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Film-insert Injection Compression Molding for Reinforced Polycarbonate with Woven Glass Fiber Oriented 90/0°, ± 45 º

Introduction

To widen the range of application for plastic materials, new polymer composites with added reinforcing materials on the plastic matrix are being developed increasingly replacing components made of metal or thick-walled plastic parts, most commonly, with short fiber glass reinforcement [1, 2]. They provide high levels of strength at extremely low weights and can be manufactured in short cycle times in large industrial quantities. Being materials reinforced with short fiber (0.2 to 0.4 mm in length, and larger fibers with lengths greater than 1mm) are affected the mechanical properties, strength, stiffness, and impact with no location of failure caused by anisotropic material due to the non-uniform fiber orientation distribution.

In the film-insert injection molding (FIM) process, the molten polymer is injected into the mold cavity where one side of the mold wall is insulated by a pre-attached film. FIM is a cost and time-effective technique eliminating various post-processing procedures (screen printing, spray painting, laminations etc.) and improving surface quality as well as durability. Many products such as automotive interior parts, cellular phone cases, logo designs on plastic products are produced using FIM method [3,4] Adhesion between the film and the substrate may be enhanced using this process as the injected hot molten resin can partially melt the film [5].

The pressure produced in this process is more uniform along the cavity wall, and lower for post filling stage, and therefore results in less residual stress as well as less part warpage [6,7] The injection compression molding differs from traditional injection molding in terms of cavity filling, where there is further melt flow and reduction of cavity volume during the packing step. The compression stage after the partial melt filling of the cavity decreases the mold pressure and clamp tonnage by 20–50%, and reduces the cycle time and residual stresses [8]

Existing studies have reported optimum material combinations for best structural performance but there is still a lack of information on polycarbonate reinforced with woven glass fiber manufactured by injection molding; therefore, this work addresses a way to expand on existing knowledge/proposals. One key aspect of this research is the introduction of woven glass fiber as reinforcement for thermoplastic polymer with fiber orientations at 0/90º and ± 45 º, maintaining the main characteristics of film injection molding , combined with compression injection molding and ensuring minimal fiber misalignment and polycarbonate degradation during process. (**Figure 1**)

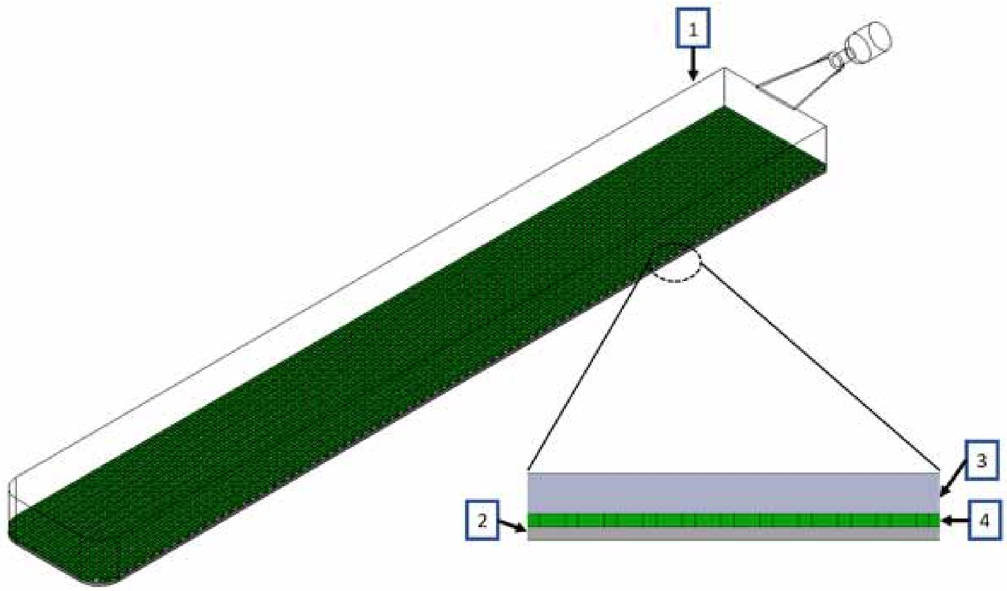

Figure 1: Components of FIM and compression. (1) Specimen of 250 x 35 mm. (2) Film of polycarbonate. (3) Polycarbonate injected. (4) Woven glass fiber oriented (90/0°, -45/45°).

