THERMOPLASTIC COMPOSITE ROD MANUFACTURING USING BIAXIAL BRAID-TRUSION

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Keywords: Braid, Pultrusion, Braid-trusion, Thermoplastic composite

Abstract
Braid-trusion is a composite manufacturing process combining braiding and pultrusion. This process produces constant cross-sections thermoplastic composite beams having angle-oriented fibers. During pultrusion, the braid is drawn through a series of dies by a pulling device. The braid is therefore solicited under tension. Braid-trusion is usually performed using tri-axial braids containing bias yarns interlaced at a specified braiding angle, and axial yarns. Axial yarns secure the braid structure and prevent large longitudinal deformation of the braid under tensile load. Few studies report the use of biaxial braids for pultrusion. The biaxial braid structure easily deforms in the circumferential and longitudinal directions under pulling force and compression into the die. The aim of this research is to investigate the effect of the braid-trusion parameters on the final structure of a biaxial braided rod and its impregnation. Commingled thermoplastic carbon fibers are used to make biaxial braids. During pultrusion, braid spool tension of 2.5, 40 and 80 N and puller speed of 50 and 150 mm/min are used to study their effects on the impregnation and void content of the pultruded rods. The experiments are performed for two different cooling die temperatures of 200 and 100 °C. The morphology of the pultruded rod is characterized using microscopy. It is observed that the impregnation, void content and surface finish of thermoplastic braided composite is influenced by the cooling die temperature, braid spool tension, and puller speed. The best results are achieved with the minimum of spool tension, speed, and cooling die temperature.

1. Introduction

Braiding is a traditional textile manufacturing technique highly attractive to create composite reinforcements due to their multi-directional fiber arrangement. Pultrusion is a composite manufacturing process that pulls fibers into constant cross-section dies to manufacture a composite structure with a continuous profile at a fast production rate. Braid-trusion (or pull-braiding) combines braiding and pultrusion techniques to manufacture high-performance composites reinforced by a braided fiber architecture. This process is an uninterrupted composite manufacturing process to manufacture constant cross-section polymer composites. Compared to thermoset braid-trusion, the number of publications on thermoplastic braid-trusion is relatively scarce. In the following, the related articles will be briefly reviewed. The braiding machine provides the hybrid thermoplastic fibers braid in front of the pultrusion apparatus. The braids are composed of hybrid yarns combining the reinforcement and thermoplastic fibers. The most common hybrid yarns are the parallel hybrid, commingled and powder impregnated yarns [1]. The braid is preheated to a temperature close to the thermoplastic filaments melting point in the pre-impregnation die [2]. Preheating the braid decrease the required time to melt the thermoplastic polymer in the pultrusion die [3]. Afterward, the braid is pulled into the pultrusion die by the pulling device. The thermoplastic polymers are melted in the pultrusion die. The pultrusion die usually consists of a conical zone allowing overfilling of the die. This overfilling creates a back-flow of polymer towards the conical zone entrance [4]. This back-flow helps create pressure to impregnate reinforcement fibers by the polymer. Finally, the composite is pulled into the cooling die to solidify the thermoplastic polymers. Michaeli and Jurss [2] introduced thermoplastic pull-braiding process using parallel hybrid yarn of propylene (PP)/glass and commingled yarn of Liquid Crystalline Polymer (LCP)/Carbon and Poly Ether Ether Ketone (PEEK)/Carbon. They used a 48 carriers braiding machine. Their die was divided in three sections for the three different thermal processes of melting, solidification, and cooling. Bechtold et al. [3] demonstrated that using contact preheating improves mechanical and morphological properties of glass/polypropylene pultruded composite. Compared to the convective heating, the shear strength increased by 50%. Studies cited above did not propose a design methodology for the braid to be pultruded, nor give specific details about the braid architecture used. It is suspected that trial and error method was used to achieve successful braid-trusion. Laberge Lebel and Nakai [5] proposed a geometrical model for tri-axial braided tube. Using this model, they manufactured an L-shaped thermoplastic beam using braid-trusion. Their model allows the design of braided preforms that achieve correct filling of the pultrusion die as well as limiting fiber friction on die walls. Laberge Lebel et al.'s model is able to represent the circumferential deformation of a braid during compression into the pultrusion die. In their work, only the circumferential deformation occurs because of the axial yarns in tri-axial braids prevent the longitudinal deformation. Their model cannot be used for biaxial braids since longitudinal deformation also occurs during biaxial braid-trusion. Memon et al. [6] produced braid-truded bio-composite tubes. They used commingled jute/polylactic acid (PLA) to braid tubular tri-axial braids with glass fiber as the longitudinal yarns. They assessed the manufacturing parameter's effect on the impregnation quality and mechanical properties. They showed the impregnation quality increases with increasing the molding temperature and decreasing the molding speed. However, the pultruded tubes' mechanical properties diminished with the higher processing temperature due to jute fiber degradation.

