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RESEARCH ARTICLE

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Real-time product weight estimation based on internal pressure monitoring in injection molding

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Abstract

In this study, we investigate a novel method for determining product weight based on cavity pressure, measured by internal sensors integrated into the mold. The ultimate goal is to find a model that is better than the linear expressions in the literature based on the cavity pressure integral. We conducted experiments using different materials (ABS and PP) to assess the effects of holding pressure and time on product weight. The relationship between product weight, the pressure integral, and holding pressure was modeled with a saturation curve. This way, the maximum product weight achievable with holding pressure can be predicted. This method represents a significant advancement in quality control during injection molding, as product weight can be predicted within the production cycle before product ejection.

KEYWORDS

cavity pressure sensors, injection molding, product weight measurement, quality control, real-time weight monitoring

Highlights

- Real-time weight prediction via internal mold pressure monitoring.
- Novel saturation curve model improves weight estimation accuracy.
- Method validated with ABS and PP materials under varied conditions.
- Enables in-line quality control in injection molding processes.
- Enhances predictive control for Industry 4.0 integration.

1 | INTRODUCTION

In industrial production, injection molding is important in producing plastic parts. One of the main challenges of the process is the mass production of high-quality products with the same parameters, which requires strict quality control. Quality control is always an additional process that increases the price of the product, so the goal is to reduce or automate it. The most expensive quality control is the use of human resources, whether it is a measurement based on SPC (*Statistical Process Control*) and using a CT (*computed tomography*) or 100% operator sorting. The product can be checked visually or according to size, mechanical properties, or other aspects, such as its weight. Product weight measurement is a simple and quick method of detecting gross defects in the final product, such as incomplete filling.[1–3]

In injection molding, the production process consists of four stages: filling, packing, holding, and cooling.[4–6] Ideally, after the volumetric filling of the product, the material is compressed or packed in the cavity, then the injection molding machine switches to the holding phase. In the holding phase, the goal is to compensate for the decrease in the specific volume of the product by maintaining the pressure. It is advisable to maintain the holding pressure until the melt freezes in the entire cross section of the gate so that no more material can flow. In this case, the product's weight does not change with a given holding pressure, even if it is maintained longer than necessary.[7] After the volumetric filling of the product, the pressure in the holding phase, and holding time determine the final weight of the product. The weight of injection molded products increases with increasing holding pressure and holding time up to a limit.

In injection molding, we can distinguish input and output parameters.[8] Input parameters are the manufacturing environment, the materials used, and the technology, while the output parameter is product quality.[9] Olga et al.[10] summarized the monitoring and control possibilities of injection molding. They categorized the process parameters into three groups: machine, process, and quality. They stated that a good correlation can be found between the quality of the part and process parameters, and also that it is hard to find the right and simple correlations because the molding process is sophisticated. Zhao et al.[11] published a comprehensive review about the current advancements in in-mold measurement possibilities with sensors and stated that it could be the key to effectively monitor part quality. Ageyeva et al.[12] reviewed current in-mold sensor technologies and highlighted the importance and the widespread use of cavity pressure measurement with different types of sensors. Horváth et al.[13,14] examined the importance of the location of cavity pressure sensors and the role of the right measuring approach to get valid results. They also pointed out how wall thickness can affect the measured results and also the final properties of the part.[15] The data measured by the sensors on the injection molding machine (input parameters) are often only partially related to the quality of the final product (output parameters). The parameters set on the injection molding machine (e.g., holding pressure) are not the same in the cavity, and the injection pressure that can be measured on the machine is always higher than the pressure that can be measured in the cavity.[16] During continuous production, the settings may not change, but the quality of the injection-molded product will likely change. The measurement system of the injection molding machine cannot detect changes within the mold, such as pressure fluctuations between cavities. According to Huang et al.,[17] traditional injection molding machine setup methods are often based on the experience of the machine operator and trial and error methods, because not all information is measured for the right decisions. For a better understanding of the injection molding process, it is necessary to measure changes where the product is created. For this, sensors placed in the mold are an excellent solution. Many types of sensors can be installed in injection molds, but pressure and temperature sensors are the most often used. Pressure sensors can provide complex information about changes in the melt and pressure, but machine capability and environmental changes can also be monitored.[18–21] In the holding phase, the pressure that can be measured in the cavity greatly depends on the geometry of the product, the injection molding technology, and the properties of the melt. As the material cools later during the cycle, we can measure the pressure of the solidified (cooled down) material, where the pressure is related to local shrinkage. From this, the change in specific volume can be calculated.[22,23]

