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Effect of the molding temperature and cooling time on the residual stresses of crystal polystyrene

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Abstract
The use of crystal polystyrene for high performance components requires knowledge of the distribution of residual stresses. The aim of this research was to analyze the influence of the molding temperature and cooling time on the residual stresses present in parts of two types of crystal polystyrene PS1 and PS2, processed by injection molding.
The results obtained using photoelasticity showed that at low temperatures the residual stresses increase due to the processes of formation and destruction of intermolecular forces. Internal stresses were reduced in the polymer specimens with greater thickness because the molecular relaxation of chains of polystyrene is facilitated by the space increase between the walls of the mold. It was concluded that the photoelasticity technique can be applied effectively in the measurement of residual stresses in injection molded crystal polystyrene parts.

Keywords: residual stresses; crystal polystyrene; photoelasticity; injection molding; Polariscope.

Efecto de la temperatura de moldeo y tiempo de enfriamiento sobre los esfuerzos residuales del poliestireno cristal

Resumen
El uso de poliestireno cristal en componentes de alto desempeño requiere el conocimiento de la distribución de tensiones residuales. El principal objetivo de esta investigación fue analizar la influencia de la temperatura de moldeo y el tiempo de enfriamiento sobre los esfuerzos residuales presentes en muestras de dos referencias de poliestireno cristal PS1 y PS2, procesadas por moldeo por inyección.
Los resultados obtenidos usando la técnica de fotoelasticidad, mostraron que a bajas temperaturas los esfuerzos residuales aumentan debido a procesos de formación y destrucción de fuerzas intermoleculares. Los esfuerzos residuales se disminuyeron en las muestras de polímero con mayor espesor porque la relajación molecular de las cadenas de poliestireno es facilitada por el aumento del espacio entre las paredes del molde. Se concluyó que la técnica de fotoelasticidad puede ser aplicada efectivamente en la medición de los esfuerzos residuales en muestras de poliestireno cristal moldeado por inyección.

Palabras clave: esfuerzos residuales; poliestireno cristal; fotoelasticidad; moldeo por inyección; polariscopio.

1. Introduction

Injection molded crystal polystyrene (PS) is used in parts for the assembly of machinery, building material, tools and manufacturing of personal protective equipment. The quality of these products is affected by the distribution of residual stresses, which can cause dimensionless changes, breaks, fractures and deformities in the manufactured parts, making them unsuitable for use.

Currently, there are several techniques for measuring residual stresses, but they are destructive techniques, such as those based on strain gage technology or the technique of X-ray diffractometry. Moreover, the volume and complexity, of the required equipment, makes it difficult to use. Photoelasticity is an attractive alternative because it is a simple, practical and non-destructive technique, which can be used to determine the stress distributions in crystal polystyrene because this polymer is a birefringent material.

The photoelasticity technique can be used in many polymers to study residual stresses and evaluate its microstructure. This technique is based on the phenomena experienced by electromagnetic waves passing through

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transparent materials, in particular, the polarization of light occurring as a result of the stresses present on objects subjected to stress [1, 2].

Joussinea et al. [3] investigated the influence of biaxial compressive load on the stress paths around Poly (Methyl Methacrylate) (PMMA) sheeting, using photo-elastic and numerical methods. In this study, both methods showed similar results and they complement each other, allowing a more precise analysis of the stresses in the PMMA films.

Residual stresses were studied on polycarbonate and compact discs (CDs), and were associated to different degrees of deformation [4, 5].These investigations have shown that the photoelasticity technique using optical microscopy is possible and provides accurate information about the state of residual stresses in the polycarbonate [4, 5].

Photoelasticity, in addition to its ability to measure the stresses at selected points of the testing parts, is a technique that also has the capacity for the immediate recognition of stress distribution. This valuable quality is an interpretation of the entire field, and it is unique for the photo-elastic method in stress analysis. Its success depends only on the recognition of a color stripe and understanding of the relationship between the stripe and the order of magnitude of the stress [6-8].

