Thermoplastic matrix composites - new generation of eco-friendly materials

P. Esfandiari
ISEP-IPP
Engenharia Mecânica
4200-072 Porto
Portugal
pur@isep.ipp.pt

J. F. Silva
ISEP-IPP
Engenharia Mecânica
4200-072 Porto
Portugal
jfs@isep.ipp.pt

P. J. Novo
ESTG-IPL
Engenharia Mecânica
2411-901 Leiria
Portugal
paulo.novo@ipleiria.pt

Abstract

The biggest advantage in the use of thermoplastic composites is the possibility of recycling and reprocessing, which is not possible with thermosetting composites. The shorter manufacturing cycle time and lower chemical emissions are, as well, other advantages.

The use of thermoplastic matrix composites creates new engineering challenges concerning the manufacturing due to their high viscosity during manufacture. For all the advantages that these materials present, it becomes useful to study and evolve the universe of composites in the direction of thermoplastics.

In this work, continuous fiber thermoplastic composites were produced and transformed by pultrusion and heated compression moulding. The manufactured composites were then tested, and mechanical proprieties were determined and studied.

Keywords

Composite Materials; Continuous Fiber; Thermoplastic Matrix; Towpreg; Carbon Fiber; Polypropylene; Pultrusion; Heated Compression Moulding.

1. Introduction

At the middle of the second decade of the 20th century, thermosetting resins still dominate the composite industry, but thermoplastics are starting to replace them offering an increased fracture toughness, higher damage tolerance, shorter processing cycle times and excellent environmental stability (Novo, P. J. et al., June 2016).

Composite materials are very important to the development of solutions in the future focused on environmental issues, because of their relatively high specific properties such as rigidity and mechanical resistance. However, the inability to recycle thermosetting polymers still makes them harmful to the environment. The solution seems to be in thermoplastics, which are recyclable, post-formable and allow cleaner working environments. However, long or continuous fiber reinforced thermoplastic matrix composites are difficult to impregnate due to the higher viscosity of thermoplastics, resulting in a less well consolidated composite with lower mechanical properties than expected.

The work here developed was carried out with the aim of trying to make the processing of continuous thermoplastic matrix composites viable without ignoring mechanical properties.

2. Efficiency and Sustainability

With the technological development and possibility of finite element analysis, composite materials are often chosen as a lightweight and high-performance solution when compared with traditional materials. In fact,

2183-3060/2018/0601-026

in industries where the cost factor is not decisive (aeronautical, aerospace) composites are already being used. Having said that, we start to see the automotive industry which is known for demanding rates of production at a reasonable price to use continuous fiber composites in their solutions.

In 2013, BMW started producing a vehicle designated “i3” consisting in an all-electric vehicle with most of the material used in its structure and body being carbon fiber. Carbon fiber is very expensive, but results in a relatively light car, allowing it to have an interesting range (Reinforced Plastics., January 2014). But the i3 isn’t a high-end luxury vehicle, it has a relatively low price for an electric car and in 2017 is still being mass produced. This raised the bar in the automotive industry and today we see more cars using carbon fiber composites.

At the end of an automobile’s life, a process of reusing and recycling parts is done and around 85% of a mainstream car be recycled (Millet, D.; Yvars, P. A.; Tonnelier, P., January 2012). Due to the nature of thermoset polymers, composites with these matrices are not possible to recycle while thermoplastics are. Furthermore, because a curing time for thermoplastic composites is inexistent, a lower cycle time is achieved, and thermoplastics are a popular approach in composites of automotive industry [2].

The manufacturing processes of thermoplastic composites in this work are possible for a large variety of materials, including glass fibers and polymers known for having a high recyclability rate such as PET (Hopewell, J.; Dvorak, R.; Kosior, E. June 2009). Industry today recognizes that composites are very important to improve efficiency, and in the case of thermoplastics, sustainability is also a great advantage.

