Quality Injection Moulding

Keywords: clamping force, cavity pressure, measurement, switchover, precision moulding, repeatability

Injection moulding without rejects is the ideal moulders try to attain. This article describes two auxiliary devices that could increase the repeatability of an injection moulding machine. Once the optimum parameters are set, the physical dimensions, weight and other physical properties of the part will stay almost constant. The two devices do clamping force measurement/control and cavity pressure switchover to holding pressure.

For injection moulding of high precision optical parts, or parts with a high added value like appliance cases, the payoff of reduced rejects is high. Figure 1 shows the part weight distribution of quality moulding and suboptimal moulding. The nominal weight is 60 g, allowable deviation is +0.1 g and -0.05 g. The white cubes denote parts within the tolerance band.

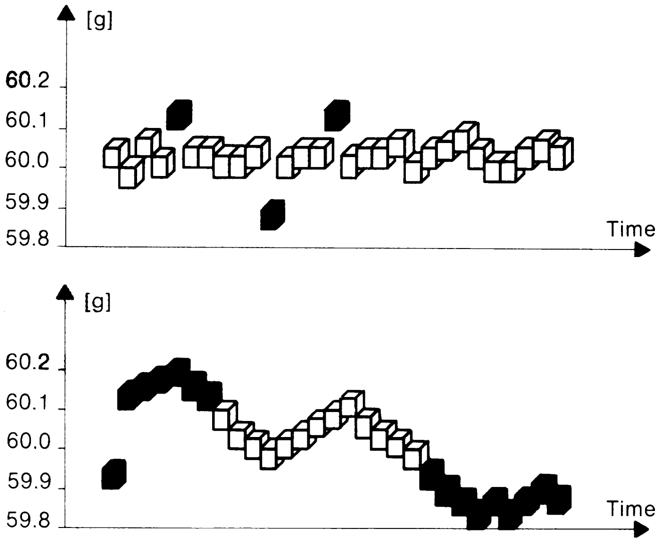

Figure 1 Quality injection moulding and otherwise

I. Clamping force measurement/control

The clamping mechanism of injection moulding machines falls mainly into two categories: toggle and direct hydraulic. The former is more widely used; the latter has the property of automatic clamping force regulation. As a result, direct hydraulic clamp machine do not need clamping force measurement/control.

Toggle clamp

A 5-point double toggle clamp is shown in Figure 2. After amplification by the toggle mechanism, the clamping cylinder, attached to the tail platen, extends, pushing the moving platen to lock the mould halves together. We will investigate in various ways how the clamping force is generated.

Clamping force

At its simplest, the rated clamping force F_o is calculated according to the following formula.

$$F_o = P_s * A * M \qquad (1)$$

where
P_s = system pressure,
A = clamping cylinder cross sectional area,
M = mechanical advantage of the toggles.
In most machines, M has a value of between 22.and 30. It is a function of the toggle dimensions and the stiffness of the toggles and tiebars.

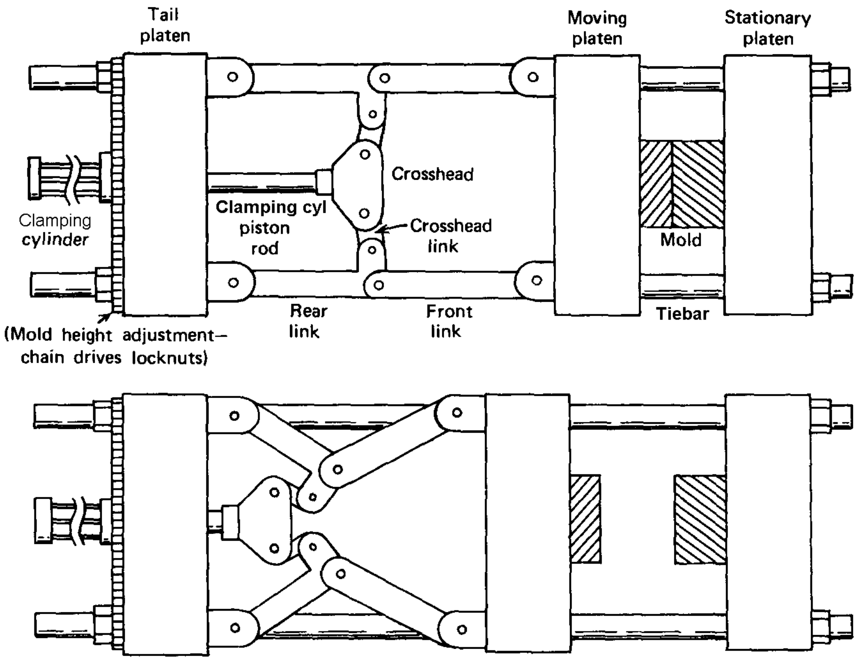

Figure 2 The 5-point double toggles

Rated clamping force and adequate clamping force
The clamping force found in the specification table of an injection moulding machine is the rated clamping force F_o. By considering the various design parameters, the machine designer calculates it using formula (1).