To monitor product weight on-line, Jia-Chen et al.[24] built a pressure sensor into the nozzle of the injection molding machine and correlated the resulting pressure integral with the weight of the product, which showed good agreement. However, this method can only be used effectively with single-cavity molds, and the effect of holding times shorter than gate freeze-off was not considered. Also, this method differs only in accuracy from the pressure measured by the injection molding machine and cannot monitor the process with greater accuracy, such as internal pressure measuring sensors can. Ying et al.[25] used the built-in sensors of the injection molding machine to improve the consistency of part weight. They adjusted process parameters in two stages and applied a linear fit between part weight and the injection pressure integral. They found a good correlation ($R^2 = 99\%$), but their model does not consider holding pressure and time; it only focuses on the temperature effect (material). They tested three different molds, but the efficiency of the method was questionable. Cheng et al.[26] applied external sensors (a nozzle and a tie-bar sensor) to optimize the injection molding process using a two-cavity mold. They found a good correlation between product weight and nozzle peak pressure, but the applied method did not improve part weight stability significantly. This also confirms the crucial importance of in-cavity measurement. Gim et al.[27] investigated the relationship between internal pressure and product weight using a closed spiral mold. Based on the results, they analyzed the effect of internal pressure on product weight. They stated that the holding and cooling section of the pressure curve has the most significant effect on product weight. It seems that they regarded the stage after gate freezing as the most important; therefore, they identified the effect of the cooling rate as a significant parameter. This contradicts reality, since after the gate freezes, only the warping of the product can be affected by mold temperature, not its mass.

Wang et al.[28] conducted experiments using a tensile specimen to find a relationship between the internal pressure curve and product weight. Their experiments established a relationship between internal peak pressure, the area under the internal pressure curve (pressure integral), and product weight. They stated that the pressure integral has a better relationship with product weight than the peak pressure that can be measured in the cavity during the cycle ($R^2 = 0.85$). However, they based their statement on a poorly chosen curve fit. A saturation curve characterizes such processes, but they fitted a quadratic curve and drew an incorrect conclusion. They did not analyze the relationship between holding pressure and the pressure integral.

Using a simple, linear fit, Krizsma et al.[29] described the relationship between product weight and holding pressure in prototype molds. Under real-life injection molding conditions, the correlations only work if the effect of holding pressure is neglected and set to a constant value. Párizs et al.[30] used a saturation curve method to find the correlation between the cavity pressure integral and part weight. They stated that the method can be effectively applied for small parts and a multi-cavity mold but their equation does not consider the effect of holding pressure change. Huang et al.[17] used a specimen mold to develop a model to calculate part weight in production. They identified the cavity pressure peak as the parameter that best correlates with part weight. This method does not properly consider holding time and holding pressure to monitor weight effectively.

Numerous studies have examined the relationship between internal pressure and product weight. A linear relationship was often established between product weight and the pressure integral, neglecting the importance of holding pressure and holding time. The relationship between the pressure integral and product weight is an insufficiently researched field in the literature. Currently, no simplified relationships and methods are available that sufficiently consider, for example, the effect of holding pressure. The goal is to develop a more effective and more easily applicable model than the currently described and published methods.

2 | MATERIALS AND METHODS

We used two materials in the experiments. The first is acrylonitrile-butadiene-styrene (ABS, Terluran GP35, Styrolution Group GmbH), a general-purpose amorphous polymer suitable for injection molding. It was dried at 80°C for 3 h before processing. It can be processed well in a wide temperature range (220–260°C). The flowability of the material is adequate; therefore, it can be used with low injection rates as well. We also used polypropylene (PP, Mol Tipplen H145F), which can be processed in a wide temperature range. Its melt flow index is 29 g/10 min (MFI, 230°C/2.16 kg). After moisture was removed from its surface, the material was dried for 30 min at 60°C. An electric Engel TL-170 injection molding machine with an integrated shutoff nozzle and a maximum clamping force of 50 t was used for the injection molding tests.

