EXPERIMENTAL AND ANALYTICAL ANALYSIS FOR ADVANCED HOT RUNNER BASED INJECTION MOLDING

[1,2]Khalid Alqosaibi,[1]Chandresh Thakur,[1,3]Hussam Noor,[1,3]Ahmed Almalki, [1]Alaauldeen Duhduh,

[1]John Coulter

[1]Manufacturing Science Laboratory
Department of Mechanical Engineering and Mechanics
Lehigh University, Bethlehem, Pennsylvania 18015
[2]King Saud University, Riyadh, Saudi Arabia
[3]Taibah University, Madinah, Saudi Arabia

ABSTRACT

A novel technology "Rheodrop" was developed to advance the process of hot runner based injection molding. The technology applies controllable shear rate to the polymer melt during and between injection molding cycles. The application method involves rotating the valve pins inside the hot drops. The intensity of the applied shear rate is controlled by adjusting the rotational speed. The shearing process reduces the viscosity of molten pseudoplastics inside the hot drops. Viscous polymer melts are more prone to produce incompletely filled products due to higher flow resistance. Hence, Rheodrop technology overcomes incomplete filling defect as well as enhances the quality of the molded parts by reducing the viscosity of the processed polymer. In addition, this technology enables processing materials at lower temperatures, which can eliminate/reduce thermal degradation for temperature sensitive materials. Analytical and experimental analysis were performed to investigate the effect of applying Rheodrop technology on the molded parts. Results show significant effect of Rheodrop technology on the molded products.

Keywords: Injection molding, Hot runner system, Rheodrop

1. INTRODUCTION

Injection molding is the most utilized process in manufacturing plastic products. It provides several advantages over other polymer manufacturing processes such as high production rate, low cost, high product quality, and the capability of fabricating complex parts. The process consists of four different phases, filling, packing, cooling, and ejection, and it has several parameters that need to be controlled for higher quality output such as processing temperature, injection pressure, fill time, mold and coolant temperature etc. The optimization of these parameters varies based on the processed polymer's properties and limitations. Based on the runner system, there are mainly two types of injection molding process. The first type and most common in industry is the cold runner system where the runner is cooled and ejected with the molded parts. The second type is hot runner systems where the polymer inside the runner is heated and maintain the molten condition between injection molding cycles. [1–3]

The quality of final product is important to the manufacturer and consumers. Numerus researches have been published investigating the quality of injection molded parts from different aspects. Idris and Ozlem investigated the effect of melt temperature on the injection molded part properties for high density polyethylene [4], they found that the melt temperature has a significant effect and determines the impact strength of the molded product. Song et al. performed an optimization and prediction study to investigate the shrinkage and warpage of thin walled molded products [5], the study involved the effect of melt temperature, mold temperature, holding pressure, holding time, injection time, and cooling time on the volume shrinkage rate and warpage amount. Also, injection molding process utilizing hot runner systems has been researched and developed by numerus researchers [6–8].

Hot runner based injection molding has been used in several manufacturing field such as medical, electrical, and electronics. Although hot runner systems are prevalent in fabricating products with thin walls and small features, there are still great challenges associated with the final product quality. Incomplete filling defect is a common issue in injection molding process especially when processing viscous material as higher viscosity means higher resistance to flow. The viscosity of the molten polymer can be decreased by increasing the melt temperature. However, the polymer melt is prone to degrade when it is subjected to higher temperature for longer periods of time. Also, thermal degradation is a critical issue when processing thermal sensitive polymers in hot runner injection molding. [3], [9]

In this research, a new technology that is called "Rheodrop" is introduced to advance the hot runner based injection molding. The technology allows precise control over shear rate in which viscosity can be controlled throughout the injection molding cycle. The technology has been presented and discussed in previous research papers with numerical analysis to validate the concept. [10–12]

2. RHEODROP TECHNOLOGY

The main components of a hot runner mold are the polymer inlet, manifolds, heating elements, runner system, and hot drops. The polymer melt flows through the polymer inlet, which is known as sprue to the runner system that distribute the molten polymer. The hot drops deliver the molten polymer from the runner to the cavities through nozzles. There is a valve pin inside each hot drop that is pneumatically controlled to open and close the gates located at the tip of each nozzle. The gates close after the filling of the cavities and remain closed during cooling time which represent the majority of the injection molding cycle. During the time of cooling and solidifying the molded parts, the temperature around the nozzle tip decreases, which causes the viscosity of the polymer melt to increase. Consequently, slug formation and partial solidification of the molten polymer occurs which lead to incomplete filling of cavities. Moldflow software was utilized to confirm the cold slug formation issue around the nozzle tip. The simulation results are shown in figure 1, which presents the fraction frozen layer in the nozzle. The simulation did not include the valve pin inside the hot drop for simplicity. The zero value correspond to blue color indicates that the polymer is completely molten, the red color represents the frozen polymer.

