THE MACHINE AUDIT:
A SYSTEMATIC EVALUATION OF INJECTION MOLDING MACHINES:
HOW TO TELL A GOOD MACHINE - OLD OR NEW

(2nd edition)

John Bozzelli
Injection Molding Solutions
Rodney J. Groleau and Norm Ward
RJG Associates, Inc.

Injection molding continues to dominate as the process of choice for the production of high volume precision plastic parts. However, the production goal of "identical" parts is not often achieved. Most molders have common part problems such as shorts, flash, warp, knit line problems, dimensional variations, etc. Causes are subject to debate and often vary with individual situations. The situation is further complicated when causes cannot be clearly defined as a problem with the machine, mold, method of processing, or resin.

This paper will focus on how to quantify a molding machine's performance so that when a problem does arise, a clear decision can be made as to whether or not the problem is caused by the machine. The purpose is to define a systematic evaluation of injection molding machines for process capability independent of the mold and auxiliaries. The intent is to establish what is required of a molding machine to be process capable. The industry does not have "world class" standards for the evaluation of injection molding machines.

What is required of an injection molding machine to provide a molder world class process capability? The answer can be found by taking the plastic's point of view. Emphasis on four plastic variables is the key to process control and capability:

Plastic flow rate
Plastic temperature
Plastic pressure
Cooling rate and time

The machine must accurately control these variables when it is melting and injecting plastic. Taking each of these plastic variables and translating them into machine requirements and limits of acceptable function provides the following tests.

PLASTIC FLOW RATE:

Precision control of flow rate as plastic is being pushed into the cavities is critical to process control because plastic changes viscosity as injection rate (fill time) changes. This is sometimes misunderstood because Melt Flow Rate is used as an industry standard to describe plastic flow. The Melt Flow test only measures one point of a viscosity curve. Figure 1 depicts a viscosity curve for a typical plastic. It is more correct to plot this on log axis, but is plotted here on linear axis to accentuate the viscosity change. If the machine cannot control fill rate (fill time), then viscosity changes. If viscosity varies shot to shot or run to run due to injection speed changes, parts will not be identical because the associated viscosity changes cause different pressure gradients across the part.[1,2] Also, varying degrees of molecular orientation may develop. Thus, the machine must have cruise control on injection rate. Tests to check a machine's ability to reproducibly control fill time are: 1) load sensitivity, 2) fill time consistency, 3) position cutoff consistency, and 4) shot size consistency.

As with all the following tests, it is recommended to use a calibrated and zeroed hydraulic pressure transducer combined with a recording method that samples the signal at least 100 samples per second. Time measurements need to be at the 0.01 second resolution. Data should be collected using a predetermined sample size and frequency; for example, five consecutive shots every 30 minutes. Keep an event log in case special events occur when long test periods are called for. Tabulate the data and display in X bar/R format. If the data is in control and specifications have been established, a capability index can be calculated as shown in Figure 2. The transducer should be attached directly to the hydraulic cylinder after the flow control valve. See Figure 3. Relying on the machine's controller and plotting capabilities is not recommended. It is wise to look over the shoulder of the machine's controller to assure proper machine performance and proper sampling rate. These tests are best performed under DECOUPLED MOLDING^{SM} conditions. That is, the hydraulic pressure in the injection cylinder should not reach the set point of first stage or boost pressure and the filling or velocity phase of the cycle should end just prior to the cavity being full of plastic. For example, if the press was stopped at the end of first stage, the part would be 99% filled or slightly short.

Equipment needed:

Injection molding machine equipped with position (stroke) transfer capability. The machine must be capable of running on semiautomatic cycle with the nozzle retracted.
Hydraulic pressure sensor as described above.
Position transducer with a resolution equal to 0.1% of full stroke.
Strip chart recorder or other recording means with 100 hertz resolution and time measurement to the 0.01 second. A fill time clock is preferred but not required for time measurements.
A mold
Plastic resin

Load Sensitivity Test:
The load sensitivity test checks a machine's ability to deliver plastic at a constant and uniform velocity as material, temperature, and other process variations cause viscosity changes to occur. The concept is to vary the load requirement of the injection unit and note the change in fill time.

Procedure: Start up the machine following your normal safety procedures making sure you are decoupled and are converting from first stage to second stage via position (stroke).

