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Melt temperature dynamic control strategy of injection molding machine based on variable structure control and iterative learning control

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Abstract

Melt temperature in the injection molding process directly affects the quality of the molded plastic product. The injection molding process is a periodic dynamic process. Many factors affect the barrel melt temperature, so precise control of the melt temperature is difficult. This paper introduces this industrial problem and presents a combined strategy using a feedback controller and an iterative learning controller to resolve the problem. Results show that this method has a high dynamic control accuracy and improves molded part mass repeat accuracy.

Keywords: dynamic control; injection molding machine; iterative learning control; melt temperature; variable structure control.

1. Introduction

The plastic injection molding process is a key plastic technique widely used in the polymerization industry. Process control of injection molding is a highly complex problem, involving the control of many key process variables, such as the barrel melt temperature. The melt temperature in the injection molding process directly affects the quality of the molded plastic product. With increasing demands for better quality plastic products, accurate control of the barrel melt temperature is important.

The barrel of the injection molding machine is divided into several constant temperature zones and controlled. The injection molding process is a periodic dynamic process which includes the clamping mold phase, the filling phase, the holding phase, plastication and the cooling phase and the opening mold phase. The melt polymer is fed into the barrel from the hopper in the plastication phase and is pushed forward by a powerful screw in the injection phase. While passing through the barrel, the raw polymer is gradually heated. The melt temperature is controlled indirectly by heating the barrel. The melt temperature is strongly influenced by many injection process variables, such as barrel heating, polymer type, melt rate, nozzle and cavity pressure, and the cooling time. Because of temperature conductivity, each temperature zone has strong coupling with adjacent temperature zones. All temperature objects have time delay characteristics, so the melt temperature object in the injection molding machine is a strong coupling, time delay, and nonlinear object. Accurate control of the melt temperature is difficult. When the injection molding machine is not in periodic operation, the barrel melt temperature control is called static control. When the injection molding machine is in periodic operation, the barrel melt temperature control is called the dynamic control. The melt temperature dynamic control is more difficult than the static control because of raw polymer passing through the barrel during the filling phase.

Gomes et al. [1] controlled each individual zone using a standalone proportional-integral-derivative (PID) controller. However, PID control led to big temperature overshoots and oscillations. Other advanced control methods are used to control the barrel temperature, for example, Taur et al. [2] employed fuzzy PID control to control the melt temperature and obtained a better control performance than PID control. Dubay et al. [3] used model predictive control (MPC), Wang et al. [4] used multivariate decoupling control and Su and Tsai [5] used variable structure control (VSC). All these methods showed effectiveness in barrel temperature static control process, but fewer dynamic process effects were considered. Because of raw polymer passing through the barrel during the filling phase, barrel melt dynamic control is more difficult than static control.

VSC has the advantage that the sliding mode has strong robustness to system disturbance and system perturbations. Hung et al. [6] and Gao and Hung [7] concluded that VSC is convenient for carrying out the decoupling by a properly designed sliding mode. In this paper, VSC and the learning control strategy are combined to control barrel melt temperature during the dynamic process of the injection molding machine.

2. Experiment platform and mathematical modeling

A reciprocating screw injection molding machine, manufactured by China HAITIAN (Ningbo, China), with model MA600/150-J5, was used in this research. The major machine specifications are listed in Table 1. The barrel is divided into four zones; each zone has a thermocouple and a heating filaments. Heating filaments powers are 200 W, 2200 W, 1100

Table 1 Major machine specifications.

Machine model	MA600/J5
Shot weight (for PS)	80 g
Swept volume	88 cm^3
Screw diameter	30 mm
Screw L/D ratio	21
Maximum injection pressure	177 MPa
Screw speed range	0–260 rpm
Maximum claping force	600 KN
Hydraulic supply pump capacity	8.4 g/s
Electric motor	7.5 kw
Machine weight (dry)	2.5 ton

Figure 2 Molded part from experiment.

W and 1600 W, respectively. The experiment platform and molding part are shown in Figures 1 and 2.

In order to obtain a mathematic model of barrel melt temperature object in the static control process, the response data of the object are needed. We use the step response method to obtain melt temperature object response data, and the system modeling method can be used to acquire the barrel melt temperature object model.

