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Tribo-mechanical characterization of reinforced epoxy resin under dry and lubricated contact conditions

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ABSTRACT

The aim of the present work is to investigate the influence of the reinforcing material and architecture on the voids content, mechanical properties and tribological behavior of fiber reinforced epoxy composite laminates manufactured by VARTM under different processing conditions. Two different textile architectures, namely unidirectional non-crimp fabrics (UD) and 0/90 plain wave (PW), were considered, reinforcing an EPIKOTE RIMR 135 epoxy matrix with glass (GF) as well as carbon (CF) continuous fibers. Optical observations revealed an unexpected trend relatively to the intra- and inter-bundle voids concentration with respect to the impregnation velocity, especially using UD-CF and UD-GF reinforcements and low impregnation rate. Tensile and three points bending tests highlighted the dominant role of fiber material and architecture on mechanical properties, whereas the presence of voids played a minor role with respect to the analyzed features. Tribological outcomes evidenced a reduction of the friction coefficient (μ) when the resin is reinforced by carbon or glass fibers. The lowest values were detected when the sliding direction of the counterbody is oriented parallel to the fiber direction for UD samples. Further reduction of μ, for both UD and PW specimens, was obtained by interposing a lubricant at the interface.

1. Introduction

Fiber Reinforced Polymer (FRP) are widely used in applications with interacting surfaces in relative motion such as seals, gears and dry slide bearing materials1 [1–3], as well as orthopaedic prostheses [4]. In this context, determining the mechanical and tribological behavior of involved components is a key factor. Carbon and glass are two of the most widespread fiber reinforcements for epoxy resin. Increasing compressive and shear strength of the resin, fibers support part of the applied load and lower the wear rate. Nevertheless, the understanding of tribological properties of glass and carbon fiber reinforced polymer is still"limited and lacks predictability" [5].

In recent years, Liquid Composite Molding (LCM) processes, such as Vacuum Assisted Resin Transfer Molding (VARTM), have gained a lot of attention in composite manufacturing. Main advantages of LCM processes are related to the capability of manufacturing geometrically complex products with remarkable precision, flexibility of reinforcement architecture and reduced human exposure to dangerous emission of volatiles. VARTM is a multi-step process defined by preform impregnation, resin cure and eventually post-cure.

During VARTM process, a multiphase flow, i.e. resin and air bubbles, moves inside the fiber preform. The combination of multiples factors, such as temperature, pressure and fluid viscosity, could lead to void formation. It is well established that these voids negatively affect the final mechanical properties. Ghiorse discussed that the interlaminar shear strength and flexural strength of carbon fiber/epoxy composites decrease by 10% and the flexural modulus decreases by 5% for each 1% void content increase in the range 0%–5% [6].

Two kinds of voids are generally observed in a composite manufactured by LCM process. A dual-scale porosity and void content can be defined and characterized measuring the intra-bundle micro-voids and the inter-bundle macro-voids. Patel and Lee [7,8] described the alternation of macro- and micro-voids, attributable to two different flow dynamics. Indeed, at low impregnation rates, due to predominant capillary pressure, the

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resin flows faster inside the tows than between them. Therefore, when the resin creates a cross flow, macro void could take place in the empty gap. When the flow rate is high, viscous forces are consequently elevate and rule the flow, yielding micro-voids formation and unsaturated spots. Other researchers, including Labat et al. [9] demonstrated that the percentage of macro/micro-voids formation is a near logarithmic function of the fluid flow velocity: macro-voids decrease with velocity whereas micro-voids increase. It is so possible, in theory, to estimate the optimal infiltration velocity that minimizes the void ratio. This phenomenology is currently subject of an amply debate, as documented in several reports dealing with void content prediction and monitoring [7–10].

As tribological loaded components, the coefficient of friction, wear rate and stress carrying capacity are materials key factors. The behavior of the contact zones during relative movements is influenced by properties of resin, fiber and their interface. Some tribological studies were carried out on fiber reinforced epoxy in dry condition with constant sliding velocity [5,11–14]. Their results showed how the presence of fibers with good tribological characteristics leads to a lower value of the coefficient of friction and a lower wear rate. Lancaster [11] argued the enhancement of the wear resistance of a polymer matrix through the mean of carbon fibers, for they support part of the load applied to the sample. Larsen et al. [5] found a μ decrease of 35% by substituting a glass fiber weave with a carbon/aramid hybrid weave in epoxy-matrix. Many of these works highlighted a strong correlation between the sliding direction and the orientation of unidirectional fibers. A low wear rate, around 10^{-16} m^3 N^{-1} m^{-1}, along with low μ (0.2) was observed by Sharma et al. [15] for CF/polyetherimide composites with reinforcement parallel to load direction. Kim et al. [16] found that the friction and wear behavior of PA12 composite samples were more dependent on the fiber ratio than on the sliding direction, reaching the lowest μ at 30wt.% of glass fiber.