Experimental

Based on the process of injection and compression, it was decided to create an insert that would be placed inside the tooling prior to injection. This insert, would be composed of a polycarbonate film adhered to a fiber oriented 0/90 and -45/45 degrees. With this the temperature of the polymer when entering the cavity, would deform the polycarbonate film in such a way that both materials adhere, allowing the fiber to remain between both materials.

Film Inserts

A polycarbonate film (Makrolon Film) of 0.85 mm thickness was laser-cut to obtain a rectangular sample with dimensions of 250 x 35 mm. The reinforced woven glass fiber with thickness of 0.38 mm, was cut oriented at 0/90 ° for one type of specimen and ± 45° for other specimens, cut in same dimension of the Makrolon film. No previous treatment was applied to the fiber.

Injection Material

Polycarbonate pellets (MAKROLON AL2407) were used as the main body matrix in this study. These pellets possess a melting temperature of 280-320 °C, a melt flow index of 19 g/10 min in rheological standard testing conditions (ISO1133), perpendicular shrinkage of 0.8 wt.% to the flow direction, and parallel shrinkage of 0.65 wt.% to the flow (ISO294-4) [9].

Method

To determine clamp force, a 3D FE analysis was performed. This model was realized with the finite element software, Moldflow. Principal characteristic is necessary for later realize studies of physical and mechanical characterization. (**Figure 2**)

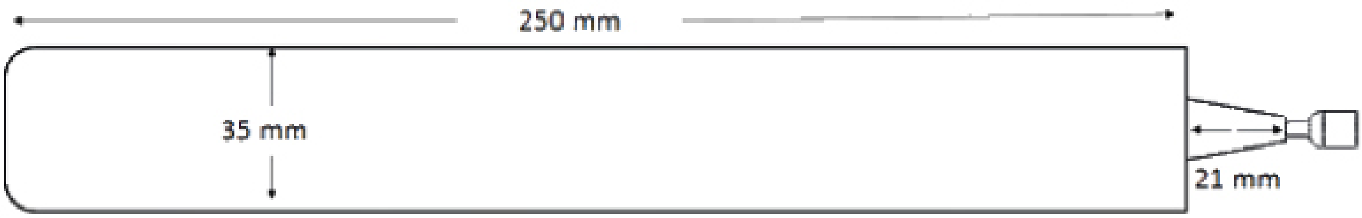

Figure 2: General dimension of specimen reinforced with woven glass fiber.

A normal filling analysis can be determined with the main equations. These equations are applicable to the flow of a polymer in the molten state and are obtained using the principles of mass, momentum and energy conservation.

$$\frac{\partial \rho}{\partial t} + \nabla + \rho v = 0 \quad (1) \text{ Continuity}$$

Where ρ is the density, t is the time, and v is the velocity vector.

$$\rho \frac{\partial v}{\partial t} = \rho g - \nabla p + \nabla n D - \rho V \; \nabla \boldsymbol{\tau} \; (2) \text{ Momentum}$$

Where g is the gravity and $\boldsymbol{\tau}$ is the shear stress.

$$\rho c_p \left(\frac{\partial T}{\partial t} + v \; \nabla T \right) = \beta T \left(\frac{\partial p}{\partial t} + v \; \nabla p \right) + n \dot{\gamma}^2 + k \nabla^2 T \; (3) \text{ Energy.}$$

Where T is the temperature field, Cp is the heat capacity, k is the thermal conductivity coefficient, n is the viscosity of the fluid, $\dot{\gamma}$ is the shear rate. In general, this three equations will be needed to provide and accurate analysis.

As the first point, the analysis was determined, which is an injection-compression analysis. The point of injection was in the initial part of the piece, so that the mesh was made from that node, the type of mesh was different in nozzle, because it was determined that this part is considered as a hot injection system and then a refinement was made in the gate to analyze how flow front can affect orientation of woven glass fiber as shown in **Figure 3**.

