Experimental Study : Thermal Variations and Pressure's Impact on Plastic Injection Molding Quality

Nur Fitria Pujo Leksonowati[a, *], Nurman Pamungkas[a] , Meilani Mandhalena Manurung[a] , Ganda Aidil[a]
[a]Mechanical Engineering Department, Politeknik Negeri Batam
Jalan Ahmad Yani Tlk.Tering Kec.Batam Kota, Kota Batam Kepulauan Riau 29461
*E-mail: nurfitriapujo@polibatam.ac.id

Abstract

This study investigates the effects of varying hot water temperatures (75°C, 85°C, and 95°C) and injection pressures (328 Bar and 928 Bar) on the outcomes of experimental tests in injection molding. Results indicate that at 75°C, 85°C, and 95°C with an injection pressure of 328 Bar, the product displayed a Short Mold defect despite a slight increase in mass. At 75°C with an increased injection pressure of 928 Bar, a White Line defect was observed, while at 85°C and 928 Bar, a defect-free part was produced with optimal mass. However, at 95°C, a Bright Color defect was evident, leading to part rejection despite a slight mass increase. The findings highlight the significance of meticulous parameter selection, with an optimal combination identified as 85°C hot water temperature and 928 Bar injection pressure for defect-free production in injection molding processes.

Key Words: Injection molding, Hot Water temperature, Injection Pressure, Optimal parameters, Product Quality

Abstrak

Penelitian ini bertujuan untuk menganalisis defect product injection molding berdasarkan hasil uji coba eksperimental dengan mesin injection molding yang dilakukan dengan variasi hot water temperature sebesar 75°C, 85°C, dan 95°C, dan tekanan injeksi sebesar 328 Bar dan 928 Bar. Hasil penelitian menunjukkan bahwa produk menunjukkan cacat short mold pada parameter hot water temperature 75°C, 85°C, 95°C, dan tekanan Injeksi 328 Bar, dan produk mengalami peningkatan massa dari 14 gr menjadi 14,5 gr. Pada hot water temperatur 75°C dengan peningkatan tekanan injeksi hingga 928 Bar, produk menunjukkan cacat white line, dan peningkatan massa menjadi 20 gr. Namun, uji coba kelima, yang dilakukan pada hot water temperature 85°C dan tekanan injeksi 928 Bar, menghasilkan bagian yang dihasilkan defect free dengan massa 20 gr, menunjukkan potensi untuk produksi berkualitas tinggi berada pada parameter ini. Sebaliknya, peningkatan suhu menjadi 95°C pada uji coba keenam menghasilkan cacat bright color, dan bagian tersebut dikategorikan reject meskipun terdapat peningkatan massa menjadi 20,5 gr. Oleh karena itu, parameter optimal yang diidentifikasi adalah hot water temperature 85°C dan tekanan injeksi 928 Bar. Hasil penelitian ini menekankan pentingnya pemilihan parameter dengan hati-hati untuk menghasilkan produk yang bebas defect.

Kata kunci: Injection molding, Hot Water temperature, Injection Pressure, Optimal parameters, Product Quality

1. Introduction

Mold making plays a crucial role as a supporting industry, given that over 70% of consumer product components are related to it [1]. The industry faces challenges due to the high demand for reduced design and manufacturing lead times, superior dimensionality and overall quality, and swift design alterations [2]. Injection molding, a widely used polymer processing technique, excels at producing intricate parts at a high rate and reasonable cost[1], [3], [4], [5] . This process is divided into three stages: filling, packing, and cooling. The procedure begins with the cavity being filled with molten resin at the injection temperature. To account for the anticipated shrinkage as the polymer solidifies, additional polymer melt is packed into the cavity under higher pressure. This stage is succeeded by cooling until the part achieves enough rigidity for ejection. The primary source of residual stress in this process is the rapid and non-uniform cooling [3], [4], [5], [6].

During injection molding process, the raw material is heated until it melts, and this molten polymer is then injected into the cavity through a delivery system and a gate under high pressure. As the cavity nears full capacity, it is kept at a steady pressure for the packing stage. This packing pressure is utilized to fill any remaining cavity volume and to offset shrinkage during the cooling stage. Once the cavity's interior stabilizes, the product is ejected from the mold[7]. The quality of the final molded part, characterized by dimensional stability, appearance, and mechanical properties, is heavily reliant on the processing variables[7], [8]. Product defects, such as warpage, shrinkage, sink marks, and residual stress, can be attributed to various factors during the production process. These defects negatively impact the products' quality and precision[1], [8], [9], [10]. Hence, it's critically important to effectively manage the factors influencing the molding procedure.