Two Wittmann-C90 tempering devices were used for temperature control. They allowed the water temperature to be set between 30 and 90°C. A Moretto X-Dry90 device, a small hot air-drying device was used for drying. Drying temperature was checked with a type J handheld thermometer. The moisture content of the materials was checked with a Mettler Toledo HX204 moisture meter.

2.1 | Four-cavity mold

Four RC15-1 sensors (Cavity Eye, Hungary) were placed symmetrically in each cavity of the four-cavity cold runner mold (Figure 1), two at the beginning (PG–post-gate)

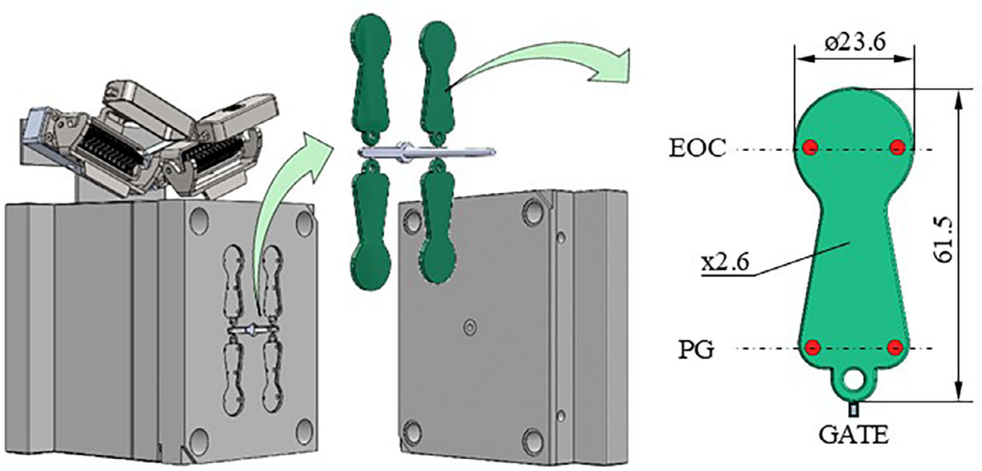

FIGURE 1 Four-cavity mold, part dimensions, and cavity pressure measurement points: Near the gate (PG–post-gate) and the end of the flow path (EOC–end of the cavity).

and two at the end of the flow path (EOC–end of the cavity). The sensors were placed in the moving half of the mold under the ejection pins.

The wall thickness of the product in each cavity is 2.6 mm, and the volume of the product is 2.54 cm^3. The four cavities were balanced, and the difference between filling and weight was negligible. The pressure measurement confirmed that filling within the cavity was symmetrical. There was no significant difference in the measured peak pressures or pressure integrals between the cavities. To confirm this, we operated the machine for 20 cycles and compared the peak and cavity pressure values at the same position in each cavity. The observed differences were smaller than the variations in the measured cavity pressure curves. We placed two sensors in the same flow path in a symmetric position (Figure 1) and found that there was no significant difference between the readings of two sensors.

The holding pressure and time were determined during preliminary experiments. The objective was to identify the minimum pressure required to fill the mold at an injection rate of 40 cm^3/s. For PP, this pressure was approximately 30 bar, while for ABS, it was about 140 bar (Figure 2). Therefore, we set the minimum holding pressures to 100 bar for PP and 200 bar for ABS. The maximum holding pressure was limited by the technology—above this pressure flash appeared. We switched to the holding phase for both materials when the volumetric filling of the cavity reached 99%. The same 40 cm^3/s injection rate was set for the injection phase and as a limit in the holding phase, allowing material packing in the holding phase.

We performed the tests with different holding pressures and holding times using the two materials (Table 1).

