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Control of Temperature Profile in the Injection Molding Process for Part Consistency

Brian Bullecks[a], Samantha Burnham[b], Gregory Campbell[a], Raghunathan Rengaswamy[a] , Ravi Kumar Mandela[a]

[a]*Clarkson University, Potsdam, NY 13699,USA, raghu@clarkson.edu*
[b]*University of Newcastle Upon Tyne, UK*

Abstract

For consistent part production in injection molding machine, it is important to make the frozen in stress homogeneous across the whole part. A good temperature profile control can achieve this. In this talk we present our results on modeling of the temperature profile of the melt pool in front of the screw. A mechanistic first principles model is built and the temperature profile is predicted. Future work will include the development of PLS type data-based models that can be used in online control.

Keywords: Injection molding, Temperature profile control, Mechanistic model, PLS data-based model.

1. Introduction

It is well known in the injection molding community that the properties of large parts are not consistent due to the non-homogenous frozen in stress in different areas of the molded part. The melt is injected into the part and the melt cools to different extent depending on the flow length and time. Because polymers are viscoelastic, the frozen in stress will thus be different in different areas of the part due to the different cooling times after the melt stops flowing. It is widely known that the conditions under which a polymer part has been molded affect the performance properties of that part. For consistent part production, it is important to control the temperature profile across the melt before the part is sent for molding. A melt pool temperature profile control that compensates for the cooling dynamics in the mold can make the frozen in stress homogeneous across the whole part. Model-based control of the temperature profile of the melt in an injection-molding machine is a possible approach to achieve part consistency. One approach is to control the temperature profile (temperature and the temperature gradient) in the melt pool as it is being generated in front of the screw. The manipulated variables that we can be used to accomplish this control are the control of the plastication pressure, the pressure on the back of the screw, during the shot production, and screw speed. This combination of control parameter manipulation will adjust the rate at which the polymer is fed to the melt pool. Therefore, these manipulated variables will allow us to control the residence time of the melt on the screw and the rate of energy dissipation transferred to a polymer melt element as it travels down the screw toward the melt pool. The first requirement for such a control is a model to predict the effect of the manipulated variables on the temperature profile. In this paper, we discuss a mechanistic model for this prediction. Future work will include the development of PLS type data-based models and also the controller.

2. The Process

The high pressure injection molding of plastics is the means by which many common plastic parts are manufactured. This process takes any of the many polymers available from their pelletized form, melts them into a hot viscoelastic fluid. The fluid is forced into the mold by closing a valve at the melt end of the screw and then moving the screw forward as a piston. The fluid cools as it is pushed into the mold and it is then packed into a mold and allowed to cool and harden into the shape of the mold. The part is then ejected as a finished product.

Figure 1 explains this process. The pelletized plastic is fed into the injection unit. Here the plastic is conveyed down the conveying section of the screw (Figure1). The screw core diameter increases at a position several screw diameters from the hopper feed section. This area of the screw where the core diameter increases is called the compression/ transition zone and it is used primarily to decrease the channel volume as the polymer melts and the void volume in the pellet bed decreases. At this point, the barrel heaters provide energy to form a melt film at the barrel interface of the solid bed and this melt film then surrounds the solid bed. The rotation of the screw and the position of the barrel relative to the polymer create shear heating. This energy generation heats and melts the polymer pellets. From this point the primary melting mechanism is due to the shear heating caused by the shear rate across the film and the polymer melt viscosity. As the polymer melts enters the metering zone of the screw and from here the polymer is deposited in front of the screw as a melt pool.

Once a pool of a pre-determined size is generated, the melted polymer is then injected into the mold in a manner similar to the operation of a syringe. When the polymer enters the mold it begins to cool and harden and at this point the mold is packed out under high pressure by the injection unit to help compensate for any shrinkage the material may have experienced while cooling and crystallizing. Once the polymer has hardened and the part is cool, the mold opens and the part is ejected.

3. Equipment and Instrumentation

The injection molding machine that is used at Clarkson University is a BOY 50S unit. This machine has a clamp force of 55 US tons and an injection pressure of 190 MPa (27,000 psi). The maximum shot size for this machine is 5.88 cubic inches. The extruder screw in this machine is chrome plated to reduce the infrared emissivity and increase the reflectivity of from the screw. Mold temperature is controlled and maintained by a Mokon Division model KS2A04 circulating water system. For monitoring of the screw rpm, a SHIMPO panel mount tachometer with a rotary pulse generator type sensor which updates the rpm 600 times per revolution is used. Further, there are three infrared temperature probes along the length of the screw and seven in the mold. These probes provide an analog of temperature with about a 5-10 millisecond settling time.

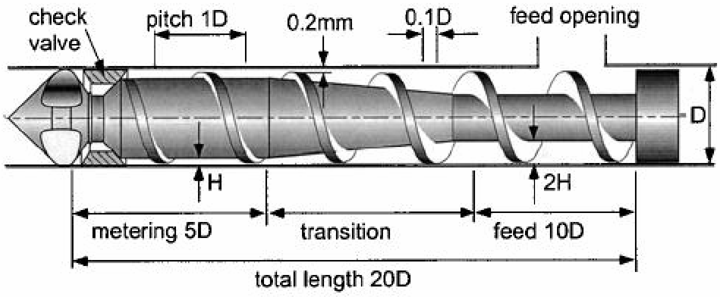

Figure 1. The Extruder [1]