Photo-elastic fringe patterns appear as contiguous bands of different colors (isochromatic). Under white light; each band corresponds to a different degree of birefringence, a fringe order and a level of stress. Photo-elastic fringe pattern can be read like a topographical map to visualize the distribution of stress with an understanding of the sequence of colors shown. The fringe pattern is caused by alternating constructive and destructive interference of between waves, which have suffered a relative delay or lag in the photo-elastic model [9].

Birefringence, *D*, observed is proportional to the applied stress when a polymeric object is subjected to mechanical stress [4]:

$$D = K\sigma \tag{1}$$

Brewster's law established that: “the relative change in the refractive index is proportional to the difference of principal strains”.

$$n_x - n_y = K(\sigma_1 - \sigma_2) \tag{2}$$

The main relation of stress in photoelasticity is given by:

$$\sigma_1 - \sigma_2 = \frac{\delta}{2 \cdot h \cdot K} = \frac{N \cdot \lambda}{2 \cdot h \cdot K} \tag{3}$$

where σ is the stress, δ is the delay, λ is the light wavelength, h is the thickness and *N* is the fringe order [6]. The constant *K* is called the optical activity coefficient or Brewster’s constant, and is a physical property of the material determined by calibration. The K value for polystyrene has a value of $5000\,Brewster = 5000 \times 10^{-12} Pa^{-1}$ [10]. For simple geometry such as a flat sheet of thickness, h, with parallel sides, the stress is determined by [4]:

$$\sigma = \frac{\delta}{K \cdot h} \tag{4}$$

Table 1.
Properties of polystyrene PS-1 and PS-2.

Properties of control	**PS-1**	**PS-2**
Range	Min	Min
Melt Flow gr/10 min	10	2
Vicat Softening Temperature °F	206	219
TensileModulusx10^5 [Psi]	4.36	4.5
Tensile Creep [Psi]	5200	6550

Source: Adapted from [7]

So the images obtained from specimens of birefringent material through a polariscope can be used to determine the residual stresses. Several studies have confirmed that the image processing techniques are reliable, effective and efficient in various areas of application such as the determination of particles concentration [11] and characterization of shape and sizes of particles [12, 13].

The present study assesses the influence of molding temperature and cooling time in the injection molding process on the residual stresses present in specimens of crystal polystyrene, using the photoelasticity technique.

2. Experimental Method

2.1. Materials

The research project was carried out with 2 references of crystal polystyrene (PS1-PS2). PS-1 is a crystal polystyrene designed for injection molding. Its high flowability and excellent thermal properties allow for rapid casting speed. PS-2 is a crystal polystyrene with high molecular weight and higher heat resistance. This excellent combination of properties makes PS-2 ideal for foam extrusion and making solid sheets of heavy caliber. The properties of the crystal polystyrene used in this study are shown in Table 1.

2.2. Equipment

Samples were injected and molded using a BOY 50M Injection Molding Machine fitted with a Mipronic control system and a three cavity mold. The dimensions and patterns of the specimen used for the study of photoelasticity are shown in Table 2 and Fig. 1, respectively.

The photoelasticity technique was applied using a linear polariscope Strainoptics ® PSV-100P (Fig. 2). Pictures were recorded using a Nikon 1000 digital camera.

Table 2.
Specifications of the specimen of crystal polystyrene.

Specimen Dimensions	Value
Weight [g]	19.21
Length [mm]	114.13
Width [mm]	50.7
Max Thickness[mm]	4.73
Min Thickness[mm]	1.8

Source: Adapted from [8]

