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MULTI OBJECTIVE OPTIMIZATION OF PRESSURE CYCLE OF ABS INJECTION MOLDING PROCESS

M. M. Radwan^{*}, A. M. Youssef[†], K. T. Ismael[‡] and M. Merdan[§]

ABSTRACT

Injection molding is defined as a cyclic process for producing identical products from a mold and it is the most widely used polymer processing operation. The main advantage of this process is the capacity of repetitively fabricating parts. Certain challenges face this process in order to get a defect free product. The control of the cavity pressure is important for maintaining the quality of the plastic product. The common practice in industry is to have a fixed value for the pressure during the filling phase and also during the packing phase of the process. This may lead to the introduction of defects in the final product. This paper presents a mathematical model and experimental verification of a strategy to control the cavity pressure profile during the filling and the packing phases to minimize the flow marks, warpage and shrinkage for an ABS injection molded product. For the packing phase, the efficient frontier method is used to obtain the optimum pressure for minimizing the combination effect between the warpage and the shrinkage. This may be used as a tool for weighing the behavior of these two defects with the variation of the packing pressure. The results showed the effectiveness of the mathematical model used for predicting the filling and pressures to minimize the investigated defects.

KEY WORDS

Injection molding process, Cavity pressure control, Elimination of the plastic product defects.

* Mech. Eng., Ministry of Military Production, Egypt, Email: eng.m_radwan@yahoo.com.

† Egyptian armed forces

‡ Egyptian armed forces

§ Modern Academy-Maadi, Cairo

INTRODUCTION

Among all the processing methods of polymers, injection molding process is one of the most important, versatile, widespread, and cost-effective operations in the mass production of complex plastic parts. This process involves melting plastic pellets and shaping this melt under high pressure and temperature in a closed mold to produce the plastic component with the required specifications [1]. The pressure of the melt (cavity pressure) that enters from the gate to the cavity plays an important role in the process because it is a direct indication of how the polymer melt behaves in the process and its effect on the quality of the part [2], [3], [4].

CAVITY PRESSURE PROFILE

For the filling phase the clamp unit keeps the empty mold closed and the screw moves forward as a ram and forces the melt into the mold cavity, the pressure used for filling the mold cavity is called injection pressure. At this stage the cavity filled with about 95% of the cavity space. The packing pressure holds for certain time to compensate the shrinkage of the plastic. Regardless of the shape of the cavity, the pressure in the cavity decreases monotonically from the maximum pressure at the point of injection to atmospheric pressure at the melt front as shown in Figure 1.

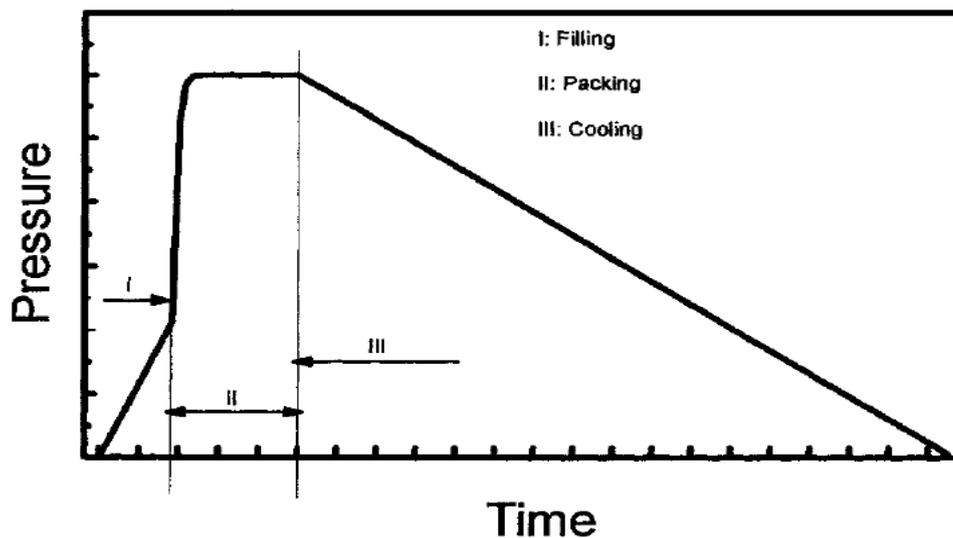


Figure 1. Cavity Pressure profile during an injection molding cycle.

