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Design and production of functional parts using machine molding technology

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ABSTRACT

Injection molding (IM) is used to process over one-third of all plastics because of its affordability and manufacturing capacity. In the IM process, a hot polymer melt is injected into a cold, empty chamber that has to have a specific form. After that, the polymer melt is allowed to solidify while being cooled under control and high pressure. When developing IM tools, such as fast tool inserts, a number of issues pertaining to material technology and tool design process arise. As a result, it's critical to suggest effective methods for creating IM tools (such as prototype or mass-produced parts). The purpose of this study is to assess how various injection molding parameters, such as analysis technologies, gate locations, melt and mold temperatures, injection times, and pressure at the end fill, affect the yield of applicable parts. A thorough assessment of the literature was done regarding the application of IM techniques to the synthesis of polymeric materials. Next, in order to look into how the IM process affects the part's quality, a numerical study is created on a fuel cell bipolar plate utilizing the Mold Flow Adviser Software Package. Based on the findings, it was noted that the analytical technology might be used for applied part simulation. Furthermore, it was discovered that a number of IM process parameters can have a big impact on the part's production quality.

Keyword: molding technology, injection molding, Mold Flow Adviser

تصميم وإنتاج الأجزاء الوظيفية باستخدام تكنولوجيا القولبة الآلية

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خلاصة

يتم استخدام القولبة بالحقن (IM) لمعالجة أكثر من ثلث جميع المواد البلاستيكية نظرًا لقدرتها على تحمل التكاليف والقدرة على التصنيع ، في عملية الحقن (IM) يتم فيها حقن البوليمرات الساخنة المنصهرة في تجويف فارغ وبارد بالشكل المطلوب. يتم بعد ذلك السماح لصهر البوليمر بالتصلب تحت ضغط عالٍ وتبريد متحكم فيه تحت السيطرة والضغط العالي . تتم مواجهة مشكلات مختلفة في تطوير أدوات المراسلة الفورية (على سبيل المثال، تطوير إدراج الأداة السريعة) المتعلقة بمنهجية تصميم الأداة وتكنولوجيا المواد. ولذلك، من المهم اقتراح تقنيات فعالة لإنتاج أدوات للمراسلات الفورية (مثل الأجزاء المنتجة بكميات كبيرة أو أجزاء النموذج الأولي). تم إجراء هذا البحث لتقييم تأثيرات معلمات IM بما في ذلك تقنيات التحليل ومواقع البوابات ودرجة حرارة الذوبان ودرجة حرارة القالب وزمن الحقن والضغط عند الملء النهائي على إنتاج الأجزاء

المطبقة. تم إجراء مراجعة واسعة النطاق للأدبيات حول استخدام طرق IM في إنتاج المواد البوليمرية. بعد ذلك، تم تطوير تحليل عددي باستخدام حزمة برنامج Mould Flow Adviser على لوحة ثنائية القطب لخلية الوقود من أجل دراسة تأثير عملية IM على جودة الجزء. ووفقا للنتائج، لوحظ أن تكنولوجيا التحليل يمكن تطبيقها على محاكاة الأجزاء المطبقة. علاوة على ذلك، فقد وجد أن المعلمات المختلفة لعملية IM يمكن أن تؤثر بشكل كبير على جودة إنتاج الجزء.

الكلمات المفتاحية: تكنولوجيا القولبة، القولبة بالحقن، مستشار تدفق القالب.

1. Introduction

The increasing demand for product quality and process efficiency is a result of the globalization of the markets for plastic products. The need for unique material specifications that can be shaped into shapes that can meet specific criteria has arisen from the sectors' rapid growth. These specifications include the following: (a) mechanical and electrical qualities; (b) mass homogeneity and high dimension accuracy; (c) minimal shrinkage and warpage; (d) surface structure; and (e) strength attributes. Numerous polymeric materials, including metal, graphite, polymers, and carbon-carbon composites, can be used to make plastic parts. Every kind of material has advantages and disadvantages. The ingredients used in polymer composites are comparatively inexpensive, and the product's applicable portions can be molded using IM or compression processes. A thorough grasp of the IM process is necessary for manufacturers to maximize product quality while minimizing process expenses. This makes it difficult to use the current molding technology to produce applied parts with special qualities like increased electrical conductivity and strong mechanical strength. Because pure plastics are mostly molded using conventional methods, it is imperative to conduct a comprehensive evaluation of the molding technology process.
Several investigations have been conducted to examine the IMM for materials composed of polymers. In 2009, Tsai K-M et al. [1] carried out an investigation to find out how process parameters affected the optical quality of lenses during injection molding (IM). Michaeli et al. (2009) [2] carried out an analytical analysis of various compression-molding techniques with respect to the quality of the optical lenses to look into things like mold design, process parameters, and plastic raw materials that affect the aspherical plastic lenses' precision during the injection molding process. A parametric study was carried out by Akbarzadeh A and Sadeghi M (2011) [3] to examine the impact of injection molding parameters on polypropylene (PP) and polystyrene (PS) shrinkage. The chosen input parameters were packing time, packing pressure, injection pressure, and melting temperature. When this machine is used to produce polymer-based micro-products, Fantoni G et

