Vol 26 (1)

Ingeniería y
Competitividad
Vol 26 (1) 2024; doi: 10.25100/iyc.v26i1.13326

ISSN
0123-3033
e- 2027-8284

Original Research

Effects of injection molding conditions on the mechanical performance of plastic parts

Efecto térmico y del procesamiento por inyección de piezas plásticas en su desempeño mecánico

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Abstract

The quality of parts manufactured by thermoplastics injection molding can be evaluated based on product weight, appearance, and presence of defects. Furthermore, the conditions of the injection process can significantly influence the mechanical performance of the molded parts. Residual stresses generated during plastic processing may contribute to the formation of cracks or premature failures when the product is subjected to external loads or forces. This study aims to evaluate the effects of the injection process on an injected part and how they affect its mechanical performance. For this purpose, specimens were injected under different process conditions and, subsequently, employed in a. Some parts were also subjected to annealing (a thermal treatment) to induce molecular relaxation, which helps to reduce internal or residual stresses generated during the injection process. Additionally, a qualitative evaluation of the distribution of residual stresses in the injected parts was conducted using the s technique to complement and validate the results of the mechanical tests. The results of the specimens injected at a mold temperature of 50°C showed a greater release of residual stresses, as indicated in photoelasticity images analyzed here, and a noticeable increase in flexural strength if the heat treatment had been applied. This suggests that more residual stresses are produced at 50°C than at the recommended mold temperature of 80°C. The heat treatment significantly improved the mechanical performance of all the parts injected in this study under different processing conditions.

Resumen

El grado de calidad de piezas fabricadas por inyección de termoplásticos se puede establecer por el peso del producto, apariencia y mínimos defectos. Adicionalmente, las condiciones del proceso de inyección pueden inducir un efecto en el desempeño mecánico de las piezas inyectadas, donde los esfuerzos residuales de la pieza inyectada generados en el procesamiento pueden promover la formación de grietas o fallas prematuras del producto durante su uso al aplicarle una carga o fuerza externa. El propósito del presente trabajo es evaluar el efecto que genera el procesamiento por inyección en una pieza inyectada en el desempeño mecánico de esta. Para tal fin, se inyectaron probetas bajo diferentes condiciones de proceso y posteriormente estas fueron sometidas a pruebas mecánicas de flexión, algunas piezas fueron llevadas a un tratamiento térmico de recocido "annealing", con el fin de obtener una relajación molecular que permita reducir sus esfuerzos internos o residuales generados durante el proceso de inyección. Adicionalmente, se hizo una evaluación cualitativa de la distribución de esfuerzos residuales en las piezas inyectadas mediante la técnica de fotoelasticidad, para complementar y validar los resultados de las pruebas mecánicas. Se halló en los resultados de las muestras inyectadas a temperatura de molde de 50 ºC una mayor liberación de esfuerzos residuales de acuerdo con las imágenes de fotoelasticidad analizadas y un mayor porcentaje de incremento en la resistencia a la flexión de estas piezas al aplicar el tratamiento térmico. Lo que podría sugerir una mayor generación de esfuerzos residuales a esta temperatura de molde con respecto a la temperatura de molde recomendada de 80 ºC. El efecto de tratamiento térmico mejora significativamente el desempeño mecánico de todas las piezas evaluadas a las diferentes condiciones de proceso.

Keywords: Residual stress, injection molding, plastic parts, mechanical properties, thermal treatments.

Palabras clave: Esfuerzos residuales, moldeo por inyección, piezas plásticas, propiedades mecánicas, tratamientos térmicos..

