M1-022 Control of key process parameters for improved product quality in injection molding process

Bambang Pramujati

Department of Mechanical Engineering, Faculty of Industrial Technology
Sepuluh Nopember Institute of Technology, Surabaya, 60111
Phone: +62-31-5946239, Fax: +62-31-5922941, Email: pramujati@me.its.ac.id

ABSTRACT

The quality of plastic parts produced by injection molding process is highly affected by several key process parameters. Examples of important parameters are melt and mold temperature, cavity pressure, injection velocity. Many studies both theoretical and experimental have confirmed that repeatability of those crucial parameters is essential. This paper presents closed loop control of process parameters in injection molding using predictive control algorithm. Development of system to allow closed loop control to be performed was also performed. This involved the usage of several sensors for temperature, cavity pressure as well as screw velocity.

A multi input multi output model has been developed in order to conduct barrel heater control. An accurate model incorporated all of the influences due to heat transfer of the surrounding zone was obtained using system identification technique. Therefore, good performance of melt temperature control was achieved for both simulations and experimental works. The developed model can also be used for any number of barrel zones on any injection molding machines.

Cavity pressure and cavity temperature control was performed by using coolant flow rate as the manipulated variable. Cavity pressure control was conducted during the coolant phase since it takes almost 80 % of the cycle time of the production. Dynamic matrix control which uses the model of cavity pressure during cooling explicitly was employed in this research. The results indicate that by altering the coolant flow rate, certain cavity profile can be obtained and maintained throughout the entire production process. Same manipulated variable was also be used to carry out cavity temperature control. A second order model with delay was derived to represent the relationship between the controlled and manipulated variables. Proportional and integral control was employed in this work. The overall control system demonstrated an efficient and effective cooling strategy.

Simplified predictive control (SPC) was employed to perform the screw velocity control. Velocity control becomes an uneasy task since it has many possible velocity profiles in order to obtain good products. Velocity profiling is important as it can be used to achieve a constant melt flow front velocity. A position transducer available on the machine was used as a feedback by extracting velocity information of it via high speed analog processing of the position voltage *signal. The simulations as well as experimental results indicate that SPC algorithm can effectively be used to control various injection speed profiles.*

***Keywords**: process parameters, melt temperature, mold temperature, cavity pressure, injection velocity*

1. Introduction

Nowadays, injection molding process is commonly used for producing plastic products. The popularity of this process is mainly due to its suitability for mass production as well as cost effective products. In addition, this process can be used to produce parts with intricate shapes. For precise and consistent product quality, it is very important to accurately control the key variables of the injection molding process, such as melt temperature, injection velocity, cavity pressure, cavity temperature and many others during each cycle. These above mentioned process parameters have been investigated as controlled variables for injection molding (IM) process [1]-[2][3].

Effective control of these parameters is essential in order to achieve good quality products. The control is complex due to the large number of processing variables that can influence the closed loop performance of these product quality parameters, which is further complicated by the multidimensional interactions that exist between them. Variations in melt temperature directly affect a number of process variables such as the cavity and nozzle pressure, the melt flow rate, and the part cooling time [3]-[5][6]. Therefore, the control of melt temperature is considered to be a critical factor in injection molding. Control techniques commonly used for melt temperature control are either basic on-off control or proportional, integral and derivative (PID) based method [3][5]. These control strategies are inadequate for the melt temperature control due to a lack of robustness and adaptability necessary for nonlinear and coupled parameters [7]. Gomes *et. al*. [5] reported that a large overshoot and settling time as well as substantial oscillations in the control moves were observed while implementing a PID controller. This results in thermal deterioration in the polymer and longer operator setup times.

The importance of cavity pressure monitoring and control to produce consistent good quality products by reducing variations in dimensions and physical properties has been the subject of study of many researchers [8]-[15]. Plant and Maher12 suggested that monitoring the cavity pressure profile was very important not only to ensure that the gate freeze-off time stayed constant but also to attain a minimum overall molding cycle time. A slow drop in cavity pressure upon screw retraction indicates that the gate is frozen, whereas a fast drop in pressure indicates that the molten polymer is exiting the mold.