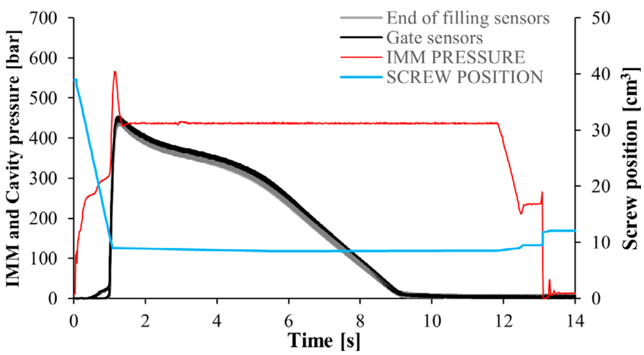

FIGURE 2 Pressure curves and screw position (PP).

TABLE 1 The injection molding parameters for the tests.

	Value	
Parameter	**PP**	**ABS**
Holding pressure [bar]	200; 300; 400; 500; 600	
Holding time [s]	1; 2; 3; 4; 6; 7; 9; 11	
Mold temperature [°C]	40	
Melt temperature [°C]	235	245
Screw rotation [m/s]	50	
Back pressure [bar]	50	
Dosing position [cm^3]	22	
Injection rate [cm^3/s]	40	

3 | RESULTS

3.1 | The relationship of part weight and holding time

With ABS, gate freeze-off occurred at 4 s; therefore, the weight of the products did not increase after a holding time of 4 seconds (Figure 3). Holding pressure determines product weight, which ranges from 10.2 to 10.55 grams over the tested holding pressure range.

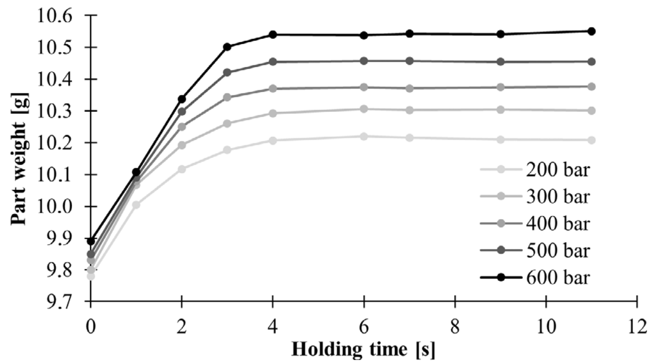

FIGURE 3 Part weight as a function of holding time at different holding pressures (ABS, melt temperature 245°C, mold temperature 40°C).

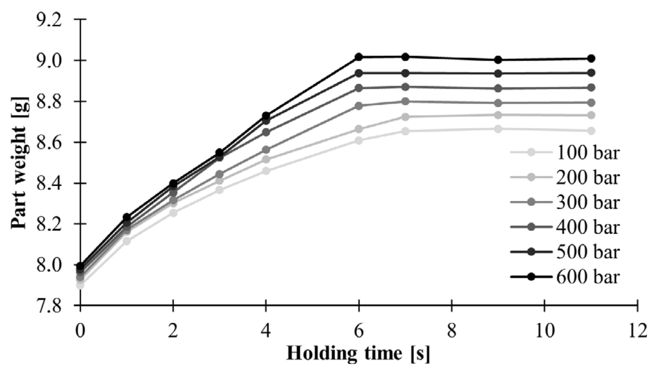

FIGURE 4 Part weight as a function of holding time at different holding pressures (PP, melt temperature 235°C, mold temperature 40°C).

In the case of PP, gate freeze-off time was 7 s (Figure 4.), which can be explained by other viscosity, chemical and physical properties of the materials. Due to the different density of PP, the weight of the PP part was between 8.62 and 9.01 grams in the tested holding pressure range. A suitable product required at least 110 bar of holding pressure. On the 50-ton injection molding machine, the upper limit for holding pressure was 700 bar, above which flash appeared.

For both materials, the weight differences between products at each holding pressure increase as holding time increases, up to gate freeze-off time. This happens because the melt can flow freely until the gate freezes. If holding pressure is reduced before the gate freezes, material can flow out of the cavity. A larger amount of material can flow out with shorter holding times because the melt is not frozen at the gate across the whole cross-section.