Axial yarns in tri-axial braids secure the braid structure and prevent large longitudinal deformation of braids subjected tensile load. That can explain why most of the previously published results used tri-axial braids to manufacture composites by thermoplastic braid-trusion. In light of the literature survey, no report was found on using biaxial braids for thermoplastic braid-trusion. The objective of this research is manufacturing a thermoplastic composite rod using biaxial braid-trusion. The impacts of braid structure, spool tension, speed and cooling die temperature are investigated.

2. Method

2.1. Materials

The commingled yarns (Concordia fibers) with 1% sizing level were used to manufacture the biaxial braid. These yarns are an intimate mix of AS4 carbon fiber (HexTow®) and PEI (Ultem®) as the thermoplastic fibers. Commingled yarns of 30K carbon fibers were wound around the bobbins. Each 30K commingled yarns contained two 12K and two 3K commingled yarn. The volume ratio of carbon fiber (V_{fY}) in 12K and 3K commingled yarns were 53% and 52% respectively. PEI material properties are shown in Table 1.

Table 1. PEI material properties.

Material properties	
Glass transition temperature (*Tg*) [7]	217 °C
Process Temperature [7]	370-400 °C
Solid specific gravity [7]	1.27 g/cc
Melt specific gravity [9]	~1.17 g/cc

2.2. Pultrusion apparatus and process

Fig. 1 exhibits the pultrusion apparatus. The pultrusion apparatus involves a creel, a preheater, four pultrusion dies, three heat chambers, a cooling die, and a puller system. The creel was equipped by a magnetic brake (Mitsubishi Powder Brake model ZX-YN) which was controlled using a microcontroller program. To apply a desired tension on the braid spool, the microcontroller varies the current in the magnetic brake and this allows to control the brake torque. Three different tension of ~2.5, 40 and 80 N were applied on the braid spool during the experiment. The braid preform was preheated to a temperature (300 °C) close to the PEI process temperature at the inlet of pultrusion line. The preheater was made of a heating tube that is wrapped by a controlled heater.