As debated in Refs. [15,17–19], a continually reversing load applied by the moving counterbody has a strong influence on the friction and wear behavior. Schön [17] measured the μ for composite in contact with composite in reciprocal sliding in order to model bolted joints of CF/epoxy material, founding a starting value of 0.65 and a peak of 0.74. Klingshirn et al. [18] investigated the influence of the volume content of short carbon fibers inside an epoxy matrix on the fretting wear rate, demonstrating the dramatically decrease of this parameter with a growing fiber content.

To authors best knowledge, studies on the different tribo-behavior of FRP in dry and lubricated conditions during reciprocating sliding have not yet been reported. Since in many mechanical applications this kind of materials are used in reciprocating movement, a more complete tribological investigation is necessary.

The aim of this study is to investigate both mechanical and tribological behavior of GF and CF reinforced epoxy, taking into account the influence of the production parameters on the laminates voids content. The observation by Patel and Lee [7,8] was experimentally checked, by means of a thermogravimetric analysis (TGA) and microscopic observations. Tensile and bending tests were executed to find a quantitative correlation between voids and mechanical properties. From a tribological point of view the system here analyzed consists in FRP laminate coupled with steel (AISI E52100) in dry and lubricated conditions under reciprocating motion.

2. Materials and methods

Composite laminates were manufactured by VARTM, reinforcing an epoxy matrix with glass (GF) or carbon (CF) continuous fibers. Reinforcing fibers were organized following two different textile architecture, namely unidirectional non-crimp fabrics (UD) and plain-weave (PW). EPIKOTE RIMR 135 mixed with EPIKURE curing agent RIMH 137, manufactured by Momentive, was employed as epoxy system. Glass fibers were boron-free E-CR from Advantex. Carbon fibers were high tenacity HTA40 from Tenax. Mechanical and physical properties of used constituents are listed in Table 1.

Four layers of reinforcement were piled in the center of the mold, lied on a release agent and covered by the peel-ply and the distribution media for each processing condition. Afterward the vacuum bag was placed on top and sealed on the mold. The impregnation rate was varied regulating the applied vacuum pressure, considering three level (500, 800 and 950 mbar) for this process variable. In Fig. 1 the experimental setup is shown, along with a schematic representation of the final laminates.

Infusion step was monitored by means of a video-camera. In Table 2 is reported the time that the resin took going from the inlet to the outlet hoses. Laminates were demolded after 24 h of cure at room temperature.

A first estimation of the void concentration was obtained by the TGA, performed using a Mettler Toledo TGA/DSC1. TGA outcomes were post-processed using the following equation, derived in Ref. [20]:

$$V_v = \frac{\rho_c^0 - \rho_c}{\rho_c^0} \tag{1}$$

being V_v the void volume ratio, ρ_c^0 is the density of the composite in the absence of voids as provided by the TGA analysis, and ρ_c the mean density measured by immersion on three specimens for each kind of plate.

Observations of the laminate cross and longitudinal sections (along plane 2–3 and 1–3, respectively) were made on a Zeiss Axioplan optical microscope. Rough grinding and polishing of specimens were previously made on a Struers Tegra Doser-5. Voids are easily identifiable as the darkest spots on the micrographs. An image processing and analysis routine was implemented to identify and measure the extension of voids. Then, void area fraction was inferred by dividing the cumulative area of detected voids by the total area of the images. Finally void volume fraction was obtained averaging the area fraction on ten different measurements.

Tensile tests were performed with reference to ISO 527-4. Four straight-sided specimens were prepared for each laminate. Specimens were cut along axis 1 (Fig. 1a,b) for both UD and PW laminates. Tensile specimens were cut with the dimensions of 250 × 25 × 1 mm^3, following the standard's prescriptions. To characterize the laminates under flexural conditions a three-point-bending test was used, as specified by the ISO 14125 standard. Four specimens per laminate were made, with dimensions 40 × 15 × 1 mm^3 and 20 × 15 × 1 mm^3 for carbon and glass fiber reinforced laminates, respectively. Cutting orientations were the same as tensile specimens.

Tribotests were executed on a Ducom Reciprocatory Friction Monitor with ball-on-flat configuration. This apparatus analyzes the tribological behavior of tribopairs: a flat material in contact

Table 1
Mechanical and physical proprieties of fibers and matrix.

	Density ($g\ cm^{-1}$)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Epoxy resin	1.18–1.20	60–75	2.7–3.2
Carbon fiber	1.76	3950	238
Glass fiber	2.26	3100–3800	80–81