Kamal et al. [9] investigated the dynamics of cavity pressure variation at different points during the IM process. A PI gain scheduling control strategy was applied to overcome the nonlinear characteristics of the process and resulted in improved control performance. However, implementation of gain controller scheduling requires a detailed knowledge of the process model dynamics and, therefore, it is difficult to apply this work to different molds and machines. Abu Fara et al. [10] employed an artificial neural network (ANN) to model the dynamic behavior of the cavity pressure during the filling and packing phases. Good setpoint tracking and regulating capabilities were achieved using ANN control systems.

Intelligent or learning control was employed to improve the closed loop control of cavity pressure during filling [11]. The learning controller not only resulted in greatly improved performance over that achieved using a traditional controller but also added some measure of robustness to model parameter variation. There was, however, no experimental verification of these simulated results. Macfarlane and Dubay [12] investigated the effects of varying molding conditions on cavity pressure and variations in part mass. The specific volume was found to be the most important factor affecting peak cavity pressure.

Approximately 80% of the injection molding cycle time is attributed to the cooling cycle during which the molten polymer in the cavity is cooled sufficiently for part ejection. Unlike the cavity pressure during filling and packing, which is affected by many parameters, coolant flow rate and temperature are the only manipulated variables for cavity pressure control during the cooling stage since the gate is already frozen. Gao et al. [15] developed a cavity pressure control scheme during cooling using the coolant temperature as a manipulated variable. A cooling water mixing system was designed to provide a cold, hot, or mixed water temperature by controlling the opening of electronic flow valves. However, it is impractical in the industrial environment since providing a continuous heated water supply for mixing would be very costly.

Many more researchers have investigated other important parameters to be controlled in injection molding process, such as injection velocity, cavity temperature, surface and mold temperature etc [16]-[22]. Then, it is apparent that significant progress has been made in controlling process parameters in injection molding. This paper is mainly concerned with the development of process control over several parameters namely melt temperature, injection velocity, part surface temperature and cavity pressure during cooling.

2. Experimental set-up

In order to perform closed loop control over several process parameters, the injection molding machine (IMM) has to be modified to incorporate several required transducers. The machine itself is equipped with a translational position transducer, having a DC voltage output of 0-10 VDC corresponding to 0-200 mm screw displacement. An interface between the computer and the IMM was provided by a data acquisition card (DAQ) PCI-6036E and a field screw terminal SCB68. The DAQ monitors the desired parameters throughout the molding cycle as well as provides an analog voltage signal to trigger the actuators. The coolant flow was measured using a flow meter, Omega FLMW 15, with a maximum capacity of 60L/min. This coolant flowrate can be manipulated by controlling the flow control valve ASCO PD-B06. Direct sensing cavity pressure sensors, Dynisco PT449, as well as type E thermocouples, are flush mounted in the mold cavity, one near the gate and another further away from it. The sensors form part of molding surface of the plastic product. The software used to conduct control simulation as well as real time application on the IMM is LabWindows CVI. It is a C-based programming language produced by National Instruments Co. This software was also used to develop graphical user interface to provide the functionality of process monitoring and control. Overall schematic of DAQ, transducers and other components in this research is illustrated in Fig. 1.

