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Model optimisation for mould filling analysis with application CAE package C-Mold

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Analysis and modelling

ABSTRACT

Purpose: The simulation of mould filling in injection process has been presented. The methodology and sources of errors during preparation of simulation has been presented.
Design/methodology/approach: The tensile test specimen has been used as a model. The experimental verification of numerical simulations of different FEM models reflecting different injection conditions has been performed. For the simulation investigations a professional computer CAE software C-Mold ver. 99.1. has been employed. The injection was performed on Kraus Maffei KM 65/160/C1. This is the injection machine equipped with modern control system that guarantees high accuracy and reparability of the process. The rich instrumentation of the machine allowed for precise recording and storing the injection parameters. Additional sensor placed inside the form allowed for monitoring the pressure run in the runner.
Findings: The aim of the research was to determine the sources of the lack of accuracy in numerical simulations of plastic flow during the injection moulding.
Research implications: Inaccuracy of the described simulations results from the fact that the authors did not have full range of plastic properties data and the tests of the resin properties were performed under slightly different conditions than these recommended by the C Mold laboratory.
Originality/value: In order to eliminate an error of the simulation the region between the end of nozzle and the last thermocouple in barrel was modeled as a part of runner. A point at the level of thermocouple was assumed to be the plastic entrance point. This “additional” part of runner was modeled both as a cold and hot runner.
Keywords: Mould flow analysis; Injection molding process; Finite element method; Accuracy of modelling

1. Introduction

Program C-Mold 99.1 is a specialist CAE software package for plastics processing simulation. The program consists of modulus allowing for analysis of [1]:

- injection moulding filling, post-filling, cooling, and part shrinkage and warpage,
- injection compression moulding,
- co-injection moulding,
- gas-assisted injection moulding,
- reactive moulding,
- blow moulding,
- thermoforming.

In the paper the results obtained from the modulus for simulation of injection moulding filling, post-filling and cooling.