In using an injection moulding machine, it is best to use the minimal but adequate clamping force F. An adequate clamping force holds the mould halves together against the cavity pressure during the injection phase.

An excessive clamping force distorts the mould and the mould cavity unnecessarily, affecting the precision of the moulded part. Furthermore, a high clamping force compresses the toggles and the mould, and stretches the tiebars, reducing the fatigue lives of the toggle pins, the mould and the tiebars.

Clamping force problem and solution
The problem with toggle clamped injection moulding machines is with only the hydraulic pressure meter available there is no way to set an accurate clamping force when the mould is installed and to maintain it constant during injection. As the mould heats up, it expands, increasing the clamping force. The solution is to attach a device to measure the clamping force and to control the clamping force to within a tolerance as mould temperature changes.

For the engineers, the following sections details how clamping force is generated. They also relate to the second device: switchover to holding pressure by cavity pressure measurement.

Mould height adjustment mechanism

Since not all moulds have the same mould height, a toggle clamped injection moulding machine has a mould height adjustment mechanism for that purpose. Basically, the tail platen is moved forward or backward so that with the toggles almost fully extended ($\theta > 0$), the mould halves just touch each other. At this time, the clamping force is zero. See Figure 3a.

To generate maximum clamping force (clamping force > 0) and to self lock, the toggles are fully extended ($\theta = 0$). This is done by extending the clamping stroke further and through the toggles, moves the moving platen forward by a_m, which is the amount by which the mould is compressed. At the same time, the tiebars, attached between the stationary and tail platens, are elongated by a_t. See Figure 3b. Self locking means even when the hydraulic pressure in the clamping cylinder is relieved, the clamping force is maintained. This could only be achieved when the toggles are fully extended.

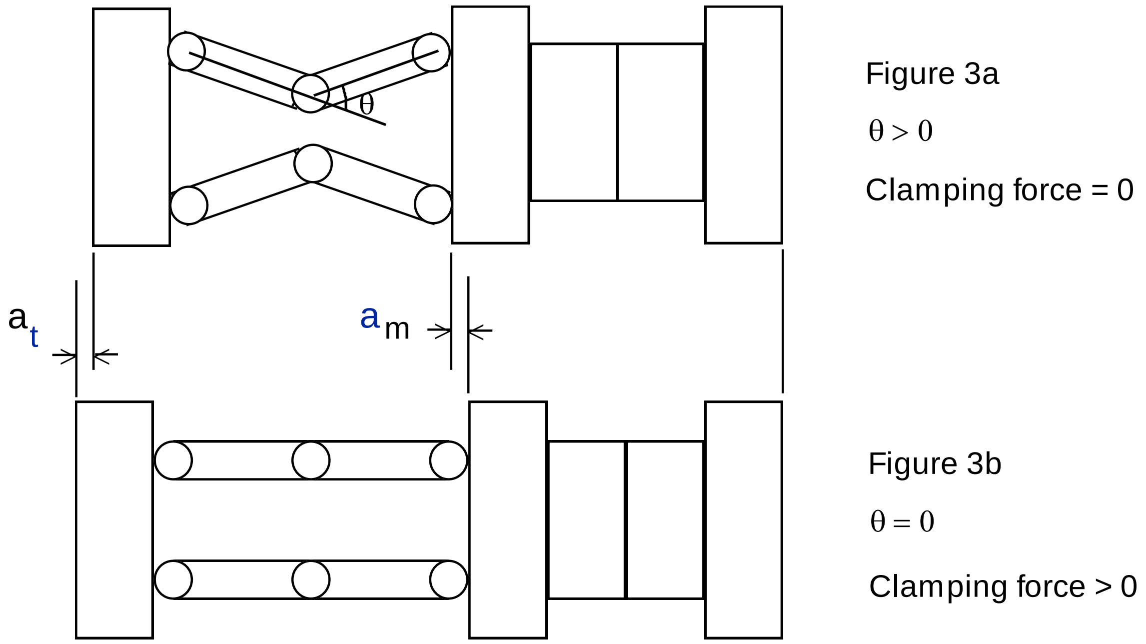

Figure 3 Generation of clamping force

As we can see, the clamping force is set when mould height is adjusted, by using the angle θ. Another way of looking at it is clamping force is generated by creating a mechanical interference. Compressing the mould and elongating the tiebars absorb the mechanical interference. The larger is the interference, the larger is the clamping force.

Revisiting clamping force

Assume the mould and the tiebars are in the elastic region at the rated clamping force. Their respective compression and elongation could be analysed using Figure 4.

In Figure 4a, at the adequate clamping force F, the mould is compressed by a_m and the tiebars elongated by a_t. Since the tiebars are long and thin, they are more flexible than the mould. Hence, the tiebars line is shallower. Technically speaking, $K_t = \tan \alpha_t < K_m = \tan \alpha_m$. As an example, with clamping force measured in tonnes and elongation/compression measured in microns (1 micron = 0.001 mm), an injection moulding machine with 60 mm diameter tiebars has α_t =9.2°, a 300mm thick, 170 mm square steel mould has α_m =64°. To facilitate the following analysis, the mould compression line is moved right to intersect the tiebars elongation line at F. See Figure 4b.