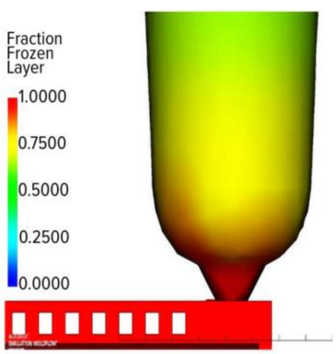


Figure 1: Cold slug formation at the nozzle tip

The concept of Rheodrop is to rotate the valve pin inside the hot drop between injection molding cycles. The rotation of valve pin applies shear rate to the molten polymer to tune their viscosity. The intensity of the applied shear rate is controlled by adjusting the rotational speed. The shearing process reduces the viscosity of molten pseudoplastics inside the hot drops. Viscous polymer melts are more prone to produce incompletely filled products due to higher flow resistance. Hence, Rheodrop technology was invented to overcome incomplete filling defect and to enhance the quality of the molded parts through precise control of the molten polymer inside the hot drop. In addition, this technology enables processing materials at lower temperatures, which can eliminate/reduce thermal degradation for temperature sensitive materials.

3. EXPERIMENTAL APPROACH

3.1. Material

Acrylonitrile Butadiene Styrene (ABS), a thermoplastic polymer was used to perform the numerical and experimental analysis of this study; particularly, grade ABS HI-121. This grade was manufactured by LG Chem and is widely used in manufacturing electronic related parts. [13]

The processing parameters recommended by the manufacturer suggests that the melt temperature ranges from 210℃ to 240℃, while the mold temperature should be within 40℃ to 80℃. Also, the ejection temperature recommended to be at 85℃.

3.2. Analytical method

The main objective of this study was to investigate the Rheodrop technology to better understand its effects in terms of rotational speed with respect to shear rate and viscosity.

The hot drop passage was designed and a CAD model was developed representing the polymer melt body passing through the hot drop cavity with the rotating pin in the middle of the hot drop. To simplify the model, only the walls of the rotating pin and the hot drop are included. Figure 2 illustrates the designed CAD model. The solid body of the model represent the polymer melt passing through the hot drop. The outer wall represents the fixed hot drop wall, while the inner wall represents the rotating pin wall.

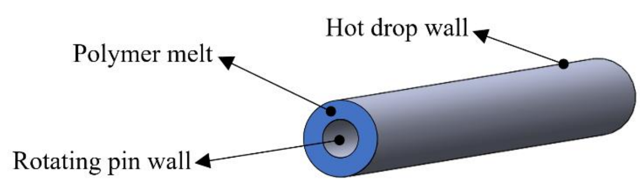


Figure 2: CAD model of the concept hot drop

The model was then imported into ANSYS Fluent simulation software for numerical analysis. This computational software is a helpful tool to calculate the shearing affect produced by the rotational velocity of the pin. Hence, the viscosity of the polymer melt is calculated.

In order to calculate the dynamic viscosity of the polymer melt under the effect of the rotational pin, the zero-shear viscosity is needed. Equation 1 along with rheological related constants was used to calculate the zero-shear viscosity analytically [14].

$$\eta_0 = D_1 . exp\left[\frac{-A_1(T-T^*)}{A_2+(T-T^*)}\right] \quad (1)$$

Zero-shear viscosity (η_0) was calculated using the temperature of the polymer melt (T) as well as the glass transition temperature (T*).

Different models are available to characterize the rheological behavior of the polymer melt including Power Law Model, Cross Model and Ellis Model. For the purpose of this study, and for ABS HI-121 material, the Cross Model was utilized to determine the viscosity profiles of the melt during the IM process. Equation (2) represents the Cross Model equation [14].

$$\eta = \frac{\eta_0}{1 + \left[\left(\frac{\eta_0 \gamma}{\tau^*}\right)\right]^{1-n}} \quad (2)$$

The viscosity (η) is calculated using the shear stress (τ^*) and the shear rate (γ).