How to cite?
Vargas-Isaza, C.A., Posada-Correa, J.V.,Urrego-Yepes, W., Castro-Caicedo, A.J. Effects of injection molding conditions on the mechanical performance of plastic parts. Ingeniería y Competitividad, 2024, 26(1); e- 22013326.

https://doi.org/10.25100/iyc.v26i1.13326

Recibido: 3-11-23
Aceptado: 02-03-24

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Conflict of interest: none declared

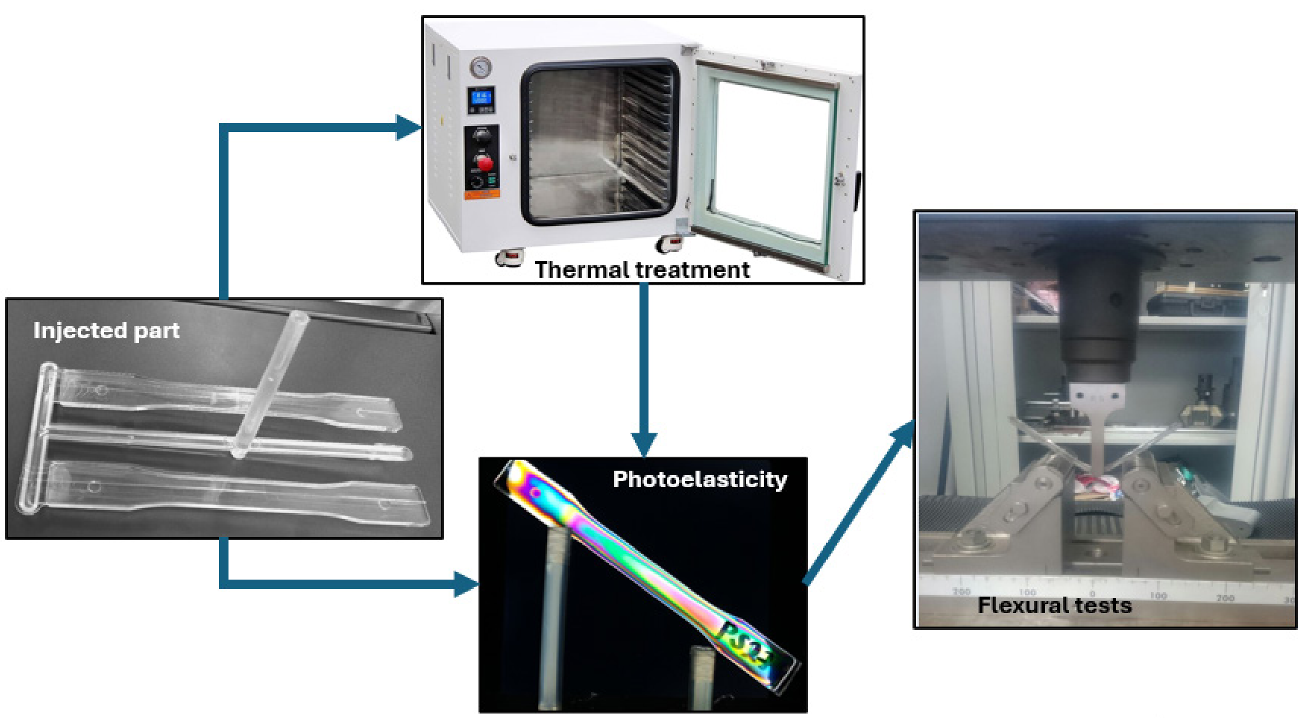
OPEN ACCESS

Why was it carried out?
The research was conducted to evaluate the influence of thermoplastic injection process conditions on the mechanical properties of the injected parts. Additionally, annealing heat treatment and photoelasticity were employed as techniques for releasing and visualizing residual stresses in materials subjected to manufacturing processes like injection molding.

What were the most relevant results?
The results of the specimens injected at a mold temperature of 50°C showed a greater release of residual stresses, as indicated in photoelasticity images analyzed here, and a noticeable increase in flexural strength if the heat treatment had been applied. This suggests that more residual stresses are produced at 50°C than at the recommended mold temperature of 80°C. The heat treatment significantly improved the mechanical performance of all the parts injected in this study under different processing conditions.

What do these results provide?
The results obtained provide insight into the importance of considering manufacturing conditions to which the materials are subjected. Both fusion and solidification processes can significantly influence the residual stresses in manufactured parts.