al. (2012) [4] conducted a study to evaluate the IMM using functional analysis in order to pinpoint its essential components and potential problems. D et al. (2013) [5] carried out research to create a method for calculating shrinkage flaws in micro-injection molding. Müller E. et al. (2014) [6] conducted an investigation to assess the possibilities for enhancing injection molding procedures through the use of dual energy signatures through two techniques: a reduction in process duration and a reduction in power level. In order to create an inverse model of injection molding for optical lens form precision, Tsai, K-M, and Luo H-J. (2014) [7] coupled a genetic algorithm (GA) and an artificial neural network (ANN). In 2014, Tsai K-M and Tang B-H [8] conducted research to suggest an injection molding window procedure for spherical lenses with the best possible form accuracy. Macías et al. (2015) [10] studied the relaxation of residual stresses in lenses plastic covers with applications in the injection molding process; Nian S-C et al. (2015) [9] investigated the setting of local mold temperature in a cooling system for warpage control of thin-walled injection molding. In order to assess the impact of material properties and manufacturing techniques on the surface textures of diamond-cut inserts used for injected plastic optics in lighting applications, Aidibe A et al. (2016) [11] conducted study. A study on energy monitoring of a plastic injection molding process using hydraulic IMMs was conducted by Mianehrow H et al. (2017) [12]. A study was conducted by Siregar R A et al. (2017) [13] to design and build IMM for manufacturing laboratories... Research on mold machining and injection molding of diffractive micro-structures was conducted by Holthusen A-K et al. (2017) [14]. Elduque A et al. (2018) [15] conducted research to examine how materials and IMM machine selection affect electricity consumption and the environmental impact of the injection molding process. A study was conducted by Hrițuc A (2018) [16] in order to identify basic and appropriate equipment for assessing the injection molding process. It was discovered that building and designing a basic piece of equipment for creating a scientific assessment of the plastic injection process is feasible. In a paper published in 2018, Zhou X et al. [17] proposed an unsupervised features extraction method that uses a sparse auto-encoder to extract melt pressure characteristics from injection molded parts. A study was conducted by Sun X et al. (2019) [18] to create a new characterization technology for injection-molded thermos-plastics warpage measurement. Plaque warpage has been seen to increase with time. A study was conducted by Mahesh Naik R et al. (2019) [19] to assess how different process characteristics related to design and control could prohibit faults. In order to predict the shortcomings of microscopic features, Zhang H et al. (2019) [20] studied the precision replication of micro features using micro injection molding. They achieved this by optimizing the mold design for large injection molding products using simulation software for injection molding and process monitoring,

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as well as a series of trials and verification. A study on the energy consumption of IMM machines powered by five different kinds of electro-hydraulic power units was carried out by Liu H et al. (2019) [21]. It was shown that employing a fixed-displacement pump powered by an asynchronous motor resulted in the power unit's highest energy usage. A study was conducted by Vassallo C et al. (2020) [22] to look into how recycling and polymer choice affected the sustainability of injection-molded parts. Three materials were used: 30% Glass-Fibre Reinforced Polypropylene (PP30GF), Polylactic Acid (PLA), and Acrylonitrile Butadiene Styrene (ABS). In order to monitor melt changes online during the forming process and examine the relationship between various parameters and quality, H-H Tsou et al. (2020) [23] conducted a study on the features extraction molding of product analysis in injection molding for intelligent manufacturing. A study on the application of machine learning techniques for injection molding quality prediction was carried out by Jung, H. et al. (2021) [24]. A number of machine learning algorithms were tested and their predictive capabilities for injection molding quality were compared.

It is sense to use numerical simulation during the design stage since the majority of molding problems are caused by injection mold building errors related to product geometry. Nevertheless, a limited number of mold manufacturers employ software simulation to verify mold designs that address material flow and cooling issues. Recently, the production industry has not taken use of the benefits provided by simulation alternatives to examine the fundamental mold designs prior to mass production. This could be because the manufacturers are unfamiliar with this kind of software, the cost of simulation software tools has escalated, and there is a shortage of skilled workers to operate the software. In order to assess the impact of molding technology on the manufacturing of applied parts, this study concentrated on simulating applied parts, such as bipolar plates, utilizing computer-aided solutions, or CAE (Computer-Aided Engineering) using MOLDFLOW. Additionally, it is anticipated that the results will provide valuable information for future research directions, particularly as a tool for the production of different goods using IM techniques. As a result, it is anticipated that the suggested simulation will help the production facility produce more components faster and at a reduced cost.