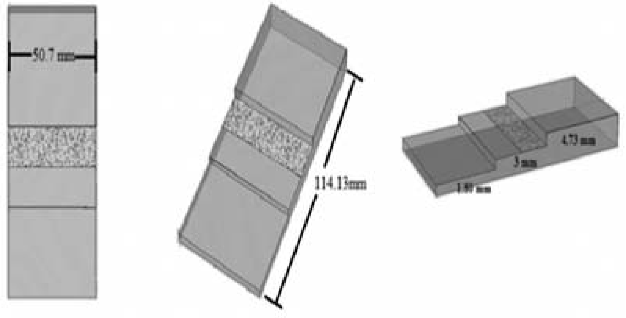

Figure 1. Specimen of crystal polystyrene.
Source: Authors

Figure 2. Polariscope Strainoptics ® PSV-100P.
Source: Authors

2.3. *Experimental Outline*

The effects of molding temperature and cooling time on the residual stresses of the two crystal polystyrenes used as references were estimated using an experimental design shown in the Table 3. The temperature levels were chosen due to the polymer is a thermoplastic that flows if heated above about 100°C. The cooling time is a suitable parameter for this extrusion machine, which was determined by operators. The tests consist of 25 assays with samples of PS-1 and PS-2 each, totaling 50 assays. The barrel was divided into four zones where the temperatures were increased progressively by 5 °C using feedback automatic control. The tests were conducted at a constant cooling time and pressure. Another eight experiments were developed with PS-1 samples at extreme conditions. For the assays 51 and 52 the temperature was increased by intervals of 20, 35 and 55 °C, with each area of barrel at constant pressure and with constant cooling time. For the assays 53 to 58 the temperature and cooling time were manipulated to observe the molding phenomenon. Experimental runs, at different temperatures of injection zones, are shown in the Tables 4, the PS2 samples were obtained at different temperatures between experiments 26 to 50, which aren´t shown because the procedure is very similar to the PS1 samples.

For each experiment, six specimen of crystal polystyrene were collected for a total of 348 molded parts, and for each specimen, photo-elastic analysis was performed. Additionally, photographs were taken at the maximum and minimum thickness of the specimens, with a total of 696 pictures. The pictures obtained were then subjected to the identification of colored stripes.

Table 3.
Experimental design

Type	Name	Units	Level
Independent Variables	Molding Temperature	°C	High, Standard, Low
	Cooling Time	s	20, 22, 30
Dependent Variable	Residual Stresses	(MPa	------------
Constant Variable	Molding Pressure	bar/psi	65
	Closing Pressure	bar/psi	160

Source: Authors

Table 4.
Experimental Design for references of crystal polystyrene PS1 at different temperatures

			Temperature of injection zones (°C)			
PS	Runs	Cooling Time(s)	Nozzle (zone 3)	Zone 4	Zone 2	Zone 1
PS-1	1	22	220	225	220	215
	2	22	225	225	220	215
	3	22	225	230	220	215
	4	22	225	230	225	215
	5	22	225	230	225	220
	6	22	230	230	225	220
	7	22	230	235	225	220
	8	22	230	235	230	220
	9	22	230	235	230	225
	10	22	235	235	230	225
	11	22	235	240	230	225
	12	22	235	240	235	225
	13	22	235	240	235	230
	14	22	215	225	220	215
	15	22	215	220	220	215
	16	22	215	220	215	215
	17	22	215	220	215	210
	18	22	210	220	215	210
	19	22	210	215	215	210
	20	22	210	215	210	210
	21	22	210	215	210	205
	22	22	205	215	210	205
	23	22	205	210	210	205
	24	22	205	210	205	205
	25	22	205	210	205	200
	51	22	185	190	185	180
	52	22	240	245	240	235
	53	30	185	190	185	180
	54	20	185	190	185	180
	55	30	220	225	220	215
	56	20	220	225	220	215
	57	30	240	245	240	235
	58	20	240	245	240	235

