Best practice for benchmarking injection moulding simulation

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Injection moulding simulation benchmarking is the comparison of predicted and actual process and quality parameters. Best practice requires that the inputs and outputs from an injection moulding simulation agree to the actual conditions of a real life moulding machine, as closely as possible. The accuracy of injection moulding simulation is influenced by many factors such as: the modelling of the part geometry, runner and nozzle, model mesh type and density, mathematical finite element solution, material data, and process settings. Validation of injection moulding simulation requires good quality process measurements from a range of transducers, measuring process pressure and temperatures at different locations and including movement of the reciprocating screw to infer flow rate and accurate and repeatable measurement methods for part deflection. The objective of this paper is to give the reader an appreciation of the important issues, to ensure the inputs for an injection moulding simulation match the actual conditions of the real life moulding machine. The inputs for injection moulding simulation are reviewed in detail, firstly considering machine performance issues and secondly considering the simulations issues. This will provide the reader with knowledge and understanding to improve benchmarking procedures.

Keywords: Injection moulding, Simulation, Validation, Accuracy, Error, Experiment

Introduction

Benchmarking is a technique used by engineers since the very beginning of Computer Aided Engineering (CAE) for injection moulding simulation. One of the earliest documented benchmarks was by Colin Austin, founder of Moldflow, in late 1970s during a trip to Japan. Colin was lecturing on a seminar tour to promote Moldflow technology, after presenting his seminar in Tokyo he designed a simple runner balancing technique on a mould for Toshiba. On his visit to the Toshiba plant the next day, the engineers informed Colin, that they had gone back to their factory the previous night, assembled a mould with inserts in it, moulded samples and their results agreed with the simulations. They were impressed.[1] At that time there was a real problem with regulating the flow of polymer melt into the runners and cavities, with overpacking in one cavity and a short shot in another cavity. Use of CAE for injection moulding simulation has progressed from flow front prediction in the early days, through to include full simulation of the injection moulding process and its variants and associated processes. The theory and practice for validation of flow analysis software is described by Austin.[2]

An important reason for benchmarking is to confirm simulation results when users are first introduced to injection moulding simulation applications. Typically an extensive study is carried out on a representative mould, machine and material combination, where filling pattern, injection pressures and part warpage are reviewed. Once results have been confirmed and practical considerations are documented, the injection moulding simulation applications are then implemented on a large scale, which demands good communications between design engineers and the shopfloor. The moulding industry is changing and improving the link between design and manufacturing, the flow of machine setup information and process response continues to be critical. It is still true today that the three key stages of the value chain: part design, mould design and production, may actually be controlled by different organisations, within a company (*see* Fig. 1). While these organisations may be independent, it is vital that the required inputs for the CAE simulation are validated by part design, mould design, manufacturing and production.

Objectives of benchmarking are to gain confidence and experience in modelling, material and simulation capability, and to then use simulation results to guide future design decisions for which designers do not have moulding data.

The following list outlines the key parameters that are typically compared by design and process engineers:

(i) filling
   a. injection nozzle pressure
   b. filling pattern, weldlines and hesitations
   c. packing cavity pressure decay
(ii) warpage
   a. deflections, out of plane

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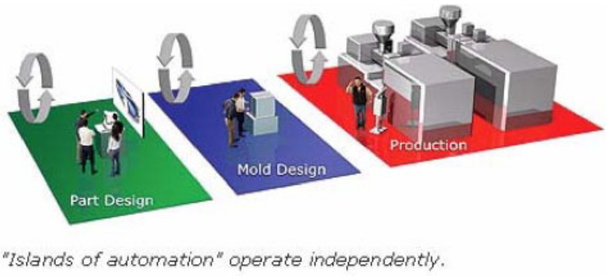


1 Three key stages of value chain ('islands of automation' operate independently)

b. in plane shrinkages.

The cooperation between the design engineer, process engineers and machine setters will improve through information exchange. Design induced limitations will be reduced by automated tools that pass information transparently between the shop floor and the design engineers, as part of a product lifecycle management system. Such a system will provide evidence of design problems and reduce anecdotal information, with an important area being the comparison of predicted and experimental data. The key to the validation of such systems is ensuring that there is good agreement between the simulations and the real world. Figure 2 shows a schematic diagram of the benchmark process. This paper will focus on the preparation of a benchmark and the importance of appreciating and understanding the inputs.