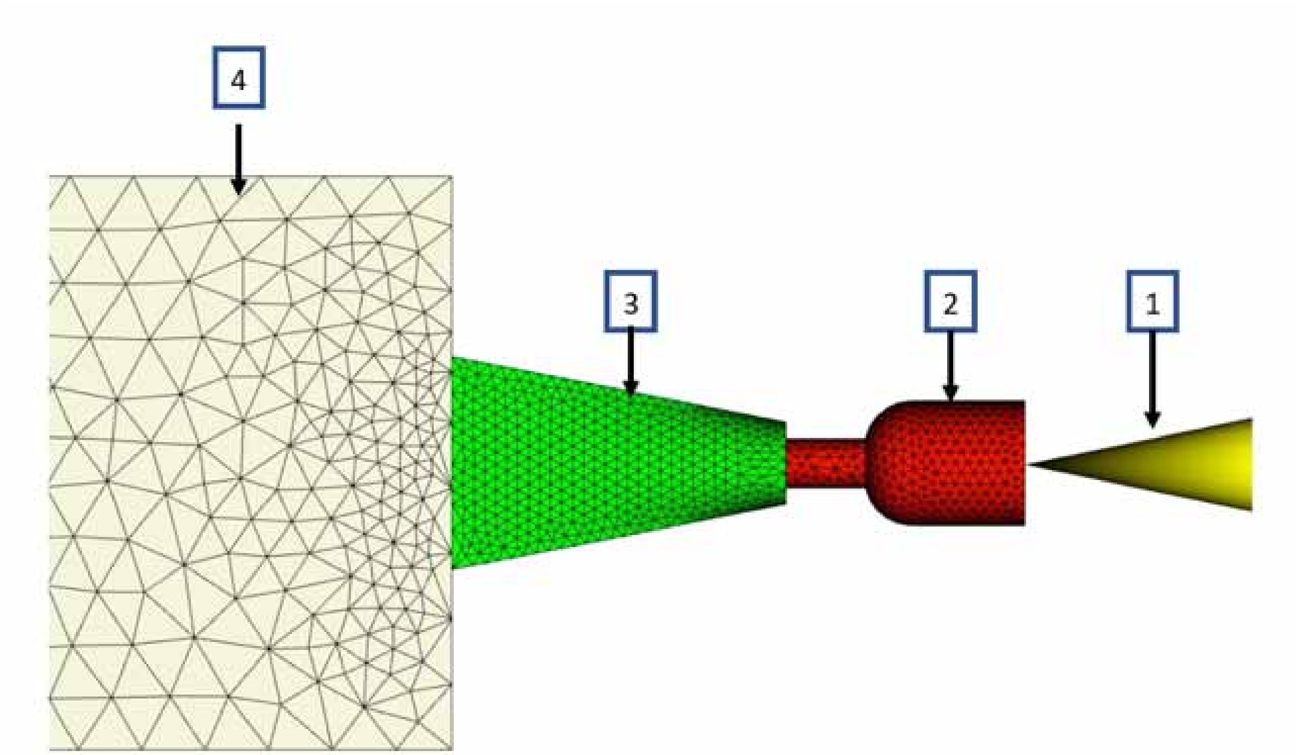

Figure 3: Section view of type of mesh used for injection, compression molding. (1) Injection location, (2) Hot runner, (3) Fan gate, (4) Specimen part

For melt flow, a fan gate is used to slow the melt as it enters to the male part, the benefits of slower the flow, improved melt orientation and reduced the chance of jetting, which affects the result of mechanical properties of the specimen.

Table 1 shows the initial conditions and **Table 2** the meshing values of the piece are shown once the 2D mesh is repaired and then the 3D meshing is carried out.

After numerical simulation a mold was designed and manufactured to be used as a film insert and injection compression mold, for a vertical injection molding machine (Battenfeld PLUS 350/75). The male part consists in a small cavity to hold the film insert during injection process, no fixing mechanism is used for film insert,

Table 1: Initial Conditions

Volume total.	22.62 cm3
Material	PC (Makrolon Al2447 Covestro)
Volume of specimen.	.04 cm3
Volume to fill.	22.82 cm3
Volume of specimen.	21.8281 cm3
Injection temperature.	320°C
Mold temperature.	100 °C
Volume of gate.	0.34 cm3
Injection time.	1.6 seg.
Projected area.	89.19 cm2

Table 2: Mesh

Type of mesh.	3D Tetragonal
Layers.	8
Nodes	12176
Injection points	1
Nodes on injection location.	1
Number of elements	61916
Tetragonal Elements	55493
Elements in hot runner	6423

the space between the male part and female part permit melt polycarbonate to continue flowing during compression stage, and also to released specimen with no using ejector pins. For compression, two single hydraulic cylinders were used. The female part, consist of a straight surface for preventing flashing in the specimen during compression stage; a hot runner system was employed in the female part, to maintain temperature of the polymer in 110ºC, this allows the melt to be at lowest viscosity with no temperature degradation when it reaches the cavity and allows polymer to flow during compression stage. The mold temperature was controlled with a water mold cooling peripheral system, for preventing heat exchange between the mold and the injection machine.