Currently, injection molding has established itself as a fundamental fabrication process in the environmental industry. It offers numerous advantages over older processes such as compression and transfer molding. These advantages include reduced labor cost, enhanced dimensional control, and shorter cure times. Therefore, injection molding emerges as an ideal technique for the low-cost mass production of plastic. Nylon, a synthetic polymer with amide linkages, is a type of polyamide that can be made from different monomers [11]. It was the first man-made polyamide, invented by DuPont in 1935. The term "nylon" is also used as a general name for fully aliphatic polyamides, distinguishing them from aramids, which are polyamides with aromatic rings. This highly versatile thermoplastic material is commonly used to make fibers, fabrics, and plastics. Its durability and chemical resistance make it ideal for specific injection molding applications, such as automotive electronic connectors, protective casings, enclosures, metal replacement parts, and high-wear mechanical components [7].

Nylon is part of a larger chemical family of materials called polyamides (PA). There are different structures within this family, including Nylon 6, Nylon 6/6, Nylon 12, Nylon 11, and Nylon 4/6, each with unique property advantages. These properties are principally related to their chemical resistance, heat resistance, water/moisture absorption, and their availability and cost. To enhance its tensile and flexural strength characteristics, nylon is often blended with fiberglass in many molded product applications. Furthermore, specialized additives can be used to fine-tune nylon's material properties. For instance, phosphorus-based additives can make nylon more flame-resistant, while antistatic additives can improve its electrical properties. This versatility and adaptability make nylon a widely used material in various industries [7], [12].

Some studies related to nylon have been conducted by several researchers, some of them are Yue Qian Bei and Ho Ming Su. In a study by Yue Qian Bei et al, the expandable packer rubber with nylon 66 cord, used for sealing formation in hydraulic fracturing, was examined. The critical failure energy of the interface between the cord and the rubber was measured using a single pull-out experiment. The Cohesive Zone Model was employed to describe the interface bonding and debonding. The study analyzed the mechanical properties and working performance of the packer rubber under varying pressures and well temperatures, finding that the packer rubber can avoid shear tear damage and function effectively in high temperatures. This research aims to provide theoretical guidance for the design of the packer rubber [13].

Meanwhile, Ho Ming Sung et al investigated the impact of the injection molding process on the tensile properties of Nylon 66 composites with varying amounts of glass fibers. The study utilized an experimental design method, mold flow analysis software, and a scanning electron microscope to analyze the effects of melting temperature, mold temperature, filling time, and packing pressure on the tensile strength, Young's modulus, elongation, and fracture mechanisms of the composites. The research found that the tensile properties of the composites increase with increasing fiber content and strain rate. It also discovered that the optimal injection molding parameters vary depending on the fiber content and the melt flow direction. This study provides valuable information for the design and application of Nylon 66 composites [14].

Building upon previous research in injection molding, Idris Karagoz conducts an investigation into the impact of mold surface temperature on the final product properties of high-density polyethylene (HDPE) materials during the injection molding process. Utilizing the Taguchi design of experiment method, Karagoz optimizes the process parameters and measures the mechanical, thermal, and morphological properties of the molded samples. The findings reveal that the mold surface temperature significantly influences the tensile strength, elongation at break, crystallinity, and melt flow index of the HDPE products. Karagoz proposes that enhancing the mold surface temperature can augment product quality and diminish the cycle time of the injection molding process [8].

In a parallel study, Chen et al present a mathematical model and a numerical solution for analyzing thermal residual stress in plastic injection molding. Their model takes into account the effect of packing bulk strain during the cooling stage and the thermo-viscoelastic behavior of the amorphous polymer. The temperature distribution of the injection molded part is determined by solving the transient heat conduction equation with a Laplace transform. Meanwhile, the residual stress distribution is obtained by solving a Volterra type integral equation using a quasi-numerical procedure. The results, illustrated with an example of a toy automobile shell, demonstrate the influence of the processing conditions and the cooling system on the residual stress and deformation of the part [10].