To ensure a decoupled set up, reduce hold pressure to zero. If hold pressure will not go below 0.5 MPa (70 psi), take hold time to zero and add the deleted hold time to the cure timer to maintain a constant cycle. Adjust the positive cutoff setting to obtain short shots with the cavity about 95-99% full making sure that first stage set pressure is never reached. Observe the fill time to the nearest .01 second and peak hydraulic pressure for three shots. Fill time is defined as the time from the start of injection to when the screw reaches the position cut off. Fill time is a measured time, not the first stage timer setting. The first stage timer may be set as a safety backup. Average these three fill times and label the average as FT_1. Average the peak hydraulic pressures, being careful not to take any spike peaks at the beginning of injection. Label this average peak hydraulic pressure as PK_1. Retract the injection unit away from the sprue bushing and prepare to purge plastic into the air. Observe all required safety precautions. Run the machine on cycle and observe the fill time and peak hydraulic pressure for three shots as the machine purges into the air. Back pressure may have to be reduced for the screw to retract during this operation. Ensure that shot size is consistent for all shots. Average these three fill times and peak pressures and label them as FT_2 and PK_2 respectively. Eq. (1) calculates the machine's load sensitivity:

$$\frac{\dfrac{FT_1 - FT_2}{FT_1}}{\dfrac{PK_1 - PK_2}{1000}} \times 100 = \%\ \text{error}/1000\ \text{psi} \qquad (1)$$

The percent error should be near zero. Slightly negative is ideal. Machines having greater than 5% error will not control flow rate as viscosity varies and should be load compensated. Costs to load compensate a machine will usually be between \$2000 and \$3000. If your machine tests below the 5% error/1000 psi (7MPa) mark, the machine has the ability to control injection rate as viscosity varies due to all causes. It will keep the shear the same.

Position Cutoff Consistency:
This test checks a machine's ability to cutoff at the identical position on cycle. It is important because controlling the amount of plastic entering a cavity during fill may effect part properties, dimensions, warp and shrinkage. Non-return valve leakage will also play a critical role in delivering the right amount of plastic to the cavity, but is a separate topic. This test is for machines fitted with a screw-position sensor that provides a readout of actual screw-position at the moment of transfer from first to second stage (boost to hold). This is usually on newer or upgraded machines.

Procedure: With the machine at steady-state and cycling with a reasonably fast injection rate (50% of maximum), record the actual screw position at transfer from first to second stage for 24 hours. Variance should not be more than 1.0% of full scale.

Fill Time Consistency:
Fill time consistency is another test to see how repeatable the injection unit delivers plastic at a constant and uniform velocity. The concept is to keep shear rate constant to stabilize viscosity.

Procedure: With the machine running on cycle and making acceptable parts, monitor fill time for 24 hours. Fill time should not vary by more than " 1%.

Shot Size Consistency:
Consistent shot size is important if the injection unit is to deliver the correct amount of plastic to the cavity within a specific time. This is more critical if the transfer mode is screw position rather than cavity pressure. Changes in shot size can cause inconsistent fill times.

Procedure: With the machine at steady-state and making plastic parts, monitor the shot size variation over a 24 hour period using the stroke transducer described above. Variation of more than " 1% is not acceptable.

PLASTIC TEMPERATURE:

Knowing the actual melt temperature helps us to understand the plastic's initial viscosity, cooling, degree of crystallinity, and the plastic's stability with respect to degradation. The screw/barrel configuration combined with the temperature control of the machine's heater bands must accurately control plastic temperature. Melt uniformity is expected but rarely achieved with standard screws.[3] Temperature set points often do not indicate actual melt conditions. Differences of 10% are common, but not acceptable. The tests used to check a machine's ability to control temperature are: 1) melt temperature, 2) nozzle temperature, 3) consistency of plasticating time, and 4) back pressure consistency.

Melt Temperature (The 30/30 Method):

<u>Procedure</u>: Check the melt temperature by preheating a thermocouple 20 ºC (30ºF) above the expected melt temperature. Make sure the machine is at steady-state, on cycle making parts. Interrupt the cycle and capture an air shot in an insulated receiver. Insert the preheated probe into the center of the melt patty. Do NOT stir. Thin or special fast response probes are not necessary or recommended. Wait 30 seconds or until the temperature stabilizes and take the reading.