The polycarbonate pellets for injection were conditioned previously on a drying machine for 4 hours before process. And the mold was prepared setting the hot runner system temperature in the female side at 110 ºC, and cooling system at 85ºC. The film insert (polycarbonate film and woven glass fiber) was placed while mold was opened. The mold closed with clamp force of 31.15 kN in 4.95 seconds, and injection pressure set on 1094 bar during 1.6 seconds, at that point compression started with two simple hydraulic cylinders (50kN) over 10 seconds to complete filling and compress the polycarbonate until the cooling stage is over.

Results

Once the simulation was carried out, the tooling for injection and compression was made, the tests were carried out to obtain the compound. It is worth mentioning that this process was not the only option for which this compound was wanted. Within those options was the compression and injection process with no good results.

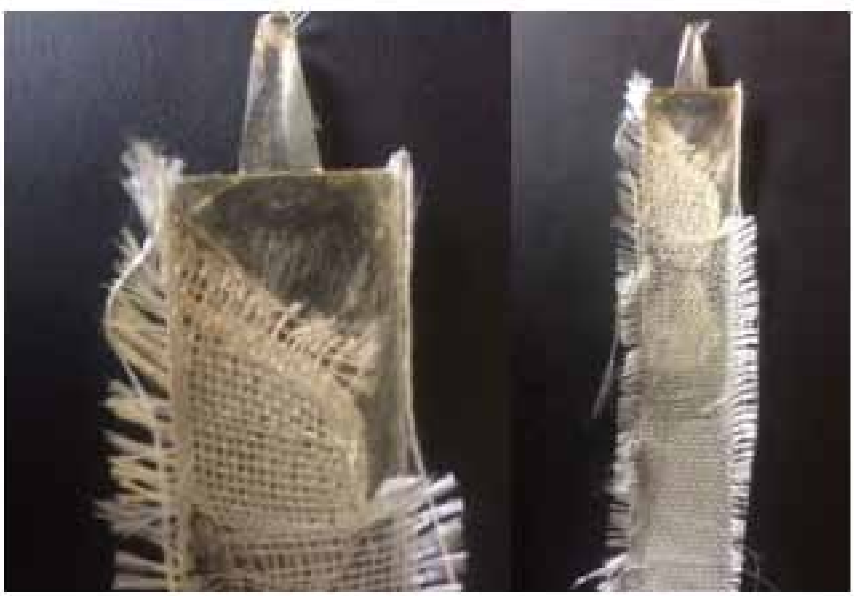

Figure 4: Degradation of polycarbonate and misalignment cause for flow advanced.

Process Justification

Injection tests were carried out, showing defects as shown in **Figure 4**, where degradation of the material can be seen due to the residence time in the injection unit and a lot of distortion of the fiber caused by the drag that caused the polycarbonate when entering the cavity.

Another defect shown in the injection process was the poor impregnation because the polymer did not completely cover the glass fiber as shown in **Figure 5** . On the other hand, the thickness of the specimen was very high as shown in **Figure 6**, the process was not constant, so it was decided to modify the process.

Figure 5: Bad impregnation during injection.

Figure 6: Very high thickness.

Simulation Results

In this section, the results of the numerical simulation are shown to determine if the injection machine and pistons remain within the range of operation required to obtain the glass fiber reinforced polycarbonate plate.

Figure 7 shows the pattern of filling and compression of the piece, it is seen that at the beginning the pistons are retracted, so the initial volume inside the cavity is greater, until the piece is compressed.