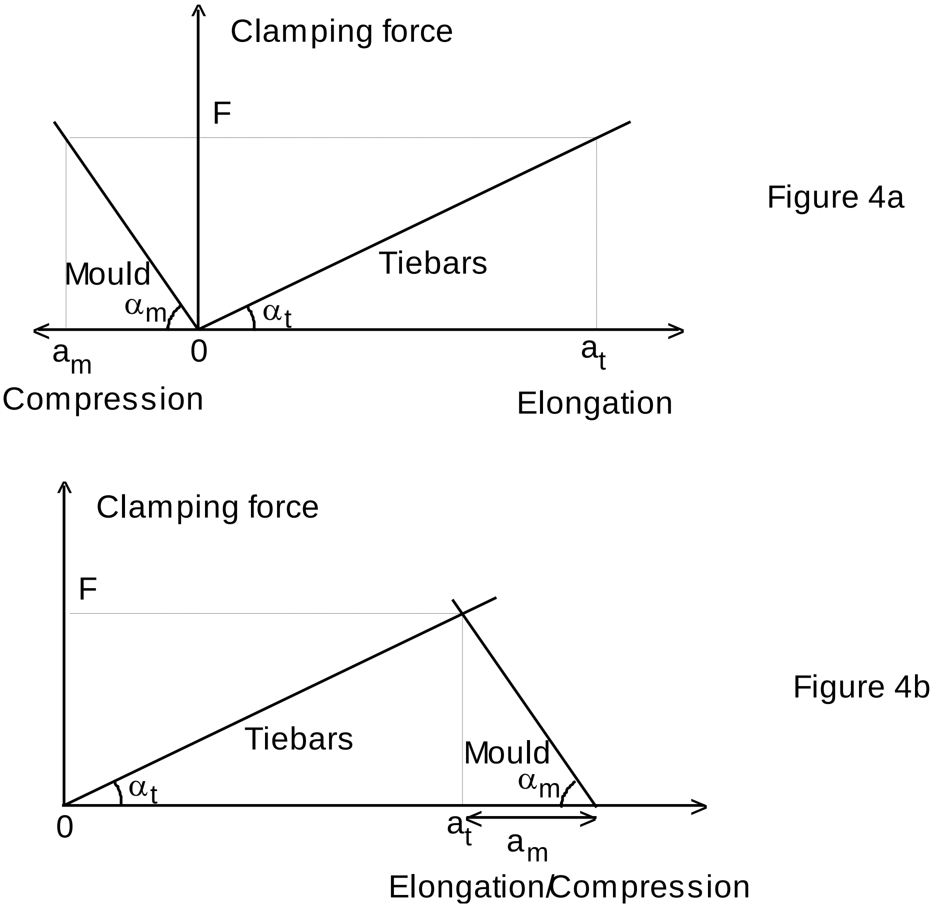

Figure 4 Clamping force analysis

When the melt is injected into the mould cavity, the clamping force is increased to F_1. See Equation (2). In practice, this increase in clamping force could be observed by a clamping force measuring device. See Figure 5.

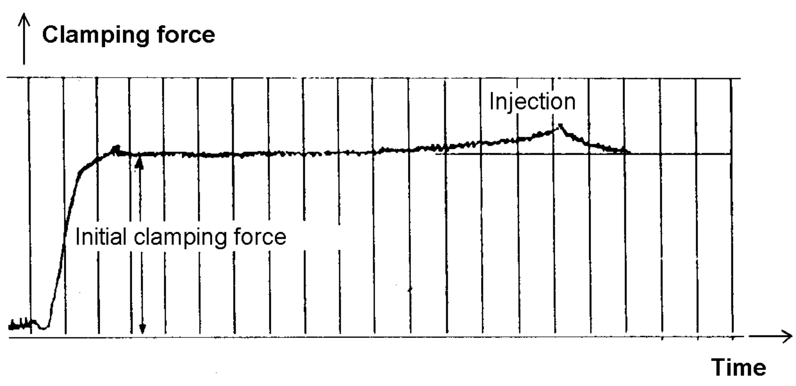

Figure 5 The effect of cavity pressure on clamping force

Figure 6 shows the free-body diagram of the mould halves with cavity pressure introduced. Each mould half is balanced by the force equilibrium

$$F_1 = F_c + F_r \qquad (2)$$

where

F_c = cavity pressure force,

F_r = residual clamping force on the mould.

