Closed loop control in injection moulding

by Tat Ming Engineering Works Ltd., May 1998, Aug 2020

1. Introduction

In an injection moulding machine, many process variables have to be controlled to assure *repeatability* of the part from shot to shot (precision). Barrel temperature, injection velocity, hold pressure, back pressure and clamping force are some such variables. Repeatability is needed in precision moulding including optical parts. *Accuracy*, closeness to the true value, is important when the settings are transferred to another machine. In some cases, the speed of response of the control mechanism is also important.

Research has shown that part weight is the single most important measure of repeatability.

1.1 Closed loop control

Closed loop control starts with the measurement of the target variable. An appropriately located transducer produces an output, usually electrical and analogue, proportional to the target variable. Closed loop control monitors the target variable and takes action to correct it when it deviates from the set value. This is so on the face of disturbances. Critical target variables are also displayed graphically, e.g. injection speed and pressure, for monitoring by the human operator.

The block diagram in Figure 1 reveals the reason for its name. Control algorithm and control action are detailed in section 7. Plant is the object to be controlled.

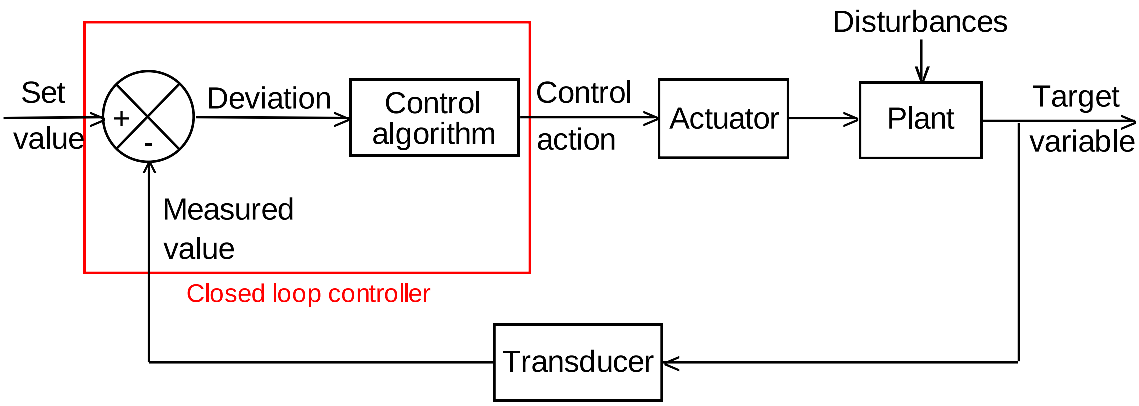


Figure 1 Closed loop control

Closed loop control can be implemented in hardware or software. In hardware closed loop control, an analogue board takes in the fed back signal *continuously* and compares it to the set value from the machine controller, computes the control action and sends it out to the actuator, e.g. a valve. The parameters for the control algorithm (See K_1, K_2 and K_3 in equation (8)) are input via potentiometers or thumbwheel switches. Tat Ming's closed loop ME55 III injection moulding machine uses hardware closed loop control.

In software closed loop control, the machine controller or a dedicated controller does the same in software, a program that the CPU (central processing unit) runs. Due to the finite sampling interval, control accuracy could be reduced. Ease of setting the control algorithm parameters is its advantage. When the machine controller is used to execute the software, there is a price advantage.

1.2 Open loop control
In open loop control, a command is given to the actuator to adjust the target variable. Whether the set value is reached is unknown as it is not monitored. Disturbances affect the target variable from attaining the set value. Disturbances are not controlled. Examples are environment temperature and moisture content of the resin. Open loop control could be adequate where precision is not required.

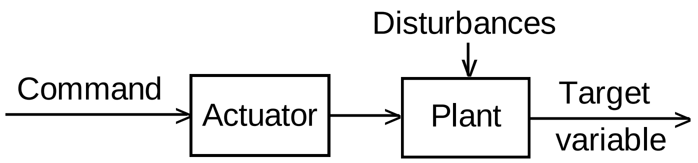


Figure 2 Open loop control

1.3 Semi-closed loop control
In semi-closed loop control, an intermediate variable related to the target variable is measured and controlled. This is done since the former is easier or cheaper to measure. In injection moulding, valve spool position is controlled in lieu of velocity control, and screw position is used to represent volumetric filling of the cavity. Disturbances outside of the loop could still affect the closeness of the target variable to the set value.

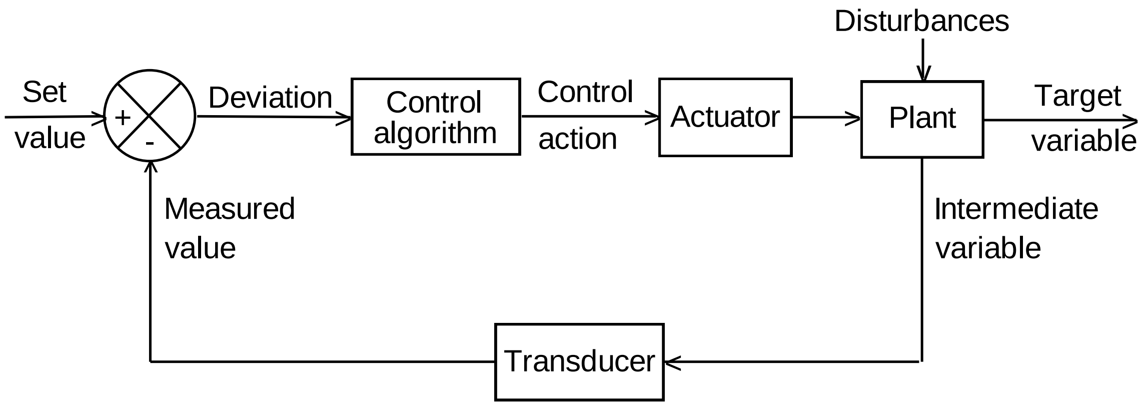


Figure 3 Semi-closed loop control

1.4 Closed loop injection moulding machine
Nowadays, barrel temperature is closed loop controlled even in an open loop injection moulding machine. A closed loop injection moulding machine refers to one in which at least the injection speed and holding pressure are closed loop controlled. More sophisticated machines also have closed loop control of back pressure, switchover, clamping force and clamp position, sometimes as options.