4. Mechanistic Model

The temperature of the polymer melt entering a mold plays an important role in determining the properties of the melt. The traditional extrusion model was first proposed by Rowel and Finlayson [2] and extended to extruders by Carley, Mallock and McKelvey [3] and was based on the barrel rotation and a rectangular channel. It was assumed that the process was equivalent if the barrel is rotated in the direction opposite to that of the screw. The velocity profile across the channel was originally proposed by Mohr, Saxton and Jepson [4]. The flow down the channel was considered to be the combination of the pure drag flow and pure pressure flow. The pure pressure flow for the isothermal Newtonian fluid was first found by Boussineq [5]. Rowell and Finalyson derived shape factors for the drag flow and pressure flow to account for the influence of the flights. Rowell and Finalyson [2], Mohr and Mallouk [6], Gore and McKelvey [7] calculated the viscous dissipation in the channel for Newtonian fluids. Griffith [8] obtained viscous dissipation for the power law fluid with temperature dependence. Fenner [9] discussed viscous dissipation in screw channels of finite width for both Newtonian and non-Newtonian isothermal flows. He stressed the difficulties of treating the regions of the flow close to the clearance.

The barrel rotation models have been extensively used as it is more complicated to solve the moving boundary layer problem for rotation of the screw. In practice, the screw is rotated and not the barrel. It is important to know that some of the variables calculated from the barrel rotation theory do not represent screw rotation in the extrusion process. For example, particle trajectories need proper frame transformation form barrel rotation to screw rotation in order to know what is exactly happening in the extrusion process from a mechanistic point of view. Dontula et.al [10] proposed a model explaining the melt temperature rise above the barrel temperature. Their theory is based on the barrel rotation and the fluid is considered to be incompressible and Newtonian. The effect of temperature and pressure on viscosity is considered and the expression for viscosity is given as

$$\mu = \mu_o e^{-b(T-T_o)} e^{cP}$$

The effects of flight are neglected and the barrel and screw are assumed to be at same temperature. The input power is dissipated as heat, as the polymer moves along the screw, some of which is transferred to the screw and the barrel. Campbell et.al [11], Campbell et.al [12] proposed a screw rotation theory, which changed the analysis of the extrusion process by converting the solution obtained in a fixed frame back to screw rotation moving frame. A new screw rotation approach was developed by Campbell et.al [13] and it is characterized by focusing on the three components of the extruder: the barrel, the helix, and the core. From the theory they showed that the velocity at the screw core can be substantially lower than the barrel velocity, particularly for deep channel screws. At constant angular velocity for screw and barrel rotation, this will lead to lower shear rates for the screw rotation and thus lower dissipation. The model is made complex with the addition of effect of flight, helix, on the down channel flow. They relied on the assumption that the viscosity changes at a slower rate and thus the velocities stream lines are not substantially locally altered due to this slow change in temperature. The viscosity varies exponentially as a function of temperature and pressure. The rate of energy production, work, through viscous dissipation is obtained by multiplying the shear stress on the screw surface by the velocity on the surface and integrating over the screw surface area. It is also assumed that all of the work done by the moving surface is converted through dissipation to thermal energy and it leads to a temperature rise in the working fluid.

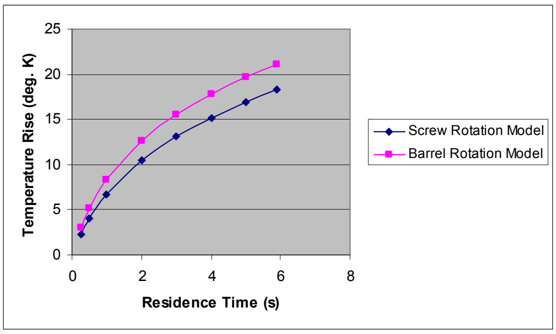

Figure 2: Plot showing the comparison of temperature increments

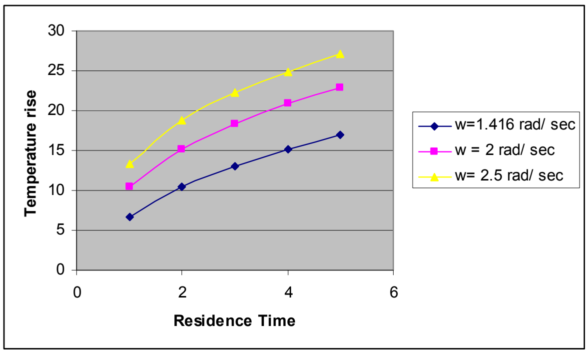

Figure 3: Plot showing the comparison of temperature rise for different angular velocities for screw rotation model

In our case study, the material taken is polystyrene and the viscosity of polystyrene is a function of temperature and pressure. Maximum residence time is calculated as the volume of the shot to the volumetric flow rate. More details can be found in the paper [10]. Temperature increments in the melt pool using barrel rotation model and screw rotation model for a specific residence time is calculated. The graph showing the increments of temperature in the melt pool using barrel rotation model and screw rotation model are shown in the Figure 2 which proves the point discussed above. The temperature increment using barrel rotation model over predicts compared to screw rotation model. Figure 3 shows the effect of the proposed manipulated variable, screw speed, on temperature rise. It is clear from the Figure 3 that screw speed has a significant effect, which would enable control of temperature profile in the melt pool.

5. Conclusions

In this paper, a mechanistic model for the Injection Molding Process as a function of the various suggested manipulated variables is generated. It is shown that the proposed mechanistic model provides a more realistic prediction for the temperature rise in front of the melt pool. The use of the proposed mechanistic model and other data-based models in online control will be a subject for future work.

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