Value of injection moulding simulation

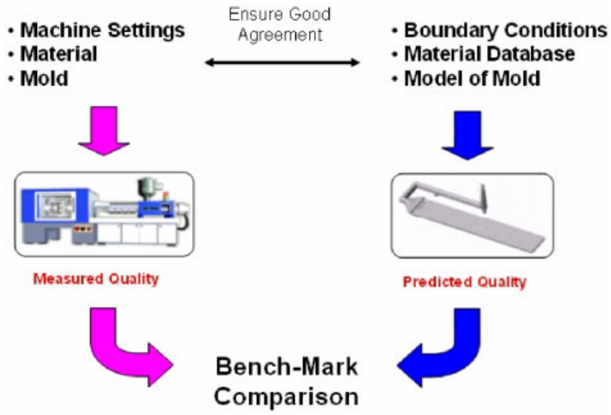
The value of injection moulding simulation are clear.[3] Injection moulding and its variants are the most successful area of simulation because:

(i) the process may be represented by a relatively simple material model, namely, the generalised Newtonian fluid which allows the viscosity of the fluid to be a function of the rate of deformation
(ii) the governing equations may be reduced to a simple form that is suitable for solution on ordinary computers
(iii) injection moulding simulation has a high return on investment.

Injection moulding demands more of part and mould designers, as experimentation after the mould is built is expensive in terms of time and money. Injection moulding simulation is relatively inexpensive in terms of project cost and offers great benefits to those using it early in the manufacturing process. The above factors bring a level of complexity to injection moulding that is not present in other plastic forming processes. All these aspects combine to make injection moulding an ideal focus for simulation. Simulation of injection moulding has a higher return on investment than simulation of other plastic forming processes.

Accuracy of injection moulding simulation

The accuracy of injection moulding simulation is influenced by many factors. If the aim of the simulation is the prediction of filling patterns and the location of any weldlines or hesitation marks, then the accurate representation of the geometry is the most critical factor.



2 Schematic diagram of benchmarking process

Errors in the modelling of wall thickness are surprisingly common. These may be due to design changes made towards the end of the design cycle not being present in the CAD model used as a basis for the simulation model, or they may be due to the tooling not exactly matching the final CAD design. In either case, when benchmarking fill pattern predictions against short shot samples, it is important to check key wall thicknesses in the simulation model against actual moulded parts. Another class of geometry inaccuracy which can arise is the simplification inherent in the modelling representation chosen. Injection moulding simulation has traditionally been based on a midplane shell representation of the part geometry. More recently, Dual Domain technology from Moldflow has allowed a solid geometry representation, but both of these modelling methods are reliant on the assumption of laminar Hele-Shaw flow and are not well suited to geometries with width to thickness ratios less than four. For such geometries, a true solid modelling representation of the part geometry is required because the errors in the Hele-Shaw approximations become too great.

If the aim of simulation is the prediction of the pressure required to fill the moulding, then inclusion of the runner, sprue and gating design is essential. In addition, if the simulation injection pressure will be compared to a measured nozzle pressure, then it is also appropriate to account for the pressure drop in the nozzle and contraction into the nozzle tip. This can be done either my including the nozzle body and contraction into the simulation model (typically assigning a property similar to hot runners) or by performing an air shot experiment. An air shot experiment is when the injection unit of the moulding machine is retracted away from the mould and an injection shot performed at the typically injection speed, but with polymer extruding freely out of the nozzle tip rather than flowing into the top of the sprue. The recorded nozzle pressure during the air shot experiment may typically be between 10 and 40 MPa and should be added to the predicted injection pressure if the simulation model begins from the top of the sprue.

Good quality material data is also important when comparing injection pressures. In this case, grade specific viscosity data is required, including pressure dependence if the injection pressures will be high (>100 MPa) and including some model to represent the entrance pressure loss, extensional viscosity or 'juncture loss' which will occur at any strong contractions, such as entering narrow gates.