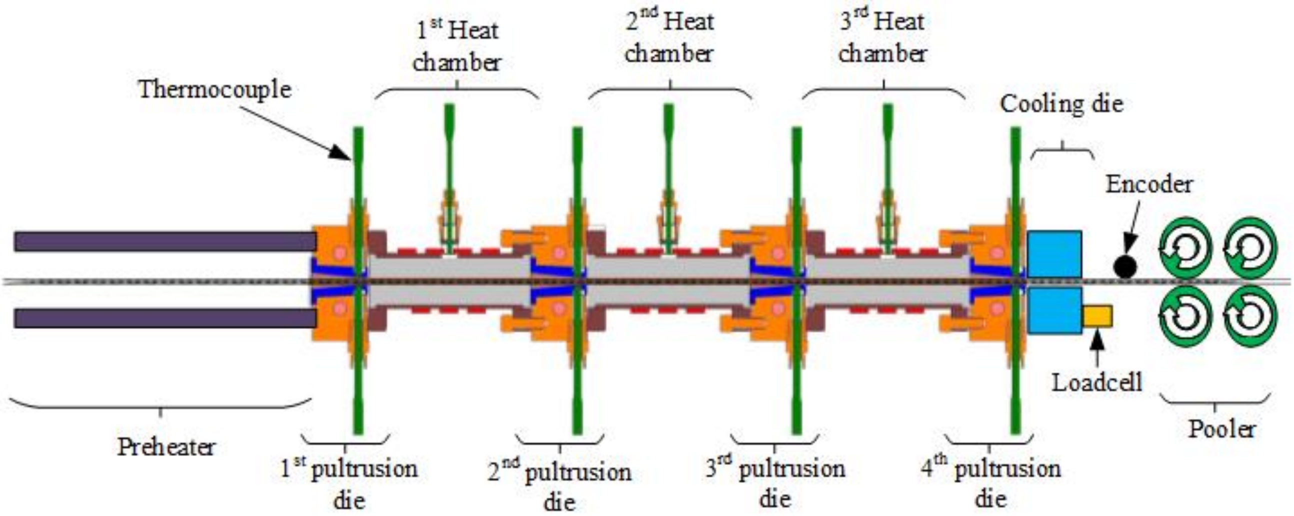

Figure 1. Schematic view of the pultrusion apparatus

The pultrusion dies consisted of four dies which made of contiguous conical and cylindrical zones. The cone angle was 5°. The length of the conical zone was 31.75 mm and the cylindrical zone was 6.68 mm for each die. The diameters (D_i) of the cylindrical zones were 5.2, 5.0, 4.9 and 4.8 mm. The 114 mm long heated chambers were connected to the pultrusion dies. The cooling die was placed very close to the last pultrusion die exit. The length of the cooling die was 50.8 mm and its diameter 4.8 mm. Cartridge heaters were embedded in pultrusion dies, heat chambers and cooling die. They were controlled using the feedback from thermocouples (type J). The cooling die was equipped by two air-cooling circuits. All pultrusion dies and heated chambers were set to the constant temperature of 400 °C. The cooling die temperature was set to 200 °C, and 100 °C during the experiment. Finally, the braided carbon/PEI pultruded rod was pulled by a pulling system. In order to study the effect of pultrusion's speed, the preform braid was pultruded at two different speeds of 50 and 150 mm/min by pulling system. Table 2 presents the manufacturing parameters performed during the experiment.

Table 2. The manufacturing parameters during experiment

Parameter	Spool tension (Kg)	Preheating temperature (°C)	Pultrusion temperature (°C)	Cooling die temperature (°C)	Speed (mm/min)
A	2.5	300	400	200	50
B	40	300	400	200	50
C	80	300	400	200	50
D	80	300	400	200	150
E	40	300	400	200	150
F	2.5	300	400	200	150
G	2.5	300	400	100	50

2.3. Braid and braid-trusion design

Biaxial braid preform was manufactured by a 24-carrier maypole braiding machine. The braiding machine mounted with 8 carriers formed a regular pattern (2/2) [8]. The braiding machine setting was adjusted to manufacture a 10 m braid with a 35° braid angle. The braid angle was selected according to unpublished preliminary work. As said in the introduction, overfilling is necessary to create impregnation flow during pultrusion. The overfilling ratio in the *i*th die ($R_{f,i}$) is expressed by the material area at die entrance over the exit area of the same die ($A_{Die,i}$). The overfilling of the dies can be calculated according to,

$$R_{f,i} = (A_{rb,i-1} + A_{p,i-1}) / A_{Die,i} \quad i=1, 2, 3, 4 \tag{1}$$

Where $A_{rb,i-1}$ and $A_{p,i-1}$ are the areas of braided reinforcement fibers and polymer, located before the *i*th die, and projected onto the *i*th die cross-section plane. Note that *i*=0 corresponds to the braided preform before entering the first die. $A_{rb,i-1}$ *is* calculated according to,

$$A_{rb,i-1} = N_Y N_f D_f^{\ 2} / 4 \cos\alpha_{i-1} \quad \text{with} \quad i=1, 2, 3, 4 \tag{2}$$

Where V_{fY} is the volume ratio of carbon fiber of commingled yarns, N_Y is the number of yarns, D_f is the carbon fiber diameter (7.1 µm for 12K and 6.9 µm for 3K [7]), N_f is the number of fibers in each yarn, and α_i is the braid angle of the braid-truded rod at the *i*th die exit. Note that N_Y, D_f, and N_f are constant throughout the braid's passage in the dies. The polymer area at the first die entrance can be calculated using the fiber volume content of the commingled yarns with,

$$A_{p,0} = (A_{rb,0} (1-V_{fY}) / V_{fY})(\rho_s / \rho_m) \tag{3}$$

In Eq. (3), ρ_s is the PEI specific gravity, ρ_m is the PEI melt specific gravity. The differences between the die areas allowed excess resin to overfill. Assuming that the braid is completely impregnated at each dies, the polymer area ($A_{p,i-1}$) entering dies 2, 3 and 4 is the area unoccupied by reinforcing fibers at die *i-1*. It can be calculated according to

$$A_{p,i-1} = A_{Die,i-1} - A_{rb,i-1} \quad \text{with} \quad i=2, 3, 4 \tag{4}$$

