Reducing Sink Mark Defect of Cup Plastic Injection by Biodegradable Material with an Injection Rate

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Abstract
In this research, the issue of shrinkage in coffee cup sleeves filled with biodegradable plastic materials is investigated. Polylactic acid (PLA) and coffee grounds are two combined materials that are difficult to form by injection molding. The quality of the coffee cup sleeves declined as their surface was reduced. This study aims to investigate the effects of various plastic injection molding parameters (including clamping force, injection pressure, injection rate, and cooling times) that influence sink marks on the molded parts. The goal is to determine the optimal conditions for reducing sink marks on the molded parts. Experimental results revealed that setting the injection speed rate to 40 cm³/s and the injection pressure to 54 bar significantly reduced shrinkage, thereby enhancing the surface quality of the product. The findings suggest that configuring the injection speed rate at 40 cm³/s, the injection pressure at 54 bar, the clamping force at 100 tons, the material's melting temperature (T_m) at 180 °C, and the mold temperature (T_w) at 60 °C effectively minimized sink marks. This optimization resulted in a smoother and visibly improved surface finish of the molded components. These results provided an important guideline for the development of injection molding technology employing bioplastic materials that use higher viscosity than generally used with synthetic plastics. Other bioplastic goods can be produced using this method with favorable outcomes.
Keywords: Plastic injection molding, Shrinkage, Biodegradable, Injection parameters

1. Introduction

The extensive utilization of resources in global trends has had a significant influence on the environment and natural resources. Manufacturing products that decompose naturally after use has emerged as a competitive alternative that minimizes impact on the environment, and exemplifies efficient resource management. As a result, using alternatives that reduce the use of finite resources and help reduce plastic waste is essential to the development of ecologically friendly materials. Biodegradable plastics can help reduce the amount of plastic waste that ends up in the environment by breaking down naturally. Biodegradability is the property of polymers that allows microorganisms to break them down into smaller molecules [1-3], which may help solve the problem of plastic waste accumulation in soil, water, and living organisms. This research aims to develop a coffee cup using biodegradable plastic materials formed and blended with coffee grounds. Quality control of molded parts is important to prevent defects such as shrinkage, weld marks, flow marks, and sink marks. Mahajan et al. [4-5] applied statical methods to determine the optimal injection molding conditions. The research focused on mold closing speeds, which had a significant effect on quality characteristics. Moayyedian et al. [6] concluded a melt temperature is the most influential for short-shot possibility by resolving the optimum levels of gate type, filling time, and melt temperature. Moreover, the factor analysis of high-density polyethylene (HDPE) in the injection process is studied for reducing shrinkage problems by Supasit et al. [7]. Various factors cause these defects, especially the injection molding parameters. This has a significant impact on the quality of the formed parts. In order to develop the quality, and avoid the defects, a number of researchers applied an optional device for solving these problems. To reduce defect rates and circumvent high-cost expenditure on new molds, Li et al. [8] presented an experimental framework aiming to implement process optimization efficiently and attain a predictable level for the quality characteristics. Masato et al. [9] described the design of a multivariate shrinkage sensor (MVSS) incorporating a spring-biased pin with a digital linear displacement transducer to measure in-mold shrinkage directly. The modeled main effects highlight the different shrinkage behaviors of HIPS and PP, indicating the need for in-mold shrinkage data. Yuan et al. [10] summarized mold temperature, melt temperature, injection speed, and holding pressure affect defects. The process parameters influence iridescent patterns by changing retardation and transmittance. Regarding these studies, the main parameters influencing the quality of plastic injection molding are such things as injection pressure, injection speed rate, cooling time, and mold temperature. From the experiment of microplastic injection molding investigation, Ong et al. [11] found that mold temperature was most significant for cavity filling. Krebelj et al. [12] studied the cooling rate effect of glass transition temperature; this research summarized the importance of volumetric relaxation in cavity pressure prediction. Yadav et al. [13] observed the influence of injection and holding pressure on thermoplastic; the results showed that injection pressure affected the mechanical properties. These studies attempted to improve the product’s quality on ordinary plastic materials. Plastic injection molding sink mark problems are a serious flaw that impairs the practical and aesthetic quality of molded items, and the uneven shrinkage that occurs during the molding process's cooling phase is the main cause of this problem. Therefore, this research focuses on adjusting parameters in the injection molding process of coffee cups made from biodegradable plastic materials to solve the problem of shrinking. Mohan et al. [14] The research aims to investigate and report the influence of injection molding process parameters on the strength, shrinkage, and twisting of parts after molding. In particular, this research focuses on how these parameters affect the shrinkage and twisting of polypropylene parts after molding. Wang et al. [15] This study focuses on addressing defects in rapid heat cycle molding (RHCM). To reduce sink marks, a 'bench form' structure for screw studs was developed, along with a lifter structure for the mold, and external gas-assisted packing was introduced. To minimize warpage, the study employed Taguchi’s methods to examine the impact of process parameters – such as melt temperature, injection time, packing pressure, packing time, and cooling time. Simulations with Moldflow software had been conducted to analyze warpages under different conditions. Signal-to-noise analysis identified the optimal processing parameters, and ANOVA quantified the contribution of each parameter. The results show that these optimized parameters can effectively reduce warpage in RHCM parts. Vanek et al. [16] This study investigates the methods, including software simulations and experimental validation, using polycarbonate test samples (optical lenses). Significant parameters such as melt temperature, mold temperature, injection pressure, and packing pressure were varied to assess their impact on geometric accuracy and visual properties. The results showed that lower melt temperatures and higher mold temperatures significantly reduce the occurrence of dimensional defects. Additionally, the design of the gate system was found to be crucial in minimizing defects and ensuring uniform material flow. Effective packing pressure was essential in reducing volumetric shrinkage and sink marks. Butt MS et al. [17] In this research, the mechanical and degradation properties of biodegradable magnesium (Mg) strengthened poly-lactic acid (PLA) composites produced through plastic injection molding have been extensively studied. These composites exhibit enhanced mechanical performance and controlled degradation rates, making them suitable for biomedical applications, particularly in orthopedic implants.