2. MATERIAL AND METHOD

2.1. Molding Methods

The main application of compression molding is in the harsh processing of thermosets, or thermoplastics, such as elastomers or fiber-filled composites [25]. The method for obtaining channels molded into polymer composite preforms is straightforward and efficient. Since polymer composite materials with large filler concentrations do not flow easily, channels can be stamped into a blank preform using compression molding. Reducing heating and cooling durations is the key to successfully completing compression molding and creating channels. Furthermore, most polymer resins can be processed at a maximum temperature of 20 to 40 ºC above their melting point. The reduced temperature differential is a challenge in terms of minimizing convection and conductive losses during the process of compressing the heated preform after it has been transferred from the heater to the mold. The design of plastic parts can be combined with numerical optimization, polymer process modeling, and design sensitivity through the use of injection molding [26]. A movable barrier based on the fluid volume approach can be created to determine the filling pattern and fill time [27].

2.2.Parts and Injection Mold Design

A square slab specimen mold of $2\,mm$ part thickness associated with channel design of rectangular cross-section of $0.5\,mm$ depth and $2\,mm$ width were designed for the experiments and molded as depicted in **Figure 1** [28],. In addition, for the aim of this research is to study effects of process parameters such as analysis technology, melt and mold temperatures, injection time and injection pressure under various molding conditions, the proposed bipolar plates channel was molded by simply IM.

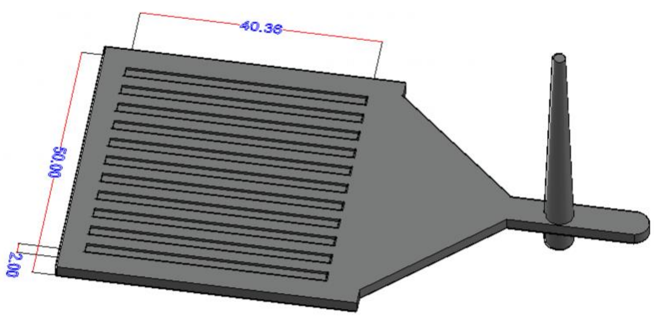

Figure 1. Shape and dimension of bipolar plate for use in PEM fuel cell

Crystalline polyphenylene (PPS) resin filled with 40 % weight percentage of carbon fibers were used as the molding material. The PPS resin supplied by Chevron Phillips Chemical was an injection grade Ryton, which with higher melt-flow index (MFI) and higher melting point of 285 ℃. The properties of Semi-crystalline PPS are summarized in **Table 1**.

Table 1. Material Properties of Semi-crystalline PPS

Sr. No	**Property**	**Value**	**Unit**

1	Elastic Modulus	13000	MPa
2	Poisson's Ratio	0.396	----
3	Shear Modulus	4660	MPa
4	Melt Temperature	285	ºC
5	Density	1.35	Gm/cm^3
6	Thermal Conductivity	0.320	W/m- ºC
7	Specific Heat	1800	J/kg ºC

In order to evaluate the effect of processing parameters on the quality of molded parts, after varied processing parameters were used. Molding parameter conditions of part are listed in **Table 2.**

Table 2. Molding conditions

Mold Level	Unit	With Channel		
		I	II	III
Melt Temperature	ºC	300	310	320
Mold Temperature	ºC	160	170	180
Injection Velocity	Mm/sec	60	90	120
Packing Pressure	mPa	42	92	142

3. Mold flow Analysis Results

Appropriate location of the gate is the most essential factor that influences the molded part quality. A well-designed gating system is very essential to obtain good quality molded part by providing a homogenous mold filling pattern. MoldFlow analysis can predict the positions of the gate locations when the input parameters are fed to it, as shown in **Figure 2**. The best gate location is represented by blue color, while the worst gate location is represented by red color. The analysis and gate location on the part is appeared with two or more selections of locations. Then, the best gate locations are required to be evaluated by running the filling analysis on various best gate locations. The gate locations analysis of the molded bipolar plate is shown in **Figure 3**. The gate should be located at right points in order to ensure uniform plastic flow in the cavity and filling should be complete as quickly as possible.