2. Temperature control
Temperature is probably the single most important variable to be controlled in an injection moulding machine.

Thermocouple is a popular temperature transducer. Its small size makes for fast response and easy installation. It is reasonably low in cost. The millivolt output of the thermocouple needs amplification before the signal could be used.

2.1 Barrel and nozzle temperature

While it is the temperature of the melt in the barrel that is of interest, practicality limits us to measure only barrel temperature. A thermocouple well is drilled into the barrel in which a thermocouple is inserted. The deeper is the well, the closer is the measured temperature to the melt temperature. Remember heat from shearing the melt is generated by screw rotation during plasticising. The ME55 III uses the deep well technique. However, a deep well, due to its distance from the band heaters, makes it difficult to control changes to set temperature. This is especially acute during start-up when overshoot must be avoided.

Cascade control uses two thermocouples in two wells, one shallow, one deep. The shallow thermocouple senses the temperature from the band heater fast (compared to the deep thermocouple) and helps to reduce temperature overshoot. It forms the inner loop. The deep thermocouple closes the outer loop.

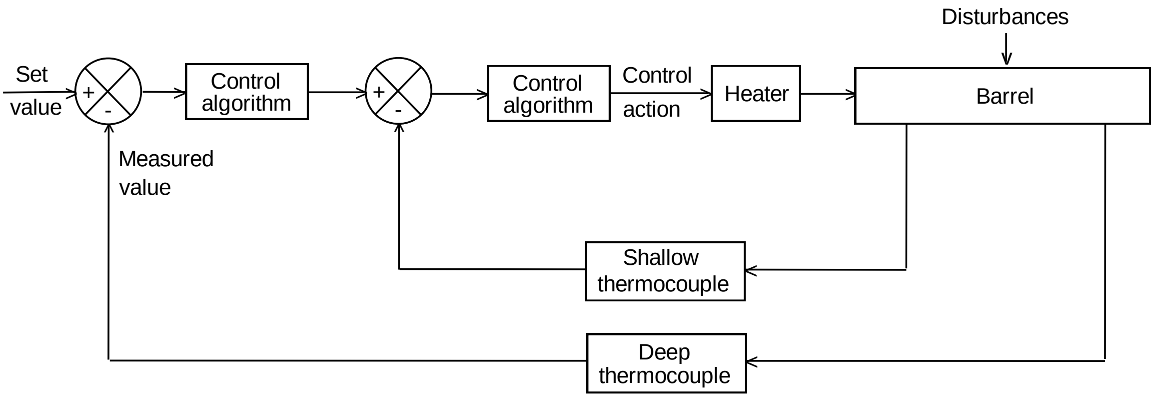


Figure 4 Cascade temperature control

For the accurate measurement of melt temperature, good contact between the well wall and the thermocouple is also essential.

2.2 Mould temperature

Mould surface temperature affects the quality, especially surface quality of the part in an important way. This includes lustre and stress. From the practical point of view, one mould temperature is used to approximate the 3-D distribution of surface temperature in the closed loop measurement.

2.3 Oil temperature

Hydraulic oil temperature should be kept below 50 °C to avoid it from degrading, and from affecting the integrity of the oil seals. Better yet, it should be held to within 2 °C so oil viscosity remains relatively constant. On-off control (see section 7.1) of the cooling water is sufficient. Oil viscosity affects oil flow rate and oil pressure. Oil temperature control is an option in the ME55 III.

3. Speed control

3.1 Injection velocity control

Second in importance only to barrel temperature control is injection velocity control during the filling stage. The constant flow front theory stipulates that the best filling is obtained when the flow front *in the cavity* moves at constant velocity. This is so despite varying mould cross section, which also affects the resistance to melt flow. A modern injection moulding machine has 5 to 10 injection stages in which different injection velocities could be specified to attain constant flow front velocity.

3.2 Proportional valve

The proportional flow valve is a device that allows a constant speed electric motor driving a fixed displacement pump to deliver 5 or more flow rates during the injection stroke. Refer to Figure 5.

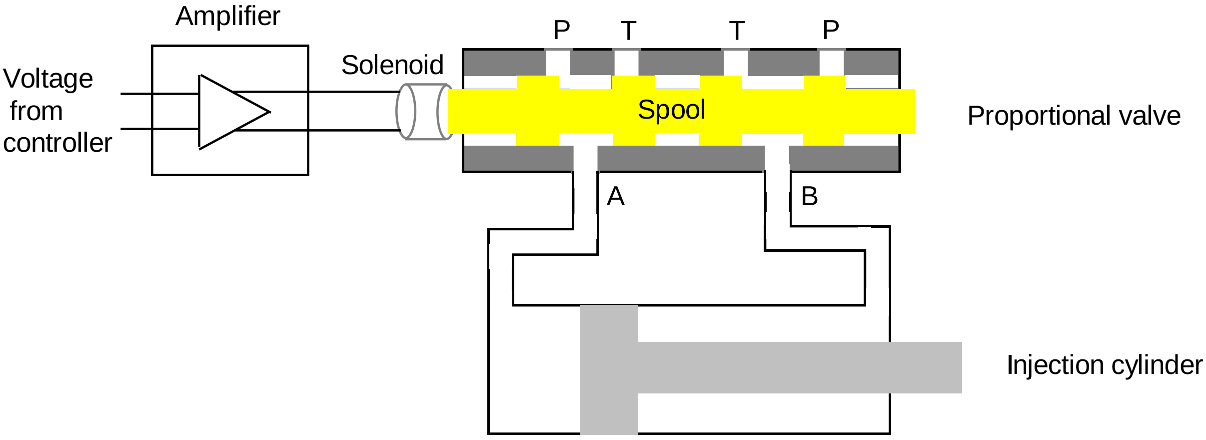


Figure 5 Proportional flow valve

The proportional valve has a spool the left and right movement of which controls the flow of hydraulic valve from P to A, and from B to T. The pump output is connected to the valve at P; the oil tank is connected at T.

The injection moulding machine controller sends a voltage to the amplifier proportional to the injection speed desired at that moment. The amplifier drives a current through the solenoid which in turns moves the spool. Since the flow rate through the valve is nearly proportional to the stroke of its spool, hence its name. As a result, the injection cylinder moves at a velocity roughly proportional to the voltage the controller sends.

