Investigation of a Hybrid Hot Runner System to Increase the Efficiency of Injection Molding and Improve the Quality of Molded Parts

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

[1]Animesh Kundu, [1]John Coulter

[1]Manufacturing Science Laboratory
Department of Mechanical Engineering and Mechanics
Lehigh University, Bethlehem, Pennsylvania 18015
[2]King Saud University, Riyadh, KSA, kalqosaibi@ksu.edu.sa
[3]Taibah University, Madinah, KSA, hhnoor@taibahu.edu.sa

ABSTRACT

Hot runner systems are prevalent in the manufacturing of thin walled polymers parts. There are great challenges in industries associated with the quality of the molded parts when utilizing a hot runner system. One of the main challenges is processing thermally sensitive materials such as Liquid Crystalline Polymers LCPs. In hot runner systems, the viscosity increases between injection molding cycles at the nozzle tip due to lower temperatures. This might cause serious problems such as incomplete filling defects.

Mainly, there are two ways to reduce the dynamic viscosity of shear thinning thermoplastics (1) increasing temperature and (2) applying shear. In this research, a novel "rheodrop" concept is developed to control the shear rate during injection molding process. Applying a shear at the nozzle will decrease the viscosity of the molten polymer. This innovative idea is suitable for temperature sensitive polymers as they might degrade when subjected to excessive heat for longer periods of time.

An analytical investigation was performed to validate the developed "rheodrop" concept which applies shear to the polymer in between filling cycles by rotating the valve pin inside the hot drop. Simulations were performed using ANSYS fluent and the results confirmed that the concept is able to produce a sufficient amount of shear to significantly reduce the dynamic viscosity between injection molding cycles.

Keywords: injection molding, hot runner systems, rheodrop

1 INTRODUCTION

Plastics industries have been growing since the first plastic compound invented by John Hyatt in 1869. Polymers have become the most used materials in the United States since 1976 exceeding the use of steel, aluminum, and copper combined [1]. Consequently, the plastic manufacturing processes such as injection molding process have evolved over the years. Injection molding is the most used process in manufacturing plastic products with capability of mass producing extremely complicated parts. There are two types of injection molding process based on the runner system: cold runner and hot runner systems [2].

As the name suggests, in a hot runner system the polymer is actively heated throughout the molding process and kept in the molten state so that the material is readily available for the next molding cycle. Performing injection molding using a hot runner system instead of a cold runner has several advantages. It reduces cycle time so that the production rate can be significantly increased. The cycle time is reduced by eliminating the need for runner solidification once the molten polymer is shot directly into the cavities. Also, eliminating solidified runners obviates the need for runner removal based finishing processes that can be required with cold runner systems [2].

Liquid crystal polymers are suitable for high throughput, low cycle time injection molding processes because the low viscosity of their melts and the fast melting and solidification kinetics. LCPs are thermally sensitive polymers making it particularly challenging to fabricate in a hot runner system. The main issue is thermal degradation which is a result of excessive heat as the plastic chain backbone starts to separate and react with each other at high temperature resulting in changes in the polymer properties. Therefore, there is a potential degradation risk when LCPs are exposed to heat for longer periods of time [3].

Various additives such as colorants are added to the polymers during injection molding processes in industry. Due to environmental issues, these colorants have been replaced with eco-friendly colorants recently. The eco-friendly additives are thermally sensitive. When processing thermal sensitive polymers or using eco-friendly fillers, the processing temperature should be controlled completely so that the polymer is not subjected to excessive heat [3].

It is difficult to maintain consistent temperature in the hot runner system due to different boundary conditions, so the temperature might get lower at some locations. As a result, partial solidification in the form of cold slugs may be formed. When manufacturing thin walled parts, the slug formation in the hot runner system may block smaller mold cavity passages causing incomplete cavity filling. The current research project was directed at arriving at a solution to this very problematic issue.

2 PROBLEM VALIDATION

A single injection molding cycle utilizing a hot runner system consists of four different phases, namely filling, packing, cooling, and ejection [4]. First, filling and packing phases start when the mold gets closed. After that, the cooling phase solidifies the parts to desired rigidity. The cooling time accounts for 80 to 85 percent of the injection molding cycle. During cooling a cold surface is created due to the direct contact between the heated manifold and the cold cavity plate as illustrated in figure 1 that shows a schematic of closed mold where the dashed lines represent the heated nozzles.