The manual mode of the injection molding machine controller was used to carry out step response experiments. One zone of barrel was heated while others were not heated and all zones of barrel temperatures were sampled. We obtained four response figures that had 16 response curves (Figure 3A, B, C and D are response curves of zones 1–4, respectively). Model Reduction was handled to these curves. By means of model identification, one separate zone temperature object can be described as a first-order time delay object. This is shown by:

$$G(s)=\frac{T(s)}{u(s)}=\frac{Ke^{-\tau s}}{K_t S+1} \tag{1}$$

where T=temperature, U=output, τ=system time delay constant, K_t=system time constant and K=proportion constant.

The least square method was used to fit curves obtained from the experiments. From the above curves, origin zone barrel melt temperature transfer function and adjacent zones coupling transfer functions were obtained. From 16 curves,

Figure 1 Injection molding experiment platform.

the four zones barrel melt temperature object transfer function matrix is listed as follows [8].

$$G(s)=\begin{bmatrix} \frac{12.2e^{-20s}}{285s+1} & \frac{6.24e^{-127s}}{142s+1} & \frac{5.8e^{-218s}}{681s+1} & \frac{5.2e^{-212s}}{764s+1} \\ \frac{8.1e^{-120s}}{2192s+1} & \frac{10.8e^{-101s}}{2742s+1} & \frac{8.1e^{-144s}}{2433s+1} & \frac{5.1e^{-208s}}{2422s+1} \\ \frac{4.4e^{-186s}}{2672s+1} & \frac{4.87e^{-161s}}{2559s+1} & \frac{9.89e^{-62s}}{2435s+1} & \frac{6e^{-148s}}{2292s+1} \\ \frac{3.5e^{-264s}}{2568s+1} & \frac{3.49e^{-211s}}{2495s+1} & \frac{7.5e^{-148s}}{2332s+1} & \frac{6.37e^{-114s}}{2812s+1} \end{bmatrix} \tag{2}$$

From the above transfer function matrix, it is concluded that barrel melt temperature control object is a strong coupling, longtime delay, and nonlinear system. This kind of object is a puzzle in control engineering application [9–13]. The biggest delay time constant is 264 s and coupling characteristics are strong, so precise control of the melt temperature is difficult.

3. Temperature dynamic effect on molded part quality

The above experiment platform (Figure 1) is used in this research work. The molding cycle time is about 22 s. The PID control method is used to test the melt temperature dynamic control results and its effect on molding part quality. It is known that temperature cycling oscillation, caused by raw polymer passing through the barrel during the dynamic injection process of the injection molding machine, results in fluctuations of part weight and dimensions due to changes in melt density and viscosity. It is also known that the nozzle temperature, being closest to the mold cavity, has the largest effect on the molded part.

Temperature dynamic control experiments using the PID control method were executed. Zone 1 (nozzle zone) temperature data were sampled and the corresponding molded parts masses were measured. The results are shown in Figure 4.

The importance of precise temperature control in every temperature zone is illustrated in Figure 4, where a strong correlation of part mass and temperature is evident.