If the aim of simulation is to predict the final warped shape of the ejected part, then the accurate reflection of the process settings in the simulation is important. In particular, packing time and packing pressure (or pressure profile), cooling time and any relative difference in coolant temperatures have a strong influences on the amount of shrinkage and warpage. In moulding practice, it is possible to halve the amount of warpage, or even change the warpage direction for some parts through changes in these process settings. Injection speed, which has a strong influence on filling pressure, is not usually a dominant influence on warped shape.

The availability of accurate material data will also influence the simulation accuracy of warpage predictions. For example, the use of grade specific pressure–volume–temperature (PVT) and thermal conductivity and specific heat data is required for accurate representation of shrinkage and warpage, as are the mechanical properties of the solidified polymer such as modulus and coefficient of thermal expansion. Shrinkage correction coefficients derived from shrinkage measurements on plaque mouldings for a range of processing conditions and geometries can also be used to improve the accuracy of shrinkage and warpage predictions.[4]

The discretisation of the geometry (into finite difference girds, finite elements or finite volume cells), will also play a key role in simulation accuracy. Areas of changes in thickness, such as the gate, should be discretised by a minimum of three rows of elements to allow an adequate representation of the thickness changes. Some discretisation methods allow the geometry surface to be altered to fit the discretisation size, but this should be avoided in injection moulding where small features such as the gate can have critical influences on simulations. For example, a geometry error in the sizing of a gate due to discretisation would lead to a delayed prediction of gate freezeoff during packing, which will have a strong influence on the shrinkage and warpage of the part.

The mesh size must also be considered with respect to the type of numerical solution being used. Traditionally, for Hele-Shaw based laminar flow simulations, a mixed finite element and finite difference method is used,[5] where a one dimensional finite difference grid is employed in the thickness direction to capture temperature, viscosity and shear rate variations. Analogously, when using a three-dimensional method, care must be taken to ensure sufficient discretisation is present through the thickness direction in all locations to provide sufficient resolution to represent the same property variations. Lower order or constant property schemes such as the finite volume method require a finer level of discretisation than finite element methods, particularly if higher order interpolations are used in the finite element formulation.

Verification and validation

At its most abstract, simulation involves using a computer to solve partial differential equations with suitable boundary conditions (mathematical model). In practice, simulation involves the transformation of the mathematical model into computer code. This involves the coding of algorithms to solve the mathematical model and the discretisation of the solution domain. Verification involves testing that the intended equation or algorithm and associated boundary conditions have been coded faithfully. Verification is not related to the process being simulated. It is a mathematical step that ensures no errors are introduced in creating the simulation code.

Validation checks that the results of the coded mathematical model have some agreement with physical experiment. Validation therefore assesses how well a particular model describes the physical process being simulated.

Analysis accuracy refers to the accuracy of the results obtained from simulation. Accuracy depends on the fidelity of the mathematical model used in the simulation, its implementation in the code, the appropriate boundary conditions (these include processing conditions), discretisation of the geometric domain in which we seek a solution and material models that describe the material's physical properties. Verification is necessary to ensure accuracy, however it is validation that provides quantitative measures of accuracy.

Accuracy is therefore not a simple comparison of simulation results and an experiment. Errors arise for the following reasons:

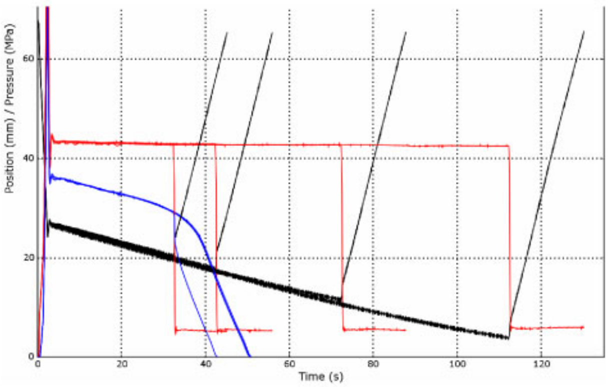
(i) software error – incorrect coding of a mathematical expression and/or its associated boundary conditions
(ii) geometrical error – import of geometry and the subsequent discretisation used to define the computational domain does not reflect the real part
(iii) material data error – material data is not appropriate for the materials used to produce the part
(iv) input error – processing conditions used in the simulation differ from those used in the manufacturing process
(v) post processing – manipulation of calculated data for post processing
(vi) experimental error – experimental data is in error often due to poor experimental technique, poor instrumentation or transducers.