MATERIALS AND MACHINE

The injection molding machine used in this investigation is; Jon Way 250SD with clamping force 250 ton, shot size 821 grams. The material under investigation is Acrylonitrile Butadiene Styrene ABS provided by Taita Chemical Company.

EVALUATION OF THE INJECTION PRESSURE

In the injection process, the flow rate must be constant for all parts of the mold in order not to get variable filling times or splashing. This would also introduce defects in the final products as well. The most common way is to calculate the maximum injection pressure at the maximum cross sectional area and apply this pressure across all the cavity space. This way may give acceptable injected products but do not use optimum pressure suitable for the current cross section being filled. It also consumes more power of the machine.

While entering the molten plastic into the cavity space, the pressure inside varies according to the cross sections that may be increased and in the same space may decrease. The objective is maintaining a constant flow rate during the filling stage across all cross sections of the cavity space to avoid any problem occurrence during filling.

The isothermal pressure drop for a disk-shaped cavity is given as follows [5]:

$$P = \frac{K_r}{(1-n_r)10^5} \left[\frac{360 \cdot Q \cdot (1+2 \cdot n_r)}{N \cdot \Theta \cdot 4\pi \cdot n_r \cdot r \cdot b^2} \right]^{nr} \cdot \left(\frac{r}{b} \right) \quad (1)$$

where:

- n_r The reciprocal of the power law exponent (= 0.2565),
- K_r Constant corresponding to melt viscosity (= 3.05×10^4),
- Q Constant injection rate (cm^3/s),
- b Half thickness of the disc (cm),
- r Radius of the disc (cm),
- N Number of gates, and
- Θ Melt flow angle.

Equation (1) correlates between volumetric flow rate, cross section area, and thickness with the pressure in the cavity. This equation is modified to be suit the variable pressure investigation as follows;

$$P = \frac{K_r}{(1-n_r)10^5} \left[\frac{360 \cdot Q \cdot (1+2 \cdot n_r)}{N \cdot \Theta \cdot 4\pi \cdot n_r \cdot x \cdot b^2} \right]^{nr} \cdot \left(\frac{x}{b} \right) \quad (2)$$

As shown in Figure 2, equation (2) will be modified to be a function of the distance (s) instead of (x) as follows.

$$P = \frac{K_r}{(1-n_r) \times 10^5} \left[\frac{360 \times Q \times (1+2 \cdot n_r)}{N \times \Theta \times 4\pi \times n_r \times \sqrt{s(2R-s)} \times b^2} \right]^{nr} \cdot \left(\frac{\sqrt{s(2R-s)}}{b} \right) \quad (3)$$

where s is the filling distance from the gate and it is variable.

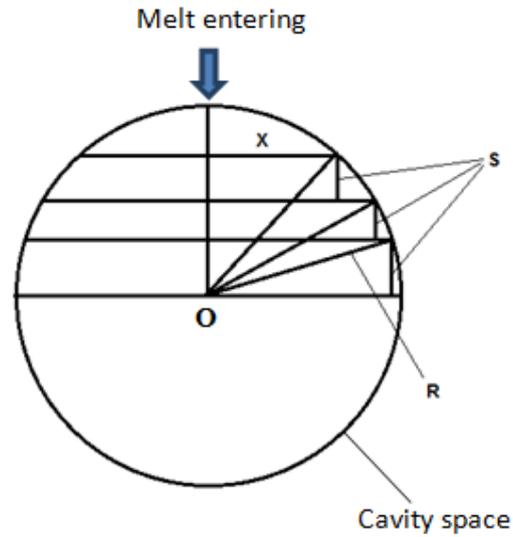


Figure 2. Designation of cavity dimensions

According to the machine settings used in this study, the injection process can be controlled for six pressure values, so the cavity space will be divided into six sectors starting from the gate (I).

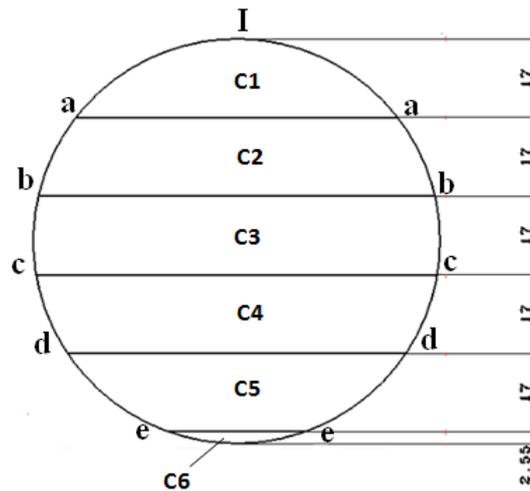


Figure 3. Sectioning of the cavity.