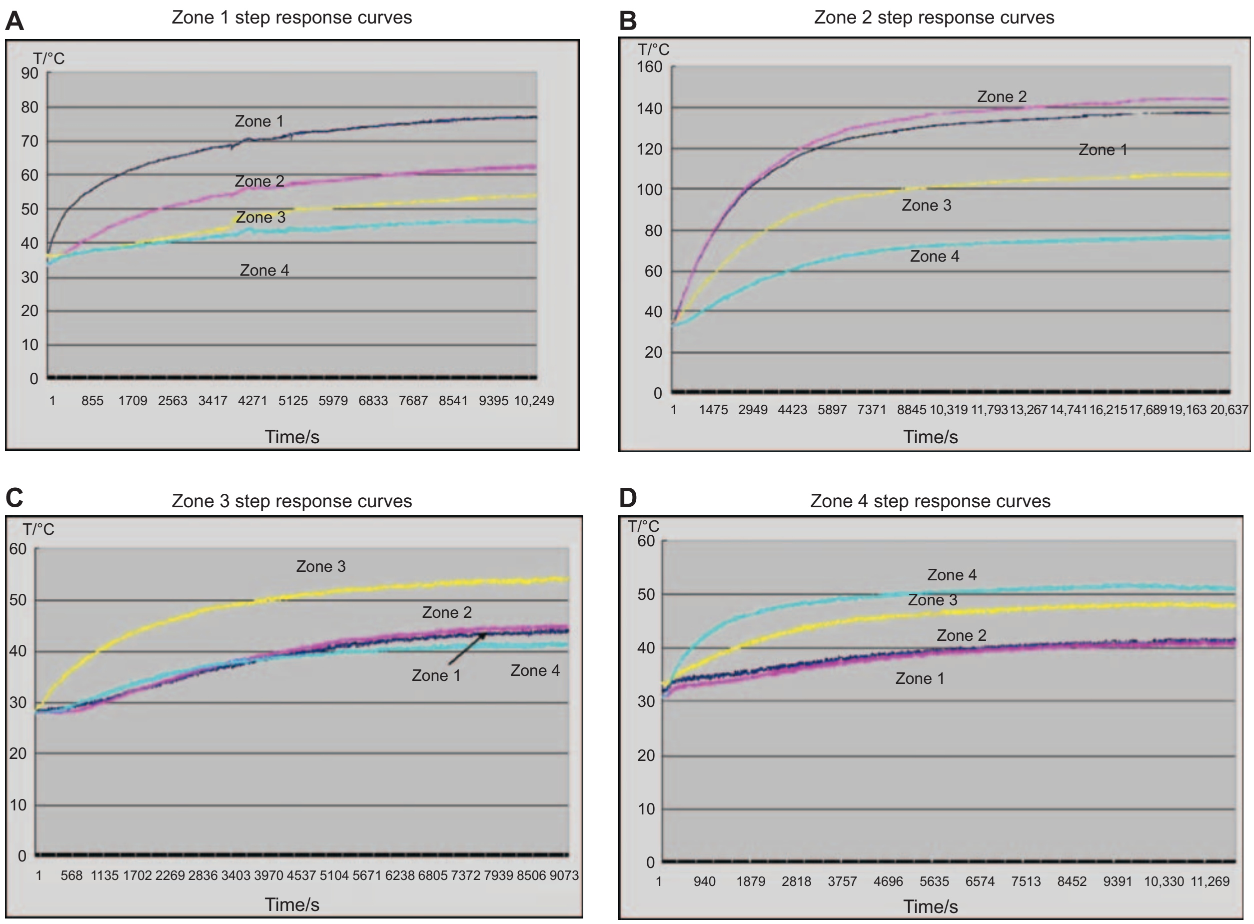

Figure 3 Step response curves.

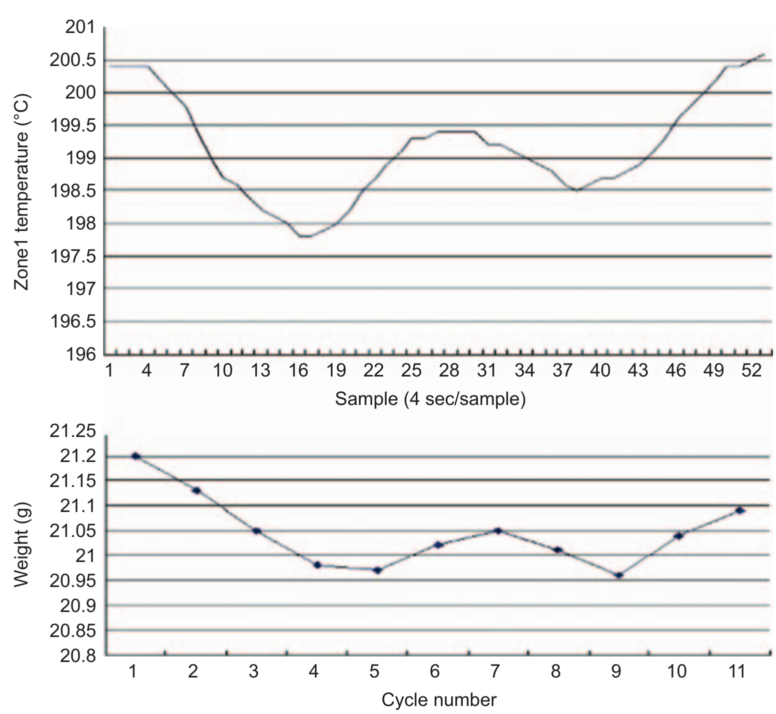

Figure 4 Dynamic temperature and corresponding part weight using PID control.

Because of the temperature object's time delay characteristic and the poor heat transmissibility of the polymer, the injection cycle does not directly correspond to temperature oscillation and part mass change. Statistical analysis from the above experiment shows that the effect of the injection cycle takes four cycles to reach the temperature oscillation and part mass.