3.3. Experimental method

A 40-ton injection modeling machine compromising a hot runner mold manufactured and supplied by POLYSHOT Inc. is utilized to obtain samples for the purpose of experimental validation. Some adjustments were made to retrofit the Rheodrop technology into the mold's hot drop. To apply the rotation to the pin, a DC motor is utilized along with a rotational mechanism assembly including supporting plates, ball bearings, and bevel gears. One valve pin was extended and modified to be assembled to the rotational mechanism. Therefore, one out of four hot drops in the hot runner mold is adopting the Rheodrop technology. Thus, one injection molding cycle provides the ability to compare conventional IM products with products made utilizing the Rheodrop technology.

The processing parameters obtained from the design of experiment is shown in table 1, where two study cases were developed. The first case study was designed to investigate the impact of the Rheodrop technology on improving the filling process at different processing temperatures. The second case study was conducted to optimize the Rheodrop technology by means of testing different rotational speeds.

Study Case # 1			Study Case # 2		
Exp. #	Temp. °C	RPM	Exp. #	Temp. °C	RPM
1	210	0	1	215	0
2	210	1,500	2	215	500
3	220	0	3	215	1,000
4	220	1,500	4	215	1,500
5	240	0			
6	240	1,500			

Table 1: Different processing parameters of the two case studies

4. RESULTS AND DISCUSSION

In this section, the numerical and experimental results of Rheodrop analysis are presented. The shear rate applied by rotating the valve pin inside the hot drop is investigated using Ansys fluent. Three different levels of rotational speeds are considered 500, 1000, and 1500 rpm. Figure 3 shows the applied shear rate in a cross section of the hot drop at the selected rotational speeds. The x-axis represents a data line from the rotating pin wall to the hot drop wall that are illustrated in the CAD model shown in figure 2. The highest shear rate is applied near the rotating wall at 0.0045 m value of x. The effect of valve pin rotation on the shear rate is decreased as we move toward the outer wall and reach the minimum at 0.009 m which corresponds to the point at the hot drop wall.

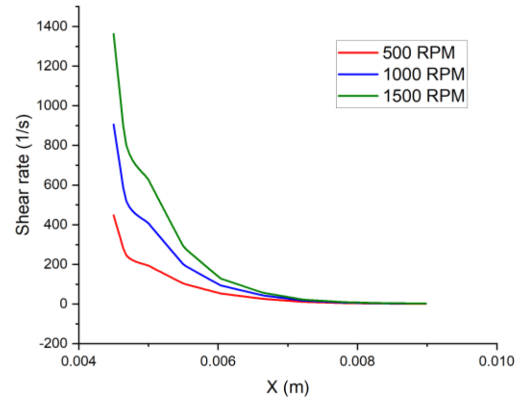


Figure 3: Shear rate at a cross section of hot drop

The viscosity of the polymer melt is influenced by temperature and shear rate. Three different levels of melt temperature were utilized in the design of experiments 210ºC, 220ºC, and 240ºC. Simulations were performed to study the viscosity behavior at the selected rotational speeds for each temperature. Figure 4 shows the viscosity in the hot drop at different temperature and rotational speeds. Overall, the minimum viscosity is around the rotating wall which correspond to the highest applied shear rate.

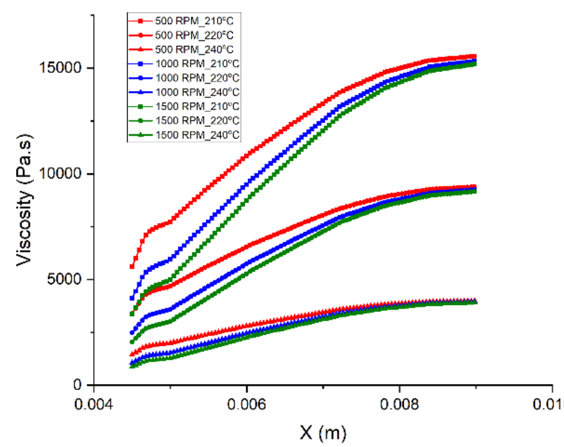


Figure 4: Viscosity at a cross section of hot drop

Samples are obtained using HI-121 material that are injected using the modified hot runner mold to validate the Rheodrop concept results obtained from the numerical simulations. For the first case study, melt temperatures of 210℃, 220℃, and 240℃ were used with conventional IM processing. Then, the concept was utilized at a rotational velocity of 1,500 RPM. All other processing parameters were kept constant for all experiments. The purpose of this case study was to distinguish the role of Rheodrop technology in enhancing the filling process.