Graphical Abstract



doi: 10.25100/iyc.v26i1.13326

Introduction

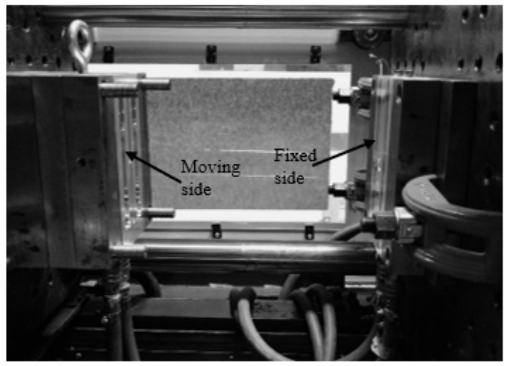
There are different methods to control the quality of injected plastic parts based on measurements of residual stresses in the part. These methods can be classified into destructive and non-destructive testing. The former include the hole-drilling technique (1), the layer removal method, and chemical attack (2). Among the non-destructive testing techniques, photoelasticity stands out. It is implemented using clear materials (such as polycarbonate) and their the refraction indices, which depend on the polarization and propagation of the light that hits the material (3). This property is then utilized to observe (residual) mechanical stresses and anisotropy in the material (4). In addition, thermal treatments can be applied to injected parts; for instance, annealing can be used to release residual stresses in a controlled manner (5–8). However, to evaluate the mechanical performance of injected parts, laboratory testing is indispensable. In this regard, several studies have investigated the effect of injection molding conditions on the quality of the injected products, which can be defined based on mechanical properties such as tensile strength, bending, hardness, and impact strength, among others (9–14). Nevertheless, no paper so far has fully studied the use of techniques to measure or estimate residual stresses in injected parts and their relationship with the final mechanical properties of said parts. It has been proven that, in injected parts, residual stresses (measured by photoelasticity) have a direct effect on the generation of deformations (8). Photoelasticity has also been used with auto parts to measure residual stresses and reveal how they can promote the presence of cracks in this kind of parts (15). Furthermore, the combination of photoelasticity and thermal treatment has shown that a longer thermal treatment can relieve residual stresses in the material (16). Still, new studies should evaluate the direct relationship between residual stresses and the mechanical performance of injected parts. This study evaluates the mechanical performance of injected plastic parts as a function of their processing conditions, post-injection thermal treatments, and photoelasticity tests. The latter were conducted to observe areas where higher residual stresses were produced, which reveals the effect that these variables can have on the injected plastic parts.

Methodology

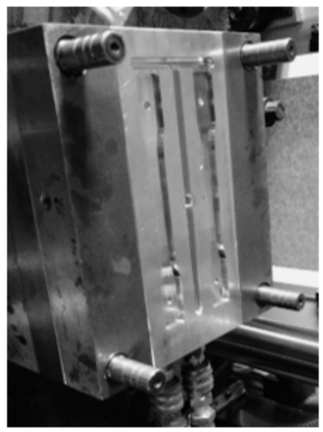
Injecting the plastic parts

Injection molding was carried out using a test specimen mold (see Figure 1). The parts were injected employing 24 different Conditions (see Table 1) that were defined based on four processing variables (remaining cooling time, packing time, packing pressure, and mold temperature). The injected material was GE LEXAN™ 144R polycarbonate. According to the manufacturer's recommendations and the literature (17), the processing variables mentioned above were defined as follows. Two mold temperatures were used: a low one of 50°C to establish if this value could produce significant changes in residual stresses and 80°C, which is the recommended temperature for polycarbonate. The average cooling times for the experiments were determined based on the analytical equation for cooling in a rectangular section (18,19). Packing pressure and time were defined previously to obtain parts that were free from sink marks and had a good superficial appearance. Two conditions were fixed: an injection temperature of 300°C and an injection time of 1 second. A Welltec 90F2V injection molding machine was used to manufacture the specimens for subsequent annealing (thermal treatment), photoelasticity, and flexural tests.

doi: 10.25100/iyc.v26i1.13326



a)



b)

Figure 1. Mold used for injecting the specimens to be analyzed. (a) Open mold and (b) detail of the cavity in the moving side of the mold.

Table 1. Experimental design to evaluate injection molding conditions.

