A Concurrent-Engineering Approach Toward the Online Adaptive Control of Injection Molding Process

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Received on December 20, 1999

Abstract

Injection molding is the most effective process to produce plastic parts of complex shape to the highest precision at the lowest cost. Considerable progress has been made over the last two decades in modeling and simulation of the molding dynamics. However, due to complex material properties and other uncontrollable disturbances, consistency of part quality cannot be assured in production. This paper presents a new approach to the problem. Based on the concept of Concurrent Engineering, we make full use of the power of simulation for the design of the part, the mold, and setting up process control parameters automatically. The control system consists of feed-forward and feedback loops with numerous sensors in each loop. With an online PC and a smart part-quality sensor, the system can control the variation of part weight many times better than existing methods.

Keywords: Concurrent, Molding, Computer Adaptive Control

1 INTRODUCTION

It is well recognized that injection molding is the most effective process for mass producing discrete plastic parts of complex shape to the highest precision at the lowest cost. Since 1974, we have been devoting our research effort to establishing a science base for the process, from characterizing the material properties to modeling the molding dynamics under transient and nonisothermal condition [1]. While the use of CAE software for injection molding has become common practice in industry today, a generic and reliable process-control methodology to ensure consistent product quality is still lacking [2].

Considerable effort has been made in the past to analyze and optimize process control at the level of machine parameters (controllable variables such as injection speed or hydraulic pressure), process variables (e.g. melt temperature or cavity pressure, which are not directly controllable) or even part quality, such as weight or thickness. From building an empirical model based on statistics of measurements to employing artificial intelligence techniques, results all depend on specific material/mold configuration on a particular molding machine; i.e. the method is not generic. No definitive correlation between a process variable (e.g. cavity pressure profile) and the part quality has been established. Accordingly, system disturbances (e.g. uncontrollable material variation or machine-to-machine characteristics) can still not be handled adaptively to ensure part quality.

This paper is a result of a new research project named Integrated Molding System (IMS) which is based on the concept of Concurrent Engineering [3]. Collaborating with industry, the project is aimed to develop necessary technologies in order to achieve "the best performance" in injection molding such that any given plastic part can be produced better (in quality), cheaper (in cost) and faster (in time-to-market).

IMS consists of three major functional components: part design, tooling technologies (mold design and manufacture) and process control. These components are treated concurrently under a strong belief described as follows:

a) The best performance begins with the best design of the part. Ill-conceived part design guarantees troubles ahead during the later stages of mold design and part production.
b) Molds should be designed the first time right without the need for costly mold trials. Simulation tools should be extensively used to supplement prior experiences.
c) Rational determination of initial setup points for process control is essential. Such determination should be based on first principles, rather than ad-hoc or heuristic procedures. Effective control algorithms are necessary to cope with unpredictable system disturbances in order to assure part-quality consistency automatically.

These were implemented and the preliminary results were very encouraging. Under a fully automated condition, an adaptively controlled machine can produce parts 10 times better in quality variation than conventional methods in some cases [4].

2 A GENERIC PROCESS MODEL

Over the past 25 years, CIMP (Cornell Injection Molding Program) has developed extensive technologies for simulating the dynamics of injection molding process under transient and non-isothermal conditions taking into account of non-Newtonian behavior of the material [1]. A geometrically simplified model (reduced to a one-dimensional flow) used by Dr. C-MOLD and Project Engineer (two of the Desktop products of C-MOLD [5], a commercial software) makes use of the following set of governing equations to model the molding dynamics of filling a center-gated-disk cavity:

$$0 = \frac{\partial}{\partial z}\left(\eta \frac{\partial u}{\partial z}\right) - \frac{\partial p}{\partial r} \quad (1)$$

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}\right)=\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\eta\left(\frac{\partial u}{\partial z}\right)^2 \qquad (2)$$

and

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho u)+\frac{\partial}{\partial z}(\rho w)=0 \qquad (3)$$

where p is pressure, T the temperature, z and r are transverse and radial coordinates, respectively. For a disk cavity, u is the radial-velocity component, η, ρ, C_p and k are, respectively, the shear viscosity, mass density, specific heat and thermal conductivity. Note that ρ in the energy Equation (2) is treated as constant during the filling stage while it is a variable in Equation (3) during the post-filling stage when the compressibility of polymer is taken into account. Dr. C-MOLD only simulates the filling stage. However, in the calculation it uses a modified Cross model to represent the viscosity of the polymer melt as a function of shear rate, temperature and pressure. The calculation is performed on an online PC.