Previous studies indicate that biodegradable materials exhibit unique and distinct characteristics, often posing significant challenges for forming processes. 3D printing has been commonly utilized for shaping such materials by converting them into filaments prior to additive manufacturing. However, there is a notable lack of research on direct forming processes using raw biodegradable materials. This study emphasizes the critical role of injection pressure and injection rate in enhancing the quality of eco-friendly plastic products. These factors are particularly crucial given the limited existing research and the inherent challenges associated with forming biodegradable materials using various parameters.

2. Materials and Methods

2.1 Biodegradable Materials

The material selected for the injection molding of coffee cups is a prototype biodegradable plastic (PLA/coffee ground: 80/20 with compounds), which has been tested for its biodegradability and has demonstrated no adverse environmental impact [18]. The material consists of polylactic acid (PLA) combined with coffee grounds, a byproduct. This mixture has desired properties such as flexibility, strength, and a shiny surface created coffee grinding oil. The injection parameters utilized in this study are detailed in Table 1.

2.2 Calculation of Injection Molding Parameters

The design of the 16 oz coffee cup has a diameter of 92 mm for the cup body. The bottom diameter is 60 mm, the height is 102 mm, and the wall thickness is 1.5 mm, as illustrated in Figure 1. The injection molding process allows for the production of two cups per cycle, with a spacing of 120 mm. The height of the pinpoint gate is 30 mm, the length of the runner is 145 mm, and the height of the sprue is 70 mm, as shown in Figures 1 and 2, respectively.

Table 1 Injection Parameters of Polylactic acid: PLA and Coffee Grounds [20]

List	Value	Unit
Density (ρ)	1.25	g/cm^3
Melt Temperature (T_m)	165-180	°C
Mold Temperature (T_w)	60	°C
Tensile Strength	38 - 47.8	MPa
Tensile Modulus	4,200	MPa
Melt Flow Index	5.9-8.46	g/10min
Shrinkage	0.3	%