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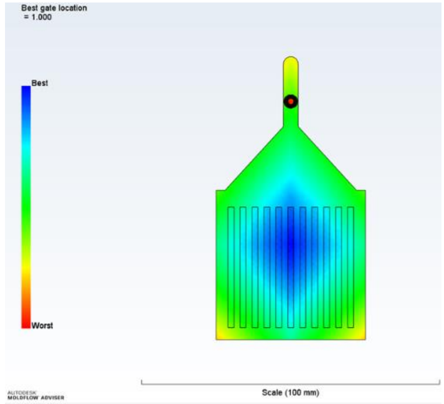
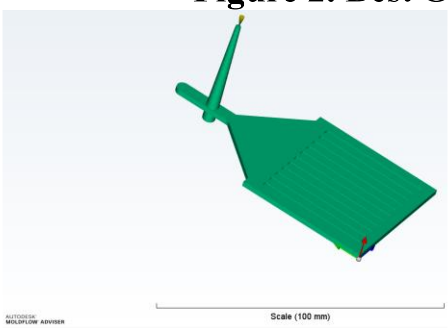
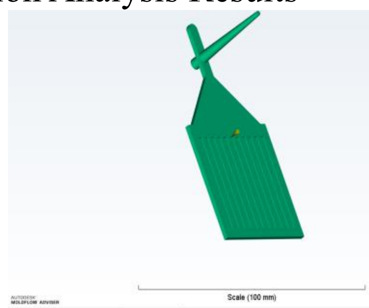


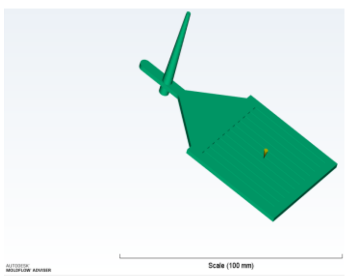
Figure 2. Best Gate Location Analysis Results



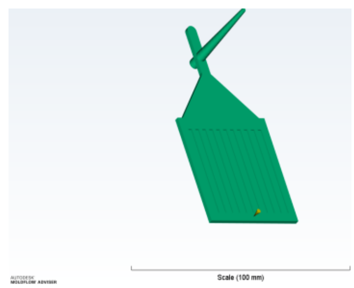
a) Location Gate 1



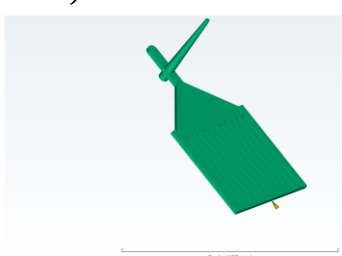
b) Location Gate 2



c) Location Gate 3



d) Location Gate 4



e) Location Gate 5

f) Location Gate 6

Figure 3. Gate locations selected in Bipolar plate

The fill time results show the paths through which the molten plastic flows and how long it will take to fill. The fill time utilizes a range of colors to reveal the first zone to fill (in red color) through the last zone to fill (in blue color), while all the

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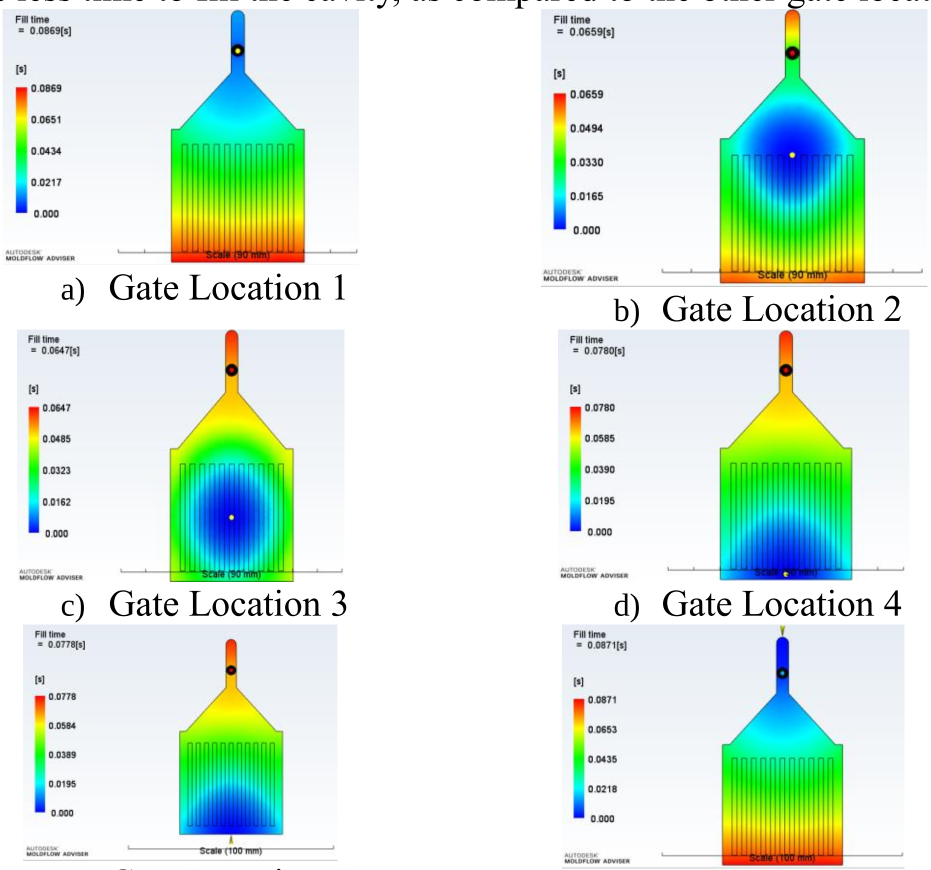
zones which have similar color are simultaneously filled. If the part which is short shot, the section which is not filled has no color. The fill time can be adopted to predict possible zones of over packing, short-shot, air traps and weld lines. The filling time results are depicted in **Figure 4**. The fill times for the gate locations are 0.0869 sec, 0.0659 sec, 0.0647 sec, 0.0780 sec, 0.0778 sec, and 0.0871 for 1, 2, 3, 4, 5, and 6 gate locations, respectively. It can be seen that the third gate location needs less time to fill the cavity, as compared to the other gate locations.