From Figure 3, the cavity pressure [MPa] will be as listed in the table below:

P_1	P_2	P_3	P_4	P_5	P_6
34	39	40	40	35	19

The injection pressure calculated above will be divided over the intensification ratio, see Figure 4, to get the corresponding hydraulic pressure (P_{ih}) [6].

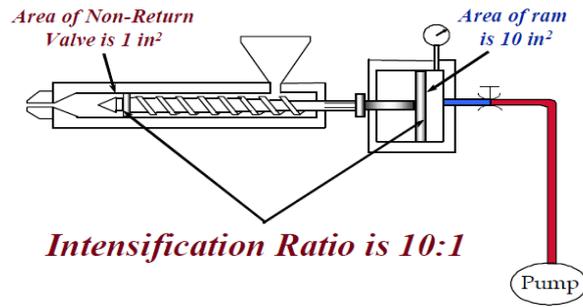


Figure 4. Intensification ratio calculation

The hydraulic pressure [MPa] will be:

P_{1h}	P_{2h}	P_{3h}	P_{4h}	P_{5h}	P_{6h}
6	6,0	6,7	6,7	6	3,2

These values will be used on the machine pressure control.

EVALUATION OF THE PACKING PRESSURE

Packing pressure is an important parameter in affecting the warpage and the shrinkage defects [7], [8], [9], [10]. The aim is to try to solve or minimize the defects that occur in the packing phase. Shrinkage and warpage are the defects investigated in this study. The published work in this field studies the optimization of the packing pressure for elimination of a single defect at a time. In this work, a multi objective optimization for the minimization of both warpage and shrinkage is carried out. This investigation used published results that studied these two defects separately [11], [12]. By using efficient frontier method, these results were optimized to get the optimum values for the packing pressure.

MULTI-OBJECTIVE OPTIMIZATION and EFFICIENT FRONTIER

Multi-objective optimization method is an area of multiple criteria decision making, which is concerned with mathematical optimization problems involving more than one objective function to be optimized simultaneously [13]. The values used in solving this problem are shown for the shrinkage defect in Figure 5 and for warpage defect in Figure 6

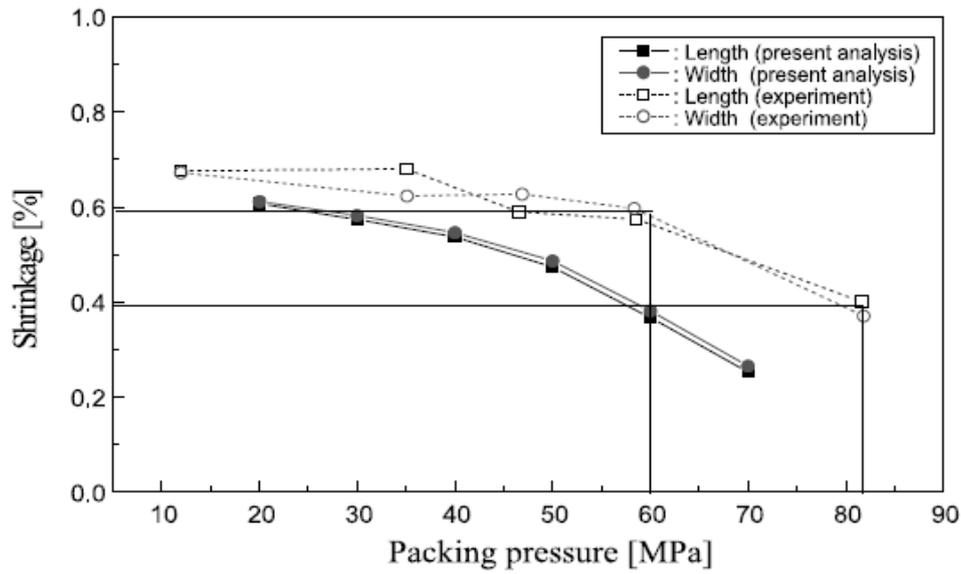


Figure 5. The effect of packing pressure on the shrinkage [11].