Source: Authors

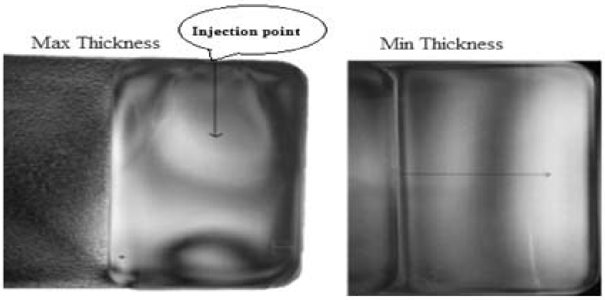

Figure 3. Identification of the stripes of specimen of PS.
Source: Authors

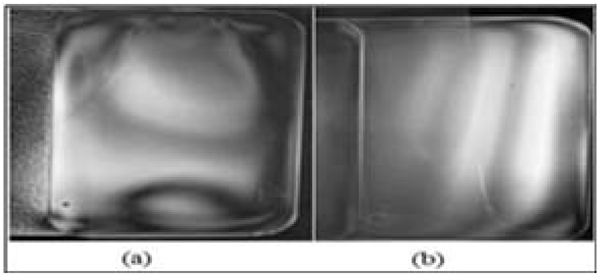

Figure 4. a) fringes of different gray scale in the specimen PS of maximum thickness; b) fringes of different gray scale in the specimen of minimum thickness.
Source: Authors

The initial step to identify the color bars was to set a reference line. In most cases, the reference direction was selected immediately, as an axis of symmetry of the test specimen, in this case, a vertical or horizontal line was sufficient [6].

The selected reference lines in the experimental tests are shown in Fig. 3. The corresponding delay was identified with the selection of the color from the color table [14].

The calculations of the stresses were performed using the Equation 4. For example, if the observed color is bright orange red at the maximum thickness of the work specimen in the Fig. 3, the stresses at this point is calculated as:

$$\sigma = \frac{998}{5000 \cdot 4.73} = 0.0422MPa \quad (5)$$

where $\delta = 998\,nm$ [10] and $h = 4.73\,mm$.

3. Results and discussion

The pattern of the fringes changes with the thicknesses of the specimens. At maximum thickness, fringes with curved shapes were observed while straight fringes were typical at minimum thickness (see Fig. 4). The injection zone was located in the maximum thickness of the mold, wherein the fringes color curves were focused around it. In contrast, the zone of smaller thickness was far apart from this zone. The position of maximum orientation was shown generally as a nearly circular band, which was usually located between the center of the molded specimen and the injection point. However, in both regions, the color fringes did not interfere with or overlap each other. In addition, the color map displayed on the specimens did not change with time.

In the molded specimens, closed fields indicated stress concentration while more separate stripes shown the decrease of stress concentration. If there are more colors present, further stress is concentrated in the molded specimen; moreover, if the isochromatic line width becomes smaller, when the internal stresses are greater. Otherwise, when a single uniform color covers a large area, this indicates that there is no stress change in the area.

Residual stresses were calculated at the maximum and minimum thickness of the specimens of crystal polystyrene. The calculated residual stresses for experiment 1were reported in Table 5.

Residual stresses obtained for the maximum thickness of the reference specimens of crystal polystyrene PS-1 were plotted in Fig. 5 for experiments 1 to 25. The maximum value for the residual stress was 0.0766 MPa and it was obtained in tests 18, 24 and 25, which were performed at low temperatures, between 200, and 210 °C for the nozzle and zone 1, while the minimum value was 0 MPa, for tests 3 to 13 at a higher temperature of 215 °C for the four zones, see Table 4. In the group of the first thirteen experiments, test 7 was highlighted, in which the maximum residual stress reached 0.0233 MPa. For tests 10 to 13, the maximum tension of 0.0247 MPa was reached at the highest temperatures as observed in the Table 4.

Table 5.
Calculation of residual stresses

Maximum thickness			Minimum thickness		
Color	**Delay δ (nm)**	**σ (MPa)**	**Color**	**δ (nm)**	**σ (MPa)**
Bright orange red	998	0.0422	Bright green (2)	1811	0.1979
Light yellow	910	0.0385	Incarnation	1495	0.1634
Yellowgreen	866	0.0366	Light yellow	948	0.1036
Indigo	583	0.0247	Green yellow	866	0.0946
Violet	575	0.0243	Yellow green	843	0.0921
Canary yellow	430	0.0182	Green blue	728	0.0796
Bright yellow	332	0.014	Indigo	583	0.0637
Pale strawyellow	275	0.0116	Deep red	551	0.0602
White yellow	267	0.0113	Yellow white	267	0.0292
Ivory	259	0.011			
Grey	218	0.0092			
Blue Grey	158	0.0067			
Grey iron	40	0.0017			