3.2 | The relationship of part weight and the cavity pressure integral

The pressure integrals in each cycle were determined using the post-gate sensor. The differences between the pressures measured by the post-gate and the end of the cavity path sensors were negligible with the technology settings used. A plot of product weight as a function of the calculated cavity pressure integral for each holding pressure and holding time shows that several product weights can belong to a given pressure integral (Figure 5.) if the holding pressure changes. Therefore, the cavity pressure integral–product weight relationship is also a function of holding pressure, as several cavity pressure integrals can belong to a given product weight. For example, in the case of the cavity pressure integral of 500 bar*s, part weight could be 10.02 or 10.15 as a function of holding pressure.

As holding time increases, the relationship between product weight and the pressure integral is not linearly proportional to the holding pressure but follows a saturation character. We assumed that the reason for the deviation from linearity is that melt may flow out of the cavity, which we verified by switching the shutoff nozzle on and off. After the holding phase, the pressure decreases, and the movement of the melt inside the cavity depends on the pressure and thermal conditions. When holding time is short, the melt may flow out of the cavity, or perhaps we apply holding pressure in the cavity with the back pressure during dosing. On injection molding machines with a shutoff nozzle, the shutoff nozzle prevents the material flowing between the mold and the injection unit after the holding phase, so the process occurring in the mold will be independent of dosage. We performed tests without the shutoff nozzle, which altered the relationship between the pressure integral and product weight when the holding time was shorter than gate freeze-off time, allowing the material to flow back through the sprue toward the machine.

The initial slope of the pressure integral–product weight function decreased when the shutoff nozzle was not operated. Therefore, material backflow was greater without the use of the shutoff nozzle. We verified this by measuring product weight—when the product was injection molded without the use of the shutoff nozzle, product weight was smaller. Therefore, the use of the shutoff nozzle improves the pressure integral–product weight correlation. This correlation improves further if a hot runner is used with a needle valve because the melt cannot flow out of the cavity.

With PP, similarly to ABS, the initial slope of the relationship between the pressure integral and product mass is determined by holding pressure, regardless of the material (Figure 6.). The differences compared to the tests carried out with the ABS material can be explained with the different properties of the materials. Therefore, the pressure integral–product weight relationship depends on both the material and the processing conditions.

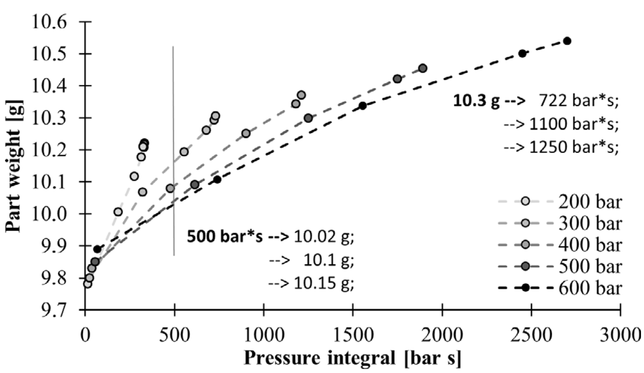

FIGURE 5 Part weight as a function of the pressure integral at different holding pressures (with ABS).

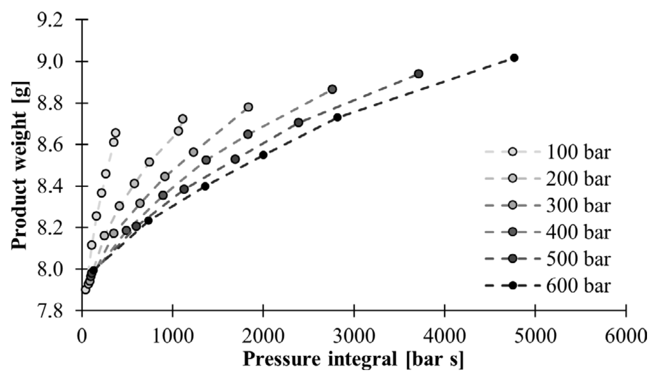

FIGURE 6 The correlation of the cavity pressure integral and part weight with the PP material and a holding pressure of 100–600 bar.

3.3 | The new method

Maximum product weight as a function of the pressure integral tends to an upper limit (Figure 7.). A saturation curve was fitted to the values determined at each pressure, the theoretical limit of which was calculated based on the pvT curve of the material.