3. Experimental

3.1. Raw Materials

The carbon fibre used to produce the thermoplastic pre-impregnated material was the TORAYCA® M30S C from Toray Industries, with a linear weight of 760 Tex. The copolymer powder polypropylene used was the ICORENE® 4014 from A. Schulman. Mechanical properties of the raw materials used are listed in Table 1.

Table 1. Mechanical proprieties of materials (Novo, P. J. et al., July 2015).

Property	PP Powder ICORENE® 4014	Carbon Fiber TORAYCA® M30S C	
	Manufacturer	Manufacturer	Experimental [5]
Linear density (Tex)	-	760	-
Specific gravity (Mg/m^3)	0.90	1.73	1.75
Tensile Strength (MPa)	24	5490	2731
Young Modulus (GPa)	1.15	294	194.5
Poisson´s ratio	0.21	-	-
Average powder size (µm)	400	-	-
Average fibre diameter (µm)	-	5	7.37

3.2. Production of Thermoplastic Matrix Pre-Impregnated Materials

There are two impregnation processes for manufacturing thermoplastic pre-impregnated materials (Novo, P. J. et al., July 2015).

- Direct melting of the polymer (ex. PCT);

- Intimate fiber/matrix contact prior to final composite fabrication (ex. towpreg).

Intimate contact processes have some major advantages like the lower costs of production of the prepreg and the non-dependence of the viscosity of the thermoplastic used as matrix. In this work, towpreg was produced using the dry powder coating equipment schematically depicted in Figure 1.

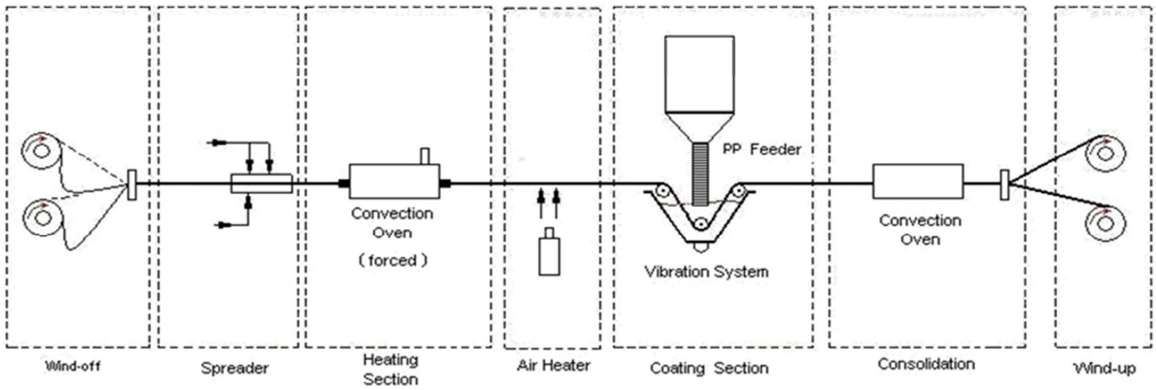

Figure 1. Powder coating line setup

The optimization of the variables for towpreg production was done in a prior work (Novo, P. J. et al., September 2014). Different processing variables and combinations were tested, and after trials, the process was optimized by the Taguchi approach.

The optimal parameters to manufacture CF/PP towpreg were:

- Convection oven: 700°C;
- Consolidation oven: 400°C;
- Linear pull speed: 6 meters per minute.

In this machine around 1800 meters of towpreg was produced which were then wrapped in 36 bobbins to transform by pultrusion.

3.3. Transformation of Thermoplastic Prepregs by Pultrusion

Pultrusion is a continuous transformation process of pre-impregnated composites to produce profiles with a constant cross-section, having the fibers disposed in the direction of the production line (Moura, M.; Morais, A. B.; Magalhães, A. G, 2011).