Source: Authors

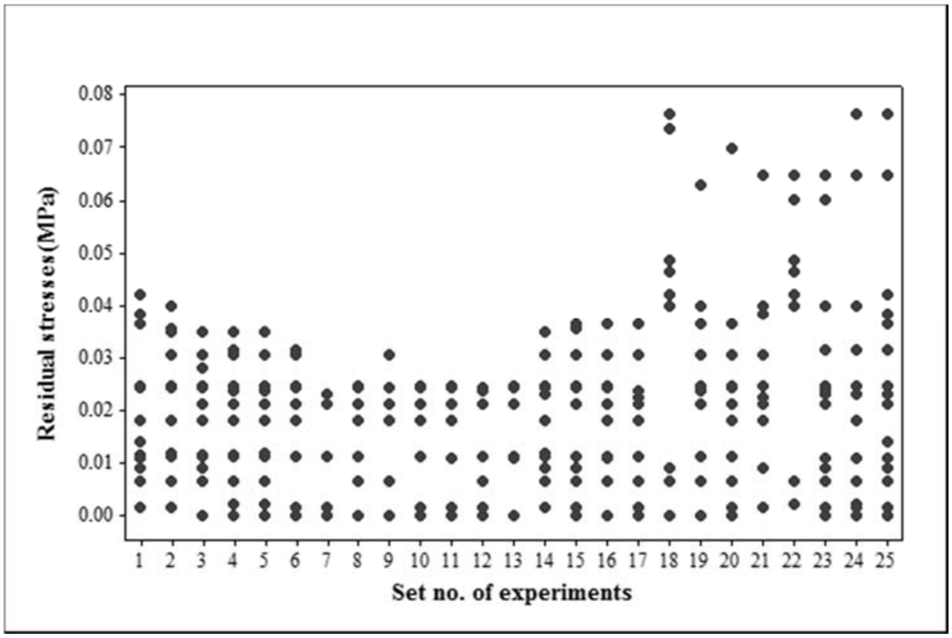

Figure 5. Experiments 1 to 25 Maximum thickness of the specimens of PS-1.
Source: Authors

The lowest residual stresses were observed between tests 7 to 13, at the higher temperature of 220°C for each zone; with the exception of essay 9. At high temperatures in the nozzle zone and the feed area, the viscosity decreased, allowing for a higher transmission of pressure, and thus, a better polystyrene packing in the mold. Similar results were obtained in PS2 samples. Low-temperature profiles develop high residual stresses in the polymeric specimens. This behavior can be interpreted qualitatively [12, 13]; polymer flow is enhanced at high temperature, the intermolecular forces are reduced and the mobility of polymer chains increases, the resistance to flow decreases, as well as the residual stresses in the molding specimen. On the other hand at low temperatures, there are two processes related to the increase of residual stresses, formation and destruction of intermolecular forces such as Van der Waals forces, which occur together with the stretching and aligning in the direction of stress of the points of the successive molecular segments separated by intermolecular bonding. The formation of intermolecular forces in the polymer causes an energy dissipation related to the change in internal energy, whereas, the destruction of secondary links results in an accumulation of potential energy is related to the change in entropy [15].