In theory, with a given holding pressure, a maximum compensation of specific volume can be achieved if holding pressure is maintained until the product cools down. The pvT diagram shows the specific volume of the material at room temperature at a pressure corresponding to the holding pressure and at the melt temperature at atmospheric pressure (ΔV_f). From the difference between the two and the volume of the cavity, it is possible to calculate how much more material could theoretically be pushed into the mold with the given holding pressure (Figure 8).

However, this is limited by gate freeze-off, the cooling of the material, and the technology, so we will never reach this limit. The relationship between the pressure integral and product weight can be described with the following saturation function:

$$m = m_0 + \Delta m_{th} \cdot \left(1 - e^{-C_p \cdot \frac{PI}{1000}}\right) \quad (1)$$

where m_0 is the total weight of the products without holding pressure, Δm_{th} is the maximum compensable product weight calculated from the pvT curves according to the given volume, C_p is the holding pressure–dependent pressure sensitivity constant, and PI is the measured pressure integral.

In the following, we determined the parameters required for the equation with a 200–600 bar holding pressure set on the machine for both materials. Δm_{th} is in a linear relationship with the holding pressure set on the machine in the case of both materials (Figure 9). These values were calculated from the pvT relationship, which is characteristic of the material. It gives the maximum theoretical product weight that can be reached with holding pressure. Based on practical experience, the weight increase of the product during injection molding is proportional to the holding pressure that can be measured in the cavity if it is maintained until the gate freezes and if there is no significant pressure drop along the flow path.

The C_p parameter is a pressure sensitivity constant determined as a function of holding pressure, which is related to the amount of material flowing back from the cavity in the holding phase and depends on the design of the injection mold and its temperature, and the state of the melt (Figure 10). Based on Figure 7., product weight at each holding pressure has a maximum since the holding phase can only be maintained up to a certain

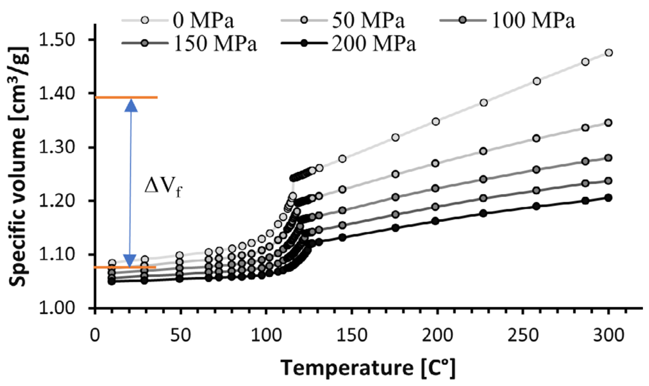

FIGURE 8 The pvT curve of the PP material–identification of the ΔV_f parameter.

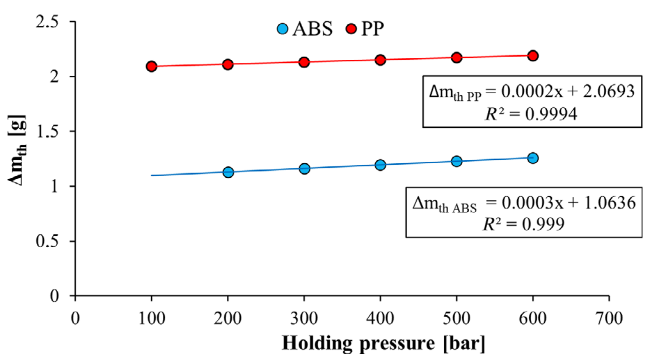

FIGURE 9 Δm_{th} as a function of holding pressure.

