Composites Part B 83 (2015) 346–351

Contents lists available at ScienceDirect

Composites Part B

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

Voids and their effect on the strain rate dependent material properties and fatigue behaviour of non-crimp fabric composites materials

R. Protz [a, *], N. Kosmann [b], M. Gude [a], W. Hufenbach [a], K. Schulte [b], B. Fiedler [b]

[a] Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology, Holbeinstraße 3, 01307 Dresden, Germany
[b] Technische Universität Hamburg-Harburg, Institute of Polymers & Composites, Denickestr. 15, D-21073 Hamburg, Germany

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form
6 May 2015
Accepted 4 August 2015
Available online 20 August 2015

Keywords:
A. Fabrics/textiles
B. Mechanical properties
B. Porosity
E. Thermosetting resin

ABSTRACT

The manufacture of composite structures is inevitably linked to the formation of voids. Several non-destructive techniques are potentially able of detecting defects, but just the exact knowledge of the effects of defects on the mechanical properties allows the definition of thresholds for the purpose of quality management. In this paper an experimental program for characterizing the effect of voids on the composite materials behaviour is presented. Therefore glass fibre non-crimp fabric reinforced epoxy composites were produced using vacuum assistant resin transfer moulding. For obtaining various void contents specially modified process parameters were used. Nominally defect free specimens are compared with flawed specimens. Tensile testing at different loading speeds and fatigue tests in tension-compression loading are performed.

1. Introduction

Composites offer high levels of specific stiffness and strength as well as an adjustable energy absorption capacity. Thus, they are ideally preferred for applications in material and energy efficient lightweight structures as used in the wind energy utilization and in aviation [1,2]. In the manufacture of composite structures voids are an unavoidable fact [3,7–11] and have been investigated by many authors. Investigations can be divided in studies on the mechanism of void formation [11–18] and in studies on the effect of voids on the mechanical behaviour [3,7–9].

The development of voids strongly depends on the manufacturing technology. The cause of voids in prepreg materials used in the autoclave process differs essentially from that of semi-finished products infiltrated in an infusion process [19]. Voids are formed in a prepreg laminate when the pressure applied to the liquid resin is lower than the opposing vapour pressure of moisture entrapped in the laminate [23,24]. Investigations to void formation and void morphology in prepreg materials were published among others in Refs. [8,9,11,20–25]. Prepreg materials are commonly used for investigating the influence of voids on the subsequent material behaviour. For example, Lambert et al. [20] showed a significant relationship between the locally largest void and fatigue life in prepreg material under uniaxial fatigue loads [20,26].

During the infusion process (i.e. the various resin transfer moulding process, RTM), the resin is injected in a mould cavity containing the textile preform. The interaction of vacuum quality, pressure of resin-injection, permeability of the reinforcement material and viscosity of the resin all have a major influence on content and geometry of the emerging voids. These parameters lead to variations of the flow rate in the fibre bundles and in the channels between two bundles. Different flow fronts of the resin support a partial infiltration leading to void encapsulation. For unidirectional [22] and for bidirectional [23] carbon fibre composites the influence of voids on the flexural fatigue performance is higher than on the quasistatic strength and increases with rising void content. In the literature there are indications of a critical void contents from which an influence of the mechanical properties are identifiable in the range from 0.3% to 6% [21–23,26–28]. This wide range results from the fact that apart from the pure void content, especially the size, the shape and the distribution of the voids as well as the type of load must be considered. Comparable results on the influence of voids on the strain rate dependent material behaviour are not known for composite materials.

The focus in this paper is put on the reproducible manufacture of laminates with different void contents in a resin transfer moulding process and their influence both on the strain rate dependent mechanical properties and on the fatigue material behaviour. The generated pore volume levels in these studies were

---

* Corresponding author. Tel.: +49 351 463 42490; fax: +49 351 463 38143.
E-mail address: Richard.Protz@tu-dresden.de (R. Protz).

http://dx.doi.org/10.1016/j.compositesb.2015.08.018
1359-8368/© 2015 Elsevier Ltd. All rights reserved.

in the range between 2% and 5% (as well as in the investigations of other authors) and thus typical for composites produced in resin transfer moulding process [7,11–18,26–30]. Most studies, investigating voids, are usually limited to unidirectional reinforced composites, see Refs. [11,25,29,30]. In this paper, a glass fibre non crimp fabric reinforced epoxy composite (GF-NCF/EP) was considered which is more related to practice. Extensive experimental studies with and without detectable defects are required to analyse the effects of voids. More detailed results of the author's studies on the influence of defects in the aforementioned material regarding its structural behaviour have been published in Refs. [3–6,31].