Figure 5 shows the samples that were molded at different temperatures using conventional IM processing. It is clear that the filling percentage decreases as the temperature decreases and the only part that was completely filled was when the melt temperature was set to 240℃. Samples injected with melt temperatures 210℃ and 220℃ were 85% and 91% filled respectively. It is suggested that the cause of incomplete filling defects on the latter cases is the result of higher viscosity melts due to lower melt temperatures, which inhibits flow.

210ºC 220ºC 240ºC

Figure 5: Parts molded at different temperatures using conventional IM

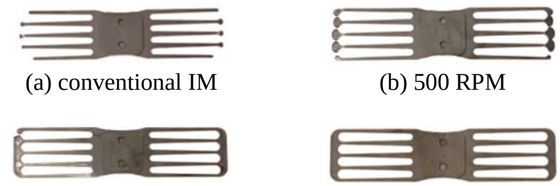
Figure 6 shows the samples that were molded at different temperatures when utilizing the Rheodrop technology at rotational velocity of 1,500 RPM. A significant enhancement is perceived in the filling processes. Samples obtained at different temperatures were all completely filled illustrating the advantage of the pin rotation in reducing the melt viscosity. The Rheodrop technology was able to enhance the filling of the samples that were molded at lower melt temperatures 210℃ and 220℃ compared to the samples molded at the same temperatures when the technology was not utilized. The enhancement is due to the shearing effect of the rotated pin, the viscosity of the injected polymer melt is reduced allowing for better flowability resulting in better cavity filling.

210ºC 220ºC 240ºC

Figure 6: Parts molded at different temps. utilizing the Rheodrop at 1,500 rpm

The rotational velocity of the pin controls the intensity of the shearing applied to the polymer melt. The higher the rotational velocity, the higher the shear rate applied to the polymer melt and the lower the viscosity of the polymer according to the Cross-Model analysis. Therefore, the second case study focuses on altering the rotational velocities, shear rate applied, while maintaining the melt temperature constant at 215℃ for all experiments. Conventional IM samples are compared to samples obtained at pin rotation of 500 RPM, 1,000 RPM, and 1,500 RPM.

Figure 7 shows a sample of the parts injected at different rotational velocities with melt temperature of 215℃. Due to the viscous characteristics of the polymer melt at this temperature, conventional IM samples showed incomplete filling defects as seen in Figure 7(a) with 87% filling. When the Rheodrop technology was utilized, the filling process was enhanced. As seen in Figure 7(b), at 500 RPM, the filling process achieved 91%. In addition, at 1,000 RPM, the filling reached 99% as shown in Figure 7(c). Finally, when the pin's rotational velocity was set to 1,500 RPM, the samples obtained were all completely filled as shown in Figure 7(d).



(a) conventional IM (b) 500 RPM

(c) 1,000 RPM (d) 1,500 RPM

Figure 7: Parts molded samples at 215ºC at different rpm

Figure 8 illustrates the pattern of improving the filling percentage with respect to the rotational velocity of the pin. As the rotational velocity of the pin increases, the filling percentages increases as well. Also, a consistent completely filled samples were obtained when the rotational velocity was set to 1,500 RPM.