Injection moulding machine benchmarking

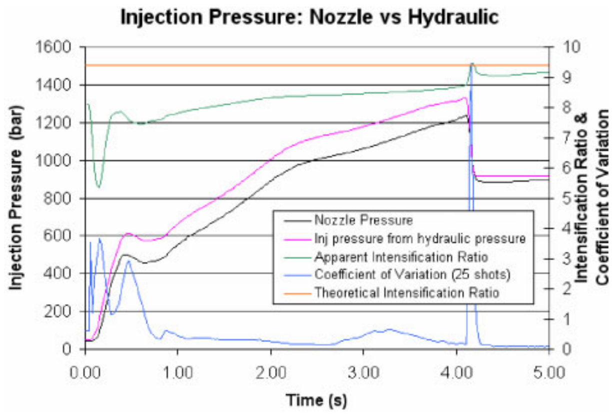
An understanding of the fundamental concepts of the injection moulding machine are required, and also specific details of the actual machine being used. It is important to have an appreciation of the links between the manufacturing and simulation worlds, and that the simulation should be treated as a virtual moulding machine. Important factors to consider are: machine capability, accurate information about screw movements, check ring valve performance, material preparation (drying), nozzle pressure or cavity pressure, not hydraulic pressure, shot to shot variations (stability), venting, sensor types and reliability.

Moulding: machine capability

Moulding machines are continually advancing, and there are a wide range of machines available. The injection stage can be pressure controlled or velocity controlled, most modern machines are velocity controlled, in open or closed control loop. There are also different methods of actuation: open loop digital hydraulics, closed loop proportional valve, and closed



3 Screw position in packing/holding stage, for worn check ring valve



4 Screw nozzle melt pressure and hydraulic pressure comparisons

loop servovalve. The packing or compression stage is a transition stage from velocity control to pressure control, typically this stage is not well controlled, until the set holding pressure is achieved. In a recent validation study at Moldflow, a moulding machine which had a set flow rate of 93 $cm^3\ s^{-1}$, actually only achieved an average flow rates of 52 $cm^3\ s^{-1}$, based on screw movement calculations, due to machine response capability. There was not indication from the moulding machine that the set flow rate was not achieved. Another Moldflow study showed that set holding pressures were not being reached until gate freezeoff occurred, due to the dynamics of the control system. An important technical requirement for the benchmarking process is a high speed data acquisition system, monitoring the injection moulding process. This will provide a accurate indication of a machines performance, and this data can then be used as the basis of the simulation inputs.

Moulding: screw movement and check ring valve performance

Process monitoring, as well as providing details of machine performance can also detect machine problems, which should always be reviewed prior to the start of a bench mark. Moulding machines that are subjected to continuous use will have problems, worn check ring values can result in incorrect flow rates and packing/holding pressures. Figure 3 demonstrates the screw moving in packing/holding up to 50% of the filling stroke due to a worn check ring valve. This screw movement continued even after the cavity pressure traces (blue) indicated that the polymer in the cavity had frozen.

Moulding: material drying

Material drying can cause process stability issues and also differences in melt viscosity. In research by Khanna *et al.*,[6] Nylon was dried for 17 h at 80, 110, 125 and 140°C, the lower temperature resulted in a higher moisture content which resulted in a viscosity difference up to 500% at low shear rates and 200% at higher shear rates.

Moulding: nozzle pressure

The ideal relationship between nozzle melt pressure and hydraulic injection pressure is shown below

$$\text{Nozzle melt pressure} = (A_{\text{Piston}}/A_{\text{Screw}}) \times \text{hydraulic injection pressure}$$

where A_{Piston} is area of hydraulic piston (m^2) and A_{Screw} is area of screw (m^2)