Residual stresses are plotted in Fig. 6 at the minimum thickness of the PS-1 crystal polystyrene reference specimens. The maximum residual stresses were found in tests 24 and 25 with a value of 0.2238 MPa, at a temperature range of 200 to 210 °C, see Table 4; furthermore, the minimum residual stresses were found from tests 11 to 13, with a temperature range of 230 to 240 °C. Specifically, high temperature favors the reduction of residual stresses by promoting the relaxation of the oriented chains and the decrease of molecular orientation. This pattern was also observed for samples of PS-2. The maximum residual stress occurred in the minimum thickness of the specimen, which was 2.92 times higher than those presented in the tests with maximum thickness, as shown in Figs. 5, 6. Furthermore, at the maximum thicknesses of the specimens, stresses equivalent to 0 MPa were measured (Fig. 5). These values were not observed in the minimum thicknesses (Fig. 6). The walls of the molding are thicker in the specimens with greater thickness, acting as an insulator that encloses heat longer in the central zone. This promotes relaxation of the polymer chains of the material, reducing the residual stress and the anisotropy of the specimens (when the polymer molecules are more aligned in one direction than the other) [17, 18].

However, although two different crystal polystyrene references were used in the experiments 1 to 50; the common factor was the reduction of residual stresses of the material with increasing temperatures in the zones of the injection. These results were supported by Postawa, 2006, who showed that the use of high temperatures of injection is more favorable for molding [19-21], because the orientation is reduced, as well the anisotropy of the material and residual stresses in the molded part. At higher temperatures the melt viscosity decreases, permitting a greater transmission pressure allowing packing of material so that it reduces the contraction of the material. Contraction is an undesirable phenomenon in the material because it causes distortion and anisotropy in the finished part. However, in the case of amorphous polymers such as polystyrene, contraction of the injected material is not favored due to the molecular structure of the polymer chains.

In Figs. 7 and 8, the residual stresses are plotted for the maximum and minimum thickness of the tests 51 to 58 of reference crystal polystyrene PS-1 at extreme conditions.

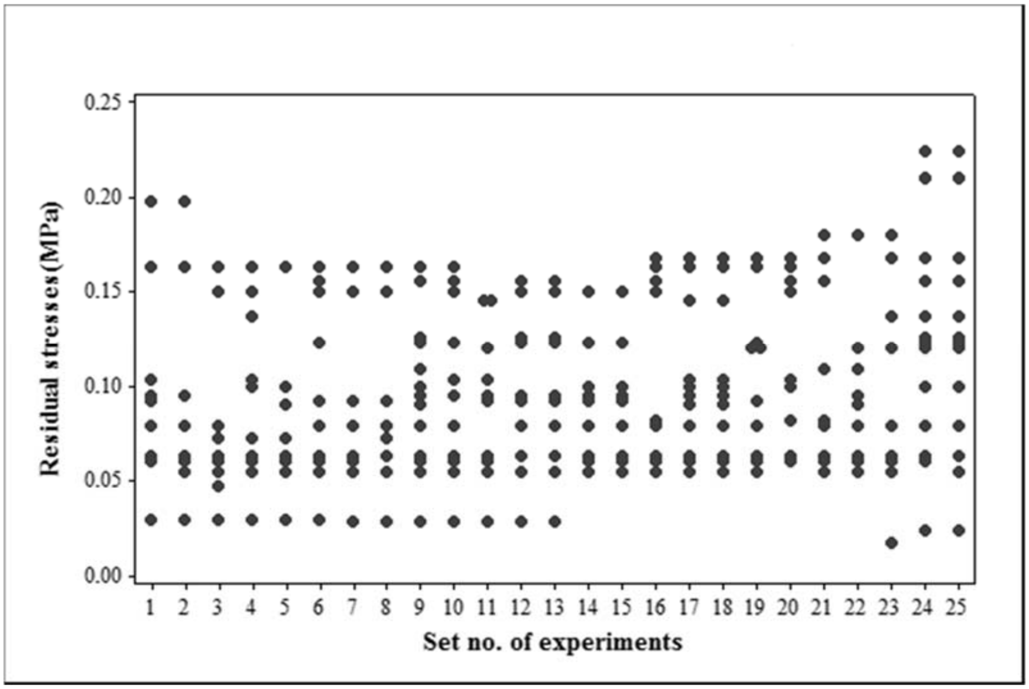

Figure 6. Experiments 1 to 25 Minimum thickness of the specimen PS-1.
Source: Authors