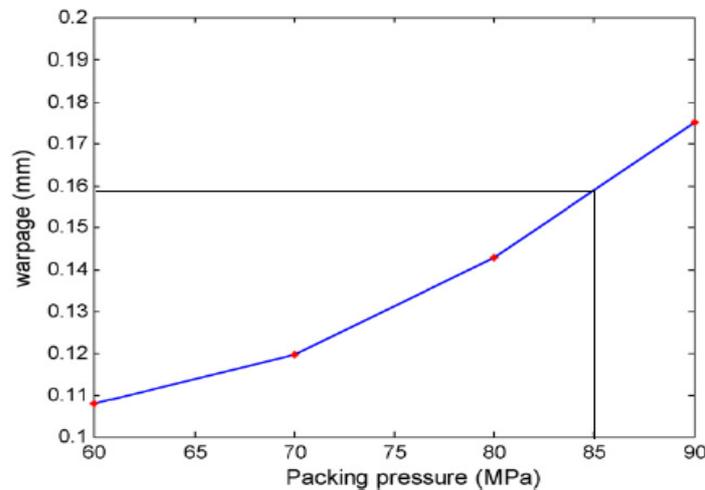


Figure 6. The effect of packing pressure on the warpage [12].

Normalizing the values from Figure 5. The effect of packing pressure on the shrinkage [11] and Figure 6 we get;

Packing Pressure [MPa]	Shrinkage [%]	Packing pressure [MPa]	Warpage [mm]
60	0.58	60	0.107
65	0.52	65	0.114
70	0.48	70	0.12
75	0.46	75	0.13
80	0.4	80	0.142
85	0.38	85	0.158

To find the efficient frontier, an analysis program was written in **MATLAB** to solve the multi-objective optimization problem.

Using best fit method the relation was found to be polynomials of 3rd order as follows:

1- Between packing pressure and shrinkage

$$S = -1.1095 \cdot 10^{-5} X^3 + 0.0024569 X^2 - 0.18809 X + 5.4158 \quad (3)$$

2- Between packing pressure and warpage

$$W = 1.4074 \cdot 10^{-6} X^3 - 0.00025683 X^2 + 0.016863 X - 0.28407 \quad (4)$$

where S is the shrinkage, W is the warpage and X is the packing pressure.

Figure 7 shows the results for the optimization problem. This can be used as a decision tool for weighing the cost of improving one goal over the other one. The points (1, 2, 3) in the figure investigate the effect of changing packing pressure along the curve. Converting the value of the warpage and the shrinkage of along any point on the curve using equations (3) and (4), the corresponding packing pressures can be obtained.

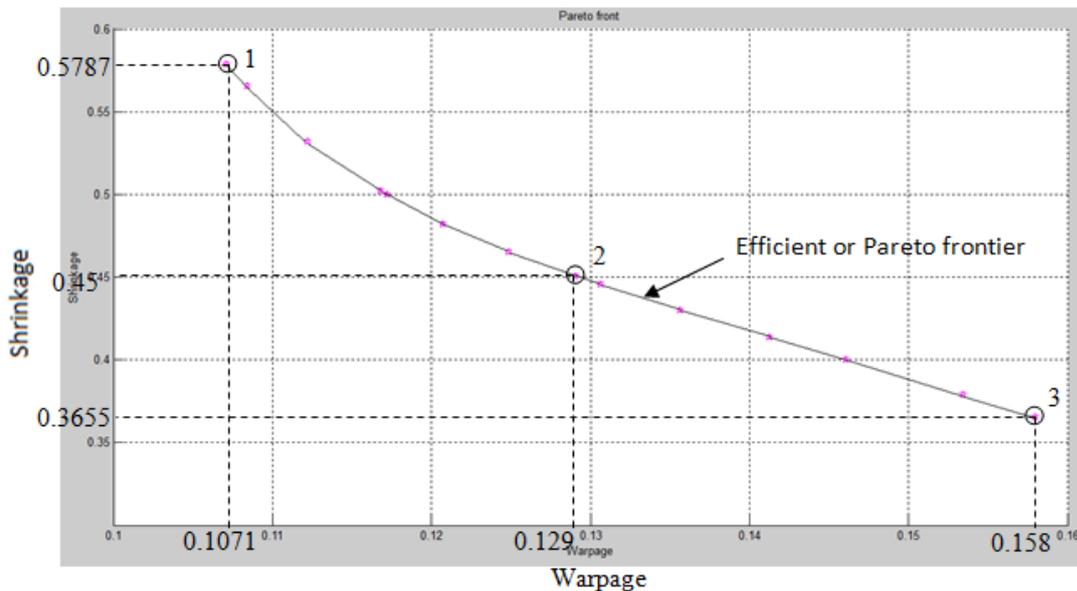


Figure 7. The efficient frontier results.