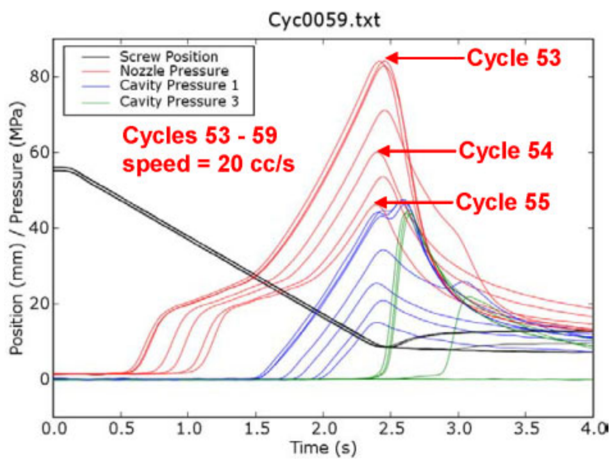
The ratio of piston to screw areas is referred to as the screw intensification ratio or gain, and is typically quoted as being approximately equal to 10, it may in fact vary considerably depending on screw and piston geometries. In practice the apparent screw intensification ratio may vary due to:

(i) compressibility of the hydraulic oil due to temperature changes
(ii) frictional effects between the screw and barrel
(iii) the influence of polymer melt compressibility during the filling process.

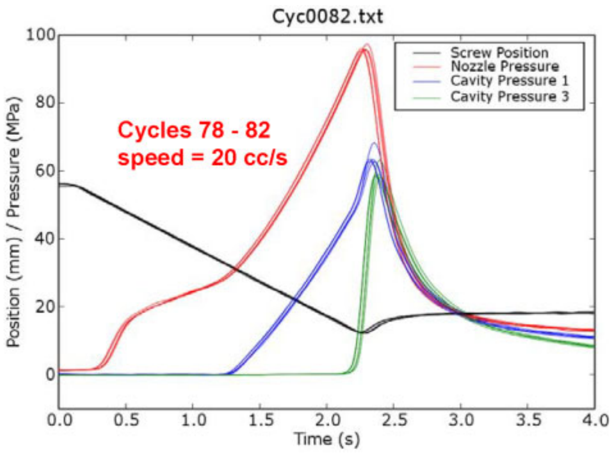
Figure 4 shows nozzle melt pressure measured using a Dynisco nozzle melt pressure sensor and nozzle melt pressure derived from multiplication of the theoretical screw intensification ratio of hydraulic pressure, showing a 10 mPa difference.[7] In practice, nozzle melt pressure is often derived from hydraulic pressure, due to difficulties of installing nozzle melt pressure sensors.

Moulding: shot to shot

Typical injection machine controllers typically have very limited capabilities for data overlaying, making it difficult to determine shot to shot variations. Figure 4 demonstrates differences in nozzle melt pressure, it is



5 Overlaid screw position and injection pressure profiles



6 **Overlaid screw position and injection pressure profiles**

important to note that the curves are the mean of 25 cycles, and the coefficient of variation is displayed, so that the quality of the data is clearly visible. Figure 5 shows successive pressure sensor and screw position traces (short glass fibre reinforced polyethylene terephthalate (PET)/polybutylene terephthalate (PBT) blend, fibre filled) immediately following a change in processing settings (injection speed). The screw position trace appears stable, but the pressure traces are not stable, this is a material effect, not a machine effect and is probably a result of an unoptimised melt preparation stage.

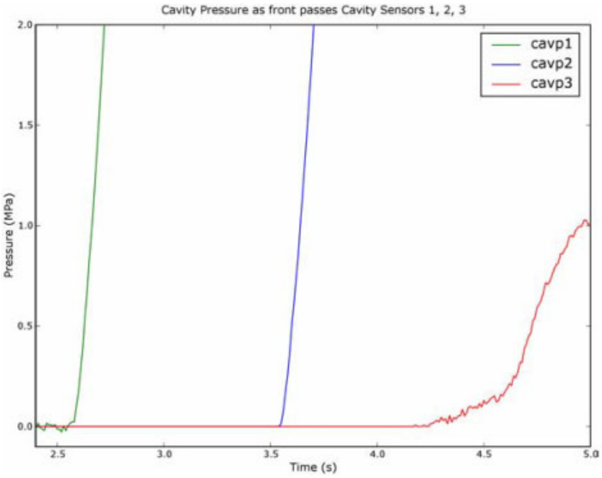
Figure 6 shows the pressure traces once the process has stabilized, the successive pressure traces typically stabilise after 5 to 10 shots.