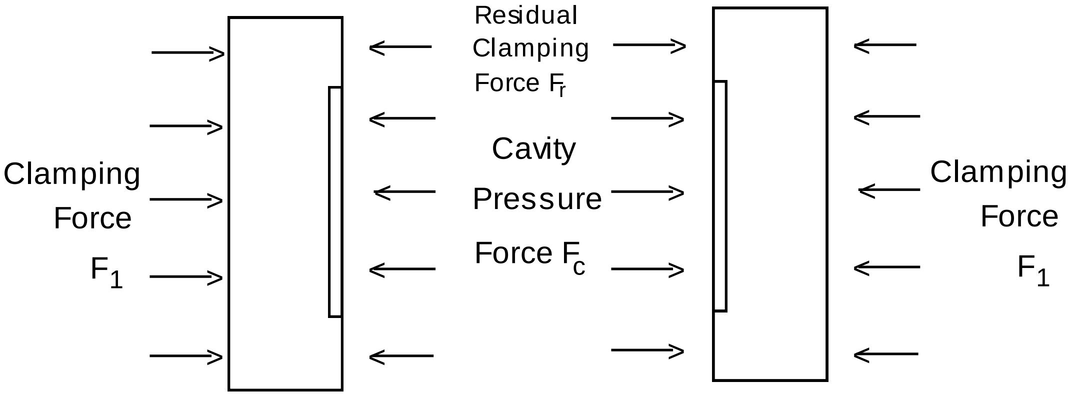

Figure 6 Free body diagram of mould halves

The cavity pressure force F_c offsets part of the clamping force F_1, leaving only F_1 - F_c to compress the mould. As a result, the mould compression is reduced from a_m to a_m'. The difference is taken up by the tiebars elongating more from a_t to a_t', increasing the clamping force to F_1. See Figure 7.

The mould opening force F_c due to cavity pressure is seen between the tiebars line and the mould line. This is the graphical way of showing equation (2).

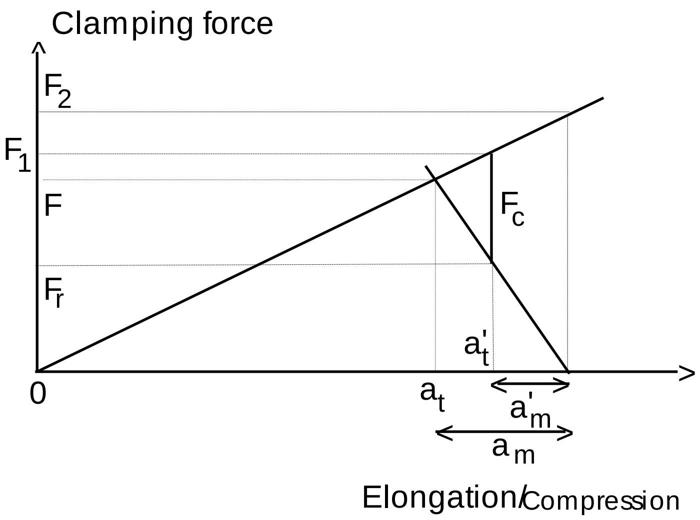

Figure 7 Adding cavity pressure

From Figures 3 and 7, one can see that the distance between the moving platen and the stationary platen is increased (by a_m - a_m') during injection. In practice, this could be measured by a dial gauge between the platens. In the extreme case when the cavity pressure is so high that the residual clamping force is reduced to zero, the mould opens and flashing occurs. At this point, the mould compression is zero, and cavity pressure force $F_c = F_2$, the clamping force when flashing occurs. See the dashed line in Figure 7.

As an example, take F = 75 tonnes, the rated clamping force of Tat Ming偲 ME75 III. For a 300 mm thick, 170 mm square steel mould, a_m = 0.037 mm. With such a mould mounted, the ME75 III toggle clamp will open at F_2 = 81 tonnes, 6 tonnes above its rating. Everything else equal, an injection moulding machine with 50 mm diameter tiebars will open at F_2 =78 tonnes, 3 tonnes above its rating.

As the mould heats up, it expands. The clamping force is increased as the mechanical interference is increased by the amount of the mould expansion. This is shown in Figure 8 in which the mould line is moved further right by the expansion, intersecting the tiebars line at a higher clamping force F". In this diagram, the tiebars are elongated more (a_t" - a_t) and generated the additional clamping force F" - F.

To restore the clamping force, a mould height adjustment is made to restore the mould (now hot) compression to a_m before the next shot is injected. Such adjustment is clamping force control.

As an example, a 300 mm thick steel mould heated up by 10^{o}C expands by 0.045 mm. On the ME75 III injection moulding machine, the increase in clamping force is 7.3 tonnes, which is almost 10% of the rated clamping force.

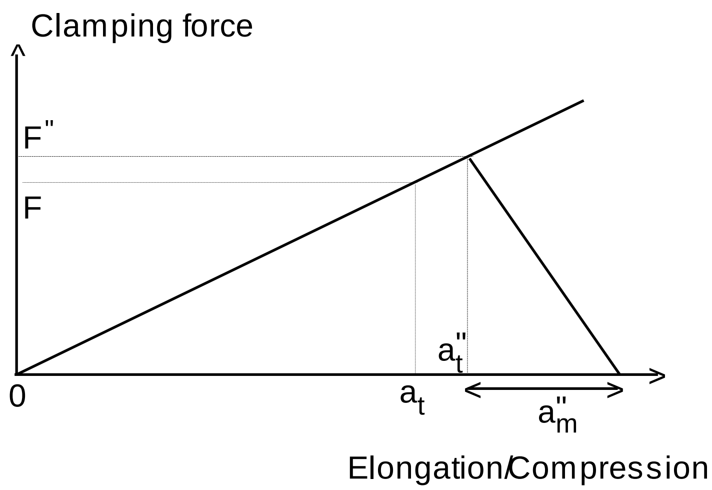

Figure 8 Mould expansion increases clamping force

No problems with hydraulic clamp
For the sake of comparison, let us do a similar analysis for a hydraulic clamp machine.
The adequate clamping force is

