SETTING OF INJECTION VELOCITY PROFILE VIA AN ITERATIVE LEARNING CONTROL APPROACH

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Abstract: Injection velocity is an important variable that affects the quality of injection molded products. Profiling the injection velocity to keep a constant melt-front-velocity inside the mold throughout the filling to ensure a uniform part is the purpose of this work. Based on a transducer designed in a previous work, the melt-front-position is measured online. An iterative learning control system, designed as the outer loop controller in a cascade fashion, is used to solve the optimization problem of setting the injection velocity profile. Experiments show that proposed system works well in ensuring a uniform melt-front-velocity when filling molds with varying geometrical shapes, without the necessity of a physically-based process model.

Keywords: Injection molding, velocity control, cascade control, iterative learning control, product quality.

1. INTRODUCTION

Injection molding, an important cyclic polymer processing technique, transforms plastic granules into various types of products ranging from simple toys to DVD diskettes and precision lens. A injection molding process typically consists of three stages, injection of molten plastic into mold cavity (filling), packing of the material under a high pressure over a given period (packing-holding), and cooling of the polymer until it is sufficiently rigid for ejection (cooling). Filling is the first stage of the process during which the materials are forced into the mold cavity through the nozzle by the screw forward motion.

Continuous development of the molding industry finds ever-expanding applications of injection molded parts, resulting in demands for rapid production of complex parts with tight precision and superior finish. The quality of the injection molded part, typically characterized in terms of its dimensions, appearance and mechanical properties, is a strong function of the processing conditions, particularly injection velocity during the filling phase. Studies have confirmed the importance of proper setting and control of injection velocity (Johnnaber, 1985, Cox and Mentzer, 1986, Boldizar et al. 1990, and Chiu and Hsieh, 1991). Accurate control of injection velocity, to precisely follow a given velocity profile has been achieved via advanced process control strategies, for examples, by the authors (Yang and Gao, 2000 and Li et al., 2001). For a given mold and material, however, how the injection velocity should be profiled to produce the 'optimal' quality part is yet unknown. It must be clarified that the injection velocity is the velocity of the screw forward motion, which is different from the melt-front-velocity inside the mold. A schematic illustration of the mold filling is shown in Figure 1, where *IV* is the screw injection velocity, V_m the melt-front-velocity in the mold, A_b the cross-section area of the barrel, and A_{mf} the corresponding melt-front-area inside the mold. It is clear that the melt-front-velocity is greatly influenced by the mold geometry. Researchers in injection molding area (Hunkar, 1975, Fritch, 1979, Schmidt and Maxam, 1993, Turng et al., 1995, and Rowland and Gao, 1994) have all

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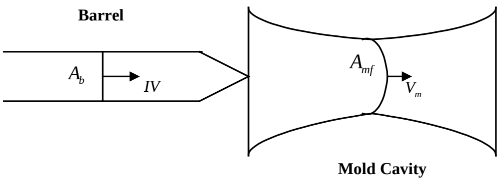


Figure 1 Schematic of mold filling

recommended that a constant melt-front-velocity during mold cavity filling should be used to profile injection velocity, to minimize non-uniformity within the molded part. This, however, cannot be implemented due to the lack of a practical melt-front flow rate measurement method.

Recently, a patented transducer has been developed to measure melt front position (MFP) during mold filling by Gao and Chen (Chen, 2002). The sensor output is linear to the melt-flow-front position within the mold. As melt-front-velocity is, simply, the derivative of the MFP, with such a transducer, the constant melt-front-velocity strategy can be translated to control the MFP to follow a constant ramp profile, as illustrated in Figure 2, where a cascade control is adopted. Consisting of two control loops, an inner injection velocity control loop that has been developed in the previous works, and an outer control loop that determines the injection velocity for the inner velocity controller. The ramp rate is the melt-front-velocity. Many existing control designs may be used for the outer loop controller, but they all require the development of a dynamic model relating injection velocity to MFP. Effort of establishing such a model based on the fundamental principles is tremendous, where the mold geometry factors and the complicated flow and material properties have to be involved. The development of such a model based on identification is inappropriate either, as this identified model will be mold dependent.