Remaining cooling time [s]*	Packing time [s]	Packing pressure [bar]	Mold temperature [°C]	
10	1.5	40	50	Cond-1
15	1.5	40	50	Cond-2
10	4	40	50	Cond-3
15	4	40	50	Cond-4
10	7.7	40	50	Cond-5
15	7.7	40	50	Cond-6
10	1.5	60	50	Cond-7
15	1.5	60	50	Cond-8
10	4	60	50	Cond-9
15	4	60	50	Cond-10

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Remaining cooling time [s]*	Packing time [s]	Packing pressure [bar]	Mold temperature [°C]	
10	7.7	60	50	Cond-11
15	7.7	60	50	Cond-12
10	1.5	40	80	Cond-13
15	1.5	40	80	Cond-14
10	4	40	80	Cond-15
15	4	40	80	Cond-16
10	7.7	40	80	Cond-17
15	7.7	40	80	Cond-18
10	1.5	60	80	Cond-19
15	1.5	60	80	Cond-20
10	4	60	80	Cond-21
15	4	60	80	Cond-22
10	7.7	60	80	Cond-23
15	7.7	60	80	Cond-24

*Additional cooling time after the injection and packing times. The cooling time includes the injection, packing, and remaining cooling times.

Thermal treatment for injected parts

To observe the effect of a thermal treatment on the plastic parts, annealing was applied to some of the specimens injected under the conditions detailed above. A hot air circulation oven was used for this purpose. In the heating program, the temperature was raised gradually up to 130°C over 5 hours. This temperature was maintained for 45 minutes. Finally, it was gradually reduced to room temperature over 5 hours. These conditions were established based on recommendations provided by the polycarbonate's manufacturer (20–22). Five replicas of each Condition selected for this thermal treatment were later used in flexural tests.

Photoelasticity tests

Before the mechanical tests, a photoelasticity test was conducted with the injected parts to observe the patterns of distribution of residual stresses in them. This technique (i.e., photoelasticity) is based on the phenomena that electromagnetic waves experience when they go through clear materials, in particular, the polarization of light—which occurs as a consequence of stresses present in bodies subjected to external or internal forces. The experimental setup employed two polarizing plates, a source of white light, and a HD-capable camera. Figure 2 shows the experimental setup used in this study to obtain the isochromatic fringes in the injected parts. These fringes represent the internal (residual) stresses that are generated in the parts during the injection process.

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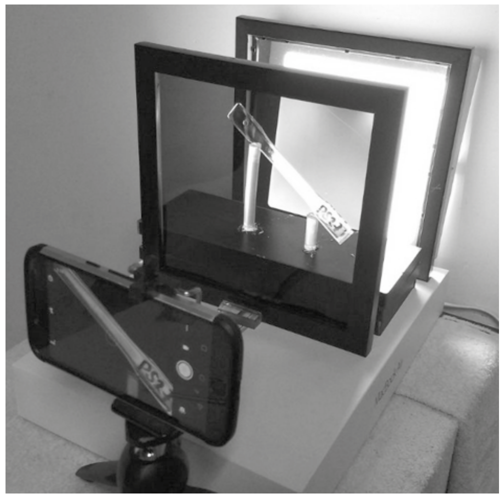

Figure 2. Experimental setup for photoelasticity tests.

Flexural tests

To evaluate the plastic parts in a real application in which they are subjected to an actual load, flexural tests were conducted combining stresses and compression forces. A Shimadzu universal testing machine was used to apply a load onto the rectangular area of the plastic part according to ASTM D790 standard for molded thermoplastic parts (23). Five replicas were produced under each Condition to obtain averages and standard deviations of their results.

Results and discussion

Flexural tests

Flexural tests were conducted with all the parts described in the experimental design, and the results are summarized in Figure 3. In the latter, the flexural strength was higher when the mold temperature had been 80°C, which is close to the recommended temperature for this material (24). This is explained by the fact that the hotter the mold the lower the cooling rate. This condition enables a better application of the packing stage, translates into heavier products with less material shrinkage, and also facilitates a molecular relaxation of the injected plastic. In contrast, at a mold temperature of 50°C, higher cooling rates are generated. Instead of stress relaxation, these higher rates promote high molecular orientation in the solidified layers of injected plastic and high concentrations of still unsolidified areas in the part. This condition facilitates an increase in residual stresses (17,25), which can affect the external load applied during flexural tests (17,26). Specifically at a mold temperature of 50°C, the injected parts do not present a clear trend in terms of flexural strength, which could be an indication of low repeatability of the injection results under these conditions.