Moulding: sensors

A machine independent process monitoring system for data acquisition is essential for injection moulding validation. The system has to be capable of capturing the true machine and process dynamics. Coates and Speight[8] describe the full range of sensors that are available for the injection moulding process. Sensor selection is determined by considering multiple factors, such as cost, robustness/reliability, dynamics, repeatability, linearity, influence of external indirect factors (such as temperature on a pressure sensor), size of measuring head and ultimately suitability. Figure 7 shows cavity pressure readings for three equidistant pressure sensors in a 1 mm rectangular cavity, filled with polypropylene at constant flow rate. The flow front is expected to reach cavp3 one second after cavp2, but it is clearly visible that the pressure rises earlier. The pressure sensor is performing correctly, but is measuring the air pressure build up due to poor mould venting.

Moulding practice: warpage

Flow front position, injection pressure and warpage are common benchmarking parameters. Warpage benchmarking can be influenced by coolant temperatures, packing pressure settings, shot to shot variations (stability) and a reliable and repeatable way of measuring warpage. Warpages measured within the tool makers mould tolerance, i.e. ± 10 μm, are really outside the bounds of the simulation world.



7 **Cavity pressure readings for three equidistant pressure sensors in 1 mm rectangular cavity, filled at constant flow rate, polypropylene**

Injection moulding simulation benchmarking

Injection moulding simulation benchmarking of CAE requires an appreciation of simulation technology and knowledge of the assumptions made in the simulation.

Simulation: filling inputs

The most important input that influences filling pattern is mould geometry, so an accurate representation of the mould geometry is essential. The most important inputs that influence injection pressure are:

(i) geometry,
(ii) switchover from velocity to pressure control stages
(iii) material viscosity
(iv) injection speed (profile or constant).

Simulation: geometry

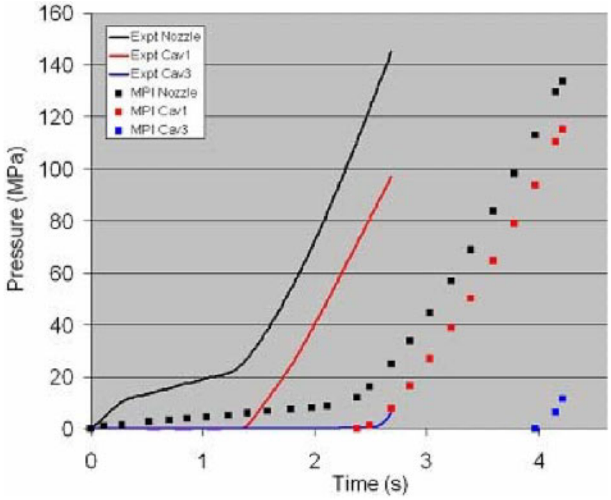
Often time is spent analysing simulation results of an intricate feature, only to find that the feature was not modelled correctly. Models are often assumed to be correct. It is always advisable to have a moulded part to review, to check for any obvious errors, it is also recommended to consider the life of the tool, as several modifications may have been performed on the tool. The model used for the injection moulding simulation may be from the part design, so the tool maker's shrinkage allowance will not be included in any dimensions. Nozzle, runner and gate geometries are not always included in a simulation model, these features can have a considerable effect on simulation results, particularly pressure to fill.

Simulation: switchover

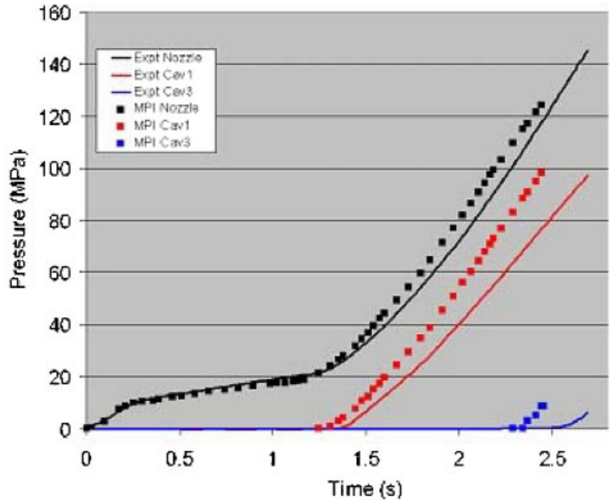
Switchover from velocity to pressure control is set by: screw position or time, in this case the full geometry must be modelled accurately, or volume percentage filled or automatic. Moulding simulation often uses the latter and it is essential to check that this is a reasonable approximation of the settings used on the moulding machine.