This different boundary condition will decrease the temperature around the nozzle tip which increases the viscosity of the molten polymer. As a result, cold slug formation occurs around the nozzle tip during the cooling phase.

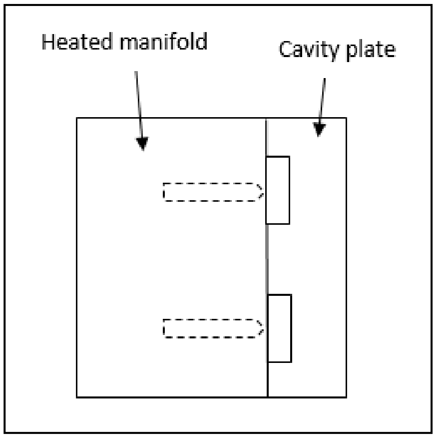

Figure 1: Schematic of closed mold

The cold slug formation will affect the product quality and could lead to incomplete filling of the cavity when manufacturing thin walled parts. A simple solution of the slug formation issue is increasing the temperature of nozzles above the recommended processing temperature of the polymer. The polymer could be maintained in molten condition and avoid the slug formation issue. However, this simple solution is not applied in case of heat sensitive polymers as excessive heat might damage the polymer's molecules. Also, it is not applied when using eco-friendly colorants because of their sensitivity to heat.

3 PROPOSED SOLUTION

There are two ways of reducing the viscosity of the material, increasing the temperature or applying a higher shear rate in the case of shear thinning thermoplastics (i.e. the viscosity of a fluid will increase with applying shear rate in case of shear thickening fluids). In case of thermal sensitive polymers, increasing the temperature to avoid polymer solidification between injection molding cycles might lead polymer degradation. Our proposed solution to mitigate issues pertaining to polymer solidification involves applying shear on the polymer melt to reduce the viscosity and maintain the molten condition at lower temperatures between injection molding cycles.

A novel "rheodrop" concept is proposed for applying a controlled shear rate to the polymer near the tip of the nozzle between injection molding cycles. Figure 2 demonstrates the method of applying shear rate. A rotating valve pin is incorporated in the hot drop nozzle. The pin would be rotated to create a controlled rotational shear on the polymer at the end of injection phase once the valve is closed. Consequently, the rheodrop concept is suitable when using a hot runner manifold that has nozzles with valve pins. We hypothesize that the introduction of shear would be sufficient for maintaining the relatively lower viscosity of the polymer without raising its temperature. In this research the hypothesis is validated by a simulation of the process using ANSYS fluent.

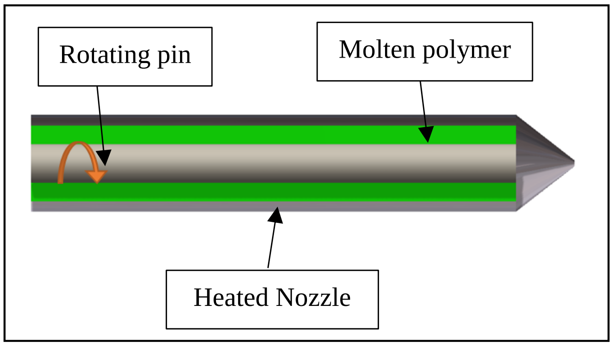

Figure 2: Representation of the Rheodrop concept

4 ANALYTICAL INVESTIGATION

The rheodrop concept was simulated using ANSYS fluent software to investigate the resultant shear rate and its effect on the dynamic viscosity of the polymer melt. The simulations were performed for a liquid crystalline polymer (Vectra E130i) which melts at 340ºC. The zero shear viscosity was calculated using equation 1 shown below[5].

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

Where η_0 is the zero shear viscosity, T is the temperature, T^* is the glass transition temperature, and D_1, A_1 and A_2 are constants.

There are several rheological models that can used to characterize the flow behavior such as Power Law Model, Cross Model, Ellis Model, and Carreau Model. The Cross model has been extensively used for polymer rheology and it is the model utilized in this research to get the viscosity profile during the injection molding process. The Cross Model equation is given by [5]:

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

Where η is the viscosity, τ^* is the shear stress, and γ is the shear rate.

To numerically validate the rheodrop concept, the hot drop that has the rotating valve pin was simplified and modeled using SolidWorks software, as shown in figure 3. The model was imported to ANSYS fluent and a mesh was generated. The solid part in the model is considered as the fluid in ANSYS so that the flow will be between inner and outer walls. The inner pin will rotate at different RPMs and the rotation effects on the shear rate and dynamic viscosity on the molten polymer will be studied.