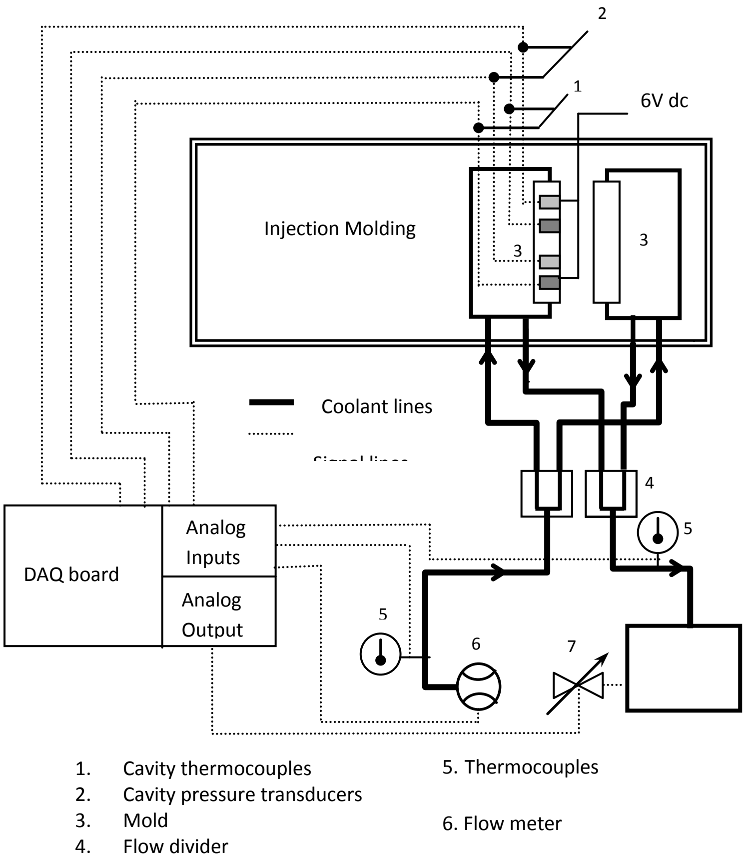

Figure 1. Overall schematic of IMM control system

3. Process control of key parameters

Melt temperature control

Barrel zones in injection molding consist of several segment of heater (zones), and hence, it is considered as a MIMO process in which interactions exist between zones. It indicates that heat transfer occurs between the barrel zones [4]. The experiment used an IMM which has 3 heater zones on its barrel. Z1, Z2 and Z3 refer to zone 1, zone 2 and zone 3, respectively. In practice, the inputs to each zone do not have direct effect on the other zones. It means that input to Z1 do not directly raise melt temperature of Z2 and Z3, Similarly, input to Z2 and Z3 are not directly sent to Z1, Z3 and Z1, Z2 respectively. This is so since these inputs go to their respective zones. However, a MIMO process model can be derived to show the direct effect of the inputs to each zones, and the indirect effect of these inputs to other zones. As shown in Fig. 2, the input to Z2 and Z3 do not directly affect the transfer function G1, but it goes through other transfer functions

G21 and G31, and therefore this additional heat is added to the output of G1 resulting in the melt temperature Z1.

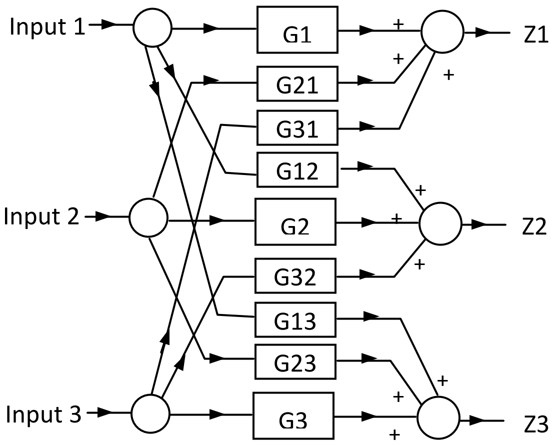

Figure 2. MIMO model for melt temperature control

Using linear time difference modeling, the temperature of zone 1 at any instant, Tz1, can be expressed as:

$$Tz1 = y_{G1}(t) + y_{G21}(t) + y_{G31}(t) \qquad (1)$$

Likewise, Tz2 and Tz2 can be expressed as

$$Tz2 = y_{G2}(t) + y_{G12}(t) + y_{G32}(t) \qquad (2)$$

$$Tz3 = y_{G3}(t) + y_{G13}(t) + y_{G23}(t) \qquad (3)$$

where:

T_{Z1} = temperature of zone 1
Y_{G1} = output of zones 1 due to heater 1
Y_{G21} = output of zones 1 due to heater 2
Y_{G31} = output of zones 1 due to heater 3
likewise for all other parameters.

Using the developed model, control simulation was performed prior to real time applications of melt temperature control. A predictive controller was used as the controller algorithm. It utilized the MIMO model explicitly to calculate the optimized control moves in order to achieve the *best* control performance. Readers interested on the predictive control theory shall visit related literatures [23]-**Error! Reference source not found.**. The real time application of melt temperature control was conducted after the successful of the control simulation of it, and the result is illustrated in Fig. 3. The setpoint temperature of zone 2 was initially set to 250°C and changed to 300°C. Zones 1 and 3 setpoint temperatures were set to 220°C and 180°C, respectively. The results indicate that the increase in the setpoint temperature of zone 2 affected mildly the temperature of zones 1 and 3. The melt temperatures of these zones were quickly returned to its corresponding setpoint values. This quick return and mild effect were due to the better modeling and use of this MIMO model. It is important for the industry to get the desired temperature in a shortest possible time within a specified control performance so that the set up time could be reduced. Besides, the stability of the controlled process has to be maintained to avoid excessive temperature oscillations, which can degrade the polymer.