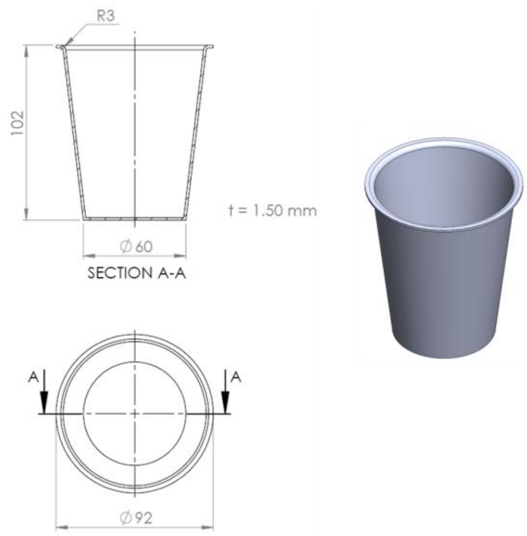


Figure 1 Coffee Cup Dimension

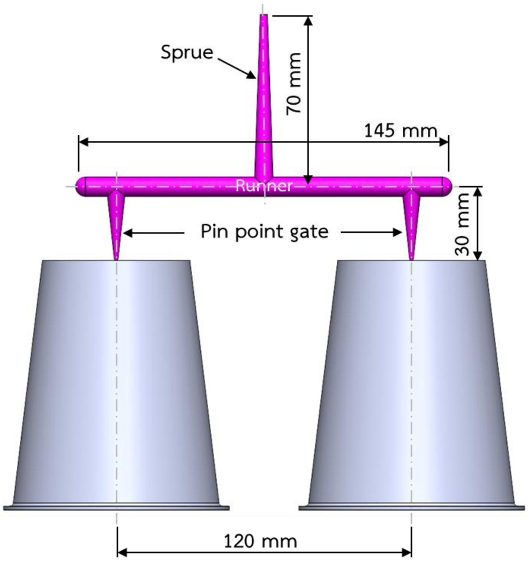


Figure 2 Cavity Layout

Formula (1) presents mass calculation of coffee cup

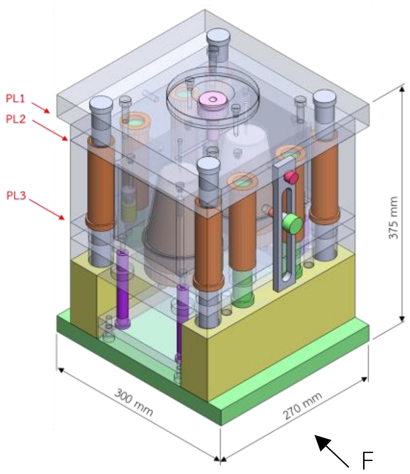
$$m = v \times \rho \quad (1)$$

where; m is mass (g), v represent as volume (cm^3), and ρ refer to density (g/cm^3).

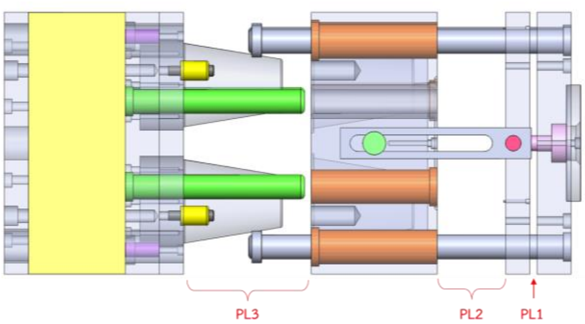
The injection volume of the workpiece is 54.53 cm^3/piece and the runner system (sprue + runner + pinpoint gate) is 10.04 cm^3. The total volume is (54.53 cm^3 x 2) + 10.04 cm^3 is 119.10 cm^3. Therefore, the weight of the workpiece per cycle injection is 148.88 g (119.10 cm3 x 1.25 g/cm^3).

2.3 Design of the Coffee Cup Injection Mold

The coffee cup injection mold, a three-plate molding type (3-plate molding), has three parting lines (PL) and a pinpoint gate for the liquid plastic in the middle area at the bottom of the coffee cup. The size of the mold is 270 x 300 x 375 mm (W x L x H) as shown in Figure 3.



(a)



(b)

Figure 3 Biodegradable Cup Molding Design (a) Mold Dimension (b) Parting Line

2.4 Injection Mold Parameters Adjusting Process

Injection molding parameters are critical in affecting the quality of manufactured components. The injection process is divided into 5 steps with a percent cycle time given: 1) mold closing (5%) 2) injection time (10%) 3) Filling time \(15%), 4) Cooling time (70%), and 5) Mold opening (5%). All 5 processes mentioned above affect the quality of the workpiece during the injection molding process as shown in Figure 4.