2. Specimen preparation

For the experimental studies, epoxy composites with glass fibre non-crimp fabric (GF-NCF) reinforcement were chosen. Non-crimp fabrics are characterised by the straightened orientation of the rovings. Due to the non-existence of crossing points in a single layer, mechanical properties such as stiffness and strength show the best possible performance. The Arrangement of reinforcing layers was $[0/+45/90/-45]_S$ consists of E-glass fibre rovings from Owens-Coring (OC111A) with a total grammage of 1309 g/m^2. Specifications of reinforcement architectures are shown in Table 1. In the following, 0° is the main fibre direction of the multiaxially reinforced composites. Using the vacuum assistant resin transfer moulding (VARTM) method, the test samples were infiltrated with injection resin RIMR 135 and hardener RIMH 137 in a ratio of 100:30. To ensure a lower viscosity the resin and the mold were heated up to 30 °C. The global fibre volume content of $V_f = 34.3\%$ was measured according to ISO 1172.

After infiltration and hardening, test specimens with dimensions of 250 mm in length, 25 mm in width and 3 mm in thickness were cut from the test plate as described in Ref. [31]. Because of the anisotropic material behaviour, specimens in angles of 0°, 45° and 90° (to the top fibre layer) were tested (Fig. 1). In order to prevent failure -caused by gripping the specimen in the test machine-aluminium-endtabs of 50 mm length which were applied to reinforce both ends of the flat specimen.

To investigate the influence of production-related defects, four laminate specifications with different void contents (V_V) between 0.02% and 4.53%, were produced by systematically adapted process parameters. The void content was calculated from microscope images of cross sections in four steps as shown in Fig. 2. Black areas in the binary image smaller than 100 μm^2 were not counted as voids because they are smaller than the fibre diameter and supposed to be fibre breakouts from the polishing process. The specification with nominally no voids appears mostly transparent, the obtained void content is $V_V = 0.02 \pm 0.02\%$. The specification with a low void content ($V_V = 1.74 \pm 0.65\%$) appears opaque with mostly small voids. The distribution of voids is homogenous in the different layers of the laminate. The specification with a high void content of $V_V = 3.75 \pm 1.10\%$ has a similar characteristic as the previous specification. The specification with large voids has the highest void content with $V_V = 4.53 \pm 5.22\%$ and an entirely different distribution of voids. The voids have a maximum diameter of 1.6 mm and are usually located between the 45°-layers in the middle of the laminate. The remaining laminate is almost free of voids and appears transparent. More detailed results of this characterisation of the tested laminates are presented in Ref. [3].

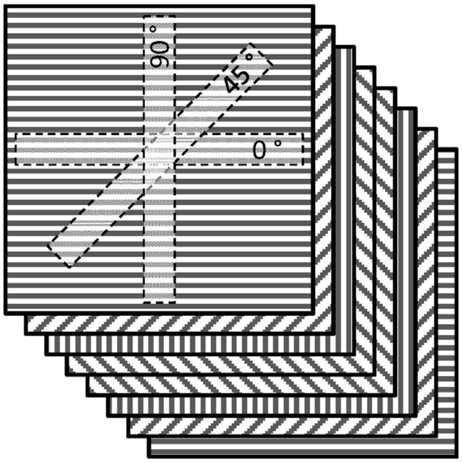

Fig. 1. Orientation of cut out test specimens.

3. Test and measuring equipment

3.1. *Quasi static tests*

For the determination of the basic characteristics, tensile tests were performed with a standard test machine Zwick 1474 at a test speed of 1 mm/min and under room temperature in accordance with ISO 527-4. The deformation of the specimen was recorded with a multisens transducer. From the obtained stress-strain diagrams Young‘s modulus, strain to failure and tensile strength are determined.

3.2. *High velocity tensile tests*

For the characterisation of materials at high loading speeds, a servohydraulic high velocity test system (SHP) INSTRON VHS 160/20 is used. The SHP enables tests of materials and components at high deformation speeds of up to 20 m/s and a maximum force of 160 kN. An upper clamping device, referred to as “quick grabber”and specifically adapted to high-dynamic tests, guarantees an impulse-like and rebound-free introduction of forces in tensile tests, as well as constant strain rates during the loading period. Aside from machine-integrated measuring equipment for recording the machine path, the force and effective acceleration, an optical measurement device is used for the analysis of the deformation and failure behaviour. Therefore the specimens are marked with a dot pattern, whose displacement is recorded with a high speed camera and analysed subsequently using the ARAMIS software.

3.3. *Fatigue tests*

All cyclic tests were performed with a test frequency of 6 Hz on a servo-hydraulic test machine. The stress ratio was $R = -1$ which is

Table 1
Specifications of examined GF-NCF reinforcement $[0/+45/90/-45]_S$.

Thread system	Orientation	Thread type, fineness, bonding	Mass share
Reinforcement	0°	OC111A roving, 2400 tex and 1200 tex, folded	48.7%
Reinforcement	+45°	OC111A roving, 300 tex	23.0%
Reinforcement	90°	OC111A roving, 200 tex	4.8%
Reinforcement	−45°	OC111A roving, 300 tex	23.0%
Stitch	–	PES filament yarn, 5 tex, tricot	0.5%