a) Gate Location 1
b) Gate Location 2
c) Gate Location 3
d) Gate Location 4
e) Gate Location 5
f) Gate Location 6

Figure 4. Filling Time for various gate locations

The results of injection pressure produced from the fill analysis is used to show the maximum value of injection pressure attained before the occurrence of the pressure / velocity switch-over during the filling phase. The pressure at specific location begins to increasing only after reaching the melt front that location. The pressure continues to increase as the melt front moves past, because of the increase in flow length between these locations and the melt front. The pressure gradient or magnitude depends on the mold polymer resistance. This is due to the compound with high viciousness requires more pressure to fill the cavity. The pressure results as shown in **Figure 5**. It can be seen that that the second gate location requires the

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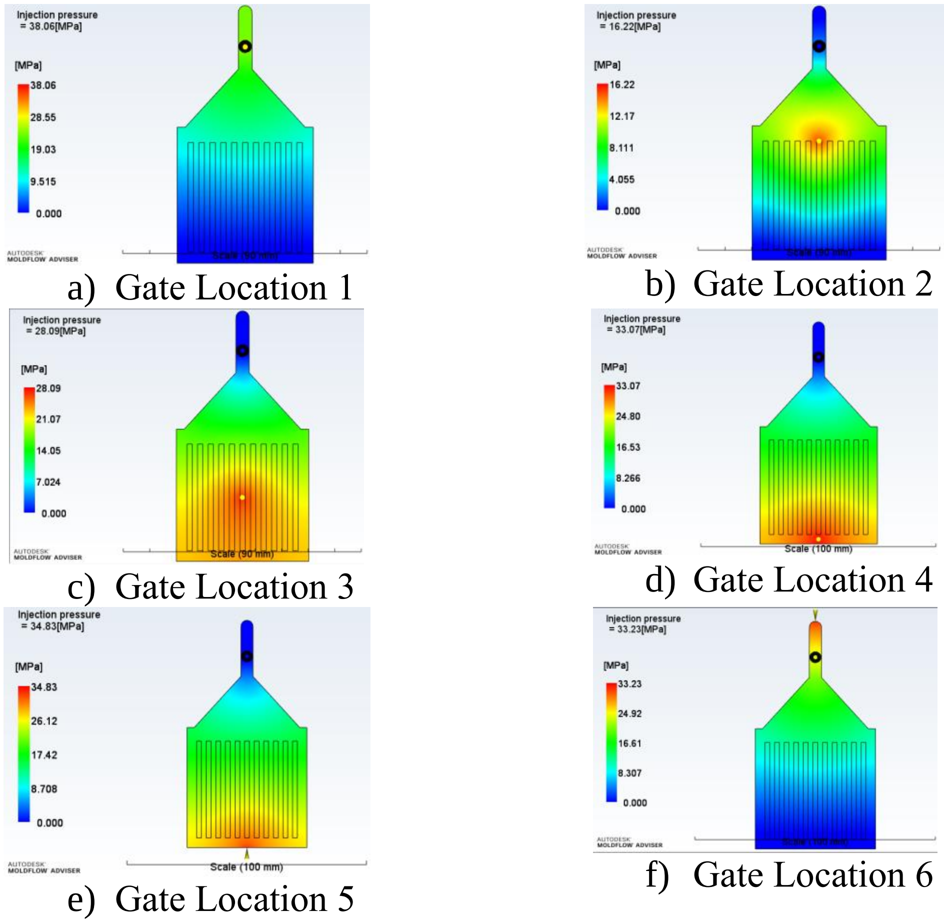
minimum injection pressure as compared to other gate locations. The pressure result shows that the second gate location requires the pressure of 16.22 MPa, while a maximum injection pressure of 38.06 MPa is attained for first gate location. Higher injection pressure represents higher shear rate occurrence and higher level of shear stress.