The probe must be heated to a higher temperature than the plastic because metal conducts heat 100-1000 times faster than plastic. Without preheating, plastic would cool onto the thermocouple forming a thin film or insulator over the thermocouple. Plastic cannot transfer heat onto the probe as fast as the metal will conduct it away. This is also true of intrusive-melt nozzle-thermocouple and is the principal reason for their poor performance.

If the temperature difference between the plastic and barrel setpoint in the front zones is more than 10ºC (20ºF), appropriate modifications must be made. This may include PID loop tuning, screw modification, change of heater band type, etc. Temperature control can also be influenced by heater zone profiles; so in this test, method of processing cannot be ruled out as a possibility.

<u>Nozzle Temperature</u>:
Poor temperature control of the nozzle can cause gate blush, splay, polymer degradation, drool, and nozzle freeze off.

<u>Procedure</u>: All safety precautions should be taken. Use of gloves, face shield, and an awareness that enormous pressures may be in the barrel due to a plugged nozzle or plastic degradation are essential. Make sure the nozzle is open and melted plastic easily flows through it. Break cycle after reaching steady-state and insert a wire thermocouple into the nozzle reaching to the nozzle's midpoint. Wait until the temperature stabilizes on the probe and take the reading.

If the difference between the nozzle set point and actual temperature in the center of the nozzle is more than 3ºC (5ºF), correct the problem. Look at thermocouple placement. It should be between the heater band and the plastic, preferably imbedded in the steel of the nozzle. Proper location is mid-length to the front third of the nozzle. This takes into account the heat loss of the nozzle when in contact with the sprue bushing. The nozzle and tip should be PID controlled; use of a rheostat type control is not recommended.

<u>Consistency of Plasticating Time</u>:
Consistency of plasticating time is important in helping to keep plastic temperature in control.. Since molding is a thermal process, consistency in time is critical. Screw rotation may vary and the amount of time the screw works on melting plastic will change. Since most of the energy necessary to melt the plastic is produced by screw rotation (shear), the temperature of the plastic can vary from one shot to the next.

<u>Procedure</u>: Monitor the plasticating time while on cycle making acceptable parts for 24 hours. Maximum variation allowed is " 5%.

If inconsistent, check screw, screw rpm consistency, investigate throat and screw feeding. Make sure the feed throat is temperature controlled, not just cooled.

The method of processing may influence this test. An inappropriate rear zone temperature will cause screw slippage. The rear zone temperature should be optimized for the resin to stick to the barrel with minimum screw slippage. Often substantial cycle time savings can be achieved with proper rear zone temperature settings.

<u>Back Pressure Consistency</u>:
Back pressure has a significant influence on both the quality and temperature of the melt. Amount of back pressure influences melt temperature temporarily. Inconsistent back pressure as the screw plasticates will vary the melt temperature providing a non-uniform melt. This can cause warp, uneven flow through hot runners, and

inconsistent filling of cavities. Note that the back pressure on one machine may not be equivalent to another machine due to different intensifying ratios. Emphasis is on plastic pressure and not hydraulic pressure.

Procedure: Monitor the back pressure on the hydraulic cylinder while the machine is on cycle making parts for 24 hours. It should not trend or vary by more than +/- 2% during the plasticating time of any single shot or from shot to shot.

PLASTIC PRESSURE:

Plastic pressure, specifically the pressure profile of a part, determines the dimensions, weight, sinks, voids, warp, and other part properties. The machine functions that relate to a part's pressure profile are injection rate as previously discussed, the transition from first to second stage, and the stability of second stage or hold pressure. Machine hydraulic pressure does not always correlate to plastic pressure in the cavity, but it must be accurately controlled and stable for process capability. Three machine tests are of value: 1) transfer time and consistency, 2) second stage pressure consistency, and 3) cushion size.

Transfer Time and Consistency:
Transfer time from first to second stage is a measure of controller and valve response time.

Procedure: Capture ten shots with the machine on cycle making parts. Measure the time it takes for switchover from first to second stage. This time starts at the end of first stage and ends when second stage or hold pressure is stable. A time of less than 0.10 second is "world class"; 0.40 second is the maximum allowed. Parts with thin sections, small gates, or fast cycles are sensitive to long delays. For consistency, monitor over 24 hours

Figure 4 shows different transfer times for two different machines. Machine A shows poor response and is a state-of-the-art 1992 machine. Machine B shows good response and is a 1972 vintage. Figure 5 shows the importance of consistency. Note the cavity pressure at end of fill. It varies from a good part to a short depending on the transfer consistency.