Usually, when the packing pressure is higher and the packing time is longer, the injected product is heavier and has less shrinkage—quality characteristics that improve the mechanical performance of the parts (27–29). Nevertheless, the standard deviations obtained in this study do not reflect this behavior. Still, the 80°C mold temperature did produce a trend: a better flexural strength was achieved with higher packing pressures and longer packing times (except for the Condition at 600 bar and 7.7 s). With a mold temperature of 50°C, the flexural behavior of the parts was highly variable without any kind of trend, which can be a reason for not recommending this temperature for polycarbonate processing.

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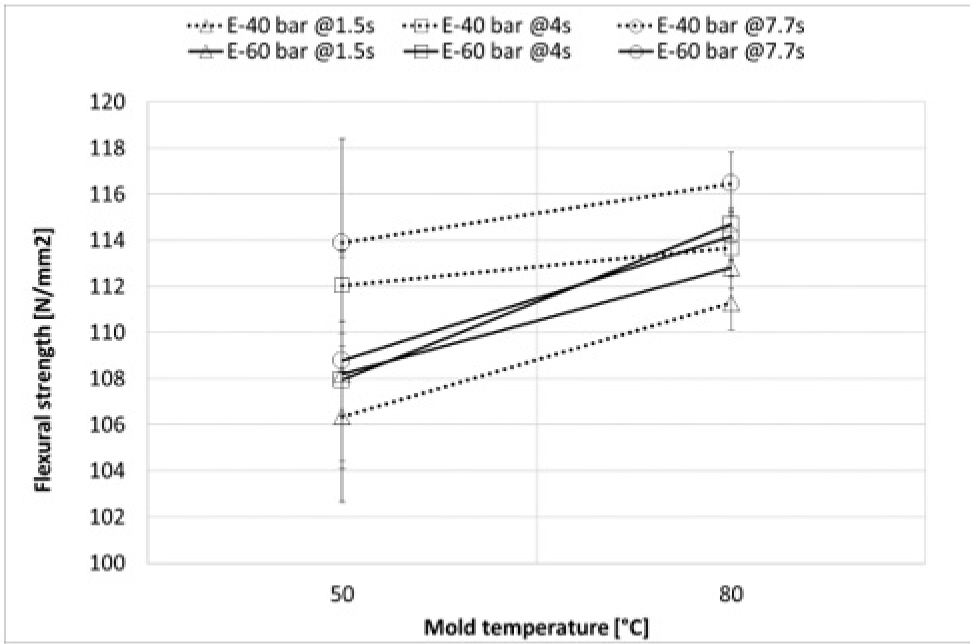
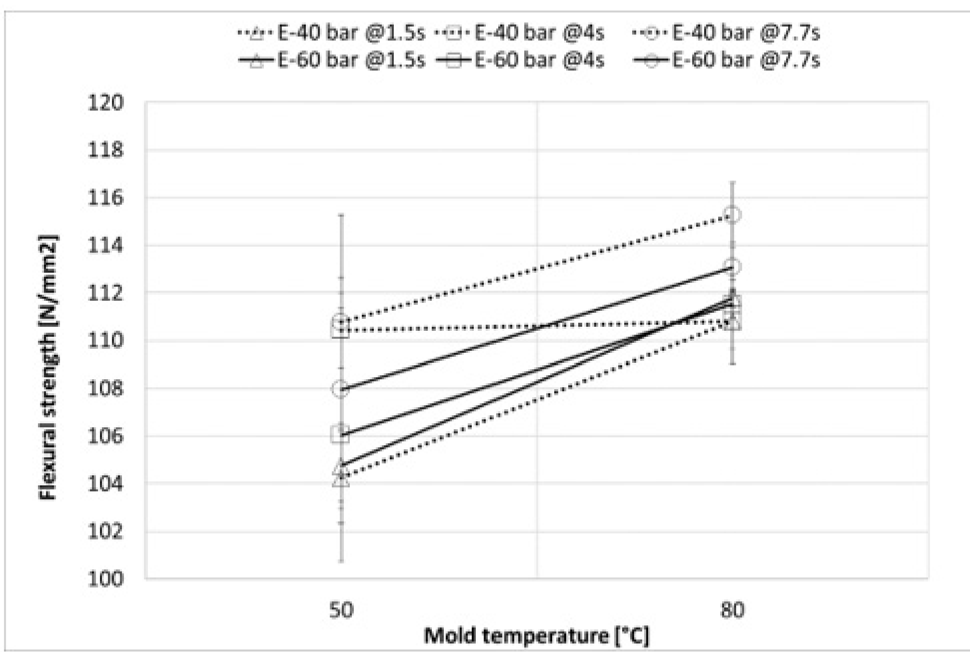
Finally, in this case, increasing the cooling time seemed to have no significant influence on the mechanical strength of the injected products, although it enables a cooling condition with greater molecular relaxation in the injected material.