Fig. 2 shows a schematic of a braid opened along the axial direction and subsequently flattened. The two squares represent the same braid but with different braid diameters. The diagonal of the rectangles is the braided fibers length (L) for a complete revolution around the braid axis. The vertical dimension is the pitch (P_i) and the horizontal dimension is the braid outside circumference (πD_i). The angle between the pitch and diagonal direction is the braid angle (α_i).

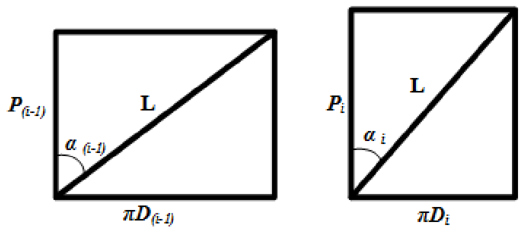

Figure 2. Schematic of a flattened braid yarn along a pitch before and after passing through die *i*

Since the diagonal change L cannot change when the braid elongates during pultrusion, a reduction on the braid circumference will inevitably result in a reduction of the braid angle and an elongation of the pitch. The initial braid pitch (P_0) and diameter (D_0), and braid-truded rod diameter (die diameter, D_i) are known. So the braid pitch (P_i) and braid angle (α_i) of braid-truded rod at *i*th die exit can be calculated with,

$$P_i = ((P_0^2 + \pi D_0^2) - \pi D_i^2)^{1/2} \quad \text{and} \tag{5}$$

$$\alpha_i = \tan^{-1} (\pi D_i / P_i) \quad \text{with} \ i=1, 2, 3, 4 \tag{6}$$

The braid diameter can be difficult to predict due to its the complex structure and unconsolidated state. However, if the yarn's fiber packing ratio (*Rf*) is considered, the braid diameter can be calculated by,

$$D_0 = 2\left((A_{rb,0} + A_{p,0}) / (Rf\,\pi) \right)^{1/2} \tag{7}$$

Finally, the fiber volume fraction ($V_{f,i}$) of the braid-truded rod at *i*th die exit is obtained by,

$$V_{f\,i} = (N_Y \pi\, D_f^{\,2} N_f) / (4A_{Die,i} \cos\alpha_i) \qquad with\ \ i=1, 2, 3, 4 \tag{8}$$

According to an initial braid angle α_0 of 35° and Eq. 1-7 the braid-truded rod fiber volume fraction, braid angle, braid pitch and overfilling ratio at each exit die are listed in Table 2.

Table 3. Designed braid pitch, braid angle, fiber volume fraction, and overfilling ratio at dies' exit

	Preform	1st Die	2nd Die	3rd Die	4th Die
Braid Diameter	6.23	5.2	5.00	4.90	4.80
Braid pitch	28.2	30.31	30.64	30.80	30.95
Braid angle	35	28.33	27.14	26.56	25.98
V_f	0.37	0.50	0.54	0.56	0.58
R_f	n/a	99.03	105.95	103.80	110.0

According to Table 3, the braid pitch and fiber volume content increase, and the braid angle decrease due to the reduction of braid diameter (die diameter).

The braid pitch was measured before and after pultrusion. The braid pitch and diameter were measured by a caliper on the braid preform and braid-truded rod at every 10 cm and 5 cm respectively. The braid-truded samples were prepared from the manufactured rods for microscopic observation. The samples were mounted in epoxy and then polished to obtain the cross-section images using an optical microscope (Metallovert, Leitz).