In view of the cyclic nature of the process, a model-free iterative learning control (ILC) method (detailed survey of ILC can be found in Moore and Xu (2000)) is explored here to control the MFP without having to develop a detailed process model. The ILC, which is simple in control formulation, has found many applications for cases where detailed process knowledge is unavailable. In such a control system, information of last cycle is used to improve the control of the current cycle. The controller can be removed after a number of cycles when a proper consistent profile has been obtained for the inner velocity control loop.

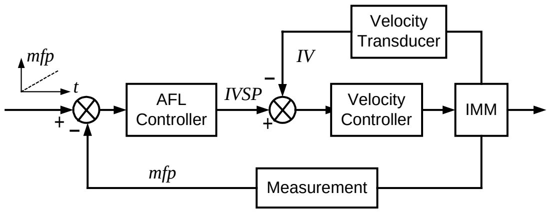


Figure 2 Block diagram of the cascade melt-flow-velocity control system

2. ILC BACKGROUND

ILC, motivated to mimic human learning process, is originally developed for the manipulation of industrial robots, in which it is required to repeat a given task with high precision. By using the repetitive nature of the processes, ILC progressively and iteratively improves the control accuracy cycle by cycle (Arimoto *et al.*, 1984). Recently, ILC has been applied to many repetitive processes, such as batch reactor, batch distillation, and injection molding (Havlicsek and Alleyne, 1999, and Gao *et al.*, 2002). In this work, the ILC approach is adopted to find a proper injection velocity profile to ensure the filling of mold cavity at a uniform melt-front-velocity.

Among many types of learning control laws proposed, a P-type learning control law is possibly the simplest, as formulated below:

$$u_{i+1}(t) = u_i(t) + L_P e_i(t) \qquad (1)$$

where $u(t)$ is the process input at time t, $e = y_s - y_m$ is the error between the output set point and real measurement; subscripts i and $i+1$ denote the cycle number and L_P is the ILC gain. It is clear that the control of the current cycle is based on the process input and the error of the last cycle in a point-to-point manner. Up to now, most of the ILC results are for the systems without time-delay. However, for many batch chemical processes such as injection molding, the effects of time delay cannot be ignored. There is a large delay between the injection velocity and the melt-front-velocity response. During injection, there exist some melt between the injection screw and the melt flow front, and the polymer melt is compressible due to its complicated visco-elastic properties. Changes in the injection velocity cannot affect the melt front flow rate instantaneously. Furthermore, the melt inside the mold cavity freezes while filling. With the development of the melt flow, the frozen layer also expands in its length and thickness, and this in turn causes increases in the delay between the injection velocity and the melt front flow rate. The long process delay as well as variations of delay during filling makes it difficult to apply the simple point-to-point ILC method. To solve this problem, control law (1) can be modified to taken into consideration of the delay term:

$$u_{i+1}(t) = u_i(t) + L_P e_i(t + t_d) \qquad (2)$$

where t_d is an estimated delay time. In this equation, the control error at time $t + t_d$ is used to update the control input at time t for the next cycle. Control law of equation 2 can be applied to cases where the time delay is exactly known. For processes with an uncertain delay, there is no guarantee that this control law will be convergent.

For a system with a varying delay bounded by h, Park *et al.* (1998) proposed to hold the control input at a constant value over the duration h, resulting a modified learning control law as below:

$$\begin{aligned} &u_{k+1}(t) = u_k(mh) + \Gamma e_k(mh+dh+\xi), \\ &\forall t \in [mh, mh+h), m \in \{0,1,\ldots,M-d\} \end{aligned} \tag{3}$$

where $e_k(mh+dh+\xi) = y_d(mh+dh+\xi) - y_k(mh+dh+\xi)$, ξ is the initial remainder, $dh+\xi$ the upper limit of delay. The system divides the process time span by the size of the time delay uncertainty h. It has been shown that the convergence can be maintained by this method (Park et al., 1998). This idea is adopted by this work. Several modifications have to be made as detailed below, considering practical issues of the process.

2.1 Division of injection velocity profile

The first modification is on the division of the filling stage time span. For a given mold, a given amount of melt needs to be injected. Changes of injection velocity profile by the ILC makes the total filling time span to vary from cycle to cycle. This creates difficulties for the division of the filling time span. Furthermore, time delay is a strong function of injection velocity, a slower injection velocity results in a larger time delay. The amount of material injected into a mold can be reasonably well represented by the distance that the screw has travelled during injection, known as injection stroke. The injection stroke is therefore used to replace the time for the ILC implementation. With this change, the time delay has also been transformed into stroke delay. As can be seen in the experimental section, the use of stroke to replace time for the ILC implementation can result in a more consistent delay for the injection stage.