(a)



(b)

Figure 3. Flexural strength of injected polycarbonate parts with remaining cooling times of (a) 10 seconds and (b) 15 seconds.

doi: 10.25100/iyc.v26i1.13326

Flexural tests of specimens previously subjected to annealing

Figure 4 compares the flexural strength values of thermally untreated and treated parts, where the latter achieved better results (as further detailed in Table 2). The untreated parts presented similar flexural strength values at mold temperatures of 50°C (Conditions 3–6) and 80°C (Conditions 16 and 20). This situation could be explained by the interaction of variables with different packing pressures and cooling times. These combinations could produce a similar effect on the molecular orientation inside the part and the amount of injected material, which are represented in material weight and density—important variables for the mechanical performance of the injected products.

The parts injected at 50°C exhibited a greater increase in flexural strength (in percentage) after the thermal treatment, showing that this mold temperature enables a greater relief of internal or residual stresses later during annealing, thus improving the mechanical performance of the injected parts (see Table 2). In the case of the parts injected at 80°C, the thermal treatment did not produce a significant increase in mechanical strength, which can be explained because this mold temperature enables more molecular relaxation during the injection process as a consequence of a lower cooling rate.

Similar to the results of the untreated specimens, the flexural strength values of treated parts did not present significant changes as the Conditions (packing pressures and cooling times) were modified. However, in general, the specimens that were subjected to the thermal treatment exhibited a noticeable increase in flexural strength. This is evidence that the molecular relaxation of the parts produced by the thermal treatment reduces residual stresses in the parts, enabling a better mechanical performance in each case. Similar results have been obtained in other studies that have found a better mechanical performance of injected plastic parts when they have been subjected to annealing (24,30).