3. Results

3.1 Braid geometry measurements

Table 4 presents the averaged measurements for both the geometries of the braid preform before pultrusion and braid-truded rod after pultrusion. The braid angle was identical to the designed value from Table 2. However, the measured preform braid pitch and diameter are significantly different from the designed values of Table 2. The braid pitch is 4.5 mm longer and the braid diameter is 1.07 mm wider than design. This difference between actual and predicted values indicates that Eq. 7 is not able to determine the preform braid diameter (D_0) accurately. This formulation does not take into account the mechanics of braid such as fiber-to-fiber contacts and fiber tension that influences yarn and braid shapes. To obtain a precise prediction, fiber-to-fiber contacts should be included in the modeling assumption. In order to achieve such goal, a finite element braid-trusion model at fiber level (micro-scale) will be developed in the future works. As expected, the braid pitch increased by passing though the pultrusion dies. The braid angles (α) were calculated using the measured pitch (P) and diameter (D) via the Eq. 6. The braid angle of braid-truded rod decreased by 37% and the braid pitch elongated by 11% after pultrusion. It can be explained that the thermoplastic fibers melt and the braided carbon fibers become loose during pultrusion. At this moment, the dies compact the braid and the tensile load elongates the braid pitch.

Table 4. Measurement on the braid preform before pultrusion and braid-truded rod after pultrusion

	Braid pitch (mm)	Braid diameter (mm)	Braid angle
Braid preform	32.7 ± 0.8	7.3 ± 0.1	35.2° ± 0.7
Braid-truded rod	36.4 ± 0.5	4.7 ± 0.01	22.15° ± 0.3

3.2 Cross-sectional observation

The liquefaction of the PEI started in the first pultrusion die. The composite impregnation is performed by passing through the 4 dies. Fig. 3 illustrates a cross-section microscopy at 200× of a portion of the manufactured rod. Whilst the white circles are indicative of the carbon fibers, the gray-colored regions are the matrix and the black areas represent the voids.

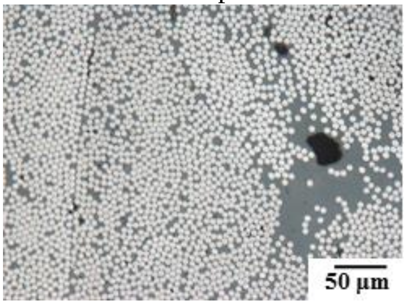

Figure 3. Microscopy image of the parameter C at 200×

3.3 Parametric studies

Fig. 4 shows the entire cross-section of the composite rod with three different spool tension of ~0.25, 40 and 80 N with speed of 50 mm/min and the cooling temperature of 200 °C (Parameter A-C). The fibers are well distributed throughout the cross-section. Resin rich regions can be observed in both along the yarn boundaries (Fig. 4a and b) and the center of the braid-truded rod (Fig. 4c). It can be seen that the void content increases when increasing the spool tension. This can be an indication that raising the spool tension condenses the carbon fiber bundles and reduces their permeability. The same behavior is also observed in Lapointe *et al.* [1] for the carbon/PEEK unidirectional yarns pultrusion. One can conclude that spool tension has a significant effect on the impregnation of thermoplastic braid-truded composites.