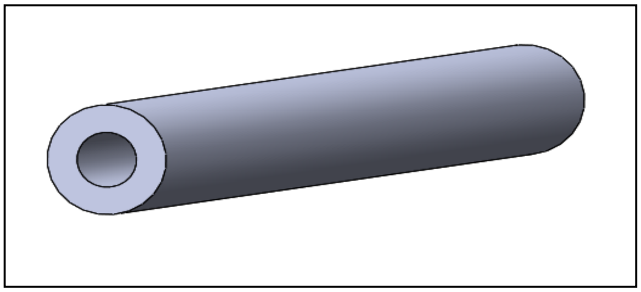

Figure 3: Simplified heated nozzle used in numerical simulation

5 MATERIAL

The material that is used in this research was Vectra E130i, a liquid crystal polymer (LCP). LCPs have long, rigid and ordered molecular chains in both the solid and melt phases unlike other semi-crystalline polymers [6]. They have unique properties that make them suitable for particular products. Vectra is selected for this research because it has been used in manufacturing thin walled products such as electrical connectors and the rheodrop concept is targeting the incomplete filling issue caused by slug formation.

The recommended processing parameters and rheological properties for Vectra E130i based on Mold Flow database are shown on table 1 and 2.

Melt temperature	340° C	Max. 345° C	Min. 335° C
Mold temperature	100° C	Max. 120° C	Min. 80° C
Ejection temp.	225° C		

Table 1: Recommended processing for Vectra E130i

A_1	38.904
A_2	51.6 K
D_1	7.50149 x10^{14} pa-s
D_2	473.15 K
D_3	0

Table 2: Rheological Properties of Vectra E130i

LCPs could be reinforced with various fillers to enhance mechanical or thermal properties [7]. A sample of Vectra E130i with 30% glass fibers filled was tested on a parallel plate rheometer to study the relationship between the viscosity and the applied shear rate, the results are shown in figure 4.

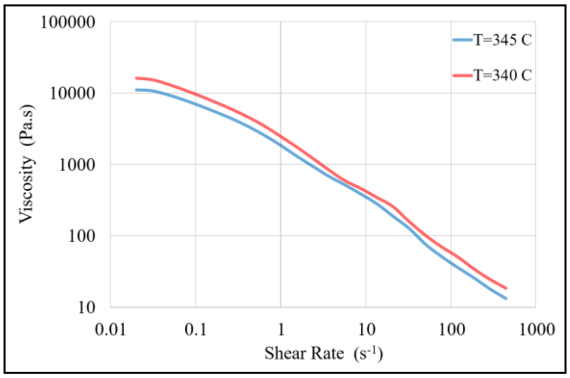

Figure 4: Rheometric analysis results for VectraE130i

Figure 4 shows the relationship between the viscosity and shear rate for Vectra E130i at two different temperatures just below the melting temperature of the polymer. It can be noticed that the viscosity significantly decreases with increasing shear rate, representative of shear thinning behavior. Indeed, this makes Vectra very easy to process in injection molding as the polymers exhibit very high shear rate during the process. In hot runner systems, the polymer will be at zero shear rate between injection molding cycles. Also, the temperature will be lower at certain areas as illustrated earlier due to different boundary conditions while cooling the products. The rheodrop concept was invented to apply shear rate between injection molding cycles to avoid polymer solidification that may cause incomplete filling when manufacturing thin walled parts.

6 RESULTS AND DISCUSSION

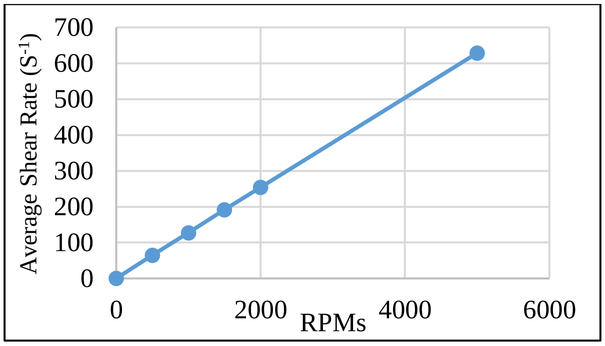

Figure 5: The average share rate at different RPMs

The resultant shear rate by the rotational speed was calculated in ANSYS software. The average shear rate in a cross section of the hot drop corresponding to different RPMs is shown in figure 5. The viscosity profile in a cross-section is shown in figure 6. In the cross section, the maximum shear rate is at the area near to the rotating pin and it starts decreasing to the minimum near to the outer wall. Consequently, the viscosity is minimum near the inner pin and maximum at the outer wall.