Three factors affects the spool position from being proportional to the applied voltage: Hysteresis, frictional force and flow force.

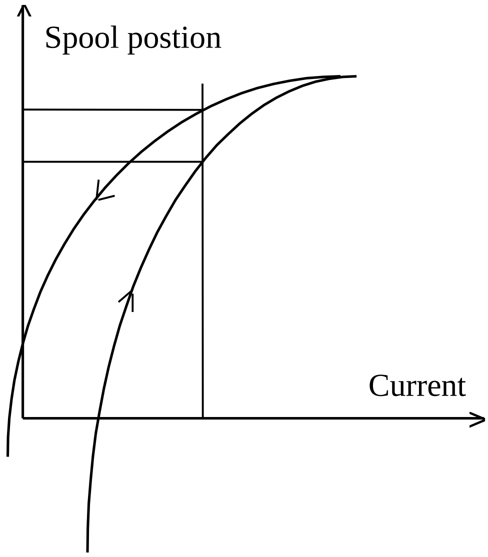


Figure 6 Hysteresis

Hysteresis is a magnetic property of the solenoid. Depending on the current increasing or decreasing, the same current does not translate to the same spool position.

Static friction prevents the spool from moving, whichever direction it is driven, until the static friction force is overcome. Once the spool starts moving, dynamic friction opposes its motion.

Flow is changed in direction through the opening at the spool. A force is generated which tends to open the spool.

If spool position could be controlled to be proportional to the applied voltage, better repeatability of flow rate could be achieved.

A proportional pressure valve controls the downstream pressure also by the spool position. The same three factors that affects spool position affect the downstream pressure repeatability.

The standard ME55 III comes with a proportional flow and a proportional pressure valve.

3.3 Semi-closed loop proportional valve

The semi-closed loop proportional valve closes the loop on spool position. All the disturbances affecting the spool from reaching its set position are nullified. Not only are the effects of hysteresis, friction and flow force eliminated, the spool position is attained much faster due to the loop. In layman’s term, the loop makes the control ‘stiffer’. Just like a sports car lover appreciates the acceleration of his/her vehicle, the high acceleration and deceleration especially of the moving platen cuts that much time from the cycle time.

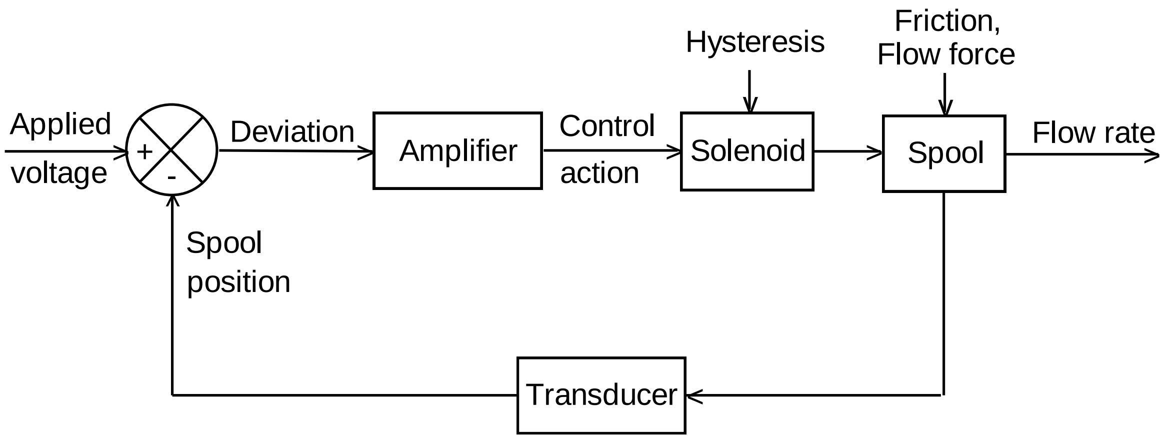


Figure 7 Semi-closed loop proportional valve

A PQ valve from Bosch is an option on the ME55 III. It is two semi-closed loop proportional valves in one housing. One controls pressure (P) out of the pump, the other controls flow (Q). Being at the outlet of the pump, it not only controls the injection pressure and velocity, but controls other pressures and velocities, e.g. mould open and mould close pressures and velocities. The PQ valve is a cost effective option to increase repeatability and ‘turbo charge your sedan’. It is highly recommended (but be advised to drive carefully).

Especially so in thin wall moulding, as the mould cools, the flow channels in the cavity solidify, increasing the melt flow resistance. Decrease in melt temperature increases the melt viscosity in a big way. Open loop and semi-closed loop control make no compensation for changes in flow resistance (disturbances) of the melt. An increased flow resistance decreases the injection velocity. Closed loop injection velocity control is essential.

3.4 The servo valve

A servo valve located on top of the injection cylinder could control injection velocity, hold pressure and back pressure. Think of the servo valve as a very precise (repeatable) and fast acting semi-closed loop proportional valve that controls the flow through the injection cylinder. When injection velocity decreases, the outer loop detects it and opens the servo valve more to restore the velocity.

A servo valve has valve spool position control built in. It forms the inner loop in Figure 8. Spool position control removes magnetic hysteresis and the effects of flow force and friction on the spool. It also improves the response speed of the valve.

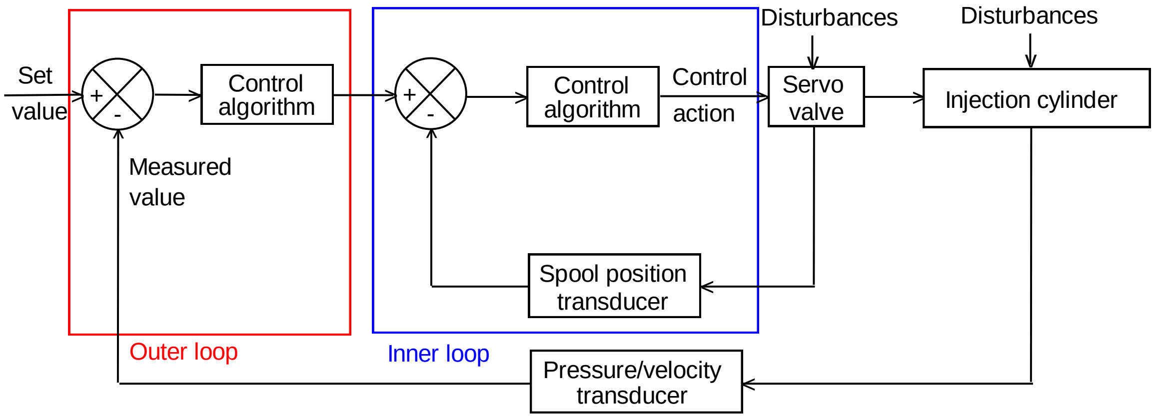


Figure 8 Closed loop control by servo valve

In pressure control, the valve opens and closes incrementally to reduce and increase respectively the pressure drop across it to control the downstream pressure.