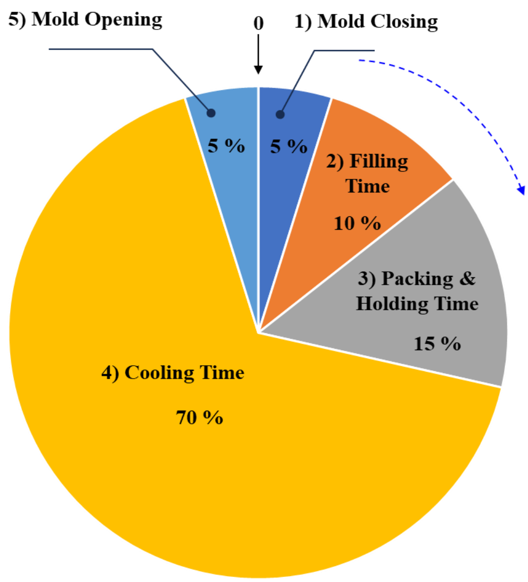


Figure 4 Plastic Injection Process [4]

2.5 Clamping force Calculation

The clamping force is the force that keeps the mold closed during the injection of plastic into the mold, preventing it from opening. The clamping force must exceed the injection pressure, an appropriate clamping force contributes to the improved quality of the injection-molded components, while insufficient clamping force may lead to defects in the parts [20]. The equation for calculating the clamping force is presented in Equation 2.

$$F = P \times A \quad (2)$$

where; F is clamping force (ton), P represent as injection pressure (kgf/cm^2), and A refer to the projected area of workpiece (cm^2)

The injection pressure P in the mold is derived from the injection molding pressure of the PLA material, which is 703 kgf/cm^2 [20]. The projected area A of the two molded components (Cavity 1 and 2) has a diameter of 9.2 cm. The area of the components is calculated as $A_1 = \pi r^2 x2$ = 132.95 cm^2 and the area of the runner is

$A_2 = WxL$ = 14.5 x 6 = 8.7 cm^2. Total projected area is 132.95 + 8.7 = 141.65 cm^2 Therefore, selected clamping force is 703 kgf/cm^2 x 141.65 cm^2 = 99.58 Ton ≈ 100 Ton. The projected area is illustrated in Figure 5.

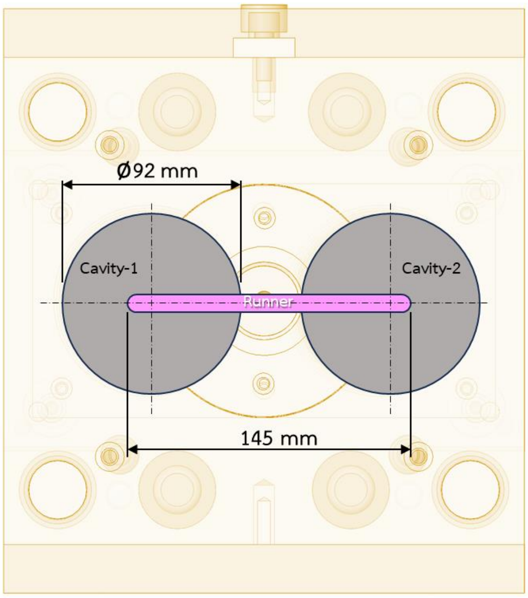


Figure 5 Projection Area and Runner

2.6 Plastic Injection Machine

Plastic injection molding machines are responsible for introducing material into the mold and workpiece as desired. There are many types of plastic injection machines which depend on workpiece design and mold size. This experiment chose to utilize a horizontal single-screw injection molding machine which is suitable for 2-plate and 3-plate molds [22]. The model HYF-1000 is shown in Figure 6, and details of the injection molding machine are shown in Table 2.

2.7 *Injection Pressure*

The injection pressure refers to the pressure applied when injecting material into the mold and creating internal pressure within the mold [23]. It is a major contributor to defects in plastic injection molding [24]. This is compared to the maximum injection pressure of injection machine; HYF-1000, PRC, with clamping force 100 Tons. Tie bar range is 360 x 315 mm. The calculation can be performed according to Equation 3.

$$P = \frac{P_{max} x\ P_{mat}}{P_{M/C}} \quad (3)$$

where; P represent as injection pressure (bar), P_{max} is maximum injection pressure (bar), P_{mat} is injection pressure of material (bar), and $P_{M/C}$ refer to injection pressure of machine (kg/cm^3). The experiment has been set: P_{max} of the HYF-1000 injection molding machine, which is 140 bar. P_{mat} of PLA is 703 kgf/cm^2 ≈ 690 bar [20], $P_{M/C}$ is 1,835 kg/cm^3 (1,799.52 bar). Therefore, the adjusted injection pressure for the coffee cup components is calculated to be at 53.68 bar, or approximately 54 bar.