Furthermore, Rizvi explores the effect of injection molding parameters on the crystallinity and mechanical properties of isotactic polypropylene (iPP), a thermoplastic polymer widely used in the industry. The study employs differential scanning calorimetry (DSC) and tensile testing to measure the degree of crystallinity, melting temperature, crystallization temperature, tensile strength, and elongation at break of iPP samples. The research discovers that the injection molding parameters, such as injection temperature, injection pressure, holding pressure, and cooling time, significantly affect the crystallinity and mechanical properties of iPP. Rizvi suggests that optimal injection molding parameters can be selected to achieve the desired properties of iPP products. The study also includes numerous references to previous studies on iPP and injection molding, providing a comprehensive overview of the field [15].

Despite the merits and efficiencies of mass production of injection molding machines, certain drawbacks, especially defects, must be accounted for and mitigated. Injection molding products can have various defects that affect their quality and performance. One of them is short-shot, which occurs when the mold cavity is not fully filled with the melted polymer, resulting in an incomplete part. This can be due to insufficient injection pressure, low melt temperature, or improper venting of the mold. Another defect is warpage, which happens when the part is distorted or twisted after cooling and ejection from the mold. This can be caused by uneven shrinkage, excessive residual stress, or improper cooling conditions. A third defect is shrinkage, which means the part contracts or reduces in size after cooling and ejection from the mold. This can be caused by high melt temperature, low mold temperature, or insufficient holding pressure. A fourth defect is burning marks, which are dark or black spots on the surface of the part, indicating thermal degradation of the polymer. This can be caused by excessive injection speed, high melt temperature, or trapped air in the mold. These defects can be prevented or minimized by optimizing the injection molding process parameters and the material selection [16].

This study seeks to bridge a significant knowledge gap in the field of injection molding, particularly concerning the use of Nylon 66 HTN 50% GF Black plastic material in the production of the Cheek PA single Dia40 product. Despite the comprehensive understanding of nylon's mechanical and physical strength, microstructure, and modeling, as well as various aspects of the injection molding process, previous research has not delved into the effects of varying cooling water temperature and molding pressure on the injection molding process using nylon 66. Furthermore, the impact of these parameters on the final product of the injection molding process remains unexplored. By investigating these aspects, the study aims to determine the optimal hot water temperature and injection pressure parameters to prevent defects in the molding process. The anticipation is that this research will not only fill this knowledge void but also contribute new insights to the field.

2. Material and Method

The machine utilized in this investigation is the ENGEL victory Injection Molding Machine, as shown in Fig. 1. This injection molding machine, a 60-ton apparatus, is capable of fabricating two-cavity molds with a tool temperature reaching up to 150°C. The machine is equipped with a hopper dryer with a capacity of 50 kilograms and a screw diameter of 25 millimeters. It can generate a specific injection pressure of up to 1230 bar and an ejector force of 100 millimeters. The machine has an opening stroke of 450 millimeters and can accommodate a maximum mold weight of 675 kilograms.

The research material, Nylon 66 HTN 50% GF Black, exhibits several key properties that are integral to its performance. It has a physical density of 1590 Kg/m³ and a minimal molding shrinkage of 0.4%, ensuring its robustness in various applications. The material's thermal stability is evident from its high melting temperature of 260°C. Its mechanical strength is demonstrated by a tensile modulus of 16000 Mpa. The processing conditions for this material are specific, with a melt temperature range of 280-300°C and an optimal melt temperature of 290°C. The mold temperature is maintained between 85-105°C, and the material requires a drying time of 6-8 hours at a temperature of 100°C. These properties, measured under controlled conditions, contribute to the material's reliability and repeatability in various applications. In this study, a variety of tools, including shock keys, cutting tools, and plug gauges, were used for precise mold setting. The mass of the produced items was accurately measured using a digital Wedderburn scale with a maximum capacity of 10 kilograms. This method ensured reliable and reproducible results, contributing to the robustness of the study's findings.