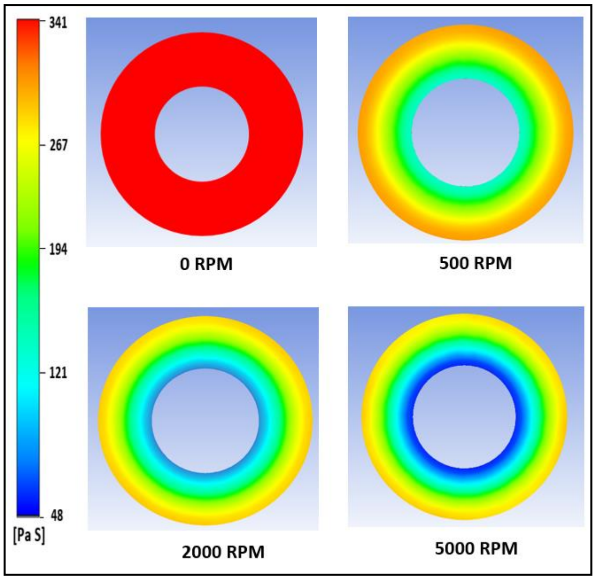

Figure 6: Viscosity Profile at different RPMs, T=613K

The viscosity at zero rpm as shown in figure 6 is 341 Pa.S which corresponds to the calculated zero shear viscosity of Vectra E130i at melting temperature 613 K using equation 1. It can be noticed in the profile that the minimum viscosity is around the inner wall and it decreases up to 48 Pa.s when rotating speed is 5000 rpm. The average viscosity of the melt at the cross section at different rpms is shown in figure 7. As shown in the figure, the average viscosity dropped dramatically when the rotation was introduced. The average viscosity decreased from around 341 Pa.s at zero rpm to 217 Pa.s at 1000 rpm. At higher rpm, the molten polymer starts to show Newtonian like behavior where the viscosity is not significantly affected by shear rate, i.e. the average viscosity is not significantly affected at higher rotational speed.

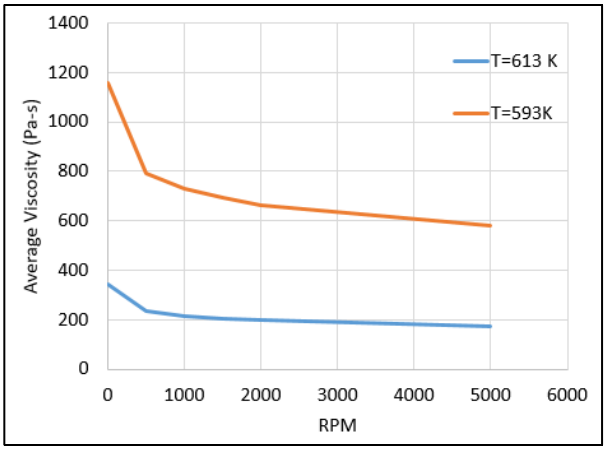

Figure 7: Average viscosity at different RPMs

The average viscosity will increase when the temperature of the polymer melt decreases as shown in figure 7. When the temperature dropped to 593 K, the zero shear viscosity was calculated using equation 1 to be 1159 Pa.s and partial solidification might occurs at higher value of viscosity associated with lower temperature. This slug formation might cause a serious defect when manufacturing thin walled parts. However, as demonstrated in the figure, the average viscosity was reduced to 578 Pa.s with the applied shear rate associated with the rotational speed.

7 CONCLUSION

The main objective of the research was to develop a potential solution to the slug formation that occurs between injection molding cycles in hot runner systems. The possible reason of the problem was explained and an innovative idea was presented to solve this problematic issue. ANSYS fluent was used to validate the “Rheo drop” concept. The concept was able to apply a sufficient amount of shear that significantly reduced the average viscosity in the hot drop where the slug formation occurs. The average viscosity in the hot drop was reduced from 341 Pa.s to 172 Pa.s when the pin rotate at 5000 rpm. We are currently working on a design that can validate the rheo drop concept experimentally. Basically, we are modifying a hot runner mold to retrofit the concept of rotating pin at different rotational speed.

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