Pressure at injection cylinder = Pump pressure - pressure drop across servo valve.

The closed loop ME55 III uses a Moog servo valve at the injection cylinder.

4. Pressure control

4.1 Hold pressure control

Once the cavity is filled, injection velocity control changes to hold pressure control. Refer to Figure 9. The hold pressure fills the cavity with melt to compensate for shrinkage during cooling. It should be profiled (lowered) against time as the cavity pressure decreases when the part shrinks. This corresponds to 4-5 in Figure 11. The same servo valve that controls injection velocity during the filling stage controls hold pressure during the holding stage. Refer to Figure 10. Hold pressure should be controlled to within 1 bar. Hold time should be controlled to within 0.05 sec.

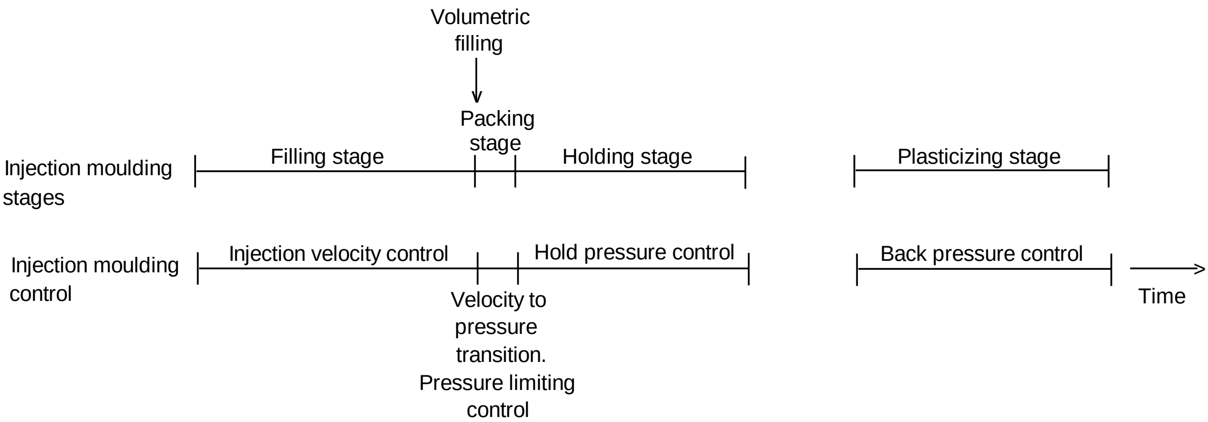


Figure 9 Injection and plasticising control

4.2 Back pressure control

Back pressure controls the tightness (density) of the melt during plasticising. A 4-way servo valve that controls injection velocity during the filling stage and controls hold pressure during the holding stage also controls back pressure during the plasticising stage. Refer to Figure 9. A 4-way valve has four hydraulic lines going into and getting out of the servo valve. Refer to Figure 10. The closed loop ME55 III uses a 4-way servo valve.

Back pressure should be controlled to within 1 bar.

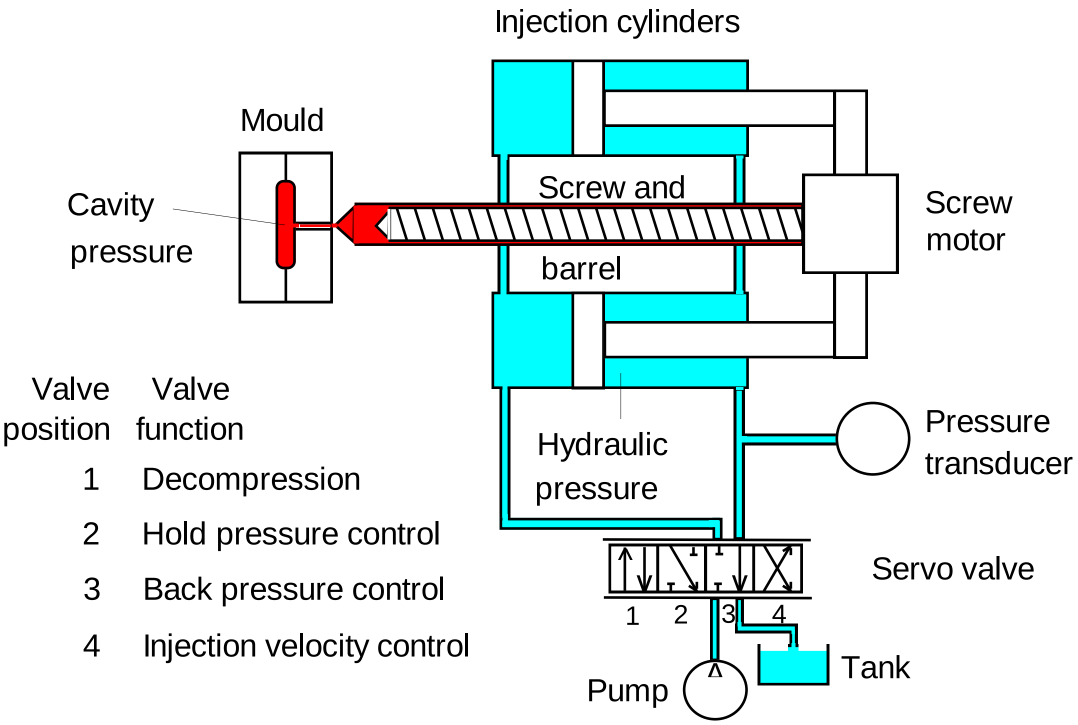


Figure 10 The injection unit

4.3 Hydraulic pressure switchover

Once the cavity is volumetrically filled, further advance of the screw packs the melt the pressure of which rises rapidly. Packing is needed to control the density of the part. To avoid overpacking, one needs to switch to holding pressure as soon as possible. In Figure 11, 1-2-3 constitutes the filling stage. At 3, volumetric filling occurs. 3-4 is the packing stage. 4-5 is the holding stage. At 5, the sprue gates solidifies, at which point the mould could open. 5-6 represents excessive cooling within the mould.