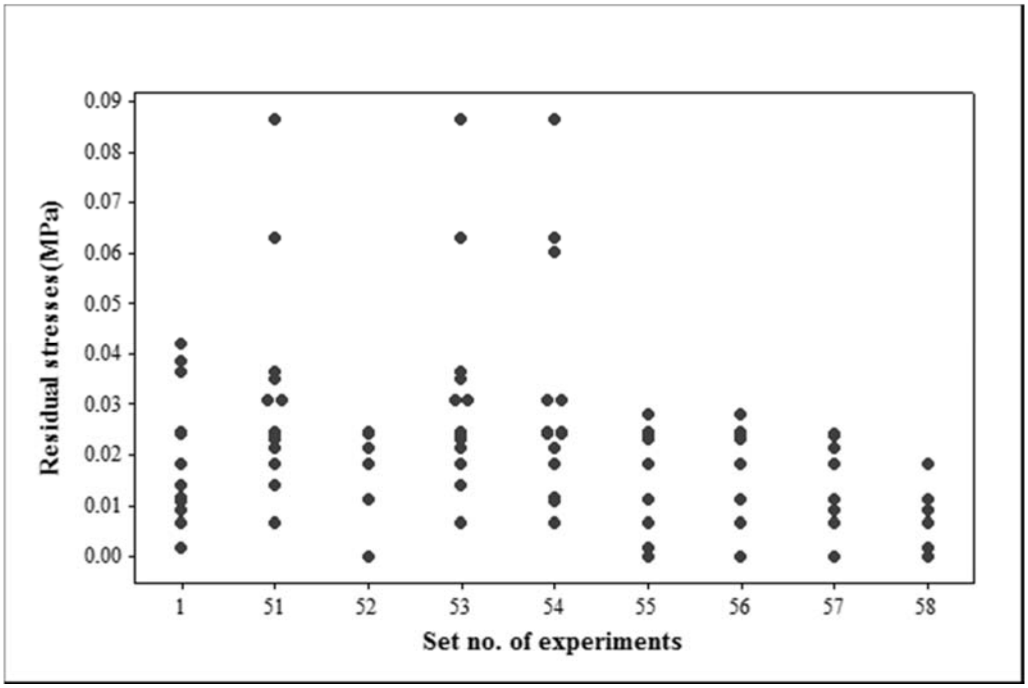

Figure 7. Experiments 1, 51 to 58 Maximum thickness of the specimen PS-1.
Source: Authors