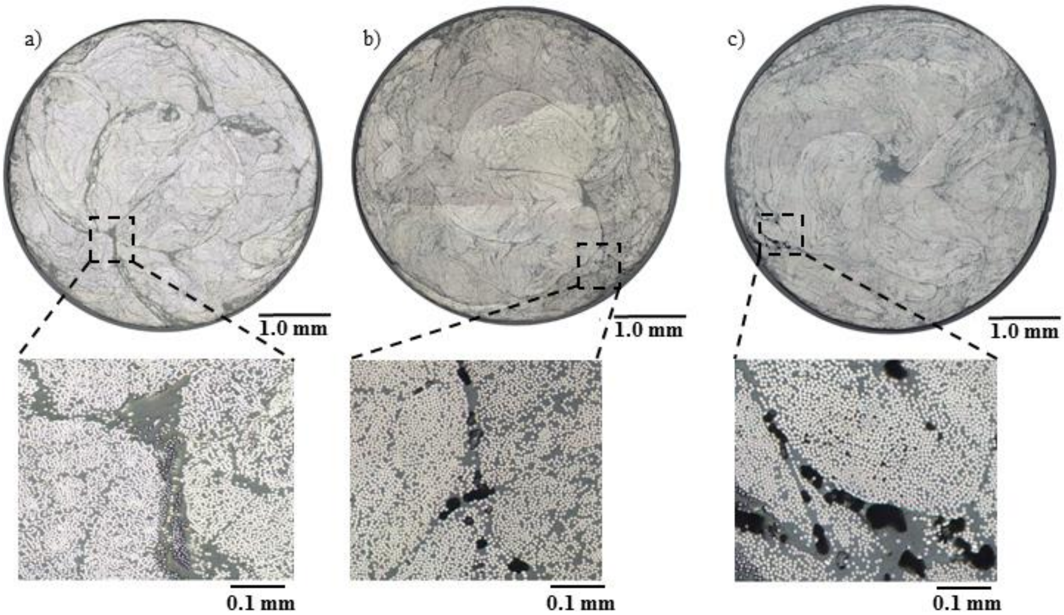

Figure 4. The effect of spool tension on the composite rod. The cross-section of manufactured rod with the spool tension of 2.5 N (a), 40 N (b) and 80 N (c).

Fig. 5 exhibits two distinct cross-sections of the composite rod manufactured with two different speeds of 50 and 150 mm/min with the same spool tension (Parameter A and F). These figures show the slightly higher amount of voids for the 150 mm/min braid-trusion. This indicates that the resin flow time was too short to allow impregnation of fiber bundles. It also can be observed that the smooth surface of the rod is roughed in the high-speed case. More investigations will be done to identify the source of bad surface finish at higher pultrusion speed.

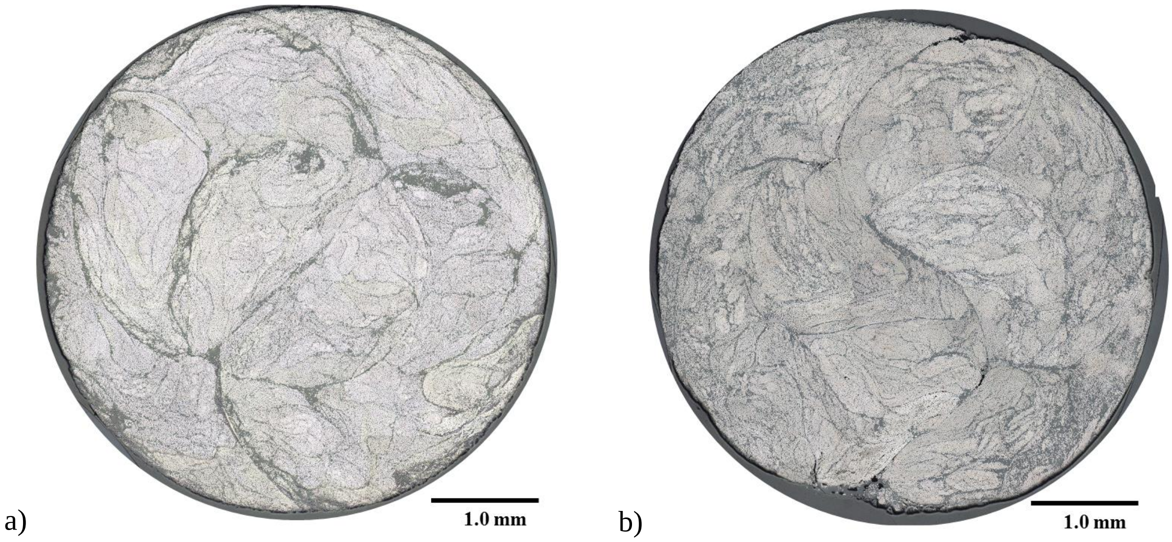

Figure 5. The effect of speed on the composite rod. The cross-section of the braid-truded rod with 50 mm/min (a) and 150 mm/min (b).

The influence of cooling die temperature on the braid-truded rod is shown in Fig. 6. The results are presented for two different cooling die temperatures of 200 (Fig. 6a) and 100 °C (Fig. 6b) with the same speed of 50 mm/min and the minimum spool tension (Parameter A and G). It is seen at Fig. 6a that surface finish at top and bottom of the image has bad quality. Reducing the cooling die temperature resulted in higher quality of the surface finish. This could be explained by faster cooling and therefore greater and faster shrinkage of the rod in the cooling die. The rod shrunk and debonded faster from the cooling die surface at the low cooling die temperature.