a) Gate Location 1
b) Gate Location 2
c) Gate Location 3
d) Gate Location 4
e) Gate Location 5
f) Gate Location 6

Figure 5. Injection Pressure Results

The results of average temperature show the average bulk temperature across the part thickness at the end of filling. Polymer melts temperature changes not only with location and time but also along with the thickness during the entire cycle of injection molding. It is very difficult to illustrate these changes in a single chart. The average temperature is used to depict the weight of the part across its thickness. It represents the energy that is transferred through specific location at specific time. The average temperature is illustrated in **Figure 6** for various gate locations. It can be observed that the highest average temperature of 336.2$°C$ is recorded for the first gate location, while the lowest average temperature of 331.4 $°C$ is attained by second gate location Therefore, from the simulation analysis of the part it is resulted as shown below in the figure in the red zone which is an

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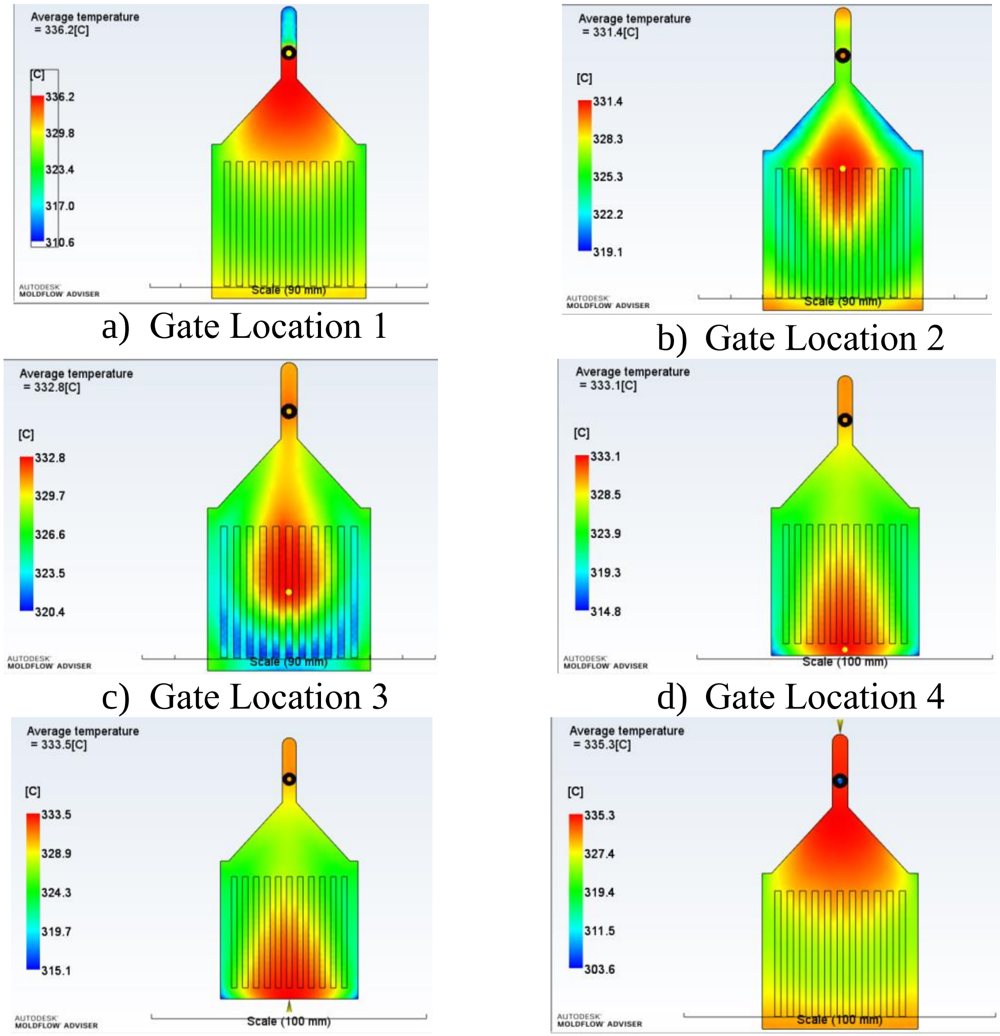
optimum value of about 220.1 $°C$. The range of front flow temperature is 106.7 to 220.1$°C$.