(a) (b) (c) (d)

Figure 1: Tools for Injection Molding Process (a). Shock Keys (b) Cutting Tools (c) Plug Gauges, (d) Digital Scale

An experimental approach is employed in this study, which encompasses six unique sampling instances. Each individual sample undergoes three experimental trials, also referred to as 'shots'. Two primary variables, the temperature of hot water and injection pressure, are manipulated in the experiment. The hot water temperature is systematically varied at three distinct levels: 75°C, 85°C, and 95°C. Similarly, the injection pressure is adjusted at two different levels: 328 bar and 928 bar. A comprehensive visual representation of the research methodology is provided in the form of a flow chart in Fig. 2.

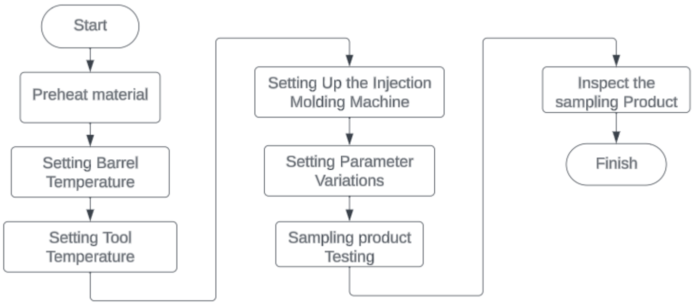

Figure 2: Primary Data Colleting Process

In this study, a hopper dryer is used to preheat Nylon 66 to quickly reach the mold temperature and remove moisture before molding, with the preheating set at 100 degrees Celsius for 6 hours. The barrel temperature is then adjusted based on the test material, Nylon 66 HTN 50% GF BLACK, as detailed in Table 1. Finally, the tool temperature (TT- 188 E) is set for mold area with a cooling system, using water as the coolant.

Table 1: Barrel Temperature

Zona	Set Value	Positive and Negative Tolerance	Minimum Monitoring
Nozzle	345°C	20°C	✓
Front	310°C	20°C	✓
Center	290°C	20°C	✓
Rear	280°C	20°C	✓
Feed	50°C	30°C	

Before setting parameters, a thorough machine inspection is conducted to ensure barrel temperature aligns with pre-set settings and cooling system is functioning optimally. Once all conditions are satisfactory, the injection process begins. Parameter variations, including three for hot water parameter and two for the injection pressure, are then configured and documented in Table 2. Product sampling is performed using an injection molding machine, with the scope of this research confined to semi-automatic injection mode. After testing, the products are examined to determine their adherence to set criteria or their classification as rejected products. Any detected defects are promptly documented and identified.

Table 2: Parameter variations

Experiment	**Hot Water Temperature**	**Injection Pressure**
1	75°C	328 Bar
2	85°C	328 Bar
3	95°C	328 Bar
4	75°C	928 Bar
5	85°C	928 Bar
6	95°C	928 Bar

3. HASIL DAN PEMBAHASAN

Figure 3 illustrates the short mold defect observed in the first experiment conducted at a hot water temperature of 75 °C and pressure of 328 bar. Short mold defects in injection molding products are typically induced by factors such as insufficient material volume, improper melt temperature, inadequate injection pressure, blocked flow paths, low melt or mold temperatures, and insufficient ventilation. These issues prevent the mold cavity from being fully filled, resulting in incomplete molded parts. To mitigate these defects, careful consideration of material selection, part design, mold design, and processing parameters is crucial. Adjustments to the injection molding process may also be necessary based on the specific requirements of the part.

Figure 3. Short Mold on the First Experiment

In the second test, conducted at a hot water temperature of 85 °C and a pressure of 328 bar, the result obtained was a short mold. Figure 4(a) displays the product resulting from these parameters. Similarly, in the third test with a hot water temperature of 95 °C and a pressure of 328 bar, the result obtained was a short mold. Figure 4(b) presents the product obtained under these conditions.

(a) (b)

Figure 4. Short Mold Defect on (a) 2^{nd} Experiment (b) 3^{rd} Experiment

In the fourth test, conducted at a hot water temperature of 75°C and a pressure of 928 bar, the result obtained was a white line. White line defects, also known as weld lines or knit lines, in injection molding products can be caused by a variety of factors. These include the use of high viscosity materials, which can obstruct the flow and form weld lines, and the presence of additives and fillers, which can alter material flow and lead to formation of weld lines. Additionally, poor mold design, such as improper wall thickness and improperly placed gates, can also cause knit lines. To prevent these defects, careful consideration of material selection, part design, mold design, and processing parameters is crucial, and adjustments to injection molding process may be necessary based on specific requirements of the part. Figure 5 shows the white line defect.