2.2 Change of controlled variable

This work uses the slope of the MFP instead of MFP itself, as the controlled variable. Even though the derivative of MFP can give melt-front-velocity, it also results in a low signal-to-noise ratio. The velocity is thus obtained by linear curve fitting of MFP measurements as the following equation:

$$D_m = V_m dt + D_{m0} \tag{4}$$

where D_m is the MFP, V_m is the slope of D_m, i.e. the melt-front-velocity.

2.3 Change of manipulated variable

For most molding machines, the velocity profile can only be set in a piecewise form as illustrated in Figure 3. It is desirable to use ramp profiles instead of step change profiles, as the step change injection velocity causes abrupt changes in MFP response, which is not desirable in this case. It is therefore decided to use the velocity ramp slope as the manipulated variable for the outer loop.

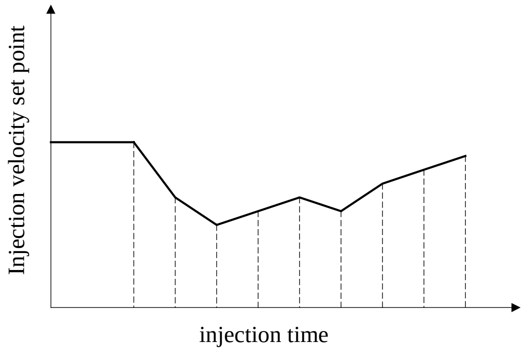


Figure 3 A typical ramp injection velocity set point profile

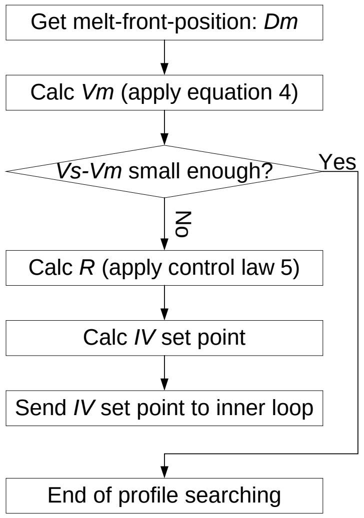


Figure 4 Flow chart of profile searching by ILC

Considering all the above practical issues with injection molding, the ILC control for searching optimal injection velocity profile can be reformulated as:

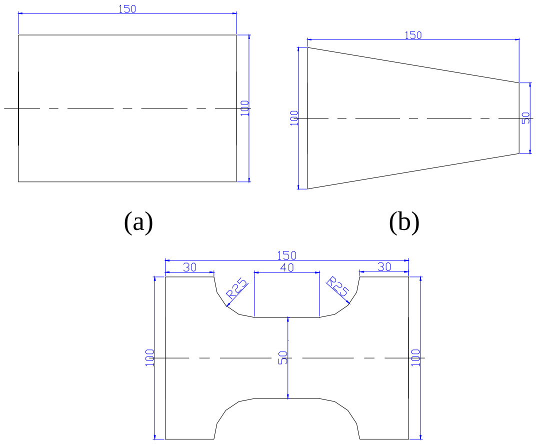
$$R_{i+1}(n) = R_i(n) + L_P e_i(n+n_d) \tag{5}$$

where $R_i(n)$ is the velocity slope at n th stroke step of the i th iteration. n_d the stroke delay, $e(n+n_d) = V_s(n+n_d) - V_m(n+n_d)$, other symbols are the same as equation 3. Figure 4 shows the overall profile searching scheme via ILC approach. The slopes of injection velocity settings are obtained by control law (5), before it is reconstructed as the real injection velocity set point for the inner loop control.

3. EXPERIMENTAL SETUP

3.1 Machine and instrumentation

The molding machine used is a Chen Hsong reciprocating screw injection molding machine, model JM88MKIII. The maximum machine clamping force is 88 ton, and the maximum shot weight is 128 g. A Temposonics series III displacement/velocity transducer, type RH-N-0200M, is installed to measure the injection displacement and velocity. An in-house designed circuit is developed to convert the MFP signal into voltage signal for measurement. The hydraulic system has been fitted with a MOOG servo valves, type J661-141, to control the injection velocity. A Pentium 133MHz PC is used as the control platform for the control of the injection molding machine. Two National Instruments data acquisition cards mounted in the PC are used to provide interface to the machine. All the programs are developed using C language under a real-time multi-task operating system, the QNX. The material used in this project is high-density polyethylene (HDPE) (SABIC Ladene).