Second Stage Pressure Consistency:
Second stage or hold pressure determines the pressure gradient from gate to end of fill of a part. Control and fast response are critical for keeping part tolerances, weight, and pressure profile.

Procedure: With the machine on cycle making parts, monitor hold pressure over a 24 hour period. It should not vary more than " 1% during a shot, unless profiled, or shot to shot. If profiled, the steps should be stable within 0.1 second. Hold pressure between machines may not be equivalent due to different intensifying ratios.

After second stage or hold pressure ends, there should be a slight time delay before screw rotation begins. This provides for less wear on the screw motor, screw tip, and eliminates an instant of high shear on the plastic.

Cushion size is also important. The purpose of a cushion is to transmit plastic pressure through the sprue, runner, gate, and cavity to pack out a part. Both shot and cushion size should remain stable and not vary significantly. Large deviations in cushion size are indicative of a leaking non-return valve or worn barrel; both items are assignable causes and should be repaired. Adaptive shot-size control is not recommended. The non-return valve will leak differently on each shot, and any adaptive control will guess wrong 50% of the time. This is known as process tampering.

PLASTIC COOLING RATE AND TIME:

Plastic cooling rate and time establish the plastic part's retained orientation, distribution of compressive and tensile stresses, warp, dimensions, and post molding stability. Consistency is more important in this thermal process than fast cycles. If cycle times vary, different amounts of BTUs are lost from the mold and thus steady state molding will not be achieved. The principal test to audit for proper control of cooling is cycle time. Proper use of a mold open timer can be crucial in obtaining consistent cycle times. Note also that cooling starts when the cavity is full - not when the cure or cooling timer starts

Procedure: Cycle the machine for 24 hours on automatic. If semi-automatic, set the mold open timer such that the cycle is not operator dependent. A cycle time variance of more than " 1.0% is unacceptable. If it varies, investigate oil temperature control and clamp speeds.

SUMMARY:

These tests provide a practical, systematic evaluation of various injection molding machines for process capability, independent of mold and auxiliaries.

Compable values for different machines, old or new, can be achieved. The latest electrical or computer sophistication in machine controls is less critical than the ruggedness and reliability of the mechanical and hydraulic components. Ultra precise controls are of questionable value on a machine whose hydraulics operate on a lower order of precision.

Tests of a machine's safety systems have not been covered. They should be checked before the machine is placed in production.

REFERENCES

1. Bozzelli, J. and Groleau, R.; "Molten Polymer Flow, a Novel Explanation for Injection Molding; The Molding Machine as a Rheometer;" Las Vegas West SPE Conference, February, 1991.
2. Bozzelli, J.; "Selection/Buying an Injection Molding Machine for SPC/SQC: Some Questions to Ask Machine Suppliers;" ANTEC, 1989; pg. 228-230.
3. Bozzelli, J. and Larin, B.; "Implementation of Advanced Screw Design for Injection Molding; How to Improve Your Productivity and Profits: A Case History;" ANTEC, 1990; pg. 257-259.

Procedure: Cycle the machine for 24 hours on automatic. If semi-automatic, set the mold open timer such that the cycle is not operator dependent. A cycle time variance of more than ± 1.0% is unacceptable. If it varies, investigate oil temperature control and clamp speeds.

SUMMARY:

These tests provide a practical, systematic evaluation of various injection molding machines for process capability, independent of mold and auxiliaries. Compable values for different machines, old or new, can be achieved. The latest electrical or computer sophistication in machine controls is less critical than the ruggedness and reliability of the mechanical and hydraulic components. Ultra precise controls are of questionable value on a machine whose hydraulics operate on a lower order of precision.

Tests of a machine's safety systems have not been covered. They should be checked before the machine is placed in production.

Figure 1: Viscosity vs. Flow Rate for a typical plastic

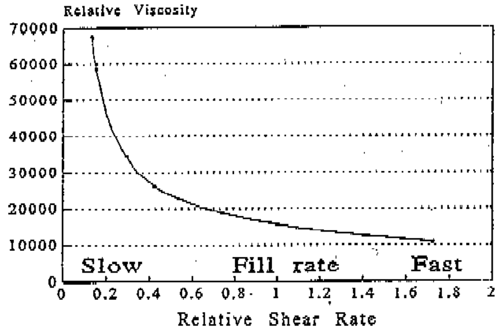

Figure 2: Data Handling