Figure 5. White Line Defect

Figure 6 presents the results of the fifth experiment conducted at a hot water temperature of 85°C and a pressure of 928 bar. A satisfactory part was obtained under these parameters, with no discernible defects on the product.

Figure 6. Product with no Defect

In the sixth test, conducted at a hot water temperature of 95℃ and a pressure of 928 bar, the result obtained was a bright color. Bright color defects in injection molding products can be attributed to several factors. These include contamination of plastic material by foreign substances such as dust, dirt, oil, moisture, or other plastic residues, degradation of the plastic material due to excessive heating, shear stress, or exposure to oxygen, light, or chemicals, inadequate mixing of plastic material with colorants, additives, or modifiers, high set temperature leading to longer residence time and more discoloration, and high screw speed increasing the shear force and causing easier discoloration. To prevent these defects, careful consideration of material selection, part design, mold design, and processing parameters is crucial, and adjustments to injection molding process may be necessary based on the specific requirements of the part. Figure 7 also displays the product of the sixth experiment exhibiting a bright color defect.

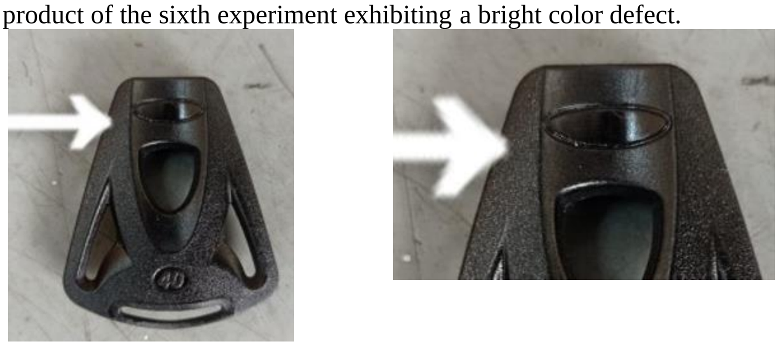

Figure 7. Bright Color Defect

The mass of injection molding products serves as a crucial indicator for characterizing and controlling the quality of injection molded products and process stability, as variations in weight inversely correlate with part quality. Working with experienced manufacturing partners skilled in controlling process parameters ensures that only the necessary amount of material is used, reducing waste and minimizing material costs. As parts become more complex, the requirements for precise measurements and absolute consistency among any part volumes are paramount. The results of the mass measurement can be observed in Table 3.

Table 3. Mass Measurement of the Product

Experiment	Pressure	Mass	Accept / Reject	Defect
1	75℃ /328 Bar	14 gr	Reject	Short Mold
2	85℃ /328 Bar	14.5 gr	Reject	Short Mold
3	95℃ /328 Bar	14.5 gr	Reject	Short Mold
4	75℃ /928 Bar	20 gr	Reject	White Line
5	85℃ /928 Bar	20 gr	Accept	No Defect
6	95℃ /928 Bar	20.5 gr	Reject	Bright Color

In the first three tests, despite increasing the temperature from 75℃ to 95℃ while maintaining a pressure of 328 Bar, all parts were rejected due to a 'Short Mold' defect. The mass of the parts increased slightly from 14 gr to 14.5 gr. In the fourth test, conducted at a temperature of 75℃ and increased pressure of 928 Bar, the part was again rejected, this time due to a 'White Line' defect, and the mass increased to 20 gr. The fifth test, conducted at 85℃ and 928 Bar, resulted in an accepted part with no defects and a mass of 20 gr. However, increasing the temperature to 95℃ in the sixth test resulted in a 'Bright Colour' defect, and the part was rejected despite a slight increase in mass to 20.5 gr.