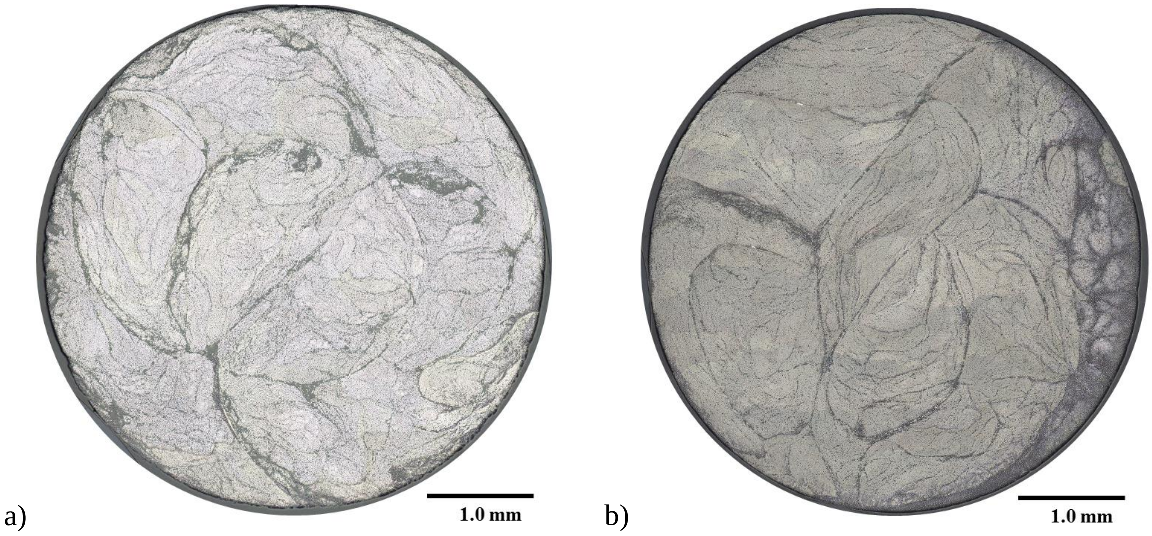

Figure6. The cross-section of braid-truded rod with cooling temperature of 200 °C (a) and 100 °C (b). Better surface finish is seen when cooling at 100 °C

4. Conclusions

A thermoplastic braid-truded rod was manufactured using the biaxial braid. The commingled carbon/PEI fibers were used to manufacture the braid with 35° braid angle. The biaxial braid was then pultruded using the multi-die pultrusion apparatus. The braid pitch and diameter was measured both before and after the pultrusion. During pultrusion, the preheater and pultrusion die temperatures were set at 300 °C and 400 °C, respectively. The spool tension, cooling die temperature, and speed were changed to evaluate their effect on the thermoplastic composite rod. The samples of the manufactured rod were prepared to characterize their morphology using the optical microscopy. It is found that these manufacturing parameters affect the thermoplastic composite rod and their effects can be summarized as,

- The braid angle of braid-truded rod decreased by 37% after pultrusion due to the dies compacting the braid and tensile load elongating the braid pitch.
- The void content raised slightly when the spool tension increased. Boosting the spool tension reduced the carbon fiber bundles permeability.
- The void regions grew with accelerating the process from 50 to 150 mm/min. The reason is the resin flow time was too short to completely penetrate carbon fiber bundles.
- The manufactured rod with the high-speed process had a rougher surface finish.
- High quality surface finish was achieved when the cooling die temperature dropped from 200 °C to 100 °C, and pultruding at 50 mm/min. It is suspected that the rod shrunk and debonded faster from the cooling die surface at the low cooling die temperature.

The impact of the braid structure such as braid angle and braid pattern will be the subject of future studies. Also, a finite element model of biaxial braid-trusion will be simulated in the future works to obtain an accurate prediction of rod fiber architecture. Finally, due to the lack of the results for the thermoplastic biaxial braid-trusion in the open literature, the obtained results could be used as a benchmark for the future works.

Acknowledgments

The authors would like to thank Bombardier, Pultrusion Technique, NSERC (CRDPJ488387-15) and Prima Quebec (R10-009) for financing this research project.

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