(a) (b)

(c)

Figure 5 Geometry of molds (a) mold insert 1, (b) mold insert 2 and (c) mold insert 3

3.2 Experiment Conditions

All the experiments are conducted with the barrel front heater temperature of 200°C. Three mold inserts with significant changes in geometry are used to test the control system, as illustrated in Figure 5. The sampling period for inner-loop velocity control is 5 milliseconds. The details about adaptive control of injection velocity for the inner loop can be found in references of Yang and Gao (2000) and Li *et al.* (2001).

4. RESULTS & DISCUSSIONS

4.1 Open loop test results

The first experiment is conducted with a constant injection velocity of 25mm/s. The responses of MFP measurements for three different molds of Figure 5 are shown in Figure 6. It is clear that with a constant injection velocity, melt-front-velocity varies with the changes in mold geometry. This indicates the necessity of profiling the injection velocity. The oscillations of MFP in Figure 6 are caused by capacitance measurements.

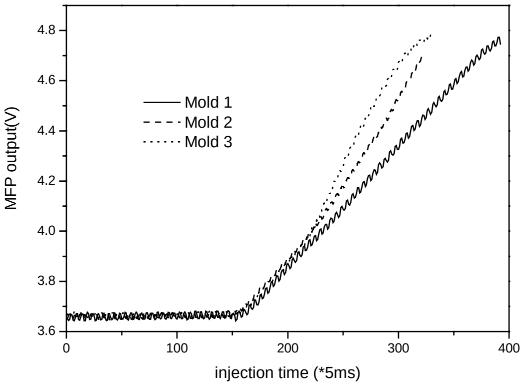


Figure 6 MFP open-loop test using different molds

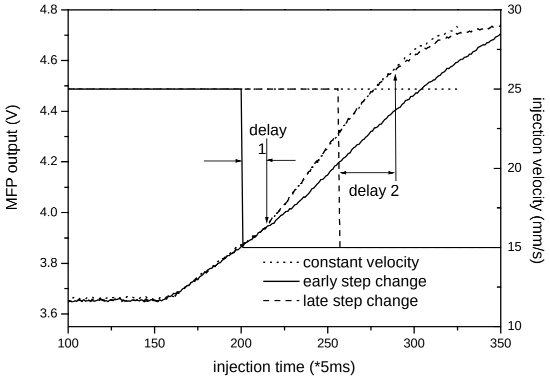
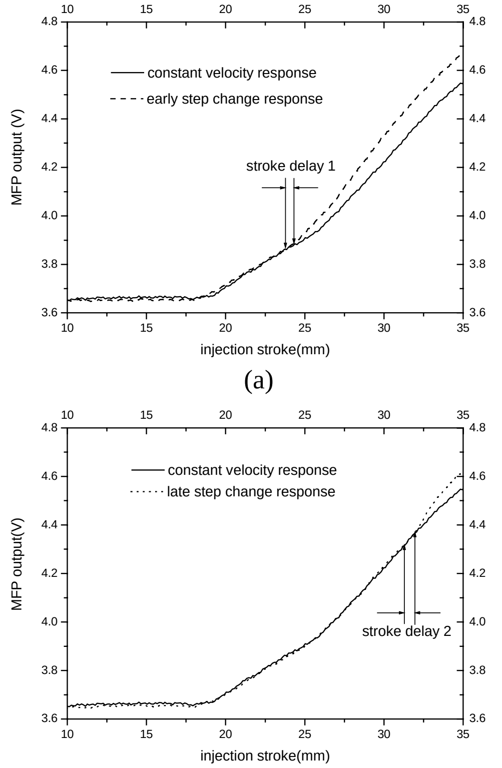