Figure 6 Plastic Injection Machine; HYF-1000

Table 2 HYF-1000 Specifications

System	**List**	**Value**	**Unit**
Injection System	Screw Size (Ø)	35	mm
	Max. Volume	160	cm^3
	Injection Pressure	1,835	kg/cm^2
	Injection Rate	90	cm^3/s
	Speed	0-200	rpm
Clamping System	Max. Mold Size	360 x 315	mm
	Max. Clamping Force	100	Ton
	Max. Open Distance	305	mm

3. Results and Discussion

3.1 Adjustment of Injection Molding Parameters

Adjusting injection molding parameters is a crucial process that significantly impacts the quality of the components. In this study, the screening parameter experiments were conducted using a novel composite material prototype, with limited prior knowledge regarding the injection molding parameters. In this phase, human insight and expertise are employed to adjust the injection parameters, which are widely utilized in empirical industrial situations and are called operational techniques. The objective is to find the best-so-far parameters for product forming which is more effective than the conventional trial-and-error method.

Therefore, this research set a number of experiments up to 2,000 shots of screening to obtain the best so far for operational guideline parameters. In order to test the problem of biodegradable coffee cup injection, the initial set of parameters is outlined in Table 3 which are impact on sink mark problem solving [13-15, 17].

Table 3 Injection Parameter

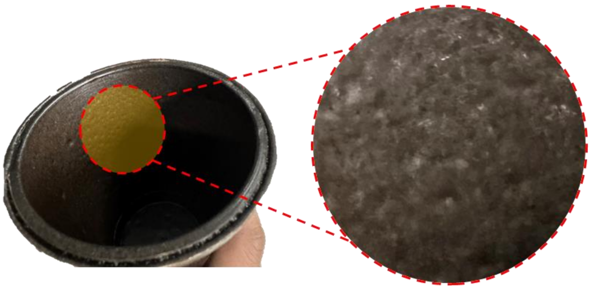
List	Value	Unit
Melt Temperature (T_m)	180	°C
Mold Temperature (T_w)	60	°C
Clamping Force (*F*)	100	Ton
Injection Pressure (*P*)	54	bar
Injection Rate (*I*)	20	cm^3/s

3.2 Injection of Biodegradable Coffee Cup

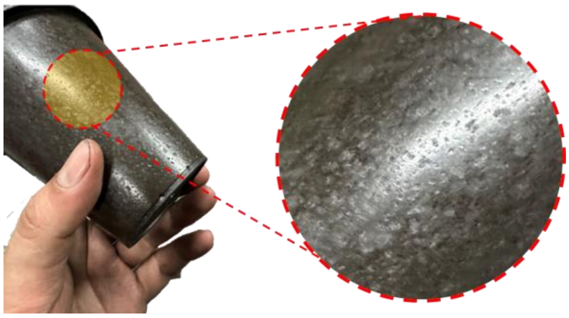
In the forming process stage, the biodegradable coffee cup mold is mounted on the injection molding machine using the initial parameters. Bio-plastic is injected into the mold (core and cavity), and the components are allowed to cool within the cooling time. Once cooled, the mold is opened, and the components are ejected from the mold, as shown in Figure 7. The results of the coffee cup components revealed the presence of sink marks on the cup's surface (both inside and outside), as illustrated in Figure 8.

Figure 7 Workpiece Ejection System

Upon analyzing the results, non-destructive testing (NDT), specifically visual inspection, was utilized to observe sink marks on both the internal and external surfaces of the coffee cup components. These marks were attributed to plastic injection molding surface allowances [25]. The findings suggest that the high viscosity of the biodegradable plastic material derived from coffee grounds is significantly higher than that of conventional synthetic materials. Consequently, the injection rate was increased in correlation with the injection pressure, as shown in Figure 9. This figure demonstrates that increasing the injection rate to 30 and 40 cm^3/s leads to a sequential improvement in the surface quality of the coffee cup components. However, beyond a certain threshold, further increases in the injection rate resulted in a decrease in surface quality, ultimately reducing the occurrence of sink marks.



Internal Surface



External Surface

Figure 8 Sink Mark Phenomena

4. Conclusion

From the adjusting parameters procedure, the results indicate that the injection molding of coffee cups utilizing biodegradable plastic derived from PLA and coffee grounds mixed significantly reduces sink marks on the components through the adjustment of injection process parameters.