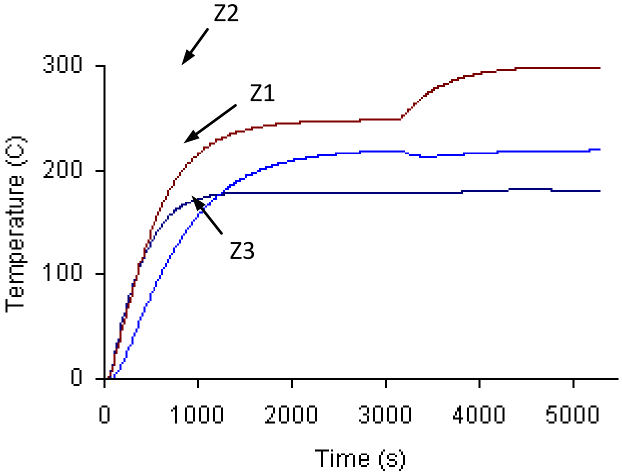

Figure 3. Melt temperature control

Injection screw velocity

Currently, IMMs have the ability to produce larger and more complicated parts and therefore, the importance of good injection velocity profiling becomes more significant for producing high precision parts. Proper injection velocity profiling specification and its accurate tracking improves the final product quality and reduces the number of rejects, and also shorten the injection time, which is a measure of productivity [21].

Predictive control algorithm was used as the algorithm in the closed loop control system. The screw position signal obtained from the available position transducer is now used as an indicator to initiate an injection velocity setpoint change. This signal was monitored and fed to the DAQ board as feedback. Reader shall visit related literatures [23]-**Error! Reference source not found.** for detailed predictive control algorithm. Unlike the original DMC algorithm, the proposed approach here used normalized multi-step open loop coefficients as the dynamic matrix. Once the desired injection velocity profile has been defined, the controller is setup such that an open loop test corresponding to the velocity setpoint profiles is performed. This can be achieved by determining and sending the required voltages to the servo-valve such that the screw injection travels with an open loop velocity as close as possible to the profiled steady state setpoint velocities.

The proposed algorithm was then implemented on a closed loop injection velocity control of IMM. Figures 4 and 5 show that good control performances were achieved for different injection velocity setpoint profiles with a stroke size of 200 mm. The solid and dashed lines represent the screw injection velocity and position at any instant time. It can be seen that the injection velocity reaches its setpoint values within approximately 0.3 s for both positive and negative setpoint changes without overshoot.

The ability of the proposed control strategy to follow various setpoint profiles well during a very short time, demonstrate that wide ranging setpoints can be specified than presently possible. This in turn would provide better control over the filling phase and therefore lead to improved product quality as well as productivity.