a) Gate Location 1
b) Gate Location 2
c) Gate Location 3
d) Gate Location 4
e) Gate Location 5
f) Gate Location 6

Figure 6. Average Temperature

3.1.Effects of Mold Temperature on Production of Molded Parts

Mold temperature is described as the cavity surface temperature in contact with the product during the injection molding process. In-mold design and condition setting, it is essential not only to maintain a suitable temperature but also to make it evenly distributed. Mold temperature in injection molding influences the cycle and quality of molding. In actual operation, it is set from the lowest suitable mold temperature in the material injection molding used and then modified appropriately in accordance to the condition of quality. **Figure 6-a** shows the effects of mold temperature on the actual injection pressure. It can be observed that increasing the

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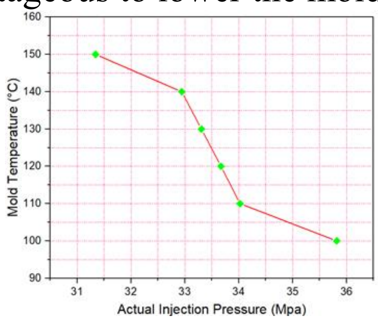
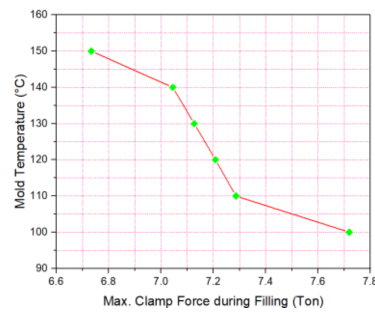
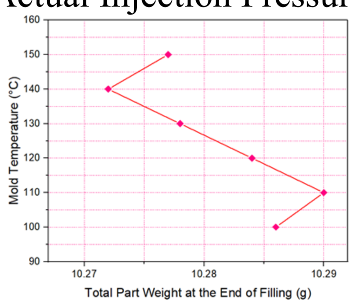
mold temperature can result in a reduction of the actual injection pressure, which may be attributed to the fact that an increase in mold temperature decreases the plastic condensation in the cavity, permitting the molten plastic to flow more easily inside the cavity, which in turn reduces the actual injection pressure**. Figure 6-b** depicts the influence of mold temperature on the max. clamp force during filling, where it can be seen that increasing the mold temperature can result in a decrease of the maximum clamp force during filling. Similarly, it can be found from **Figure 6-c** that increasing the mold temperature can also reduce the maximum clamp force during cycle. The impacts of mold temperature on the total part weight at the end filling and the overall total part weight are illustrated in **Figure 6-d** and **Figure 6-e**, where it can be seen that the part weight at the end of filling and total part weight are seen to be reduced with increasing the mold temperature. **Figure 6-f** shows the mold temperature impacts on the maximum shear stress at the wall. It can be seen that increasing the mold temperature can result in a reduction of the maximum shear stress at the wall. This can be explained by as the crystalline polymers crystallinity of increases, the plastic stress cracking resistance decreases, so it is advantageous to lower the mold temperature.



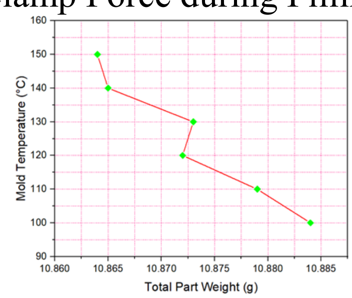
a-Effect of Mold Temperature on the Actual Injection Pressure



b-Effect of Mold Temperature on Max. Clamp Force during Filling



c-Effect of Mold Temperature on Total Weight at the End of Filling



d-Effect of Mold Temperature on Total Part Weight

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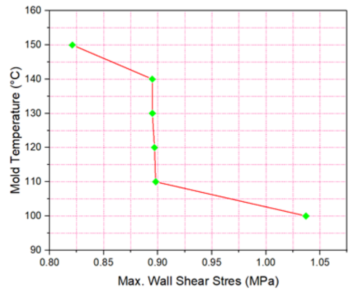
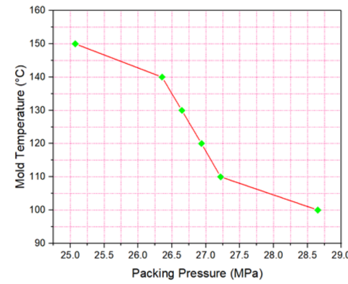


e-Effect of Mold Temperature on maximum wall shear stress

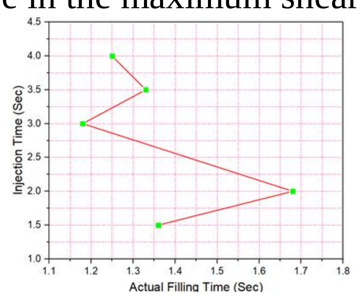


f-Effect of mold temperature on the packing pressure

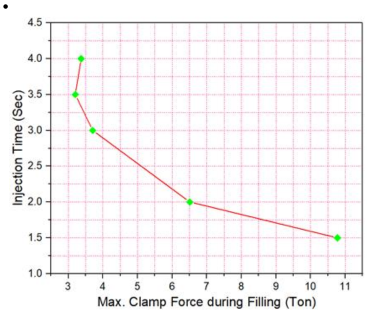
Figure 6. Effects of Mold Temperature on Production of Molded Parts