Figure 7 Illustration of the time delay variation

The second experiment is conducted with mold 3 to demonstrate the delay variation. As shown in Figure 7, the MFP responses are obtained, one with a constant injection velocity of 25mm/s (dotted line), one with a step change injection velocity profile of 25-15mm/s with the step change introduced at 1000ms injection time (solid line), and one with the same step change profile but different step time of 1275ms (dashed line). Take the MFP response of constant injection velocity as the reference, the point where the MFP measurement begin to diverse from the reference line can be considered to be the starting time of step change response, and the time difference between step change time and the starting response time is the time delay. It can be seen from Figure 7 that the late step change obviously has much larger than delay than the early step change. The time delay changes not only with the melt flow development but also with injection velocity. The measurements are treated differently by using the injection stroke as the x-axis. The results are shown in Figures 8a (early step change) and b (late step change). The delay variation



(a)

(b)

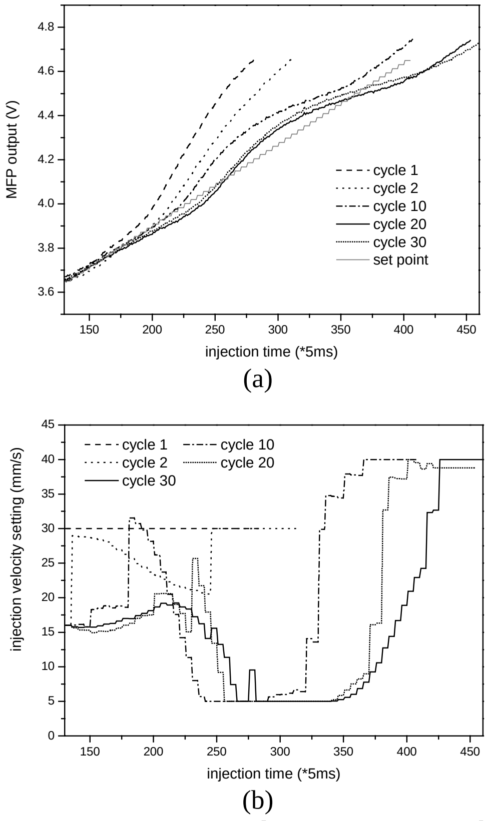
Figure 8 Illustration of delay in terms of stroke (a) delay 1: early step change and (b) delay 2: late step change in stroke shown in Figure 8 is obviously much smaller than the delay in time of Figure 7, indicating the advantage of using the stroke.

4.2 Implementation of the ILC approach

The first step in the ILC controller design is to determine the number of steps for the filling stage. Previous works suggests that five steps of velocity profile are sufficient to achieve a satisfactory constant melt-front-velocity (Chen, 2002). Considering the fact that most injection molding machine provide 10 points injection velocity setting, i.e., 9 steps of velocity profile, so, it has been decided to use 9 steps for the velocity profiling in this work. The second issue is to determine the learning gain L_P. A large gain causes strong changes in the velocity setting and faster convergence rate, while a small gain results in a smaller change of velocity profile and a slower convergence rate. L_P has been determined to be 35 for this work after trail and error. The set point for MFP slope, V_s, is selected to be 1.0 in equation 5. The stroke delay term, n_d, is determined to be one step by the above open loop test results.

4.3 ILC search results and discussions

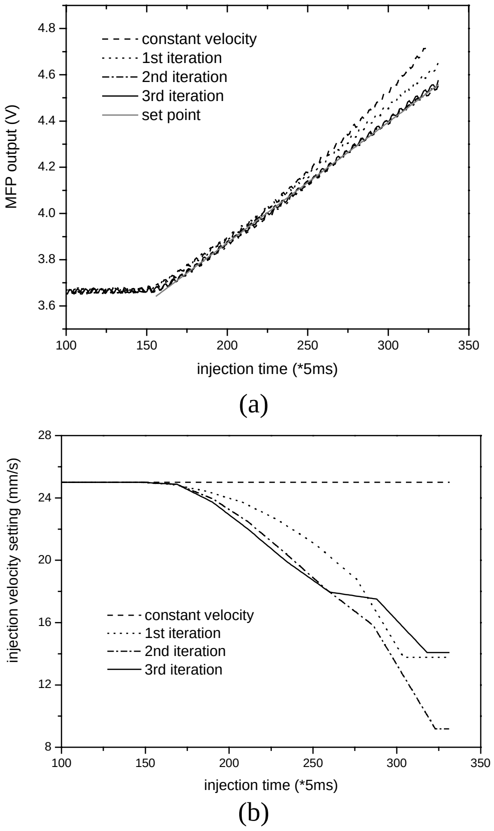
To illustrate the problem with the straight forward application of the point-to-point ILC of equation 2, experiment is conducted with the injection velocity settings directly adjusted by the error between the MFP set point and measurement. The resulted melt-front-position responses are shown in Figure 9a, with the corresponding velocity settings shown in Figure 9b. It is clear that the MFP is far from a straight line even after 30 learning cycles, indicating that the point-to-point direct learning method cannot work well. No significant improvement can be made with changes in learning rates.