F = P * A (3)

where
P = the clamping pressure,
A = the clamping cylinder cross sectional area.
Clamping force is easily set as it is proportional to P, which, nowadays, is set through a proportional pressure valve. Mould height adjustment is done by extending or retracting the clamping cylinder rod to accommodate different mould heights. When the mould heats up and

expands, it simple pushes the clamping cylinder rod back into the cylinder, but does not increase clamping force. In other words, the clamping mechanism has the automatic regulation property. Clamping force measurement and control is not necessary.

The clamping force measuring device
Since fast response is not needed, a strain gauge-based device is sufficient to measure and control clamping force. The simplest means is a strain gauge attached to the tail or stationary platen, which deflects under the clamping force.

Alternatively, a strain gauge is attached to a tiebar which extends as the mould is locked. An assumption is made that the tiebars are evenly stretched which may not be true if the mould faces are not parallel, the mould cavity is not symmetrical or the tiebars are not balanced out of the factory.

The strain gauge output is amplified and digitally displayed. The display is calibrated to read in tons. Such a device is sufficient to help the operator set up an adequate clamping force initially (during mould height adjustment). When for example a 5% deviation from the initial clamping force is detected (after the mould is closed but before injection), the operator could do a mould height adjustment to restore the clamping force to its original value.

Alternatively, the computer in the injection moulding machine could set up the clamping force during the initial mould height adjustment, and to restore the clamping force by another mould height adjustment when a prescribed deviation is detected.

II. Injection
The injection of melt into the mould cavity is made up of three phases: the filling phase, the packing phase and the holding phase.

The injection phases could be vividly illustrated using the cavity pressure curve. Figure 9 shows the ideal curve which is achieved when the switchover to holding pressure is optimum. The switchover is sometimes called velocity to pressure transfer, where velocity refers to injection velocity and pressure to holding pressure.

The filling phase starts at 1. In the filling phase, the melt is injected into the cavity at a certain velocity. At 2, the melt reaches the cavity pressure sensor. Due to the viscosity of the melt, pressure starts to rise. The cavity is volumetrically filled at 3. Further screw advance compresses the melt up to 4 when the machine switches from injection pressure to the much lower holding pressure. At the holding phase, the low holding pressure incrementally fills the cavity as the part cools to compensate for the shrinkage. At 5, the sprue gate is frozen and the holding pressure could be removed (and the mould could be opened). 1-2-3 makes up the filling phase. 3-4 is the packing phase. 4-5 is the holding phase. Further cooling occurs in 5-6.

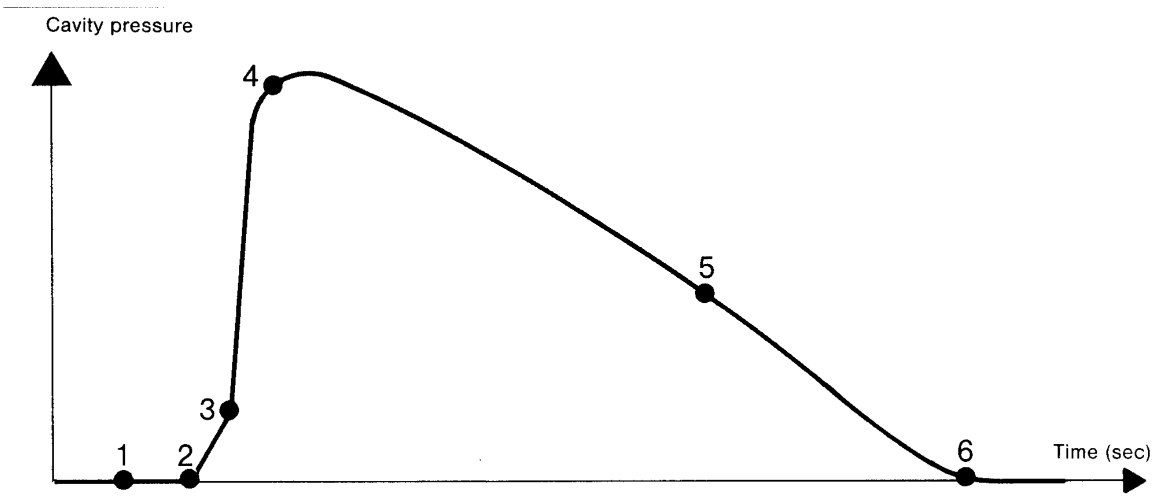

Figure 9 Ideal cavity pressure curve

Overpacking and underpacking

An overpacked cavity pressure curve is shown in Figure 10b. It is characterized by a pressure peak in the packing phase. The pressure peak is caused by the delay in switchover to holding pressure, so the high injection pressure is still applied after volumetric filling. The pressure peak is relieved at the switchover to the lower holding pressure. Here lies an often overlooked cause of flashing which is easily detected if one has cavity pressure sensing.