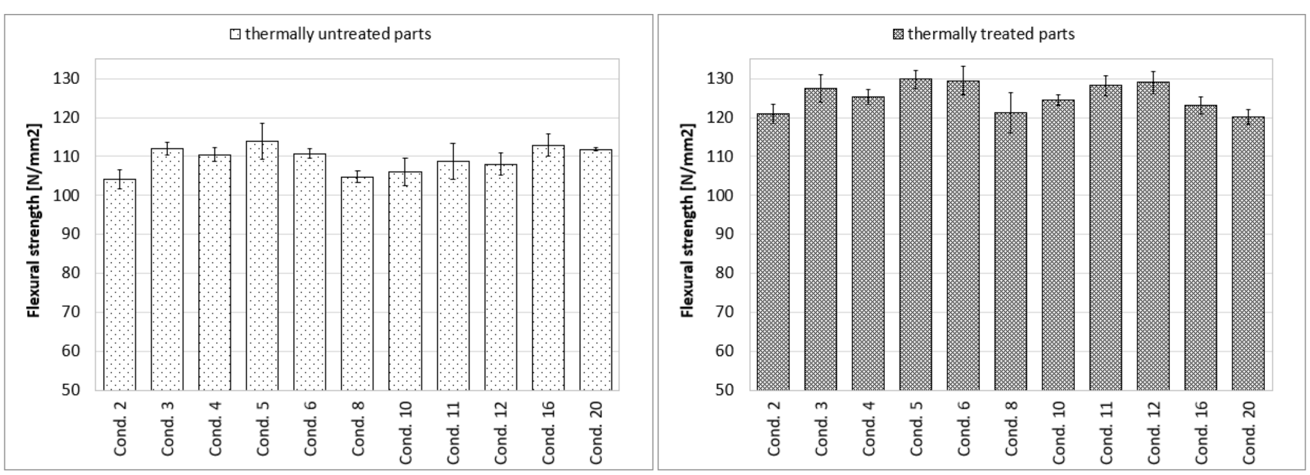


Figure 4. Flexural strength of untreated and treated polycarbonate parts.

doi: 10.25100/iyc.v26i1.13326

Table 2. Flexural strength increase (in %) obtained in thermally treated specimens.

injections	increase
Cond 2	13,75%
Cond 3	12,02%
Cond 4	11,80%
Cond 5	12,31%
Cond 6	19,10%
Cond 8	13,59%
Cond 10	14,81%
Cond 11	15,15%
Cond 12	16,32%
Cond 16	8,28%
Cond 20	6,90%

Photoelasticity tests

Figure 5 shows a summary of the pictures taken with the photoelasticity experimental setup detailed above. They represent each one of the Conditions compared in Figure 4 and Table 2. A change in the distribution pattern of residual stresses can be observed in the specimens that were subjected to the thermal treatment. Comparing untreated and treated injected parts, a change in isochromatic fringes can be observed in the latter. In particular, untreated specimens show darker shades and grays compared to their treated counterparts, which exhibit lighter tones that seem to represent areas with fewer residual stresses. Sometimes, this reduction in stresses improves the flexural strength of the parts, as it occurred with Conditions 6, 8, 10, and 12. After the thermal treatment, the specimens obtained under Conditions 16 and 20 (which included a mold temperature of 80°C) showed lighter tones. As explained above, since the moment they were injected, these parts presented fewer residual stresses than their 50°C counterparts. This could explain why the mechanical strength of these parts was not improved significantly when the thermal treatment was applied. Although this test is only qualitative, it established that there was an important change in the distribution of residual stresses, which could be reflected in a higher flexural strength of injected parts subjected to annealing compared to those injected under the same conditions but without a subsequent thermal treatment (Figure 4 and Table 2). Vargas et al. (31) conducted a quantitative analysis of this kind of injected parts using the photoelasticity technique. They determined that injected plastic flow was the most influential variable in the generation of residual stresses when there was a homogeneous distribution of temperatures in the mold.

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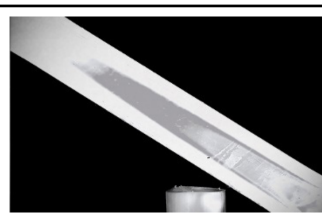
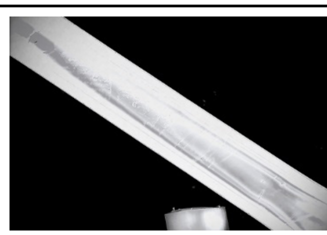
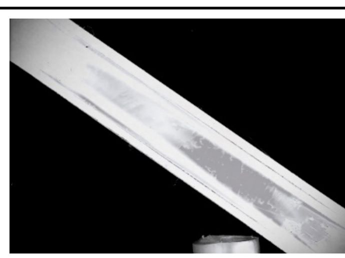
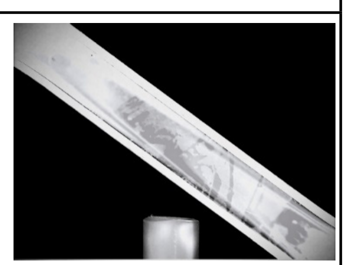
	Untreated	Treated
2		
3		
4		
5		
6		
8		
10		