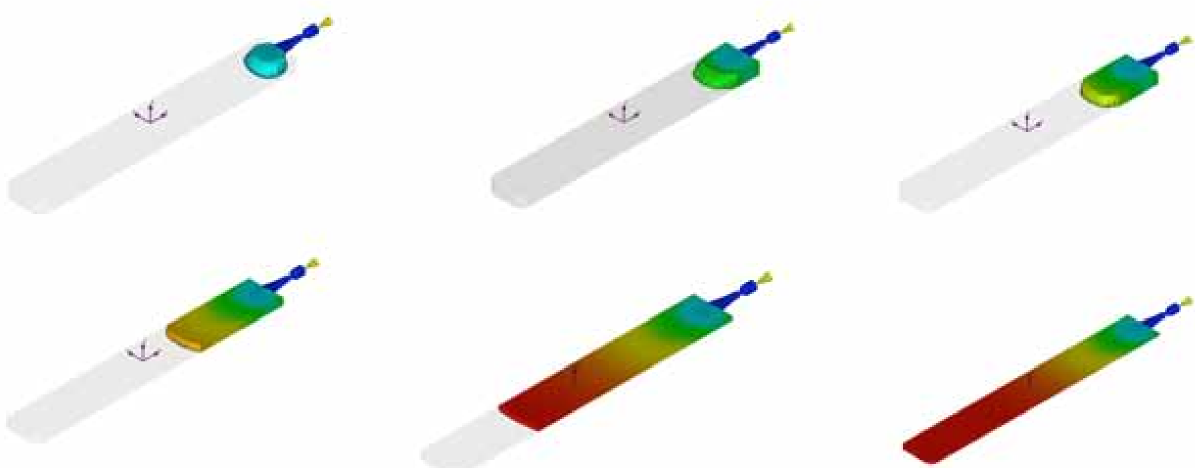

Figure 7: Filling and compression pattern.

Table 3: Simulation Results.

Total mass	23.3219 g
Specimen mass.	23.3260 g
Gate mass.	0.3759
njection pressure.	14.98 Mpa.
*Clamp force.	12.19 Toneladas.
Swicth over.	1.67 segundos.

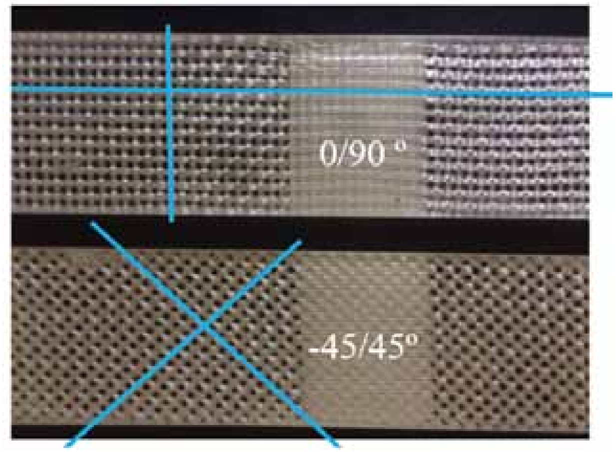

Figure 8: Visual inspection of polycarbonate reinforced with woven glass fiber oriented in 0/90° and -45/45°.

As results of the simulation, the following values were obtained, as shown in **Table 3.**

FIM and Compression

Once the tests were done and discarding the injection process, the inserts were made, creating an adjustment between the cavity and said inserts, this with the purpose that the fibers were completely immovable allowing the flow of the polycarbonate without altering the orientation of the fiber. As shown in the figure 8, the orientation of the fiber with respect to the injection process was greatly improved at first sight. **Table 4** and **Table 5** show the measurements made with a goniometer.

Table 4

Results for fiber orientation θf in degrees for 0/90º specimens.

Specimen	P1-0-90º		P2-0-90º		P3-0-90º		P4-0-90º		P5-0-90º	
1	0,00	90,00	0,00	90,00	3,00	90,00	3,00	91,00	0,00	89,00
2	0,00	90,00	0,00	90,00	3,00	92,00	4,00	89,00	0,00	89,00
3	0,00	90,00	0,00	90,00	3,00	91,00	4,00	93,00	0,00	90,00
4	0,00	90,00	0,00	90,00	4,00	91,50	5,00	92,00	0,00	91,00
5	0,00	96,00	0,30	90,00	4,00	90,00	6,00	93,00	0,00	89,00
6	0,00	94,00	0,40	90,00	2,60	90,00	5,00	93,00	0,00	91,00
7	0,00	94,00	0,00	90,00	4,00	90,00	5,00	93,00	0,00	91,00
x	0,00	92,00	0,10	90,00	3,37	90,64	4,57	92,00	0,00	90,00
s	0,00	2,58	0,17	0,00	0,60	0,85	0,98	1,53	0,00	1,00
CV	0,00	0,03	1,73	0,00	0,18	0,01	0,21	0,02	0,00	0,01

Averaged Values	PT-0	PT-90
xT	1,61	90,93
sT	0,43	1,01
CV_T	0,27	0,01

Table 5
Results for fiber orientation θf in degrees for ± 45 specimens.