A rapid rising hydraulic pressure at the injection cylinder is a close approximation to detecting the packing stage. Detecting the hydraulic pressure rising to a certain level could be used to switch to holding pressure. According to our definition, this is only semi-closed loop control. Oil seal friction and melt viscosity limit the relationship between cavity pressure and hydraulic pressure from being proportional. The compressibility of the melt also generate a delay before the hydraulic pressure is sensed. A hydraulic pressure transducer works in a much more friendly environment than a cavity pressure transducer. It is cheaper and easier to install and is a good trade-off for the most accurate switchover method described next. The ME55 III supports hydraulic pressure switchover as an option.

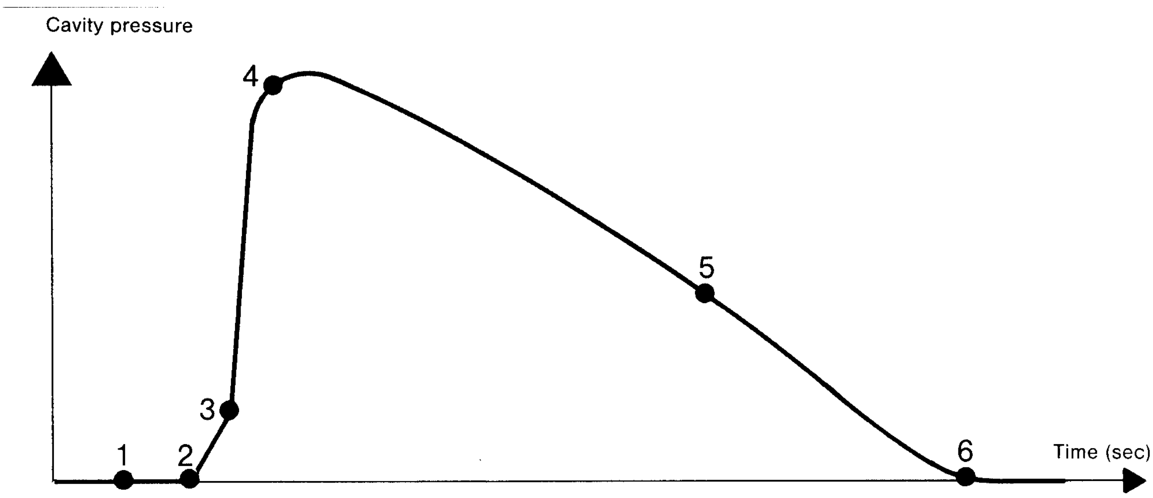


Figure 11 Ideal cavity pressure curve

4.4 Cavity pressure switchover
Located where the action is, cavity pressure measurement provides the most accurate signal for switchover to holding pressure. At point 3 of the ideal cavity pressure curve, the cavity is volumetrically filled. The switchover should take place at this moment. The switchover point is detected by sensing the cavity pressure reaching that particular level. Alternatively, an intelligent chip detects the kink in slope at 3 and signals to the machine controller. The latter method was used by Kistler's SmartAmp.

This method is limited to cases where an impression left by the transducer is tolerable. In a multicavity mould, each cavity needs to have its own cavity pressure transducer. The ME55 III supports cavity pressure switchover as an option. Both the cavity pressure level and SmartAmp detection methods are supported.

4.5 Cavity pressure control
A measure of precision is the repeatability of the cavity pressure curve. The cavity pressure curve of an ideal shot is taken. By controlling the injection speed and holding pressure, this pressure curve is mimicked in subsequent shots. In other words, instead of a profiled injection speed during filling and a profiled hold pressure during holding, the ideal cavity pressure curve is used to provide the set value. The machine computer must be capable of recording the ideal curve. Due to the rapid rise of cavity pressure in the packing stage, a fast response 4-way servo valve is needed. Unlike a 3-way valve, a 4-way valve provides acceleration and braking action. A 3-way valve depends on the resin resistance to provide the braking action.

5. Force control

5.1 Tiebar tension control
In a toggle clamped machine, it is not easy to measure clamping force using only the hydraulic pressure meter. Since all the clamping force is taken up by the tiebars, their elongation could be measured to measure the clamping force. This is done by attaching strain gauges to one or more tiebars.

If tiebar tensions are assumed even, the clamping force is four times the tension measured on one tiebar. Clamping force is adjusted during mould height adjustment. If the mould temperature increases, the clamping force is also increased. A mould height adjustment before the next injection would restore the original clamping force. As the mould cavity deforms, so are the part dimensions. A constant clamping force keeps the deformation constant.

Strain gauges at multiple tiebars has the added advantage of detecting tiebar imbalance which is the main cause of tiebar breakage.

Strain gauges attached to a platen to measure its bending under load is another way to measure clamping force.

5.2 Clamping force control

Clamping force control is simpler to implement in a hydraulic clamped machine. The pressure at the clamping cylinder is measured and it is proportional to the clamping force. On the ME55 III, closed loop clamping force control is a standard feature. Clamping force could be controlled to within 400 kgf.

In injection compression, the mould is held slightly open during injection, then the melt is compressed by the mould closing completely. This is sometimes accomplished by profiling (increasing) the clamping force as a function of time. On the ME55 III, injection compression is an option.