(a)

(b)

Figure 9 Point-to-point direct iterative searching of the injection velocity setting (a) MFP responses and (b) corresponding velocity settings



(a)

(b)

Figure 10 Experimental test of proposed ILC searching method on mold 2: (a) MFP responses and (b) corresponding velocity settings

The proposed search method as ILC control law (5) is thus tested on mold insert 2. The injection stroke for filling this mold is 37.5mm. This stroke is divided into 9 steps as [16.50, 18.83, 21.17, 23.50, 25.83, 28.17, 30.50, 32.83, 35.17, 37.50], where 16.50 is the starting point when the melt front reaches the transducer. Figure 10a shows the measurement throughout 3 iterations of learning. The initial injection velocity is set to be a constant of 25mm/s. The corresponding MFP response, as indicated by the dashed line, accelerates due to the continuous decreasing of the mold cross-section area. After only two iterations, the third cycle’s MFP response, shown by the black solid line, overlaps well with the set point (grey solid line). The corresponding injection velocity profiles are shown in Figure 10b. Clearly, a decreasing velocity profile, as shown in the solid line of Figure 10b, can deliver a uniform filling of mold insert 2.

The mold 3 with stronger changes in the mold shape is used to test further the designed profile searching scheme. The injection stroke is divided differently as [16.5, 19.0, 21.5, 24.0, 26.5, 29.0, 31.5, 34.0, 36.5, 39.0], due to the mold change. The ILC search scheme is applied to this new mold without any other changes. Again, the initial injection velocity is set to be a constant 25 mm/s. The MFP responses are plotted Figure 11a. It is clearly shown that after three iterations, the MFP response is very close a straight line. The corresponding velocity profiles are shown in Figure 11b. Due to the delay, the velocity setting after 350 samples has no effect on the MPF response, and it was thus set to be constant as shown in Figure 11b.

5. CONCLUSIONS

The necessity of profiling the injection velocity to keep a constant melt-front-velocity throughout filling to produce uniform injection molded parts is demonstrated. An ILC is modified to search an "optimized" injection velocity profile to ensure the filling of mold cavity at a uniform rate, without the need of developing a process mold. The proposed system has been successfully applied to two molds with significant changes in geometry.

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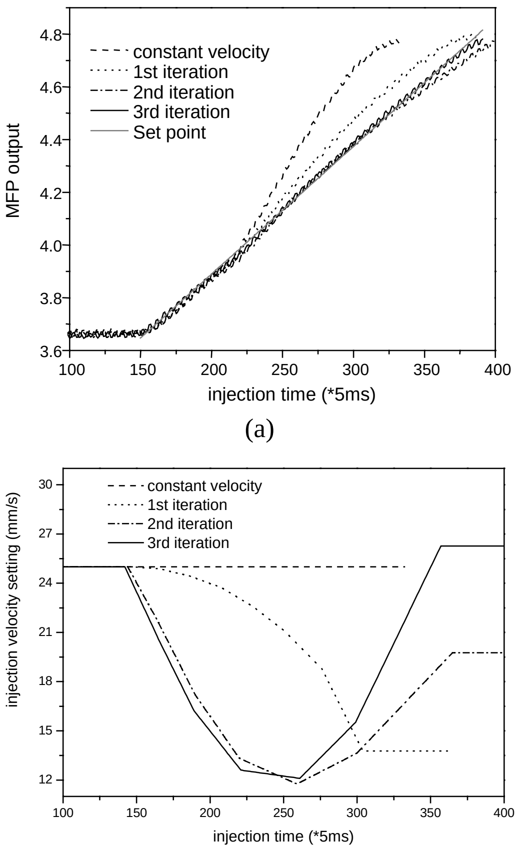

(a)

(b)

Figure 11 Experimental test of proposed ILC searching method on mold 2: (a) MFP responses and (b) corresponding velocity settings