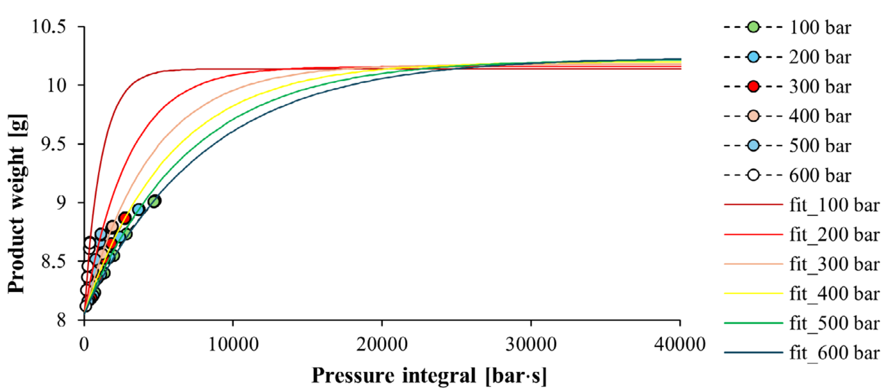

FIGURE 7 Part weight as a function of the cavity pressure integral and the maximum available product weights at different holding pressures (PP).

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pressure and time. The maximum possible product weight under the given production conditions can be obtained by fitting the correlation to the maximum product weights produced with the given holding pressure. The equation describing the upper limit:

$$m_{upper\ limit} = m_0 + K_0 \cdot \left(1 - e^{K_1 \cdot \frac{PI}{100}}\right) + K_2 \cdot \frac{PI}{100} \tag{2}$$

where K_0, K_1, and K_2 are fitting constants, which depend on the parameters of the injection molding technology and the environment (mold geometry, gate, material, temperatures), PI is the pressure integral, and m_0 is product weight without holding pressure.

On the diagram of the pressure integral–product weight processing window, which describes the relationship between product weight and the pressure integral, the lower limit, i.e., the machine limit, was set to 2000 bar holding pressure (Figure 11) based on Equation (1). In this case, the machine limit is an empirical value, which may vary depending on the injection molding machine.

3.4 | Validation of the new method

By determining the lower and upper limits, we obtain the processing window in which product weight can be determined, given the pressure integral and the holding pressure. The machine limit of 2000 bar is an empirical value, which means a pressure of 2000 bar in the cavity. This value cannot be reached or exceeded in real-life production conditions or only in special cases. Using the test result, we determined Δm_{th} and Cp for PP and ABS. We only present the equations for PP since the results in the case of ABS are similar. The maximal additional product weight in the holding phase and the holding pressure–dependent pressure sensitivity constant in the case of PP:

$$\Delta m_{th} = 0{,}0002 \cdot P_{hold} + 2{,}0693 \tag{3}$$

$$Cp = 106{,}29 \cdot P_{hold}{}^{-1{,}067} \tag{4}$$

$$m = 8{,}05 + (0{,}0002 \cdot P_{hold} + 2{,}0693) \cdot \left(1 - e^{-\left(106{,}29 \cdot P_{hold}{}^{-1{,}067}\right) \cdot \frac{PI}{1000}}\right) \tag{5}$$

Based on the equations obtained, using the established pressure integral–product weight, Equation (5), we examined the calculated product weight based on the equation and measured the product weight using a holding pressure of 200–600 bar (Figure 12.). We also performed the calculation using a simple linear fitting, often

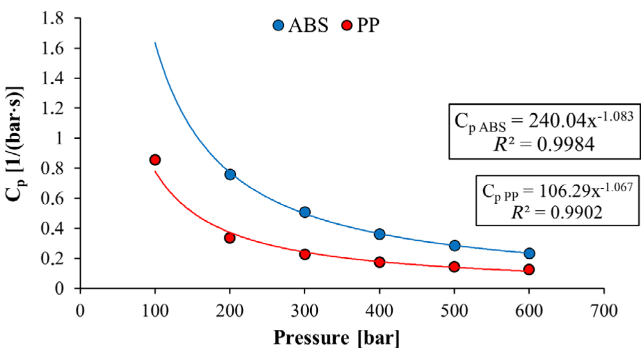

FIGURE 10 Dependence of the pressure sensitivity factor Cp on the holding pressure.