In this work, thermoplastic composites were manufactured using a 10 kN pultrusion line equipment installed in ISEP and schematically depicted in Figure 2. This equipment is divided by 5 main parts:

1. Bobbin holder;
2. Guidance system;
3. Pultrusion head:
    a. Pre-heating furnace;
    b. Pressurization die;
    c. Consolidation die.
4. Pulling system;
5. Profile cutting system.

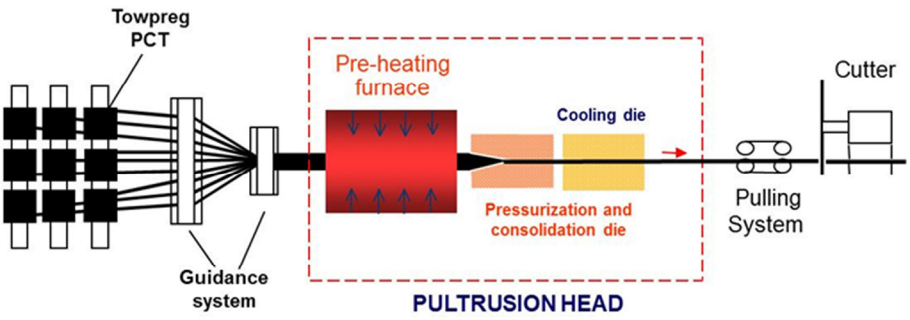

Figure 2. Pultrusion line

The number of towpreg rovings used to produce a 20x2 millimeter cross section was 36. During pultrusion various parameters were tested and the optimal for processing this towpreg are presented in Table 3.

Table 2. Pultrusion parameters

Condition	Pre-heating oven (ºC)	Heated die temperature (ºC)	Cooled die temperature (ºC)	Pulling speed (m/min)
1	160	200	25	0.2
2				0.3

During pultrusion two pulling speeds were used to study the variation of properties of the composites with the increment of rate of production. With the temperatures listed in Table 2 and 0.2 and 0.3 meters per minute of pulling speed, it was possible to produce the composite profile without having difficulties in the process.

3.4. Transformation of pultruded composites by heated compression moulding

Heated compression moulding was carried out in a 200 kN Gislotica heated plate press installed in ISEP to manufacture a composite laminate. The pultruded composites were placed in a frame and a PTFE based releasing film was used to sustain temperatures as high as 250°C. In Figure 3 the assembly for heated compression moulding can be seen.

Figure 3. Set-up ready for processing

The produced laminate is in Figure 4.

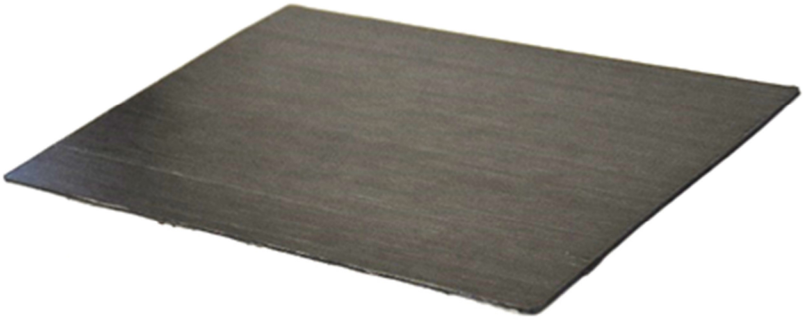

Figure 4. Laminate

To manufacture the laminate the pultruded material was heated up to 250°C and maintained that temperature for 10 minutes to ensure the uniformity of temperature in all areas inside the mold. Then, a compression force was done to consolidate the laminate. Finally, it was cooled down and the laminate was taken out of the mold.

4. Results

Manufactured composites were tested to evaluate the mechanical properties obtained. Tests were carried out in a 100 kN Shimadzu® universal testing machine installed in ISEP to obtain flexural properties in accordance to ISO 14125. Calcination tests were carried out in a Nabertherm® LHT08/16 muffle furnace following a new method developed for carbon fiber composites (Novo, P. J. et al., June 2016). Conditions 3 and 4 are referred to composites transformed by heated compression moulding.

