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Influence of injection molding on the flexural strength and surface quality of long glass fiber-reinforced polyamide 6.6 composites

D. Teixeira [a,b], M. Giovanela [a], L.B. Gonella [c], J.S. Crespo [a,*]

[a] Centro de Ciências Exatas e da Tecnologia, Universidade de Caxias do Sul, Rua Francisco Getúlio Vargas, 1130, Caxias do Sul, 95070-560 RS, Brazil
[b] NTC Moldes e Plásticos, Rodovia RS 122 km 69.92, 63900, Caxias do Sul, 95010-550 RS, Brazil
[c] IFRS Câmpus Caxias do Sul, Rua Avelino Antônio de Souza, 1730, Caxias do Sul, 95043-700 RS, Brazil

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ABSTRACT

The objective of this paper was to process a polyamide 6.6 composite reinforced with long glass fibers (50 wt.%) using a design of experiments to determine the processing conditions that simultaneously maximize the flexural strength and the surface quality of the molded composite. The analyzed factors were the barrel temperature profile, the injection speed and the screw speed. To maximize the flexural strength response variable and the surface quality, all studied parameters should be maintained at the higher levels. The analysis of microstructure of composites molded demonstrates that this combination of parameters promotes a greater orientation of the fibers in the outer layers, as well as prevents the migration of glass fiber to surface of the composite. This kind of microstructure is favorable to a better surface quality, and a greater flexural strength.

1. Introduction

The use of thermoplastic composites in engineering applications has increased considerably in the last few years. These materials combine ease of processing with a good resistance to corrosion, low specific gravity and high mechanical strength. In conjunction with recyclability, these characteristics enable these materials to be used in automotive applications [1–3]. In this context, the low density is of environmental interest because it relates directly to the amount of fuel a vehicle consumes and the quantity of CO_2 it emits. For example, the reduction of only 4 kg in the mass of a midsized car enables savings of up to 36 L of fuel during a vehicle's useful life, which is equivalent to a reduction of 75 kg in CO_2 emissions during the same period [4]. In this class of materials, the thermoplastic composites reinforced with long glass fibers (long-fiber thermoplastics—LFTs) stand out. Typically, these composites are manufactured using the pultrusion process, in which the continuous glass fiber filaments (rovings) pass through a polymer impregnation unit. Thus, the glass fiber is completely enveloped by the polymer material, and subsequently, this mix is cut into pellets of the desired length (from 10 to 25 mm). With this process, it is possible to obtain pellets containing completely aligned glass fibers that are substantially longer than composite pellets reinforced with short fibers (short-fiber thermoplastics—SFTs) [5,6]. Because of these characteristics, the market estimates an increase of 5% per annum for this type of material [7,8]. In the LFT composites, the initial length of the fibers (pre-processing) is longer than 10 mm, which facilitates manufacturing products containing fibers with a residual length close to 1 mm [9,10]. The long fibers provide the final product with better mechanical properties and a better surface quality [6,7,11,12]. In automotive applications, high mechanical strength combined with a pleasing visual quality is a common demand. These two properties can be difficult to obtain simultaneously [13].

The mechanical and surface properties of the LFT composites are influenced by their microstructure (length, orientation and dispersion of the fibers). In turn, the microstructure is influenced by the processing conditions and the geometry of the mold that is used to manufacture the composite [14–16]. It is known that artifacts molded from glass fiber-reinforced composites may display an undesirable visual aspect: the presence of glass fibers on the surface of the product. The surface tends to exhibit white spots that are caused by the exposed fibers, which can limit the application of the composite when a favorable visual appearance is required. This aspect can be controlled if adequate process parameters are used during the processing of the composite [13].

In the literature, several studies correlate the injection process parameters and the mechanical strength of LFT composites [15,17–19]. However, few studies correlate these parameters with the visual quality of the composite [20]. In view of these facts, the present study was

* Corresponding author.
E-mail address: jscrespo@ucs.br (J.S. Crespo).

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aimed at assessing the influence of injection process variables, such as screw speed, injection speed and barrel temperature profile, on the flexural strength and the visual appearance of the LFT composites. A design of experiments (DOE) of the 2^3 factorial type was used to determine the combination of process parameters that would best maximize simultaneously the flexural strength and the surface quality of the LFT composite [17,21].

2. Experimental details

2.1. Materials

The composite used was polyamide 6.6 (PA 6.6) reinforced with long glass fibers (50 wt.%/31 v%) with an initial length of 11 mm. This material is manufactured by Ticona (Florence, Kentucky, USA), reference GF50-02 BLK. This quantity of fiber in the composite was chosen because the maximum reinforcement effect for flexural strength is obtained at the 40–50 wt.% level of fiber glass [1,14,22].

2.2. Preparing the specimens

To mold the specimens of the PA 6.6 composites with long glass fibers, a mold was constructed to produce a square plate (128 × 128 mm with a thickness of 3.55 mm). To inject this plate, a 3.2 mm thick edge gate was used combined with a fan gate. The objective of the fan/edge combination channel is to provide an injection flow that is as uniform as possible over the molded plate (unidirectional flow in the longitudinal direction of the plate). The distribution channels have a 7 mm diameter (Fig. 1a and b), and the entire system of distribution and feeding channels was optimized for the injection of LFT composites to avoid breaking the fibers during the process [18,23].