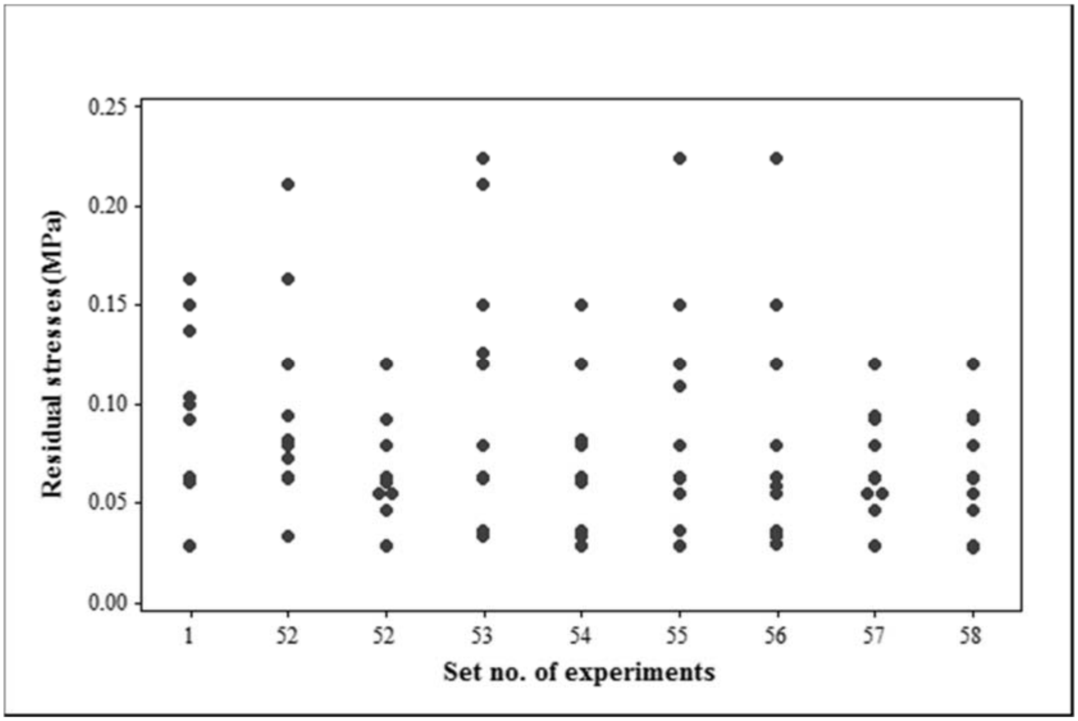

Figure 8. Experiments 1, 51 to 58 Minimum thickness of the specimen PS-1.
Source: Authors

The maximum values of the residual stresses obtained from test 1, 51 and 52 are shown in Table 6 (Fig. 7, 8). These results corroborate the influence of temperature on the residual stresses, since these tests were performed with the same reference of crystal polystyrene (PS-1) and equal cooling times; only the temperature was manipulated to extreme values. It was observed that internal stresses were found to be four times higher in magnitude in the tests at extreme low temperatures compared to the tests performed at extremely high temperatures, wherein the thermal contraction was higher, the cooling in the specimens molded was slower, allowing further movement of the molecular chain segments, which increased the likelihood of molecular order before solidification.

Although at the extremely high temperatures, such as those used in the tests 52, 57 and 58 (with an average temperature of 240°C), the residual stresses obtained were the lowest of all experiments performed, the molded specimens showed imperfections such as burrs, contours with material surplus, this was due to overheating of the material by an increase of injection temperature [1]. Also, the internal tensions increased with low temperatures, as shown by the test 51 in which the specimen was incomplete. This defect was due to the fact that the material did not reach the processing temperature at this low melting temperature.

The behaviors of residual stresses was very similar with equal processing temperatures and with different cooling times, for example, the temperature conditions, in the tests 51, 53 and 54, were low and similar, with cooling times of 22, 30 and 20 seconds, respectively, also, the observed residual stresses were similar (See Fig. 8).

Table 6.
Maximum Residual Stresses of tests 1, 51 and 52

Set No. of experiments	Maximum value of residual stresses (MPa)		Average temperature conditions in the injection °C
	Maximum thickness	Minimum thickness	
1	0.0422	0.1634	220
51	0.0866	0.2106	185
52	0.0247	0.1203	240

Source: Authors

The cooling time is a factor affecting the residual stresses of the specimens, due to the relaxation of molecules of polymer. This relaxation is greater at longer cooling times, thereby decreasing the orientation and internal tensions. However, in this study the gap between the cooling times is small, and its influence was not observed. Besides, previous studies [19] found that in the processing of polymers, the temperature is the most influential factor on the residual stress rather than the cooling time.

4. Conclusions

Photoelasticity is a practical, low cost technique and can be applied effectively in the measurement of residual stresses for injection molding crystal polystyrene helping to control the quality of products. The residual stresses decreased considerably with high temperature profiles in the injection molding process. However, extremely high temperatures cause other problems, such as sink marks, burrs and contraction that reduce the quality of the final product.

The residual stresses are higher at lower thicknesses of the molded specimens because the cooling of thin walls in the molded part is faster than in areas of greater thickness.

During the investigation it was found that of the manipulated variables, temperature and cooling time, the most important variable to control the injection molding process of crystal polystyrene is the temperature, since, it is causing a greater impact on internal tensions of the molded specimen.

The results obtained from the images are consistent with previous studies, showing that the image processing and analysis could be performed by an algorithm and software to optimize the injection molding process.

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