4. Conclusion

This study presents the outcomes of experimental tests conducted under varying Hot Water temperatures of 75℃, 85℃, and 95℃, and Injection Pressures of 328 Bar and 928 Bar. The results revealed that the product manifested a Short Mold defect at the temperature parameters of Hot Water 75℃, 85℃, 95℃ and Injection Pressure of 328 Bar, despite the mass of the parts increasing slightly from 14 gr to 14.5 gr. At a Hot Water temperature of 75℃ and increased Injection Pressure of 928 Bar, the product exhibited a White Line defect, and the mass increased to 20 gr. However, the fifth test, conducted at 85℃ and 928 Bar, resulted in an accepted part with no defects and a mass of 20 gr, indicating the potential for high-quality production under these conditions. Conversely, increasing the temperature to 95℃ in the sixth test resulted in a Bright Color defect, and the part was rejected despite a slight increase in mass to 20.5 gr. Therefore, the optimal parameters identified are a Hot Water temperature of 85℃ and Injection Pressure of 928 bar. These findings underscore the importance of careful parameter selection in achieving defect-free injection moulding products

References

[1] Mustafa Kurt, O. Saban Kamber, Yusuf Kaynak, Gurcan Atakok, and Oguz Girit, "Experimental investigation of plastic injection molding: Assessment of the effects of cavity pressure and mold temperature on the quality of the final products," *Mater Des*, vol. 30, pp. 3217–3224, 2009.

[2] Fu MW, Fuh JYH, and Nee AYC., " Undercut feature recognition in an injection mould design system. ," *Comput Aided Des* , vol. 31, pp. 777–790, 1999.

[3] Yang Y and Gao F., " Adaptive control of the filling velocity of thermoplastics injection molding," *Control Eng Practice* , vol. 8, pp. 285–296, 2000.

[4] Shi F, Lou ZL, Lu JG, and Zhang YQ., "Optimisation of plastic injection moulding process with soft computing.," *Int J Adv Manuf Technol*, vol. 21, pp. 656–661, 2003.

[5] Zhai M, Lam YC, Au CK, and Liu DS, "Automated selection of gate location for plastic injection molding processing.," *Polym Plast Technol Eng* , vol. 44, pp. 229–242, 2005.

[6] Huang MC and Tai CC, "The effective factors in the warpage problem of an injectionmolded part with a thin shell feature.," *J Mater Process Technol* , vol. 110, pp. 1–9, 2001.

[7] J. Gelston, " Plastic injection molding with nylon: Material strengths and applications. ," AIM Processing Small Plastic Parts Blog.

[8] İ. Karagöz, " An effect of mold surface temperature on final product properties in the injection molding of high-density polyethylene materials. ," *Polymer Bulletin.*, 2020.

[9] K. , Kyas *et al.*, " Measuring of temperature and pressure in injection mold. ," *International Journal of Mathematics and Computers in Simulation,* vol. 6, no. 6, pp. 599–607, 2012.

[10] X. , Chen, Y. C. , Lam, and D. Q. Li, " Analysis of thermal residual stress in plastic injection molding. ," *Journal of Materials Processing Technology,* , vol. 101, no. (1-3), pp. 275–280, 2000.

[11] R. , Rulkens and C. Koning, "Chemistry and Technology of Polyamides. , ," *Polymer Science: A Comprehensive Reference*, pp. 431–467, 2012.

[12] D. S. , Choudhari and V. J. Kakhandki, "Comprehensive study and analysis of mechanical properties of chopped carbon fibre reinforced nylon 66 composite materials.," *Materials Today: Proceedings.* , 2020.

[13] Yue Qian-bei *et al.*, "Mechanical properties of adhesive interface for the expandable packer rubber with nylon 66 cord under high pressure and high temperature," *J Pet Sci Eng*, vol. 218, no. 110972, Nov. 2022.

[14] Ho Ming Hsiung, Hwang Jiun Ren, Wang Pin Ning, and Kuo Shun Chi, "Study on Tensile Properties of Nylon 66 Reinforced Composites," in *Proceedings of the 2016 International Conference on Education, Management, Computer and Society*, Atlantis Press, 2016.

[15] S. J. A. Rizvi, "Effect of injection molding parameters on crystallinity and mechanical properties of isotactic polypropylene," *International Journal of Plastics Technology*, vol. 21, no. 2, pp. 404–426, 2017.

[16] Ankush Mourya, Arshit Nanda, Kartik Parashar, Sushant, and Rajender Kumar, " An explanatory study on defects in plastic molding parts caused by machine parameters in injection molding process," in *Materials Today: Proceedings*, 2023, pp. 656–661.