4. Dynamic control strategy of melt temperature

4.1. Feedback variable structure control

Consider the single-zone temperature dynamic model as shown in Eq. (1). Each zone decoupling is treated as a disturbance to this zone. First-order object is used to simplify the time delay object. $e^{-\tau s}$ Therefore, the model in the transfer function matrix Eq. (2) is transformed as follows:

$$G(s)=\text{Diag}\left\{\frac{K_1}{(K_{t1}s+1)(\tau_1 s+1)},\frac{K_2}{(K_{t2}s+1)(\tau_2 s+1)},\frac{K_3}{(K_{t3}s+1)(\tau_3 s+1)},\frac{K_4}{(K_{t4}s+1)(\tau_4 s+1)}\right\} \quad (3)$$

Uncertainty parameters of above the melt temperature model can be represented as follows: $\dot{X}=(A+\Delta A)X+Bu+DT_L$, $Y=CX$, $E=Y_r-Y$, where Y is system output, Y_r is set temperature and E is temperature tracking error.

The dynamic sliding surface can be designed as follows [5]:

$$s=\ddot{e}+P\dot{e}+Ie \quad (4)$$

where s=sliding surface, $e=y_r-y$, P and I are constants and $P>0$, $I>0$. As long as $P>0$ and $I>0$, the sliding motion on the surface (4) will guarantee asymptotic stability. The switching control law is as follows:

$$u_{vsc}=\begin{cases}u^+, & s>0\\ u^-, & s<0\end{cases} \quad (5)$$

4.2. Iterative learning control

A learning control strategy should be introduced in order to overcome dynamic disturbance of the filling phase. Because the injection molding process is a periodic process, iterative learning control (ILC) can be used to overcome the disturbance of the filling phase. A proportional-derivative (PD), type ILC is used here.

$$u_{ilc}=u_{k+1}(t)=u_k(t)+K_p e_k(t)+K_d \dot{e}_k(t) \quad (6)$$

The disturbance is generated by the filling phase. The injection molding machine controller will know when the filling phase is beginning. Therefore, with feedforward of ILC, the oscillation amplitude of the melt temperature dynamic control will decrease.

4.3. Combined dynamic control strategy of melt temperature

The combined VSC and ILC dynamic control strategy of the melt temperature is shown in Figure 5. The control output is as follows:

$$u=u_{vsc}+u_{ilc} \quad (7)$$

VSC control can guarantee the control accuracy in an idle state and dynamic stability in the dynamic process of the injection molding machine, while ILC can *learn* dynamic disturbance of filling phase and improve dynamic control accuracy of the melt temperature.

5. Experimental results

The above control strategy of the melt temperature is implemented in the controller of the experiment platform based on digital signal processor (DSP), to test the control performance. VSC and ILC controller parameters are turned in simulation to qualitatively provide a reasonable start for later experimental investigation. The type of resin used for the experiments was polypropylene (PP). All zone temperatures are sampled by a k-type thermocouple. The sampling period is 4 s and the injection molding machine automatic operation period is about 22 s. The control results presented here are for zone 1 (nozzle zone) and zone set temperature is 200°C. At the same time, the corresponding molded part mass is measured. After 10 cycles, the melt temperature dynamic control achieved the desired precision. Results of the experiment are shown in Figure 6.

Statistical analysis of the results in Figures 3 and 6 are listed in Table 2. They show that the barrel temperature dynamic control error is <±0.4°C and the molded part mass repeat accuracy improved from 0.73% to 0.23%. Results indicated that the proposed method has better temperature control accuracy and weight repeat accuracy of molded parts than PID feedback control.

The type of resin used for the experiments in Figure 6 was PP. Polyvinyl chloride (PVC) is another polymer used in the plastic industry. In order to further verify the performance of the proposed control method, PVC was used in another experiment and the mold was the same as in Figure 6. The processing temperature of PVC is lower than the processing

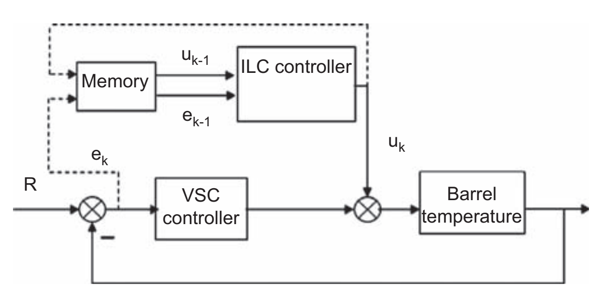

Figure 5 Combined dynamic control strategy of melt temperature.