Simulation: viscosity

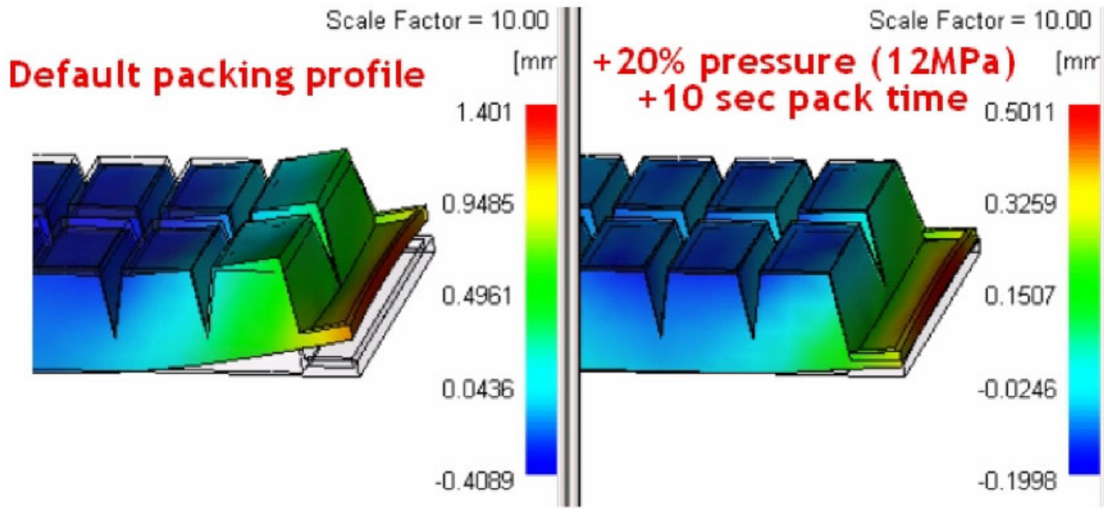
In the situation when a material is not present in the material database it is common practice to choose 'similar' material based on melt flow index (MFI) or viscosity, using the same polymer family, similar levels of



8 Experimental and predicted injection pressures



9 Experimental and predicted injection pressures



10 Default and actual packing/holding pressure profiles

filler and perhaps the same manufacturer. It may be expected that a 10% difference in filler weight percentage gives $\sim$10% difference in pressure prediction. If using material data from a different manufacturer expect up to 40% difference in pressure. This is because viscosity is also indirectly affected by the material's thermal properties.

Simulation: injection speed

It is important to set the correct injection velocity (flow rate profile). Figure 8 shows the experimental and simulation results compared, where the flow rate used in simulation was determined from readings on two cavity pressure sensors. The difference in position between the sensors and the time difference for the flow to reach the sensors was used to determine an injection speed for the simulation. However injection speed calculated this way shows poor agreement with measured pressures. Figure 9 shows the results of simulation using the actual screw velocity profile of the machine used in the experiment. The prediction of pressure is greatly improved.

Simulation: packing pressure

Injection moulding simulation has many built-in features to make running a simulation easy. One feature is the automatic packing/holding pressure profile, which uses by default 80% of the maximum injection pressure for 10 s. Often the actual pressure profile is overlooked.

Figure 10 illustrates the effect of using an arbitrary pressure profile on warpages results. This example serves to highlight the need for users to appreciate any settings that are determined by the simulation program for the purpose of making the program easier to use.

Conclusions

Benchmarking of injection moulding simulation requires a systematic approach to problem elimination when comparing simulation and moulding practice.

Many different factors may be the cause of error.

1. Machine capability and response time.
2. Material preparation, characterisation and stability.
3. Measurement methods (pressure or deflection).
4. Geometry inaccuracies.
5. Variation in process settings used in experiment and inputs to simulation software.

Awareness of these points is essential when comparing simulation results to those obtained on moulding machines.

Fortunately, even without perfect agreement, simulation can provide great insight into performance sensitivities to process, geometry and material. These sensitivities may be used by engineers to improve product design and process settings for actual production.

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