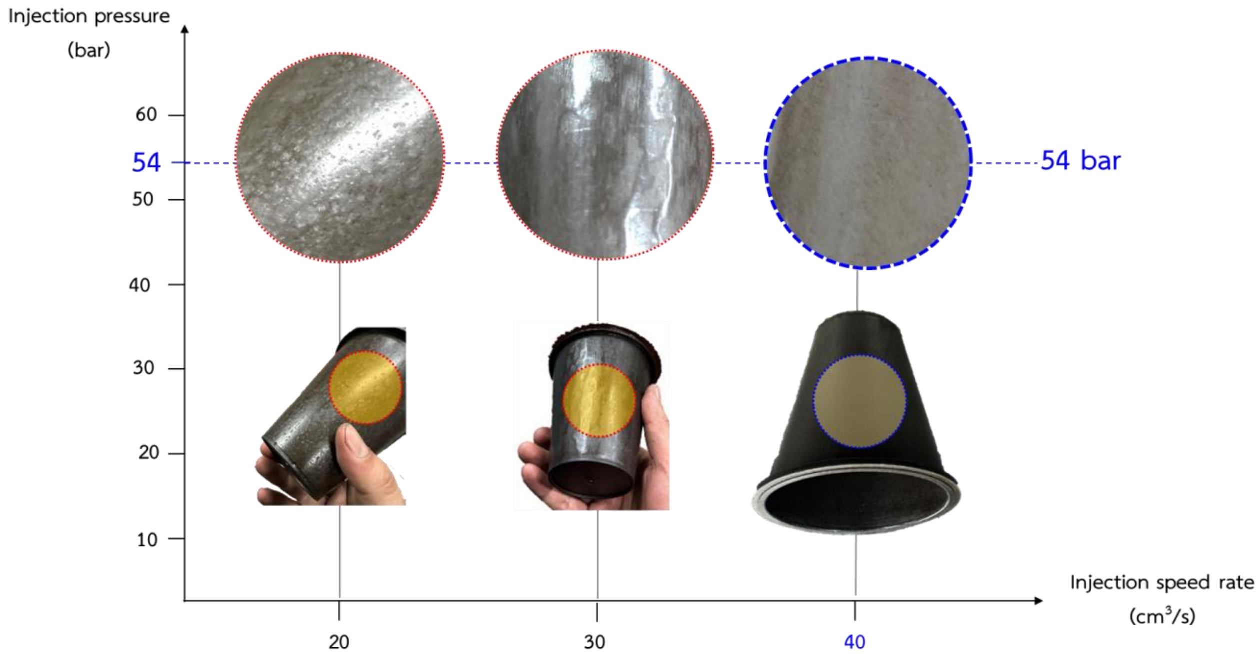


Figure 9 Sink Mark Problem Solving Result

The experiments thus demonstrated that setting the injection speed rate at 40 cm³/s and the injection pressure at 54 bar, along with a clamping force of 100 tons, a melting temperature of the material (T_m) at 180 °C, and a mold temperature (T_w) at 60 °C, effectively minimized sink marks, resulting in a smoother and visibly improved surface quality of the components. The adjustment of the injection speed rate has a direct impact on reducing sink marks, as the high viscosity of the material requires increased injection speed to facilitate better flow within the mold and complete filling of the mold. This clearly illustrates the relationship between injection rate and injection pressure in addressing surface quality issues of the components.

This research focused on parameter adjusting results outperform a new operational guideline to solve the quality improvement in the bio-plastic injection process which is different from [6-7] and [10-11] in terms of the material sustainable used, especially in a new eco-friendly biodegradable plastic which is difficult to form by the injection process.

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6. Reference

[1] Kim MS, Chang H, Zheng L, Yan Q, Pfleger BF, Klier J, et al. A review of biodegradable plastics: chemistry, applications, properties, and future research needs. Chem Rev. 2023 Jul 20;123(16):9915-39.

[2] Harkal VA, Deshmukh SP. A review on biodegradable polymers: used as packaging materials. GSC Biol Pharm Sci. 2023;25(2):107-15.

[3] Filiciotto L, Rothenberg G. Biodegradable plastics: standards, policies, and impacts. ChemSusChem. 2021;14(1):56-72.