Table 3. Mechanical properties of tested conditions

	Condition	Pulling speed (m/min)	Flexural Properties		Fiber content		Flexural properties / Fiber volume fraction	
			Modulus (GPa)	Strength (MPa)	Mass (%)	Volume (%)	Relative Modulus (GPa)	Relative Strength (MPa)
Pultrusion	1	0.2	63.8 (±4.0)	211.2 (±18.8)	62.6	46.4	137.6	455.2
	2	0.3	44.9 (±2.0)	134.9 (±14.7)	63.1	47.1	95.3	310.8
Compression Moulding	3	0.2	73.8 (±4.0)	265.7 (±11.9)	63.2	47.2	156.3	562.9
	4	0.3	70.4 (±9.5)	209.4 (±8.8)	63.0	47.0	149.9	445.5

By a simple analysis of Table 4 it's possible to understand that the increasing of pultrusion speeds affects significantly the flexural strength of these composites. This is expected because a reduction in exposure time to temperature and pressure during processing, leads to a lower quality of impregnation. The percentage of voids is likely to be higher resulting in a less well-consolidated composite.

The conditions transformed by heated compression moulding improved considerably the mechanical properties, especially in the case of the composite with higher pultrusion speed. The reason is the improved impregnation due to the relatively higher exposure time to heat and pressure in the heated plate press, allowing the polymer to migrate throughout the laminate filling the spaces between fibers and reducing voids.

Fiber content in the conditions were somewhat similar meaning pultrusion helped to uniformize the amount of polymer in the pultruded composites. It seems that there was no loss of polymer by degradation in heated compression moulding, which is expected knowing that processing temperatures were lower than degradation temperatures of this polypropylene (Novo, P. J. et al., June 2016).

5. Conclusions

The aim of this work was to study the variation of properties when higher pultrusion processing speeds were applied, and to understand if heated compression moulding would improve the mechanical properties of pultruded composites.

The first part of this work consisted in the production of carbon fiber and polypropylene towpreg and 36 rovings were successfully produced to transform by pultrusion. In the pultrusion process, speeds of 0.2 and 0.3 meters per minute of processing were used.

Mechanical properties obtained allowed us to conclude that flexural strength and modulus decreased with increasing speeds of pultrusion, yet the composites transformed by heated compression moulding increased mechanical properties substantially, especially the ones pultruded at higher speeds.

Finally, it's important to note that continuous fiber thermoplastic composites are an interesting approach not only for efficiency, but also for environmental and sustainability issues. More research should be done with more affordable materials like glass fiber to meet the demands of industries such as automotive industry.

References

Reinforced Plastics. (January 2014). Carbon Fibre and cars – 2013 in review.

Millet, D.; Yvars, P. A.; Tonnelier, P. (January 2012). A method for identifying the worst recycling case: Application on a range of vehicles in the automotive sector.

Hopewell, J.; Dvorak, R.; Kosior, E. (June 2009). Plastics recycling: challenges and opportunities.

Novo, P. J.; Silva, J. F.; Nunes, J. P.; Marques, A. T. (June 2016). Processing of carbon reinforced thermoplastic pre-impregnated materials.

Novo, P. J.; Silva, J. F.; Nunes, J. P.; Marques, A. T. (July 2015). Advances in thermoplastic pultruded composites.

Novo, P. J.; Silva, J. F.; Nunes, J. P.; Marques, A. T. (September 2015). Pultrusion of fibre reinforced thermoplastic pre-impregnated materials.

Novo, P. J.; Silva, J. F.; Nunes, J. P.; Marques, A. T. (September 2014). Advanced Thermoplastic Carbon Fibre Reinforced Pultruded Composites.

Moura, M.; Morais, A. B.; Magalhães, A. G (2011). Materiais Compósitos.

Novo, P. J.; Nunes, J. P.; Silva, J. F.; Marques, A. T. (June 2017). Processing of carbon reinforced thermoplastic composites.