THE SAMPLE SIZE AND NUMBER OF REPLICATIONS

The experimental verification of the results required the determination of sample size and the repetition of an experimental condition so that the variability associated with the phenomenon can be estimated. Equation (5) determines the sample size required for this investigation [14].

$$SS = \left(\frac{Z_{\alpha/2}}{E} \right)^2 \cdot \hat{p} (1-\hat{p}) \quad (5)$$

where SS is the sample size, $Z_{\alpha/2}$ is the Z value for the required confidence level, \hat{p} is the percentage of the sample that picks a particular answer, expressed as decimal, and E is the confidence interval (also called margin of error), expressed as decimal.

Using equation (5) to compute the number of repetitions for each run and taking the average results when determining the defect.

$$Z_{\alpha/2} = 1.96 \text{ (for 95\% confidence level).}$$

$$\hat{P} = 0.5 \text{ (a suggested in reference [14]).}$$

The value of the margin of error will differ in this case. The first step is to compute the value of (E) for each case and then find the sample size corresponding to the values of (E).

$$\text{For the shrinkage } E = 1 - \frac{0.3655}{0.5787} = 0.37$$

$$SS = \left(\frac{1.96}{0.37} \right)^2 * 0.5(1-0.5) = 7.02$$

$$SS = 8 \text{ runs}$$

$$\text{For the shrinkage } E = 1 - \frac{0.1071}{0.158} = 0.33$$

$$SS = \left(\frac{1.96}{0.33} \right)^2 * 0.5(1-0.5) = 8.8$$

$$SS = 9 \text{ replications}$$

Taking the maximum number of runs to be the greater number, so every run will be repeated 9 times.

MEASURING INSTRUMENTS

The un-aided eye was used to investigate flow marks on the surface of the product. The warpage was measured by digital dial gauge and shrinkage was measured using a digital micrometer Both instruments have the sensitivity up to 0.001mm.

VERIFICATION OF THE FLOW MARKS

Verifying the flow mark will be by checking the surface of the part for the existence of flow marks, cold shots, splashes and change of color. This inspection is performed by the un-aided eyes after cleaning the part surfaces. The acceptance criterion is the defects-free surface of the aforementioned defects.

MEASUREMENT OF THE WARPAGE

In measuring the warpage, the flatness of the surface will be measured. For that, the surface of the sample, cf. Figure. 8, is measured along four paths and each path was divided into four sectors.



Figure 8. Picture of the surface of the sample.

The results of the average warpage for each sample group were:

Packing pressure [MPa]	Warpage [mm]
60	0.106
75	0.144
85	0.193

MEASUREMENT OF THE SHRINKAGE

For measuring the shrinkage, the difference between the diameter of the samples and the mold diameter is measured. The values are measured by the digital micrometer at 4 different orientations for each sample and for every sample group. Then the average shrinkage for each sample group was:

Packing pressure [MPa]	shrinkage [%]
60	0.239144317
75	0.164272031
85	0.089107067

DISCUSSION

The visual inspections of the sample surface, showed that it has a good and smooth appearance and there is no change in the color of the part surface. No signs of the

flow marks on the part surface after injecting the mold by using the optimized filling pressures.

For the warpage, it can be seen from Figure 9 that the warpage values increase with increasing the packing pressure. The two curves have the same trends. The difference between the predicted and the actual warpage within the working pressure range does not exceed 0.035mm.