The specimens were molded at *NTC Moldes e Plásticos* (Caxias do Sul, RS, Brazil) with a HAIHANG-HHF128X injection molding machine using a clamping force of 127 t and a universal type screw with a L/D ratio of 22. Before processing, the LFT composite was dried for 12 h at 80 ± 5 °C in an oven with forced air circulation [23]. From each molded plate, three specimens were machined for the flexure test (Fig. 1a) according to the ASTM: D790, all parallel to the injection direction of the molded plate. The specimens were machined in a CNC milling machine (brand ROMI, model D600) using a 5 mm diameter end mill with a 4000 rpm spindle speed and an 8 mm/s feed rate. This molded plate was also used to verify the surface quality of the molded LFT composite.

2.3. Design of experiments (DOE)

The influence of the process parameters on the mechanical properties and the surface quality of the LFT composite was analyzed through DOE of the complete factorial type with three factors and two levels (high and low), resulting in eight treatments (2^3). Four replicas were executed to obtain reasonable information regarding the experimental error [24], resulting in 32 samples in total. The analyzed controllable factors were the heating profile of the barrel, the screw speed and the injection speed. These factors were selected because they have a relevant influence on the surface quality of the composite and its mechanical strength [15,20,23]. The remaining factors (injection pressure, mold temperature, holding pressure and holding time) were maintained constant at levels that are recommended in the literature [15,23]. The high and low levels of the controllable factors were also defined according to recommendations by the composite manufacturer [23], regarding the capacity of the injection machine that was used to mold the specimens.

The analyzed response variables were the composite's flexural strength (under the ASTM: D790) and surface quality. The surface quality was quantified based on three assessment parameters: gloss, roughness and visual assessment. Table 1 shows the process parameters that were used and the random order of the tests. The statistical calculations were performed with the help of the Minitab® software, version 17 [21,25]. The flexural strength was chosen to evaluate the mechanical resistance of the composite, because it is a test method adequate to use with fragile samples (with low elongation to failure) [1]. Furthermore, this method is affected by the differences in the microstructure along the thickness of the sample, because the sample is subjected to a stress variation that is not uniform along its thickness.

The gloss analysis was performed with the help of a Multigloss 268 plus (Konica Minolta) glossmeter. The gloss (or specular reflectance) is related to the ability of a surface to reflect light and can be defined as the finishing degree of a surface that is approximated to a theoretical standard defined as the standard mirror. For practical purposes, this reference is standard glass plate to which an arbitrary value of 100 gu (gloss unit) is attributed. To perform the measurement, the glossmeter emits a beam of light over the sample with a specific angle of incidence (ϕ_i). Then, the device measures the fraction of light that is reflected from

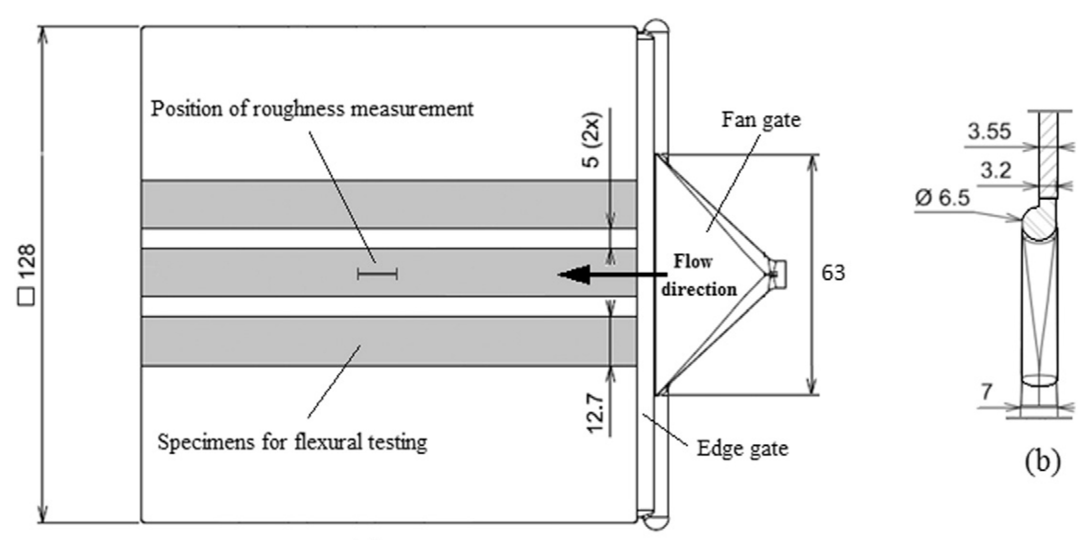

Fig. 1. (a) Molded plate and arrangement for machining the specimens; (b) cross-section of the injection channel.