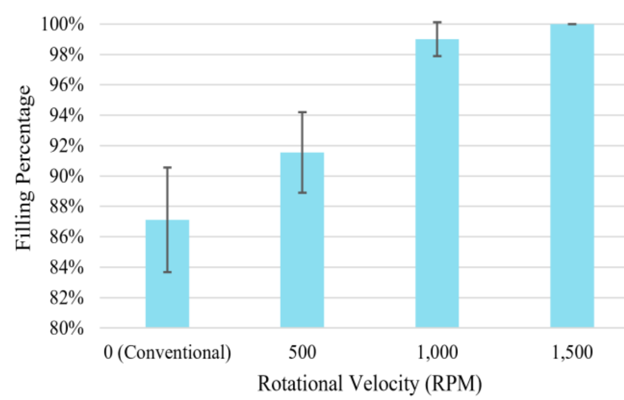


Figure 8: Improvement in filling percentage resulting from Rheodrop technology

CONCLUSION

Rheodrop technology was introduced to improve the quality of molded product of hot runner systems. Numerical simulations were performed to study the melt viscosity at different temperature levels and at different level of shear rate. Samples were molded at different temperatures with and without applying Rheodrop technology. The results showed that the molded samples at lower temperature levels 220ºC and 210ºC were defected as the cavities were incompletely filled with conventional IM. When the Rheodrop was utilized, the molded samples were perfectly filled at all selected temperatures Finally, Rheodrop technology was tested at different level of rotational speed 500, 1000, 1500 rpm and fixed melt temperature at 215ºC, the results showed that the cavity filling enhanced with increasing rotational speed to reach consistent 100% filling at 1500 rpm.

REFERENCES

[1] P. Unger, *Hot Runner Technology*. München: Carl Hanser Verlag GmbH & Co. KG, 2006. doi: 10.3139/9783446430631.

[2] D. V. Rosato, D. V. Rosato, and M. G. Rosato, Eds., *Injection Molding Handbook*. Boston, MA: Springer US, 2000. doi: 10.1007/978-1-4615-4597-2.

[3] P. Kennedy and R. Zheng, *Flow analysis of injection molds*. Carl Hanser Verlag GmbH Co KG, 2013.

[4] İ. Karagöz and Ö. Tuna, “Effect of melt temperature on product properties of injection-molded high-density polyethylene,” *Polym. Bull.*, Apr. 2021, doi: 10.1007/s00289-021-03695-w.

[5] Z. Song, S. Liu, X. Wang, and Z. Hu, “Optimization and prediction of volume shrinkage and warpage of injection-molded thin-walled parts based on neural network,” *Int J Adv Manuf Technol*, vol. 109, no. 3–4, pp. 755–769, Jul. 2020, doi: 10.1007/s00170-020-05558-6.

[6] S. B. M. Yasin, Z. Ahmad, S. N. S. Ismail, N. F. M. Sani, and Z. A. Zulkifly, “Analysis of Weld Line Movement for Hot Runner System,” in *Proceedings of the Second International Conference on the Future of ASEAN (ICoFA) 2017 – Volume 2*, R. Saian and M. A. Abbas, Eds. Singapore: Springer Singapore, 2018, pp. 883–890. doi: 10.1007/978-981-10-8471-3_87.

[7] D. O. Kazmer *et al.*, “Multivariate Modeling of Mechanical Properties for Hot Runner Molded Bioplastics and a Recycled Polypropylene Blend,” *Sustainability*, vol. 13, no. 14, p. 8102, Jul. 2021, doi: 10.3390/su13148102.

[8] J. Gim, B. Kim, and B. Rhee, “VALVE GATE OPEN LAG TIME IN CONVENTIONAL HOT RUNNER SYSTEM,” Proceedings of the Society of Plastics Engineers’ Annual Technical Conference (SPE ANTEC), Orlando, FL, USA. 2018.

[9] L. H. Sperling, *Introduction to physical polymer science*, 4th ed. Hoboken, N.J: Wiley, 2006.

[10] C. Thakur, K. Alqosaibi, A. Kundu, and J. P. Coulter, “Development of Advanced Hybrid Polymer Melt Delivery Systems for Efficient High Precision Injection Molding,” *Journal of Manufacturing Science and Engineering*, vol. 142, no. 7, p. 071004, Jul. 2020, doi: 10.1115/1.4046833.

[11] K. Alqosaibi, C. Thakur, H. Noor, A. Duhduh, and J. Coulter, “INTELLIGENT HYBRID HOT RUNNER SYSTEM FOR OPTIMIZED POLYMER PRODUCTS,” Antec 2020.

[12] K. Alqosaibi, C. Thakur, H. Noor, A. Duhduh, A. Kundu, and J. Coulter, “Investigation of a Hybrid Hot Runner System to Increase the Efficiency of Injection Molding and Improve the Quality of Molded Parts,” TechConnect Briefs, 119–122 (2019).

[13] “ABS │ LG Chem.” https://www.lgchem.com/product/PD00000013 (accessed Oct. 24, 2019).

[14] Beaumont, John P., *runner and gating design handbook*, illustrated, revised ed. Hanser, 2007.