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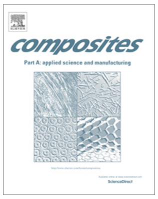

Experimental study of defect formation during processing of randomly-oriented strand carbon/PEEK composites

Benoit Landry, Pascal Hubert *

Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montréal, Quebec H3A 0C3, Canada

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ABSTRACT

An investigation of the moulding defects formed during compression moulding of randomly-oriented strand carbon/PEEK composites is presented. The cause of defect formation was identified as non-uniform shrinkage due to a high coefficient of thermal expansion at the onset of crystallization. Panels with void content ranging from 0% to 1.3% were moulded by releasing the moulding pressure at specific temperatures during the cooling process. Mechanical tests showed a reduction in specimen compressive strength from 15% to 25% for a void content of 0.63–1.3%. It was concluded that the high concentration of porosity near the surface of the panels was the likely cause of the strength reduction.

1. Introduction

Randomly-Oriented Strand (ROS) composites consist of chopped unidirectional pre-impregnated tape and are processed like a bulk moulding compound [1]. These materials are capable of producing highly complex parts compared to continuous fibre composites, which are generally limited to simple parts having small curvature and thickness variations. From a manufacturing standpoint, ROS composites are less labour intensive than continuous fibre tapes, since cutting and preforming is not required. They also have higher fibre volume fraction than traditional short fibre composites, thus higher mechanical properties. ROS composites are intended to be used for small intricate net-shaped compression moulded components having features such as varying wall thickness, tight radii, reinforcing ribs and mould-in holes, thus being an attractive alternative for metallic components.

Recent studies by Feraboli et al. [1–3] investigated the mechanical properties of composites formed from carbon/epoxy sheet moulding compound (SMC). It was shown that the material exhibited in-plane isotropic behaviour, with modulus comparable to that of continuous fibre quasi-isotropic laminates, while strength was significantly lower. The technology was employed to manufacture front and rear control arms for the Lamborghini *Sesto Elemento*, where a weight saving of 27% was obtained compared to the forged aluminium construction [4]. The Boeing 787 features composite window frames moulded from the commercially available HexMC™ SMC, offering a weight saving of almost 50% and superior damage tolerance when compared to a traditional aluminium frame [5]. The excellent formability of compression moulded thermoplastic ROS composites has also been demonstrated in several studies. Van Wijngaarden et al. [6] compression moulded a deep flange out of carbon/PEEK ROS composites, where it observed that the flow of the material at the processing temperature was greatly influence by the applied pressure. LeBlanc et al. [7] investigated the influence of processing pressure and strand geometry on the filling of a 25 mm deep rib cavity moulded from carbon/PEEK ROS composites. A feasibility study on the manufacturing of a carbon/PEEK rotorcraft door hinge featuring net-shaped holes was presented by Eguémann et al. [8]. Bearing tests showed that the door hinge exhibited similar strength to that of a steel counterpart, with a weight reduction of 84%. Mechanical properties of carbon/PEEK ROS composites were also studied in detail by Selezneva et al. [9,10], where strand length and part thickness were identified as the key parameters.

Similarly to injection moulding of short fibre reinforced thermoplastics, compression moulding of ROS composites is carried out at high pressures [7,8]. This favours the filling of the mould cavity at the melt temperature, and also helps compensate the thermal and crystallization shrinkage (for a semi-crystalline matrix) of the material during cooling. The latter is important in order to prevent localized loss of contact between the material and the mould, which could compromise the compaction quality of the material and lead to defect formation. This phenomenon, shown schematically in Fig. 1, can occur due to non-uniform shrinkage caused by an in-plane temperature variation [11], or in a complex feature where compaction is applied indirectly [7]. Furthermore, the high

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* Corresponding author.
E-mail addresses: benoit.landry3@mail.mcgill.ca (B. Landry), pascal.hubert@mcgill.ca (P. Hubert).

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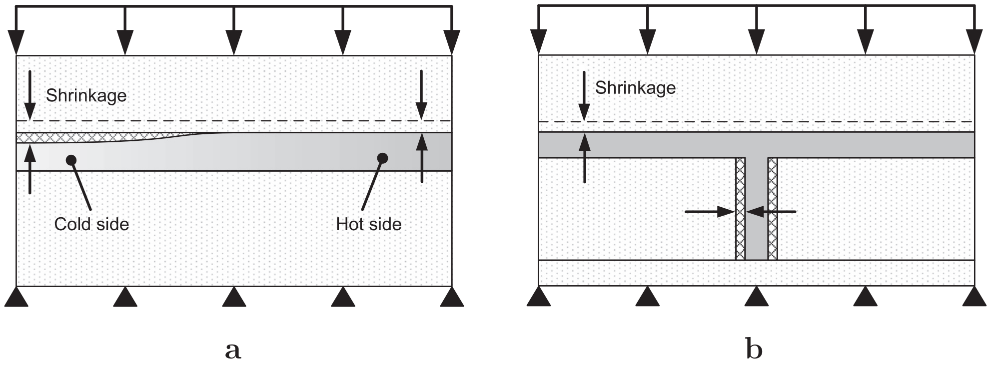

Fig. 1. Schematic of two circumstances where the loss of contact (shown in cross-hatched regions) between the material and the mould can occur during cooling of a compression moulded ROS composite part. (a) Non-uniform shrinkage due to an in-plane temperature variation [11]. (b) Indirect compaction in a complex feature [7].

out-of-plane modulus of ROS composites owing to its high fibre volume fraction substantially reduces the ability to compensate for shrinkage, making it challenging to manufacture defect-free complex shaped part.