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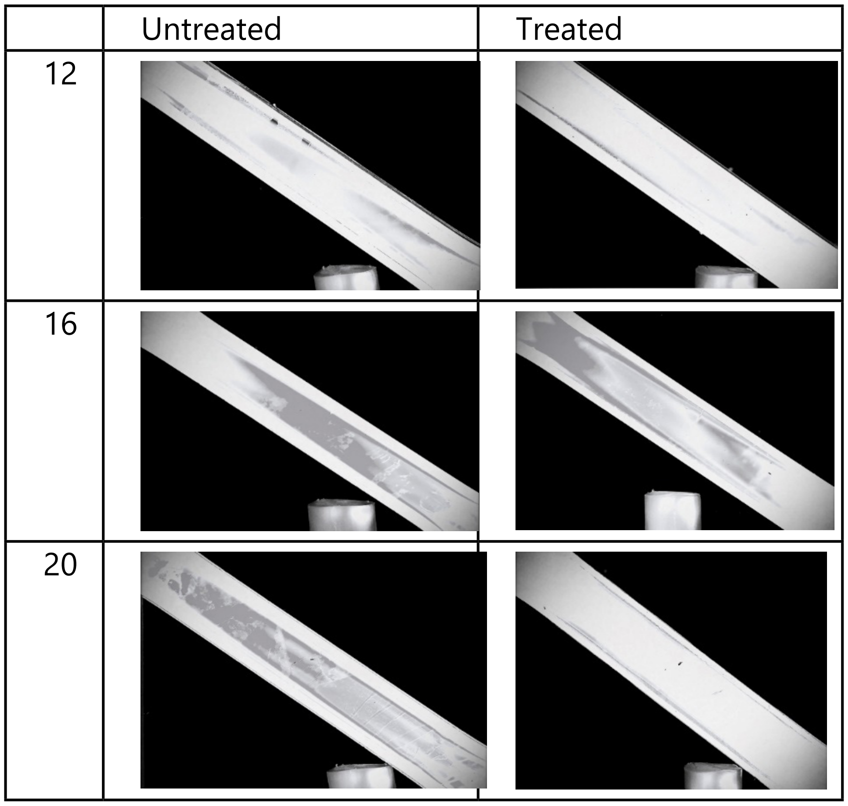

Figure 5. Photoelasticity images of the residual stress patterns in the specimens

Conclusions

The mechanical behavior of the specimens showed that those injected at a mold temperature of 80°C presented less variations in flexural strength—which could be an indication that 50°C results in a more variable injection process and greater residual stresses. For this reason, the recommended mold temperature for polycarbonate is 80° C and above. This temperature produces a slightly higher flexural strength when pressure and packing times are increased. However, the corresponding standard deviations are not evidence of a predominant effect of these processing conditions. Likewise, longer cooling times seem to have no effect on the mechanical performance of the injected parts. This opens up the possibility of evaluating higher packing pressures and longer cooling times to produce different levels of molecular contraction and relaxation, which could result in greater variations in residual stresses and the final mechanical performance of injected parts.

Annealing—the thermal treatment applied here—improved the mechanical performance of the injected specimens because it relieved residual stresses generated during the injection process. This was confirmed in the flexural tests, where the parts injected at a mold temperature of 50°C presented a greater increase in flexural strength (in percentage), which could be associated with the generation of more residual stresses under this condition that were later relieved during the thermal treatment. Said increase was also observed in the isochromatic images. Although post-injection annealing can take a long time, it can be justified for certain kinds of plastic parts. This study established that photoelasticity is a viable and easy-to-implement technique to evaluate residual stresses in a quality control system. Its qualitative results can be extended to the numerical determination of these stresses. Future studies can

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explore other (although destructive) quality control techniques. For instance, chemical attack can be used to reveal the behavior of residual stresses in the form of early cracks or defects in plastic pieces and how they are relieved using thermal treatments.

Acknowledgments

The authors would like to thank the Polymers Laboratory and the Translation Agency at Instituto Tecnológico Metropolitano and Universidad Nacional (both in Medellín, Colombia) for providing the means and resources to carry out this study.

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