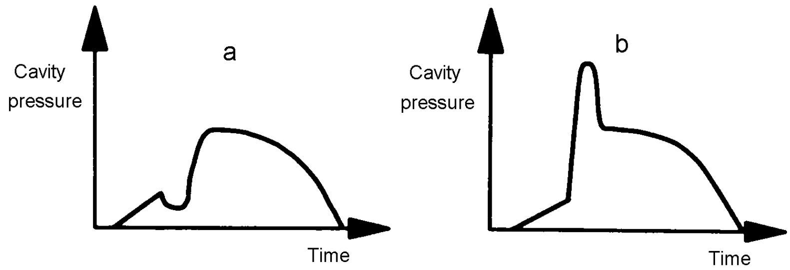

Figure 10 Underpacked and overpacked cavity curves

Refer to Equation (2) or Figure 7. The momentary cavity pressure peak could produce a momentary F_c big enough to reduce the residual clamping force F_r to zero, causing the mould to open and the part to flash. To remove the flashing, the straight forward thinking would be to increase the clamping force. Reaching the limit of the machine偲 rated clamping force, one would even move the mould to a bigger machine. Even if the increased clamping force overcomes flashing, overpacking adds weight and stress to the part and makes the part more difficult to demould. An alternative is to reduce the injection pressure. Too low an injection pressure causes defects such as sink marks. In actuality, the problem is easily and better solved by switching over earlier to get back to the ideal cavity pressure curve. In precision injection moulding, overpacking creates a reject.

An underpacked curve is shown in Figure 10a. It is characterized by a pressure dip in the packing phase. The switchover occurs too early, before the cavity is volumetrically filled. Part of the filling takes place at the lower holding pressure. Subsequently, the screw advance increases the pressure. The part has reduced dimensions, is underweight, has sink marks and surface marks. It is again a reject.

A device that switches over at volumetric filling would avoid the problems of overpacking and underpacking and produces the ideal cavity pressure curve. Switching is initiated at point 3 and completed in point 4 in Figure 9.

Methods of switchover

The available means to switchover in a modern injection moulding machine, in increasing order of accuracy, are

1. injection time,
2. screw position,
3. hydraulic pressure,
4. nozzle pressure,
5. cavity pressure.

Injection time switchover

Temperature affects the viscosity of the melt, which presents resistance to the advance of the screw. Increased resistance slows down the screw and prevents the cavity from filling in the given injection time. On the other hand, reduced resistance would lead to overpacking. Injection time switchover is the only means available in injection moulding machines without screw position and pressure sensors.

Screw position switchover

Screw position switchover is not affected by temperature nor viscosity. This is the preferred method in machines with screw position potentiometer. Like injection time switchover, screw position switchover could be considered open-loop as screw position is not a direct measure of volumetric filling. A leaky nozzle misleads the machine computer into switching over before the cavity is filled. So could a worn screw valve and a worn injection cylinder. Furthermore, if the screw diameter is large relative to (the cube root of) the mould cavity volume, variation of 0.1 mm could give an overpacked or underpacked fill. Despite its deficiencies, this is the most widely used switchover method in a modern injection moulding machine most probably because it is a standard (not optional) feature.

Hydraulic pressure switchover

The packing of the melt in the mould cavity has to be balanced by the hydraulic pressure driving the screw forward. A rise in the hydraulic pressure during injection could be used to signal the switchover. Due to a roughly 10:1 ratio between the twin injection cylinders and the screw cross sectional areas, the injection cylinder hydraulic pressure is less than the screw tip pressure by the same ratio. The pressure drop at the runners and sprue gate separates the cavity pressure from the screw tip pressure. The compressibility of the melt (between the cavity and the screw tip) delays the time the pressure is felt. As a result, hydraulic pressure is not an accurate detector of the volumetric filling point. However, hydraulic pressure switchover does have the advantage of the sensor working in a congenial environment (oil temperature below 50^{o}C, oil pressure at system pressure (usually 140 bars)) and the sensing is independent of the mould (not attached to the mould). Hydraulic pressure sensor is usually an option in an modern injection moulding machine.

Hydraulic pressure, nozzle pressure and cavity pressure sensing locations are shown in Figure 11.