3.2.Effects of Injection Time on Production of Molded Parts

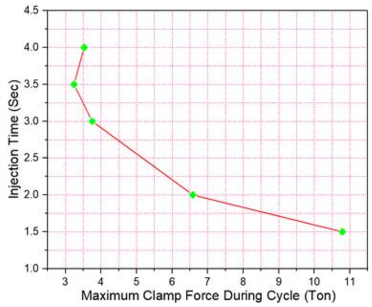
Injection time plays a key role in the injection molding process, including the produced parts quality, but especially the effect it produces on the financial bottom line. The injection time is the time it takes for the mold to fill completely. **Figure 7-a** shows the effects of initial injection time on the actual filling time. It can be observed that when the injection time is reduced below 3 secs, the actual filling time is increased. However, when the injection time is above 3 secs, the actual filling time is reduced. **Figure 7-b** depicts the influence of initial injection time on the maximum clamp force during filling, where it can be seen that increasing the injection time can result in a decrease of the maximum clamp force during filling. Similarly, it can be found from **Figure 7-c** that increasing the injection time can also reduce the maximum clamp force during cycle. The impacts of injection time on the total part weight at the end filling and the overall total part weight are illustrated in **Figure 7-d** and **Figure 7-e**, where it can be seen that the part weight at the end of filling and total part weight are seen to be reduced with increasing the injection time. **Figure 7-f** shows the injection time impacts on the maximum shear stress at the wall. It can be seen that increasing the injection time can result in an increase in the maximum shear stress at the wall.



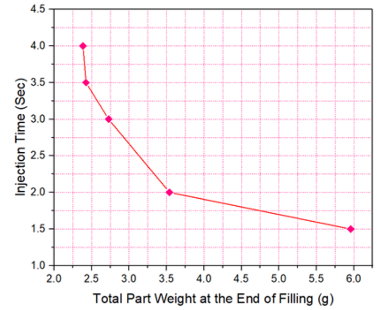
a- Effect of initial injection time on the actual injection pressure



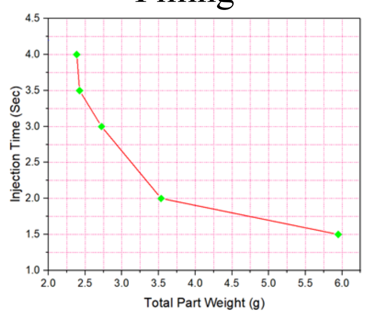
b- Effect of initial injection time on Maximum Clamp Force during Filling



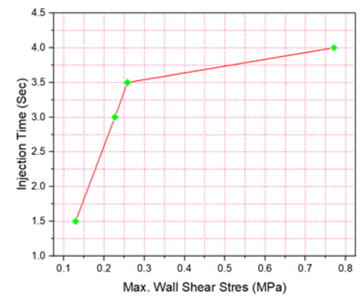
c- Effect of initial injection time on Maximum Clamp Force during Filling



d- Effect of initial injection time on Total Part Weight at the End of Filling



e- Effect of initial injection time on Total Part Weight



f- Effect of initial injection time on Maximum Shear Stress

Figure 7. Effects of Injection Time on Production of Molded Parts

4. Conclusion

Based on the results of this research, the following conclusions are drawn:

a) . It was found that using 3D analysis technology for thin-walled parts produces comparable results to using Dual-Domain analysis technology, but requires more computational resources and time to run the analysis.
b) Appropriate location of the gate is the most essential factor that impacts the molded part quality. A well-designed gating system is very essential to obtain good quality molded part by providing a homogenous mold filling pattern. MoldFlow analysis can predict the positions of the gate location when the input parameters are fed to it.
c) It was shown that the mold and melt temperatures affects the actual injection pressure, clamp force during filling and cycle, total weight of the part, wall shear stress of the part, and packing of the produced parts.
d) Injection time can also influence the initial filling time, clamp force during filling and cycle, total weight of the part, wall shear stress of the produced part.
e) % end of fill pressure affects the clamp force during filling and cycle, total

weight of the part, wall shear stress and packing of the produced part.

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