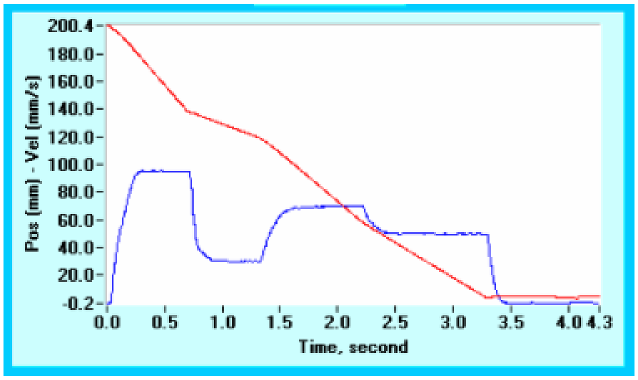

Figure 4. Closed-loop injection velocity control-setpoint 1

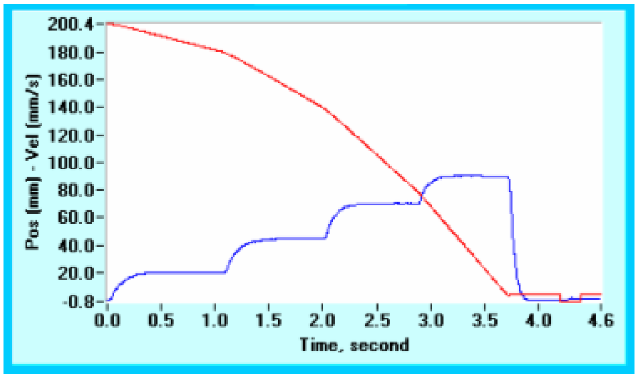

Figure 5. Closed-loop injection velocity control-setpoint 2

Part surface temperature

Part surface (cavity) temperature profiles are consistent from cycle to cycle as illustrated in Figure 6. It indicates fast increases in temperature as melting polymer is injected inside the mold, and then followed by slow cooling to a lower temperature. The product will then be ejected after the temperature reaches its ejection temperature. This rapid change in temperature causes this parameter very difficult if not impossible to be used as a controlled variable.

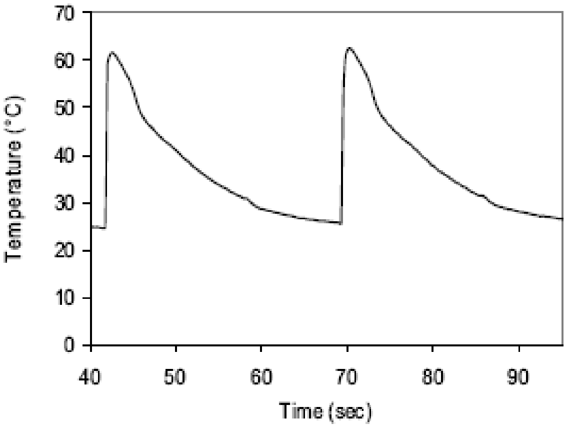

Figure 6. Cavity temperature profile every cycle

An experiment was conducted to observe the dynamic response of the part surface (cavity) temperature over two injection cycles using a constant coolant temperature and flowrate. Figure 6 shows relatively consistent temperature profiles for each cycle, having a rapid increase while the melt was injected, followed by slow cooling to a lower temperature. An initial consideration was to have the controlled variable be the part surface temperature over the injection cycle. However, from Fig. 2, the rapid changes in part surface temperature during filling makes it difficult or practically impossible to use this type of profile as a typical part temperature setpoint, especially when the setpoint may have to be changed. Using the repetitive temperature pattern characteristic, a controlled variable that does not change as rapidly as the part surface temperature can be used and is to be determined.

Let define a variable of average cycle temperature, as the temperature in the cavity from the beginning to the end of a single cycle which represents the average temperature of the part experiences inside the mold over one cycle, which can be expressed as,

$$T_{avg} = \frac{\int_0^{t_{end}} T(t)dt}{t_{cycle}} = \frac{\sum_{k=1}^{N} T(kT)}{N}$$

where t_{cycle} is the cycle time, T is the instantaneous temperature recorded at each sampling interval, and N is the total number of samples per cycle, $T(kT)$ represents the discretized form of $T(t)$. This parameter is analogous to the heat transfer inside the mold while being responsive to changes in the coolant medium.

Two most obvious parameters affecting the cavity temperature are temperature and flow rate of the coolant media [16]. Although coolant temperature is believed to have the strongest effect on the surface and mold metal temperature, the effect is the slowest as suggested by the large time constant and delay [17]. Coolant flowrate was then selected as the manipulated variable, since developing mechanism to quickly change the flow rate can be easily realized.

Proportional and integral was used during the implementation of the part surface temperature control. The controller can be expressed in discrete form as follows

$$M_N = M_{N-1} + \ k_c + \tfrac{T}{T_i} \ E_N - k_c E_{N-1} \qquad (4)$$

Figure 7 shows that good control performance with minimum overshoot and oscillation was achieved when using PI controller in cavity temperature control system.