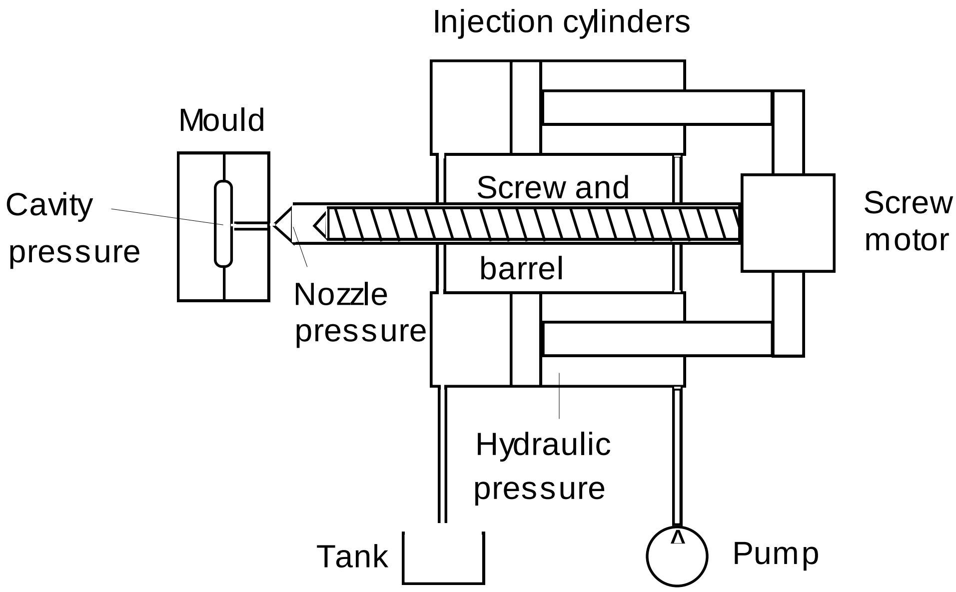

Figure 11 Hydraulic pressure sensor in the injection cylinder

Nozzle pressure switchover
Nozzle pressure is also called injection pressure, which is the pressure of the melt in the nozzle or at screw tip. Nozzle pressure switchover is improved over hydraulic pressure as the compressibility of the melt cushion is avoided. The environment is harsher (melt temperature below 400^{o}C, melt pressure at 1400 bars, the melt could be corrosive/abrasive), and the sensor face must be flush with the barrel interior wall. This switchover method is not often used except in research.

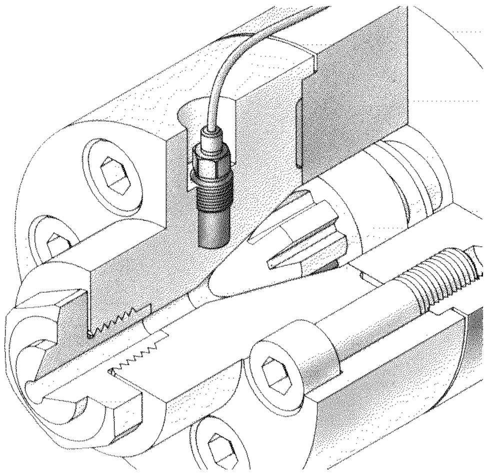

Figure 12 Nozzle pressure sensor

Cavity pressure switchover
The most accurate measure of volumetric filling is via cavity pressure. Two methods are in common use: direct and indirect. In direct cavity pressure measurement, a sensor in the mould senses the melt pressure in the cavity. Direct cavity pressure measurement is the more accurate of the two, but requires one to drill a hole at the mould for the sensor. Since it is inconvenient to

remove the sensor, one needs to dedicate at least one sensor per mould. In a multicavity mould, cavity pressure measurement requires one sensor per cavity, increasing the sensor investment further.

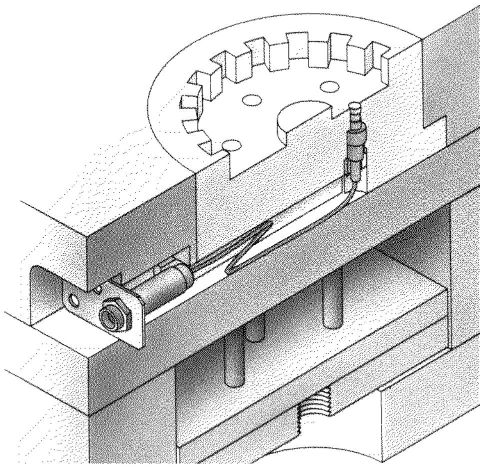

Figure 13 Direct cavity pressure sensor

In indirect pressure measurement, a force sensor is placed behind an ejector pin the other end of which is in contact with the melt. Cavity pressure could be calculated from force/ejector pin cross sectional area. The temperature at the sensor is much less than that of the melt. With indirect cavity pressure switchover, the sensor is not dedicated to the mould (mould independent), which comes in handy when mould changing is often. It also reduces the sensor investment. Due to the friction at the ejector pin, indirect cavity pressure sensing is less accurate than its direct cousin.

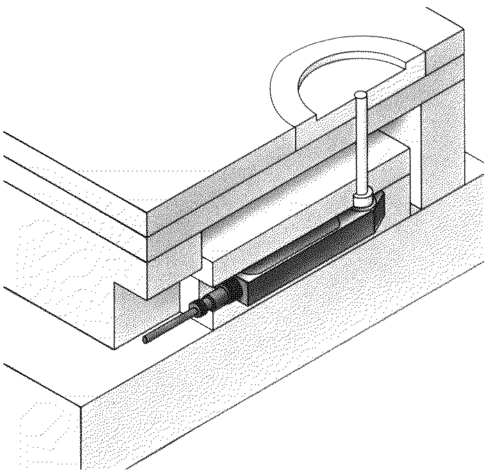

Figure 14 Indirect cavity pressure sensor

Where the required quality on the surface of the moulded parts does not allow marks either by the sensor or the ejector pin, a strain sensor that measures mould deformation could be used. After calibration in a test mould (which has a cavity pressure sensor), it may be used for cavity pressure measurement in the production mould (which does not have a cavity pressure sensor but has the calibrated strain sensor).