One of the C-MOLD simulation outputs is a set of optimized process conditions. Through an interface program in the IMS, a complete file of machine setup points is directly transferred to a PC-based machine controller. This feed-forward loop initiates the molding operation on the machine as shown in Figure 1. However, an Advanced Product of C-MOLD has to be used for mold and part design where more detailed information are crucial, e.g. precise prediction and optimization of cycle time, shrinkage and warpage of the final product. Such activities are typically taken place in advance and done off-line.

3. A MULTI-LEVEL PROCESS CONTROL SYSTEM

There are many variables involved in the injection molding process. Some are machine parameters (Level 1) which can be independently controlled by conventional (e.g. PID) control methods. Others are process variables (e.g. melt temperature, cavity pressure, etc., we call them Level 2) which depend on the combination of Level 1 variables and cannot be controlled independently. The third level parameters (or Level-3) define part quality in various ways, either quantitatively or qualitatively. Consistency of part quality in production is a major concern; we chose part weight as the quality criterion because it is possible to detect and control indirectly using an intelligent online sensing system based on continuous monitoring of mold separation during the process.

Figure 1 shows such a multi-level control architecture that consists of a feed-forward loop and three feedback loops in a hierarchical structure centered around a high-performance personal computer (PC). After the feed-forward loop as described before, all machine parameters are independently controlled. A number of process variables (e.g. melt temperature, cavity pressures etc.) are continuously monitored in the Level-2 feedback loop via a data-acquisition system as a part of the process-control computer. In Level 3, a high-precision LVDT is mounted across the parting line of the mold plates to monitor the momentary separation of mold core and cavity plates which takes place at the end of filling and the early part of the post-filling stages.

An algorithm has been developed to monitor and manipulate the profile of mold-separation history to keep the variation of part weight from shot-to-shot to a minimum. The quality (weight) control is fully automatic by feeding the same amount of material into the mold adaptively in each injection cycle based on the mold-separation signal. The phenomenon of mold separation (without flashing) is the result of excessive force exerted on the mold walls due to high cavity pressure at the end of fill which momentarily exceeds the clamp force of the machine setting. The system automatically determines the fill-to-pack switchover point and continues to control the mold-separation profile by manipulating the hydraulic pressure in the post-filling stage. Such control overrides the initial settings of switchover point and packing pressure. A schematic diagram of a molding machine and its control system is shown in Figure 2.

4. PRELIMINARY RESULTS AND DISCUSSION

A series of molding experiments has been carried out to test the validity of the control scheme. Experiments were done on a Boy 50T injection-molding machine modified with a Moog servo-valve in its hydraulic system. The machine and mold (a rectangular plaque) are fully instrumented with sensor at all three levels. They are connectted to the process computer through a 16-channel data-acquisition system.

Two materials have been used: an amorphous polycarbonate (Teijin Panlite AD-5503) and a semi-crystalline polypropylene (Exxon 7032-E7). DR. C-MOLD generated the initial process condition, and the system has the ability to make adjustments online if needed. Figure 3 shows typical traces of three important variables when the mold-separation control is turned on. It can be seen that the cavity pressure measured by the first transducer (Pc1) located near the gate increases steadily first during cavity-filling, and then abruptly at the end of fill. The system switches the control from fill to pack based on a hydraulic-pressure value, learned adaptively from the previous shot. Accordingly, the mold-separation signal takes off at the end of fill. It reaches to a maximum value very quickly in the packing phase, and then decays gradually to zero at the end of the molding cycle. This condition was met by adjusting the hydraulic pressure automatically as shown in the figure.

Table 1 summarizes the results in weight variation for each batch of around 100 shots of the molded plaque with polycarbonate. Four control methods were used for the purpose of comparison. The first column in the Table shows the result obtained by using hydraulic pressure (Ph, scaled by a factor of 10) to control the fill-to-pack switchover point, a typical method used by almost all controllers for injection molding machines. The statistical data were derived from 100 shots which has a mean value part weight of 9.839 gm, and a standard deviation of 0.0144 gm. The values for process setting, Pl, are given under the table for melt temperature (Tm), mold-wall temperature (Tw), packing pressure (Pp), packing time (tp), cooling time (tc), and ram velocity (Vr), respectively.

The second column is the result from using ram position (Yr) to control the switchover point, another common method. This batch of experiments contains 200 shots, and under slightly different process settings, P2, which has the ram velocity in three steps. The statistics show that there is little change of the average part weight, but a drastic increase in standard deviation.

The third column is the result from using the maximum cavity pressure (Pc) to control the switchover, but under the process condition of Pl. Again, the average part weight has little change, but the standard deviation is much smaller than both previous cases. This is by no means a surprise because cavity pressure directly affects the state of the material in the mold. There has been