[4] Chacinski T, Sutowski P. Common defects in injection molding of plastic products and their influence on product quality. J Mech Energy Eng. 2021;5(1):7-14.

[5] Mahajan LD, Ulhe PN. Analysis of Injection Molding Process to Reduced Defects (Short-Shot). Int J. Eng Technol Manag Res. 2018;5(6):113-9.

[6] Moayyedian M, Abhary K, Marian R. The analysis of defects prediction in injection molding. Int J. Mech Mechatron Eng. 2016;10(12): 1883-6.

[7] Manokruang S, Chainawakul A. Optimal Factor Analysis in the Injection Process of High-density Polyethylene Plastic Screw Caps to Reduce Shrinkage Problems: A Case Study. Kasem Bundit Eng J. 2023;13(2): 162-76.

[8] Li Y, Chen JC, Ali WM. Process optimization and in-mold sensing enabled dimensional prediction for high precision injection molding. Int J. Interact Des Manuf (IJIDeM). 2021:1-7.

[9] Masato D, Kazmer DO, Panchal RR. Analysis of in-mold shrinkage measurement for amorphous and semicrystalline polymers using a multivariate sensor. Int J. Adv Manuf Technol. 2023;125(1-2):587-602.

[10] Yuan S, Qiu Z. Influence mechanism of injection process parameters on iridescent pattern defects on optical molded parts. J. Appl Polym Sci. 2023:e55144.

[11] Liparoti S, Speranza V, Pantani R, Titomanlio G. Modeling of the injection molding process coupled with the fast mold temperature evolution. J. Electrochem Soc. 2019; 166(9):B3148.

[12] Krebelj K, Halilovič M, Mole N. The cooling rate dependence of the specific volume in amorphous plastic injection molding. Int J. Adv Manuf Technol. 2019;103:1175-84.

[13] Yadav R, Pancharya A, Kant R. Influence of injection and holding pressure on tribological and mechanical behavior of injection moulded thermoplastic. Mater Today Proc. 2021; 41:915-20.

[14] Mohan M, Ansari MN, Shanks RA. Review on the effects of process parameters on strength, shrinkage, and warpage of injection molding plastic component. Polym Plast Technol Eng. 2017; 56(1):1-2.

[15] Wang X, Zhao G, Wang G. Research on the reduction of sink mark and warpage of the molded part in rapid heat cycle molding process. Mater Des. 2013;47: 779-92.

[16] Vanek J, Ovsik M, Stanek M, Hanzlik J, Pata V. Study of Injection Molding Process to Improve Geometrical Quality of Thick-Walled Polycarbonate Optical Lenses by Reducing Sink Marks. Polymers. 2024;16(16): 2318.

[17] Butt MS, Bai J, Wan X, Chu C, Xue F, Ding H, Zhou G. Mechanical and degradation properties of biodegradable Mg strengthened poly-lactic acid composite through plastic injection molding. Mater Sci Eng C. 2017;70: 141-7.

[18] Qin M, Chen C, Song B, Shen M, Cao W, Yang H, et al. A review of biodegradable plastics to biodegradable microplastics: another ecological threat to soil environments. J. Clean Prod. 2021;312:127816.

[19] 3D4Create. PLA, ABS, Nylon & PETG Shrinkage & Compensation: Essential Facts. Available from: http://3d4create.com/ [Accessed 10th June 2023].

[20] Poszwa P, Brzek P, Gontarev I. Influence of processing parameters on clamping force during injection molding process. In Advances in Manufacturing II: Mechanical Engineering. 2019;4: 287-99.

[21] RTP company. Molding and Processing Guidelines for PLA (Polylactic Acid) Compounds. Available from: www. rtpcompany.com/ technical-info/molding guidelines/pla-compounds/ [Accessed 2024].

[22] Rosato DV, Rosato MG. Injection Molding Handbook. Springer Science & Business Media; 2012. p. 12-3.

[23] Tim A, Turng LS, Gramann P, editors. Injection Molding Handbook. Hanser; 2007.

[24] Saporit A, Quadri C, Kloth N, Capdevila X. The effect of rate of injection on injection pressure profiles measured using in-line and needle-tip sensors: an in-vitro study. Anaesthesia. 2019 Jan; 74(1):64-8.

[25] Mohanraj T, Sivakumar K, Pradeep T. Application of non-destructive testing in plastic injection molding. J. Polym Eng. 2022; 42(5): 245-58.