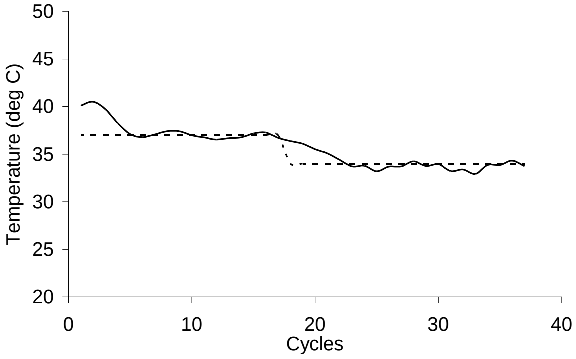

Figure 7. Cavity temperature control using PI controller

Cavity pressure during cooling stage

As mentioned earlier in the introduction, the ability to maintain cavity pressure every cycle ensures consistent good quality product [13]. Cavity pressure represents how the pressure change within the mold cavity as molten polymer entering the mold till the part is ejected. Cavity pressure during cooling is considered important since cooling stage takes up to 80% of the injection cycle.

Coolant flowrate was used as the manipulated variable and predictive controller was employed as the controller algorithm in the paper. Time constant τ which indicates the time from the end of the packing to the time at which the pressure decreases to 63.2% of the pressure at the end of packing was selected as the controlled variable since it yielded the most distinct change in response when a step input in the coolant flow rate occurred. Figure 8 illustrates the cavity pressure change due to two different coolant flow rates.

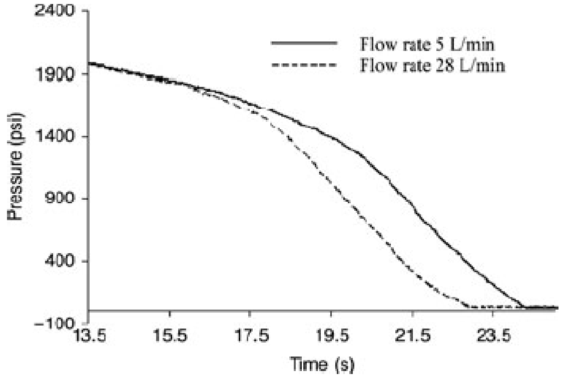

Figure 8. Cavity pressure profiles with two different coolant flow rate during cooling

Figure 9 shows closed loop cavity pressure control using τ_{sp} of 4600 ms for injection cycle 47 and 48, with τ of 4606 ms and 4601 ms respectively. This result indicates that similar peak cavity pressures lead to almost identical τ and hence the cavity pressure profiles, verifying that the controller performs well. Figure 10 illustrates that good control performance with the time constant following the desired setpoints of 6500, 5500 and 4000 ms were achieved using predictive control. The results show that the desired change of τ during cooling phase was attained.

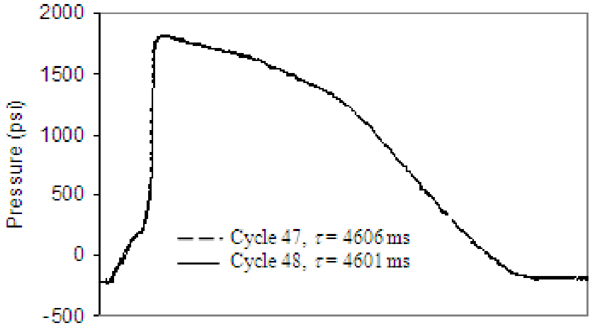

Figure 9. Cavity pressure profiles of two different cycles with comparable τ

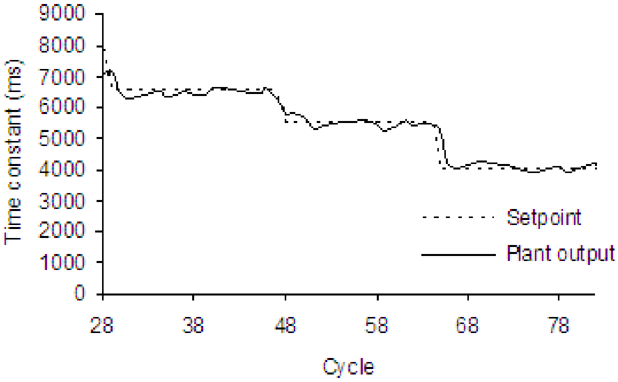

Figure 10. Real time application with various desired time constants

4. Conclusion

Several approach to control key process parameters in injection molding process were implemented with good results, which include melt temperature, injection screw velocity, part surface temperature and cavity pressure during cooling. By providing several transducers on industrial plastic injection machine, process parameters can be easily monitored and controlled, and hence can lead to improved product quality and productivity. In view of the wide use of plastics today, improvements in their manufacture would benefit not only the interested parties but society as a whole.

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