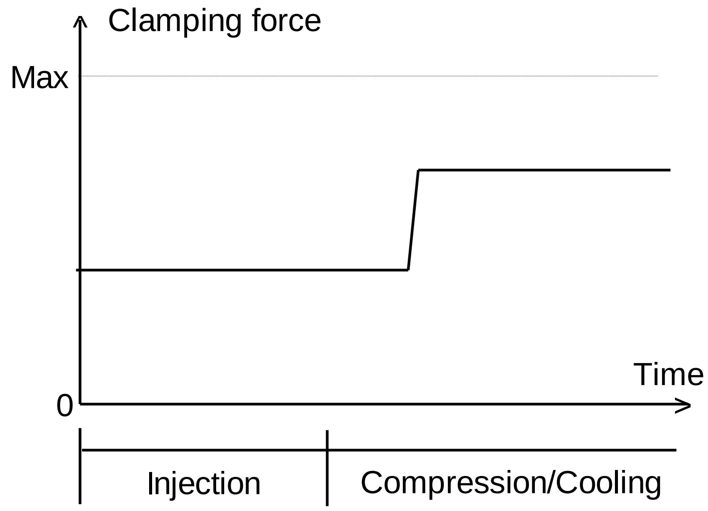


Figure 12 Profiling clamping force in injection compression

CD replication is an important application of injection compression. By opening up the mould slightly during injection, injection compression reduces the injection pressure in this thin wall application. Moulded in stress is also reduced, avoiding warping.

6. Position control

6.1 Screw position sensing

Screw position sensing is needed during filling, in locating the switchover position, in decompression and in plasticizing. Screw position control is done by the machine controller.

Two screw positions determine shot size: the end of the plasticising stroke p and the switchover position to hold pressure s. Shot weight is proportional to their difference, p - s. Their precise control is important in controlling part weight consistency. By profiling (slowing down) the injection velocity and the plasticising speed, more precise p and s could be attained.

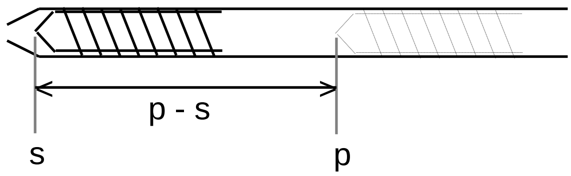


Figure 13 Screw position sensing

6.2 Clamp position control

In injection compression, the mould is held slightly open during injection. The opening is of the order of 1 mm. After injection, the melt is compressed by the mould closing completely. This is sometimes accomplished by profiling (reducing) the clamp position as a function of time.

On the ME55 III, injection compression is an option. The opening could be as big as 25 mm. The repeatability is within 0.1 mm.

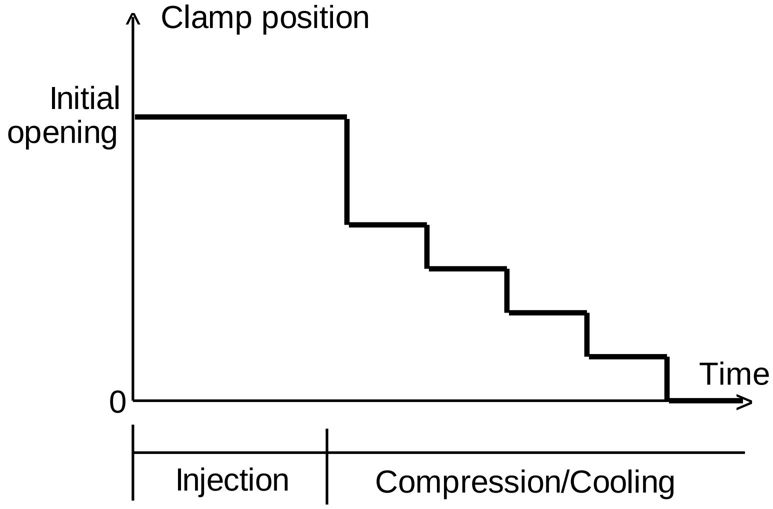


Figure 14 Profiling clamp position in injection compression

7. Control algorithm

Once a deviation e between the set value and the measured value of the target variable is detected, manipulation on e is needed to produce the control action, which e.g. controls the amount the heater is turned on or the valve is opened.

e = set value - measured value

In increasing order of sophistication, four commonly used algorithms are detailed below. The more sophisticated the control algorithm, the faster and closer to the set value is attained after a change in set value or a disturbance. The running example is barrel temperature control.

7.1 On-off control

The sign of e determines the control action. If e is positive, turn on the control action fully; if e is negative turn off the control action fully.

On-off control action = 100% if $e > 0$
0% if $e < 0$ ……………………………………………(1)

The characteristics of on-off control is persistent oscillation of the target value around the set value. In barrel temperature control, this is due to the thermal inertia of the heater, the barrel and the melt and the separation between the thermocouple and the heater.

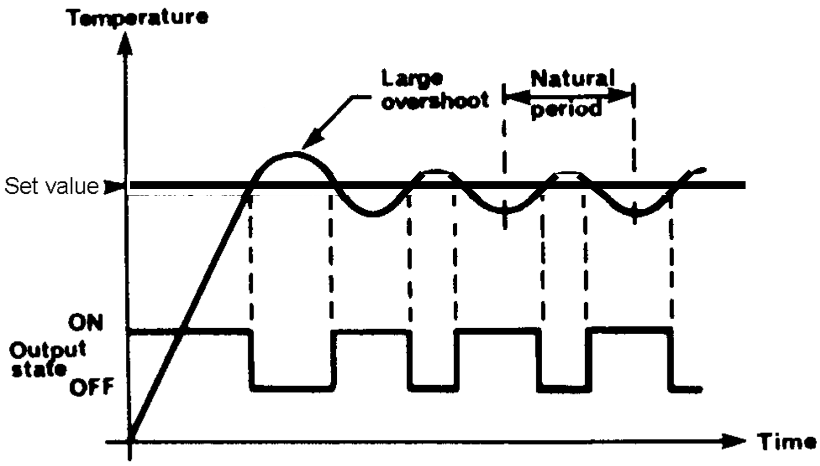


Figure 15 On-off control

7.2 Proportional (P) control

If the temperature controller could 'step on the brake' when the measured temperature approaches the set temperature from either side, the oscillation characteristic of on-off control could be reduced or eliminated. Such is the basis of proportional control.

Proportional control action = K_1 e + 50% ....(2)

In barrel temperature control, the natural convection into the atmosphere cools the barrel whether the band heaters are turned on or off. The 50% added to the proportional control action in equation (2) assumes 50% of the heat generated by the band heaters are lost this way. When this assumption is incorrect, manual reset of this percentage is possible. See equation (5).

