for local void characterisation in the composite microstructure. Optical microscopy and combustion/digestion only allow sampling of the voids in small volumes of the part [26]. Optical microscopy is also limited to two-dimensional (2D) planar imaging, which can result in misleading interpretations of void shape, e.g. categorising long cylindrical voids as small ellipses from their cross-sections [11,13]. Combustion or digestion gives only the scalar void fraction, and no information regarding the void size, shape or clustering. Through-thickness optical measurement only works for transparent materials such as composites with glass fibre reinforcement [27]. Ultrasonic C-scan imaging is commonly used for quality control by detecting delamination and large dry spots. It has also been applied to detect general attenuation, which is in turn correlated to the void content, thus providing an estimate of local void concentrations across the entire part surface [4,28]. However, the ultrasonic wavelengths are too large to provide sufficient resolution to determine void size and shape, and may not detect intrabundle micro voids at all [29].

X-ray computed tomography (CT) provides higher resolution than ultrasound, due to higher frequency and the fact that transmission imaging detects density variations whereas reflection imaging (ultrasound) only detects interfaces. Imaging by CT also results in reduced dispersion compared to ultrasound due to using electromagnetic radiation instead of sound waves. A three-dimensional (3D) volume representational image can be constructed from the multiple projected images taken during sample rotation under the X-ray beam. CT imaging of composites has mostly been focused on prepreg materials [30–33]. In prepreg consolidation experiments, long thin cylindrical voids, which are parallel to the fibres have been discovered, showing the improved visualisation abilities compared to 2D through-thickness microscopy which would show any such void as a pinhole [31,32]. CT imaging showed similar long thin voids in material prepared from compression-moulded prepregs [34]. The enhanced ability of 3D volume rendering in CT imaging, to characterise void morphology, compared with 2D microscopy has been illustrated [33]. Unprecedented quantifications of the distribution and size of individual voids have been achieved with CT imaging [33,34]. However, CT-imaging has not been widely used thus far for the void characterisation of resin-infused composite parts, with the exception of the study by Schell et al. [35] that presents 2D scans of infusion-induced voids, and Vila et al. [23] that illustrates *in-situ* voids imaged during the process of infusion in a single fibreglass roving. The greater variation in local void size, shape and clustering makes CT-enabled 3D visualisation of voids even more important in the case of infusion compared to laminated material produced from prepreg. In addition the use of synchrotron radiation computed tomography (SRCT) allows for higher resolution compared to lab-scale micro-focus CT (μCT).

The major limitations on CT-imaging are the cost of the equipment and the time required for data management to prepare and analyse the images. As equipment is improving and more efficient and user-friendly image analysis software is developed, CT is emerging as the preferred technique to characterise small-scale defects in composite materials. This study concerns a 3D examination of the morphology, size, distribution, concentration and location (or homology) of the voids in composite samples made with RTM using X-ray CT, image analysis and statistical analysis. The intention of this study is to improve the understanding of the mechanisms of void formation during resin infusion into a complex multi-axial reinforcement preform and to detect defects that could affect in-service damage development.

2. Materials and methods

2.1. Laminate manufacture

Rectangular laminated composite plates of 800 mm × 400 mm × 4 mm were manufactured by RTM with unidirectional flow along the length using a constant pressure difference of 200 kPa. Hexcel's resin system HexFlow RTM 6 was used with an aerospace-grade unidirectional (UD) carbon fibre weave. The fabric architecture, shown in Fig. 1, consists of UD carbon fibre tows held together by biaxial woven glass fibre yarns in both warp and weft directions. The laminates were laid up with a quasi-isotropic stacking sequence of $[0/-45/90/+45]_{2S}$. The primary flow direction during infusion was along the 0° axis. Analysis