A device based on cavity pressure sensing could detect the volumetric filling point accurately. Switchover could be initiated by comparing the actual pressure with a set value equals to the cavity pressure at point 3 in Figure 9.

Alternatively, Kistler has developed SmartAmp which detects the volumetric filling point. SmartAmp contains a charge amplifier for the quartz type cavity pressure sensor and a chip which uses the principles of artificial intelligence to detect the kink in the pressure curve at volumetric filling. Usually, the learning takes the first few shots.

Monitoring the cavity pressure curve

The cavity pressure curve provides more information of the process in the cavity than can the nozzle pressure or hydraulic pressure curves. The nozzle pressure sensor is always surrounded by the melt and cannot measure the process pressure during the cooling period. Neither nozzle nor hydraulic pressure can detect the seal off point in Figure 9, the point when the mould could open. Determination of the seal off point reduces cycle time.

Research has shown that that peak pressure and the area under the pressure curve affect thin wall and thick wall mouldings respectively in an important way.

Figure 15 shows the overlapped cavity pressure curves of three shots of thin wall moulding like cups and covers. The deviation of peak pressure is found to be a good measure of the quality of the moulding and should be monitored for quality control purposes.

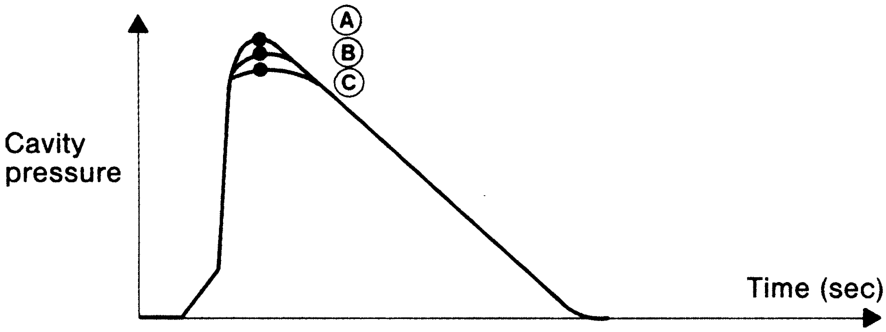

Figure 15 Peak pressure is important in thin-wall moulding

Figure 16 shows the overlapped cavity pressure curves of three shots of thick wall moulding like gear wheels. The deviation of area under the pressure curve is found to affect the dimensions of the moulding significantly and should be monitored for quality control purposes.

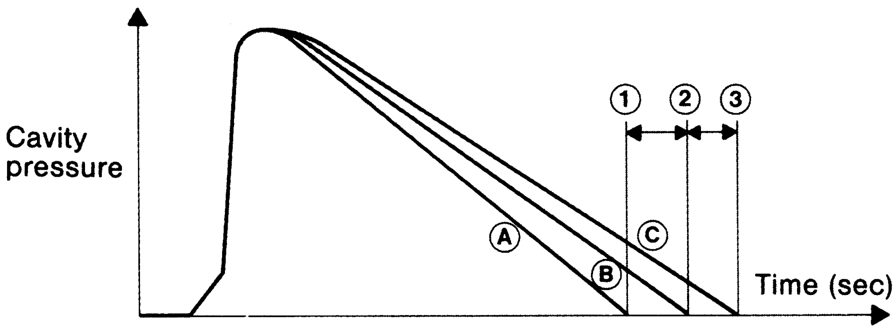

Figure 16 Pressure curve area is important in thick-wall moulding

AQCS (Automatic Quality Control System) is an instrument from Kistler could monitor peak pressure or area under the pressure curve as well as detecting the switchover point. Tat Ming 偲 ME III series of injection moulding machines support the interface to Kistler SmartAmp and AQCS.

Reproducing the cavity pressure curve

If the ideal cavity pressure curve is reproduced every shot, the quality of the moulding is almost guaranteed. To do so, one has to find the ideal curve for the part, record it in the machine computer and ask the machine to reproduce it in subsequent shots. Note that melt temperature and mould temperature also affect the cavity pressure curve in an important way. They should also be held constant.

A machine with such a capability has a responsive closed loop servo controlled injection unit. By measuring the actual cavity pressure and comparing it to the ideal, any deviation is minimized by controlling the injection pressure and injection speed. Unlike the cavity pressure switchover device or AQCS, this capability is not that of an auxiliary device but is that of a new machine altogether. It is mentioned here to put the cavity pressure viewpoint in perspective.

Unit 919, Tower A, Regent Centre,
63 Wo Yi Hop Road,
Kwai Chung, NT, Hong Kong.
Tel: (852) 2790-4633, Fax: (852) 2797-8774
Email: tatming@netvigator.com
Web site: http://www.tatming.com.cn