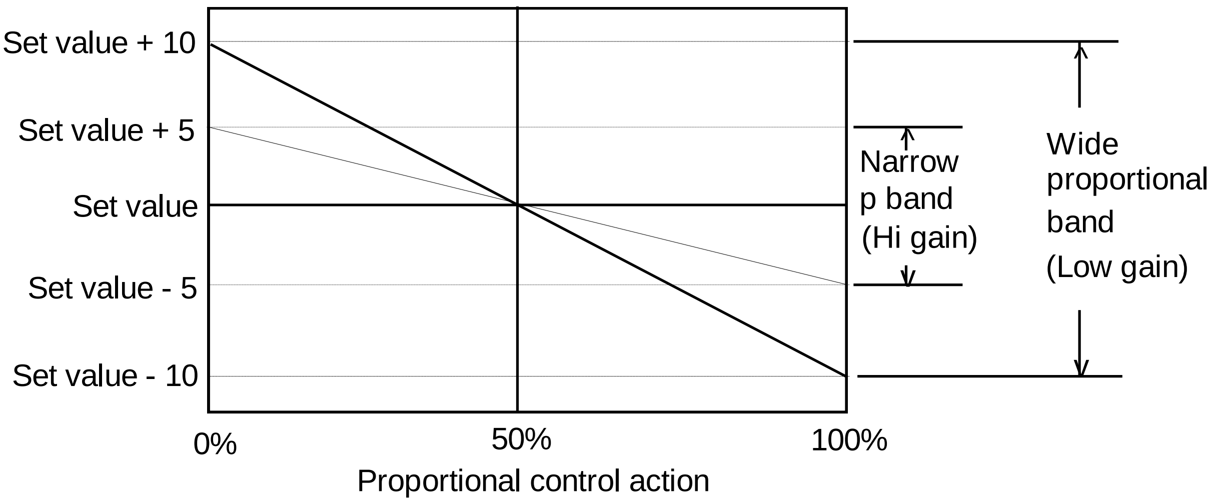
The higher is the gain K_1, the more sensitive is the control since a small deviation is amplified more. When the gain is very high, the slightest change in e will cause the actuator to move rapidly from one extreme to the other, i.e. the control action becomes on-off.

Proportional band is the reciprocal of gain. It is the range of values of the target variable (barrel temperature) which causes the actuator (band heaters) to move from one end of its travel (100% control action) to the other (0% control action). Proportional band is somewhat more intuitive than gain. Refer to Figure 16. Equation (2) becomes

Proportional control action = e /(proportional band) + 50% …………………………………(3)

A proportional band of +- 5 °C (= 10 °C) around the set temperature is usual. This proportional band corresponds to K_1 = 1/(10 °C) = 0.1 / °C.

The heater is turned on 50% of the time (50% control action) at the set temperature. 2 °C below the set temperature, the control action is 70% (= (2/10)*100% + 50%). 2 °C above the set temperature, the control action is 30% (= - (2/10)*100% + 50%). Within the proportional band, the control action is proportional to the deviation from the set temperature.



Narrow proportional band = 10 °C. Gain = 1/(10 °C) = 0.1/ °C

Wide proportional band = 20 °C. Gain = 1/(20 °C) = 0.05/ °C

Figure 16 Proportional band and gain

When the measured temperature becomes steady, its deviation from the set value is called offset. Refer to Figure 17. From equation (2),

Offset = (Proportional control action - 50%) / K_1 ....(4)

From equation (4), we see that offset is non-zero as long as proportional control action is not 50%. However, the higher is the gain, the smaller is the offset.

Negative offset occurs when the environment is too hot so that at 50% control action, the band heaters supply more heat than is used up by the resin and dissipated to the atmosphere. On the other hand, when the environment is too cold, the band heaters could not keep up with the dissipation. The offset is positive.

Figure 17 shows the case of a positive offset. At steady state, the control action is 75%. The offset is 2.5 °C (= (75% - 50%)*10 °C)).

Offset could be corrected manually by turning the reset screw available in some controllers which shifts the proportional band so it is no longer centred at the set value. Refer to Figure 18.

Equation (2) is changed to

Proportional control action with manual reset = K_1 e + 50% + r% ....(5)

In the case of Figure 17, r% = 25%.
From equation (5),

Offset = (Proportional control action with manual reset - 50% - r%) / K_1 ....(6)

At 75% control action, the offset is now zero.

For controllers without the reset screw, the offset could be removed by adjusting the set temperature. In the case of Figure 17, raise the set value by 2.5 °C. At steady state, there is still an offset of 2.5 °C from the new set temperature, but the measured temperature is now right on at the original set temperature.

The hold pressure control of the closed loop ME55 III uses P control.

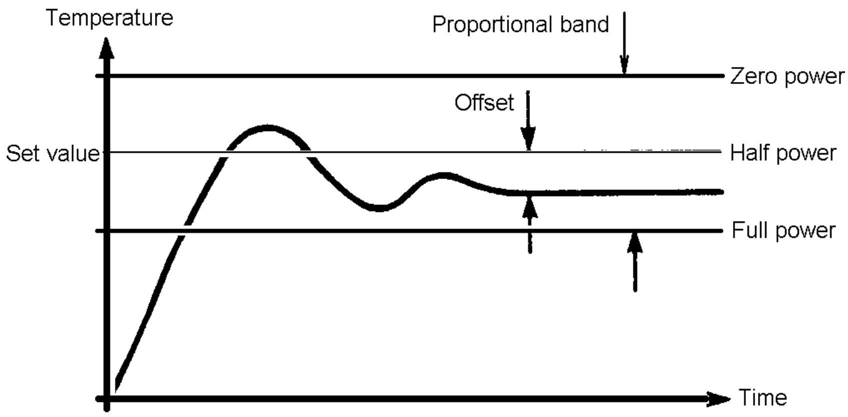


Figure 17 Proportional (P) control

7.3 Proportional plus derivative (PD) control
Derivative control accounts for the trend by being proportional to the time rate of change of the deviation. As temperature approaches the set value at a fast rate, the brake is stepped on harder to reduce or eliminate the overshoot. As a result of reducing the overshoot, the set temperature is reached in a shorter period of time. Comparison of Figures 17 and 18 attests to this.

PD control action = K_1 e + 50% + K_2 de/dt ....(7)

K_2 has the unit of time/°C, e.g. seconds/°C. A K_2 of 60 s/°C means that if measured temperature is below set temperature (e is positive) but is approaching set temperature at a rate of 1 °C every 15 s (de/dt = - 1/15 °C /s), *reduce* the control action by 4% (= 60 * (-1/15) x 100%) points.