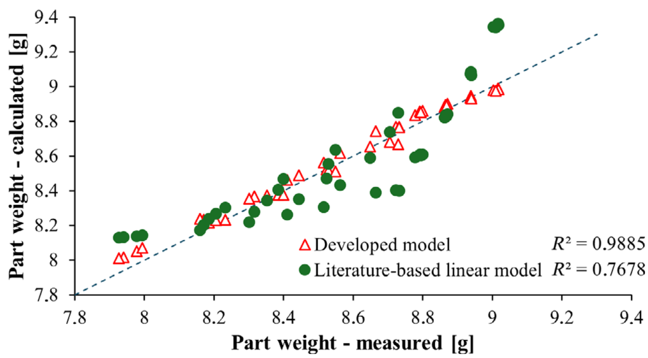

FIGURE 12 The difference between the measured and calculated part weight as a function of the measured weight–based on our model and the model in the literature.

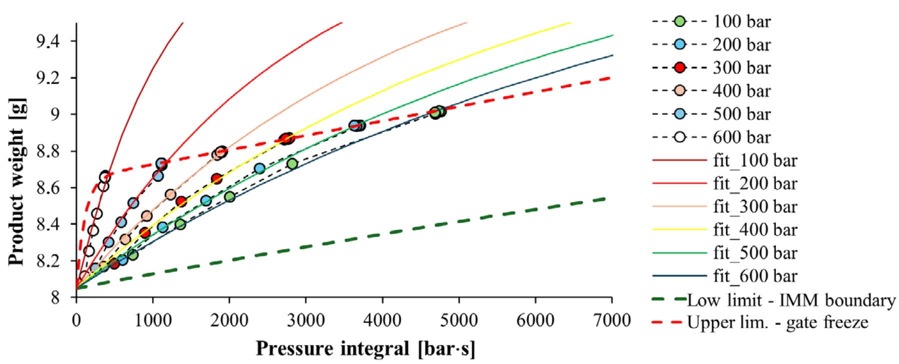

FIGURE 11 The relationship between product weight and the pressure integral – the mechanical limit and gate freeze-off are marked (PP).

published in the literature, which does not consider the effect of holding pressure.[28,29]

With our method, using holding pressure and the pressure integral, the error between the calculated and measured product weight was significantly smaller compared to the literature method. The R^2 value of our method was 0.99, while the R^2 value of the linear fitting described in the literature is 0.77. Based on the results, with the fitting method we used, the largest error between the measured and calculated product weight was below 0.96% in the 200–600 bar holding pressure range. The given value with a linear fit was an order of magnitude larger.

It can be stated that based on the pressure integral and the pressure peak that can be measured in the mold, product weight can be determined more precisely than with a linear fit if the relationship has been determined for a combination of at least three different pressures and at least three holding times when the gate freezes. With the equation, expected product weight can be calculated in a wide range and thus can be monitored online.

4 | SUMMARY

This study introduces a novel method for predicting product weight in injection molding with the help of internal cavity pressure sensors. The method correlates the pressure integral measured during the injection molding cycle with the final weight of the product. We used acrylonitrile butadiene styrene (ABS) and polypropylene (PP) and examined the impact of various holding pressures and holding times on product weight. A key outcome is a robust relationship between the pressure integral and product weight, modeled with saturation curves. With this method, the maximum additional product weight can be estimated based on the pressure integrals of the cavity pressures. The study shows that the relationship is not linear but follows a saturation pattern, which reflects the physical limits of material filling and shrinkage compensation within the cavity. The study confirms that the pressure integral alone is not a reliable enough predictor of product weight—peak holding pressure needs to be measured as well. A more accurate representation of the process requires a saturation curve in modeling the relationship between the pressure integral, holding pressure, and product weight. This approach opens new possibilities for enhancing quality control in injection molding by enabling real-time monitoring and feedback. Future work should focus on extending this method to more complex mold geometries and a wider range of polymer materials and integrating the model into fully automated control systems for industry 4.0 applications.

AUTHOR CONTRIBUTIONS

Conceptualization: J. G. K. and S. H. *Methodology*: J. G. K. and S. H. *Software*: S. H. *Validation*: J. G. K. Investigation: S. H. *Writing—original draft*: S. H. *Writing—review* and *editing, visualization*: J. G. K and S. H. *Project administration*: J. G. K. *Funding acquisition and Supervision*: J. G. K. Both authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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