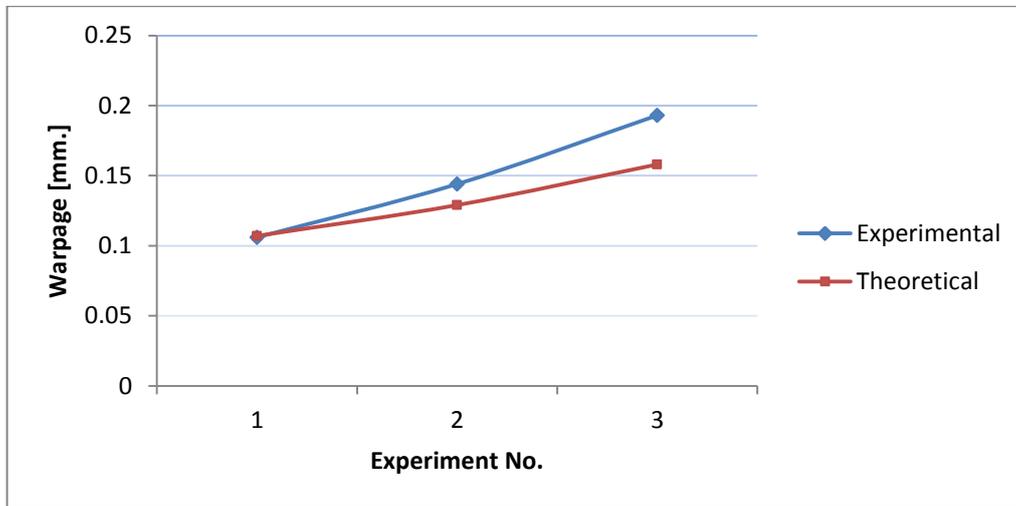


Figure 9. Experimental and theoretical warpage.

For the shrinkage, it can be seen from Figure 10 that its values decrease with increasing the packing pressures and also with the same trend of the predicted one. The values of the experimental results are better than the predicted ones with nearly the same difference. The difference between the two curves does not exceed 0.33%.

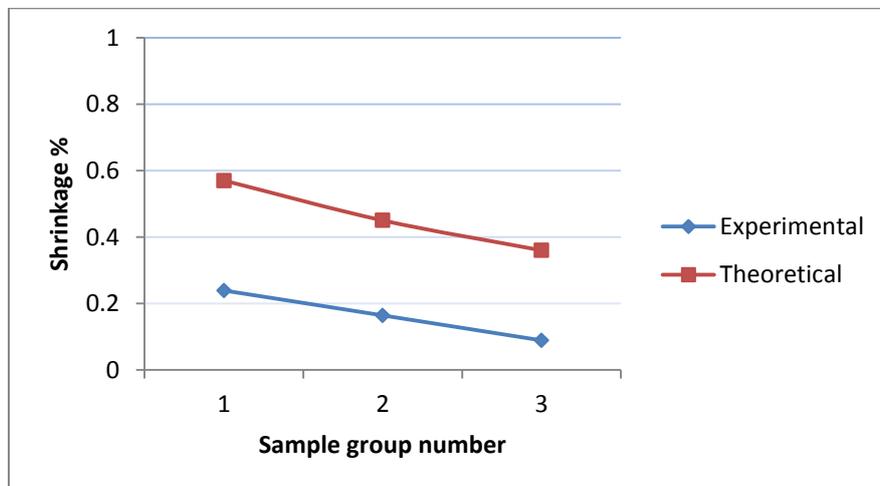


Figure 10. Experimental and theoretical shrinkage.

CONCLUSIONS

In this study the effect of the cavity pressure on the part quality was investigated through a mathematical and experimental work. The flow marks as a part of the plastic part defects was studied by introducing a relation between the injection flow rate and the filling distance with the filling pressure on a disk shape product. An efficient frontier had been done to optimize the warpage and the shrinkage defects simultaneously. Experimental validation was carried out and the results showed that:

- 1- There are no flow marks on the surface of the product after using the proposed variable filling pressure profile.
- 2- The effect of the warpage increases with increasing the packing pressure. The average deviation between predicted and experimental results of the warpage was 0.035 mm. This value is better than the general flatness tolerance [0.1mm] according to ISO1101:2004 standard for geometrical tolerancing.
- 3- The effect of shrinkage decreases with increasing the packing pressure. The highest value of the shrinkage was 0.23%. This value is less than the typical value for this material [$\leq 0.44\%$] according to ASTM D955 and ISO 294-4 [15].
- 4- The efficient frontier that obtained can be used as an indicator and a guide in compromising the warpage and the shrinkage with the packing pressure. This is a powerful tool for weighing the cost of improving one aspect versus the other one.

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