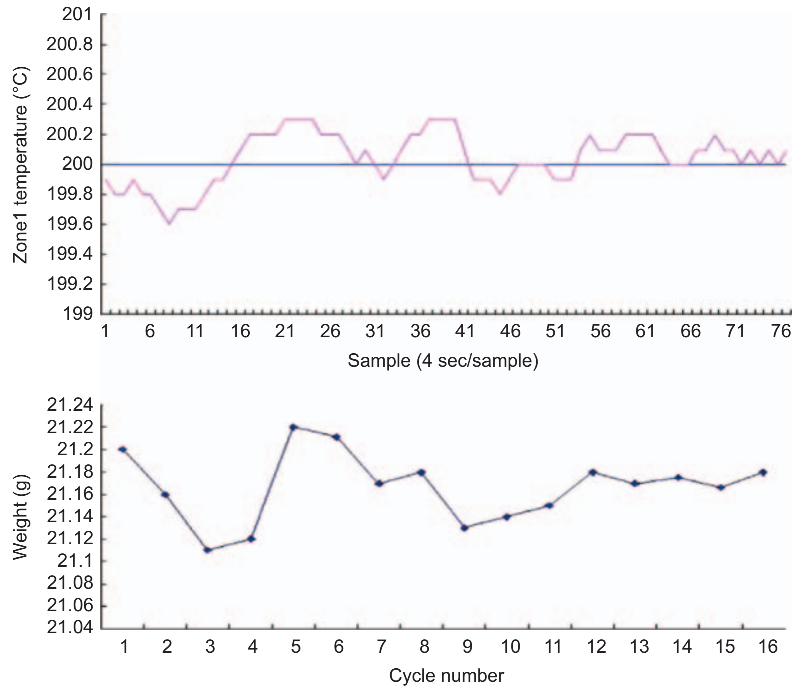

Figure 6 Dynamic temperature and corresponding part weight using proposed control strategy using PP.

Table 2 Experiment Statistical results.

	PID in Figure 3	Proposed method
Maximum error (temperature)	2.2°C	0.4°C
Mean (weight)	21.0464 g	21.1713 g
Standard (weight)	0.0723 g	0.0309 g
Maximum (weight)	21.2 g	21.22 g
Mass repeat accuracy	0.73%	0.23%

temperature of PP, so the barrel temperature of zone one in this experiment is set as 190°C. The experiment results are shown in Figure 7.

From the results and in Figure 7, it is seen that the temperature dynamic control error of zone 1 is <0.6°C and this becomes smaller after several operation cycles. Correspondingly, from statistical analysis of the experiment results in Figure 7, the average mass of the molded parts is 28.2057 g and the molded part mass repeat accuracy is

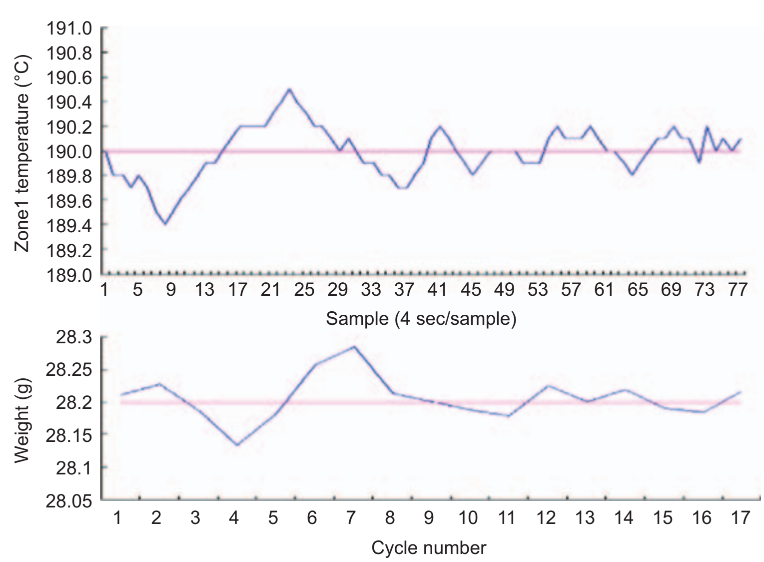

Figure 7 Experiment results using PVC.

0.28%. Therefore, these results verify the effectiveness of the proposed control method again.

6. Conclusions

The paper presents a dynamic control strategy for barrel melt temperature control of the injection molding process based on VSC and ILC. VSC can satisfy static control demand of the melt temperature and ILC is used to learn about and overcome the dynamic effect of the filling phase of the injection molding process. This control strategy is implemented in designed injection molding machine controllers based on DSP. The results in the experiment platform show that the control strategy presented can achieve satisfactory control precision and is efficient in barrel melt temperature control of the injection molding machine.

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