PD control action does not remove the offset at steady state. At steady state, de/dt (the time rate of change of the deviation) is zero in equation (7), which then becomes the same as equation (2). Offset could be removed manually by adding r% to equation (7) or automatically by the integral action to be discussed next.

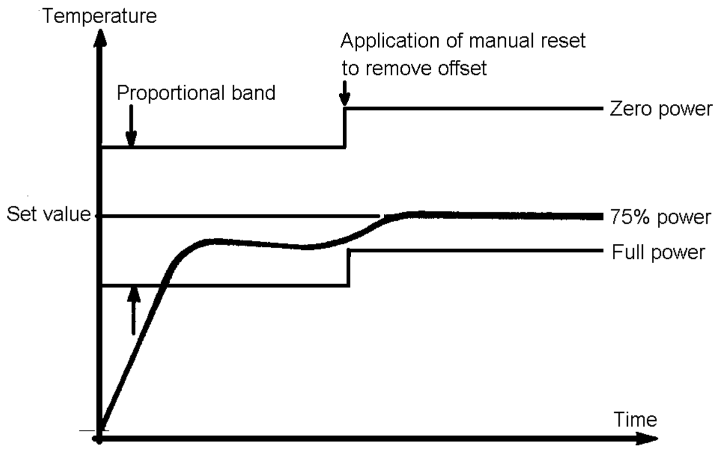


Figure 18 Proportional plus derivative (PD) control

7.4 Proportional plus derivative plus integral (PID) control

The PID control action removes the offset automatically by adding a term which is proportional to the time integral of the deviation. When there is an offset, its integral would increase with time to remove the offset. Comparison of Figures 17 and 19 attests to this.

The integral action slows down the response of the system, which could be counteracted by an appropriate derivative action.

$$\text{PID control action} = K_1\, e + 50\% + K_2\, de/dt + K_3 \int_0^t e\, d\tau \quad \text{...}(8)$$

K_3 has the unit of /°C /unit time, e.g. /°C /second. If the deviation is 4 °C, a K_3 of 0.1 /°C /s adds 0.4% (= 0.1 /°C /s * 4 °C x 1 s) points of control action every second.

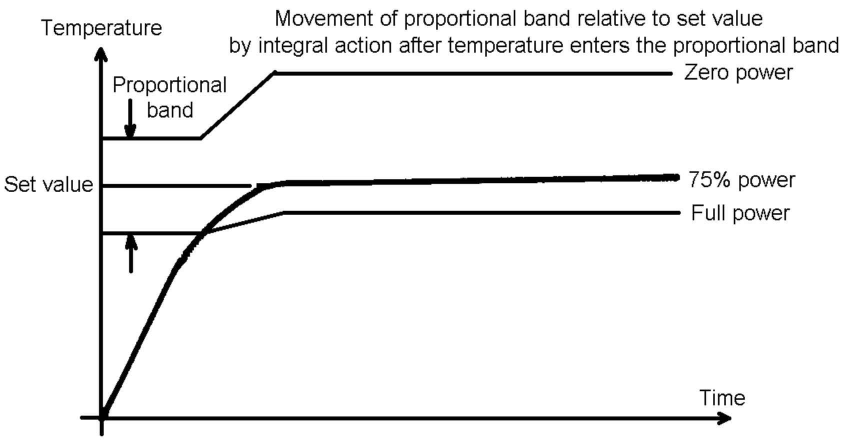


Figure 19 Proportional, differential and integral (PID) control

The injection velocity control of the closed loop ME55 III uses PID control.

8. Not a panacea

Closed loop control adds precision to injection moulding, but it does not solve all the injection moulding problems.

An incorrect setting of the switchover point could lead to filling the remainder of the cavity with the low holding pressure. Closed loop control of injection is not able to correct inappropriate injection velocity set values. The monitoring of the critical variables like injection speed, injection pressure and cavity pressure does provide us with clues how to adjust set values.

Leakage (internal or external) of hydraulic oil, wear of non-return valve and screw, breakage of a tiebar, etc. contribute to instability of the injection moulding process. They are malfunctions that could be detected with the help of the monitoring, but must be fixed before quality products continue to be moulded.

9. Other control methods

9.1 Feedforward control

Closed loop control is also known as feedback control as the target variable is measured and fed back for comparison. The drawback of feedback control is that it is after-the-fact: control action is taken only after a deviation is detected. Sometimes, after-the-fact is too late.

Feedforward control measures the disturbances and anticipating their effects on the target variables, take control action accordingly. Feedforward control is used in conjunction with feedback control.

9.2 Adaptive control

Adaptive control is most easily explained by adaptive screw position control. Shot weight w is proportional to the difference between the end of the plasticising stroke position p and the switchover position to hold pressure s. Refer to Figure 14. Note that p and s are *absolute* positions as measured by the injection potentiometer.

$$w = k (p - s)$$

If p and s both deviate from their set values, their effects on w could be doubled. The non-repeatability is especially acute when w is a small percentage (e.g. 30%) of the machine shot weight, i.e. p - s is a small percentage of the machine injection stroke.

In adaptive shot weight, a *constant* amount d is subtracted from p to become the new switchover point (set value). The deviation of p therefore does not carry over to affect shot weight.

$$w = k (d)$$

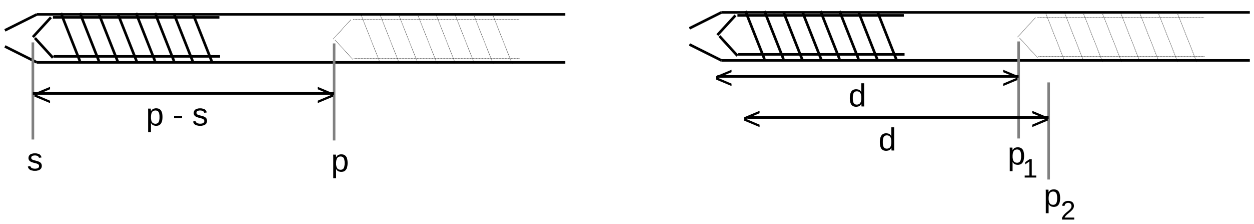


Figure 20 Adaptive shot weight

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