Porosity is one of the most detrimental defects formed during manufacturing of composites [12]. It is known to have a significant effect on matrix-dependent properties of continuous fibre reinforced polymers (CFRP), mainly because it is the source of stress concentrations and can act as failure initiation points [13]. The most significantly affected properties include interlaminar shear [14–16], transverse tensile [15,17], flexural [18], and compressive strength [19]. It is also widely accepted that the longitudinal tensile properties of CFRP are not affected by voids [15,17]. To the authors' knowledge, there are no published studies on the effect of porosity on the mechanical properties of ROS composites. This information is valuable since complex regions of a ROS composite part are likely to have considerably high void content due to partial compaction, in addition to defects caused by the loss of contact during cooling.

This paper presents an investigation of the moulding defects formed during cooling of ROS carbon/PEEK composites. Optical microscopy was used to identify the defects, while thermomechanical and dynamic mechanical analyses were utilized to better understand the nature of the mechanisms responsible for their formation. An experimental method was developed in order to reproduce the moulding defects and identify the temperature range during cooling at which they are formed. Finally, the effect of moulding defects on mechanical properties was quantified by comparing the compressive strength of specimens having different levels of moulding induced defects.

2. Experimental procedures

2.1. Material

The material studied was a unidirectional carbon/PEEK slit tape, 6.35 mm wide and 0.136 mm thick, with a fibre volume fraction of 59%. It has a glass transition temperature (T_g) of 143 °C and a melting temperature (T_m) of 343 °C. The manufacturer's recommended processing temperature is between 370 °C and 400 °C. The slit tape was cut into 25 mm long strands using a Kingsing Machinery Co. Limited (Shanghai, China) automated tape cutter, model KS-915.

2.2. Thermal analyses

Two thermal behaviours of the material during processing were characterized. The out-of-plane thermal and crystallization shrinkage were first measured by thermomechanical analysis (TMA). The second analysis was performed using dynamic mechanical analysis (DMA), and aimed at better understanding the void formation mechanism in play when the pressure is lost during cooling. A detailed methodology for both experiments is presented in the following sections.

2.2.1. Thermomechanical analysis

The experiments were performed on a TA Instruments (New Castle, DE) Q400 Thermomechanical Analyzer equipped with a MCA70 cooling accessory and a macro-expansion probe. Two 6.3 mm square specimens were cut from a 4.3 mm thick defect-free continuous fibre carbon/PEEK panel with a stacking sequence of $[45/-45/0/90]_{4S}$. The thermal expansion of each specimen was measured from 25 °C to 380 °C in the direction perpendicular to the fibres (ε_{33}). The test setup is shown in Fig. 2a. Before the experiment, the specimen thickness was measured with a preload of 0.05 N. It was then sandwiched between two quartz discs coated with Frekote 700-NC release agent. Quartz has a linear coefficient of thermal expansion of 0.33 $\mu\varepsilon$/°C [20], which is negligible compared to that of carbon/PEEK laminates. The setup was heated to 380 °C at a rate of 1 °C/min, under a constant load of 0.1 N. A 10 min temperature hold was then performed in order to completely erase the crystallization history of the material [21]. Finally, the setup was brought to room temperature at the same rate. The slow cooling rate was selected to minimize thermal lag in the specimen, since the heat transfer mechanism of the TMA is convection. A total of two samples were tested.

2.2.2. Dynamic mechanical analysis

All experiments were performed on a TA Instruments Q800 Dynamic Mechanical Analyzer, equipped with a compression clamp 15 mm in diameter. The specimen geometry was the same as that used for the TMA tests. The test setup is shown in Fig. 2b. Before each experiment, the compression clamp surfaces were coated with Frekote 700-NC release agent. The specimen thickness was measured with a preload of 0.1 N and the setup was heated to 380 °C at a rate of 10 °C/min under a constant load of 0.1 N, followed by a 10 min temperature hold to ensure isothermal condition. Afterwards, a compressive load of 0.3 bar was applied. This load was high enough to ensure a good contact between the specimen and the clamp, without inducing any flow of material at 380 °C. The setup was then brought to room temperature at a rate of 1 °C/min. This cooling rate was selected for the same reason stated in Section 2.2.1. During cooling, the distance between the two clamp surfaces was kept constant, while the load was acquired. A total of two samples were tested.

2.3. Panel manufacturing

Flat panels were moulded in an instrumented hot press, shown in Fig. 3a. The setup was inserted in an MTS (Eden Prairie, MN)