Specimen	P1-45°		P2-45°		P3-45°		P4-45°		P5-45°	
1	44,00	-45,00	43,00	-41,00	41,00	-42,00	37,00	-45,00	44,00	-42,00
2	44,10	-44,00	43,00	-41,00	41,00	-42,50	37,00	-46,00	44,00	-42,00
3	42,50	-42,00	43,00	-40,00	43,00	-42,00	38,00	-47,00	45,00	-42,00
4	44,00	-42,00	43,00	-42,00	45,00	-42,00	38,00	-47,00	45,00	-42,00
5	46,00	-44,00	40,00	-42,00	42,00	-42,00	39,00	-48,00	45,00	-43,00
6	46,00	-43,00	40,00	-41,00	45,00	-42,00	39,00	-48,00	44,00	-43,00
7	46,20	-43,00	41,00	-40,00	45,00	-42,00	40,00	-47,00	44,00	-44,00
x	44,69	-43,29	41,86	-41,00	43,14	-42,07	38,29	-46,86	44,43	-42,57
s	1,40	1,11	1,46	0,82	1,86	0,19	1,11	1,07	0,53	0,79
CV	0,03	-0,03	0,03	-0,02	0,04	0,00	0,03	-0,02	0,01	-0,02

Averaged Values	PT +45	PT -45
xT	42,48	-43,16
sT	2,60	2,23
CV_T	0,06	-0,05

Discussion

The polycarbonate is degraded due to the residence time of the material inside the injection unit, this is because when placing the polycarbonate film with the fiberglass, it is complicated to carry out manually and considering that there is no a fastening system, it does something complicated.

The temperature of the polycarbonate could not be below 320, because it did not allow the advance of the flow during the compression stage, which is why it was found that one of the polycarbonates that withstands the temperature of 320-325° was Makrolon.

During the simulation, values could be obtained that agree with the physical characteristics that were counted, such as pistons and injector machine. However, in the simulation, the partial or total adhesion etween the two types of polycarbonate cannot be determined. Another important factor with which simulation does not count, is how to determine the orientation of the fibers oriented during the injection and later the compaction. It is worth mentioning that this factor was determining on foot machine and making several settings to obtain the desired results.

Specimens of polycarbonate reinforced with 4% of woven glass fiber at 0/90°and ±45° orientation have demonstrated small fiber orientation distortion. For the case of 0/90° specimens, the maximum deviation is show in the specimen with 2.58° that represent a misalignment cause by compression stage where injection flow is getting cooler, which also happened in 0° where the maximum standard deviation is 0.98°. These figures demonstrate that film injection and compression molding for the process used is controlled and few distortions is evident. Specimens at + 45° have a standard deviation of 1.86°, and for fibers at -45° have a value of 1.11°.

From the measurements for the +45 fibers, the standard deviation is 2.60° and 2.23° for -45°, those values are bigger than the values obtained for each specimen, one possible reason is a small fiber deviation due to the preparation of the film insert, but a less controlled repeatability due to manual skills needed. In general, the misalignment of the sample is small, and a small fiber misalignment is concluded for the film injection and compression process.

Conclusion

Traditional methods of injection and compression, are not feasible to reinforce the polycarbonate with glass fibers, this because the fibers lose their desired alignment. Some of the traditional processes such as thermoforming and compression have shown that there is no complete adherence between fiberglass and polycarbonate.

In this article it was demonstrated that a material reinforced with fiberglass can be obtained, without having to chemically attack the fiber previously. As future research, the physical and mechanical properties of the material must be obtained to determine if an improvement is obtained.

Acknowledgements

The authors appreciate the assistance provided by the material testing laboratory at IPN ESIME Ticomán in the development of the mechanical test, especially to Mr. David Anaya Gallegos. Also to Polimeros y Compositos S.A de C.V for providing the material, manufacturing machinery, the mold injection and the injection tests to obtain the material used for this research. Mr. Omar Solorza is also grateful to CONACYT-Mexico for their doctoral fellowship #446307.

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