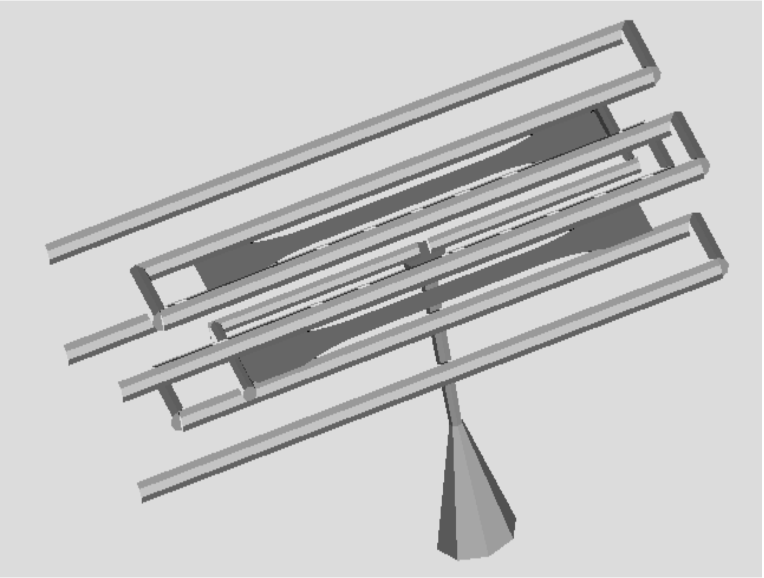

Fig. 1. Geometry model

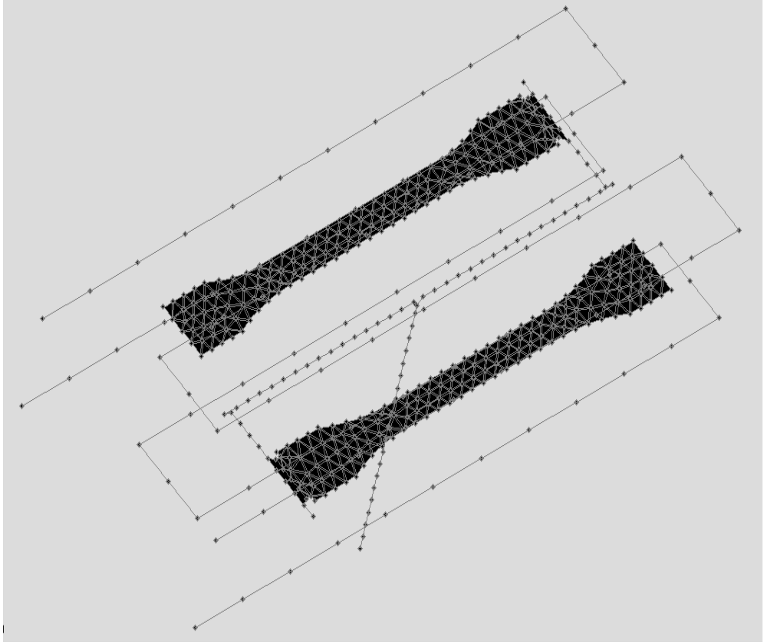

Fig. 2. FEM model

2. Preparing the input data for the simulation

For the proper simulation of injection mould filling it is essential to have the proper input data. These data can be divided to three groups:

- FEM model of the element together with runners, cooling channels and form parting plane,
- plastic properties used for processing (mechanical properties, thermal properties, pVT data, tabulated specific heat, tabulated thermal conductivity, processing properties, cross-WFL viscosity and MFI index), cooler and form materials,
- injection mould machine parameters.

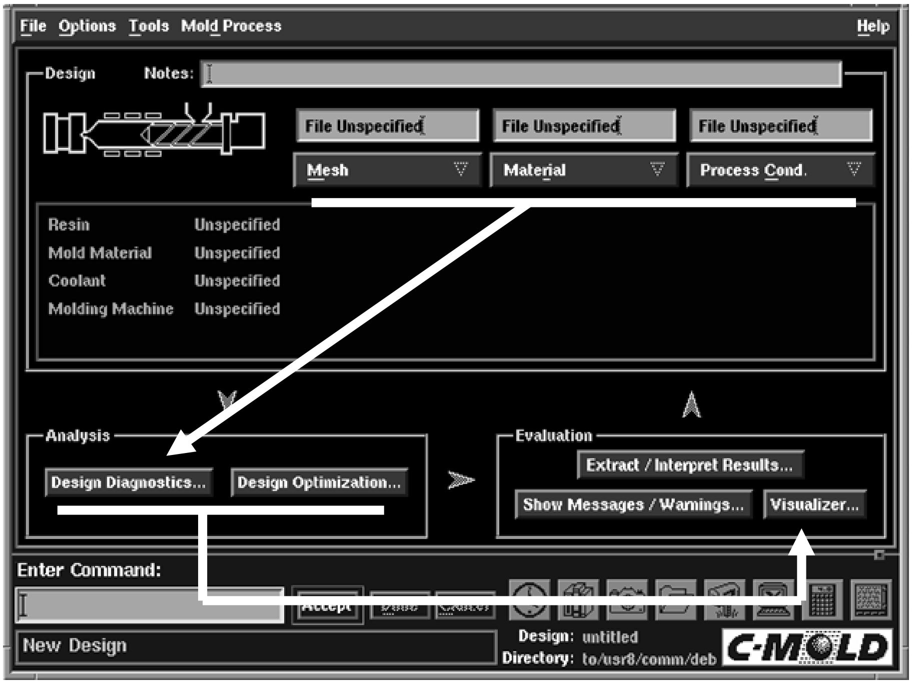

Fig. 3. C-Mold Control Panel

2.1. FEM model

As a sample element the tensile test specimen was used. The geometry of the element as well as the runners and cooling channels and the form parting plane were prepared with use of C-Mold Modeler modulus (Fig.1). C-MOLD Modeler is a powerful computer-aided engineering modeler, developed specifically for the creation of three-dimensional, continuous, thin-shell, finite-element mesh models. C-MOLD Modeler's tools include the geometry editor, topology editor, attributes editor, and mesher:

- the geometry editor is used to create a geometric model, which consists of points and edges, together with surfaces that they may border or lie upon. Edges will be connected to form closed loops, representing topological boundaries. The geometric model constitutes the underlying model upon which topology, attributes, and finally, the mesh, are constructed.
- the topology editor is used to define closed-loop sequences of geometric edges to represent bounded areas. The result is a continuous shell model. It is composed of bounded planar and surface areas, called *regions* and *surface regions,* respectively. These regions and surface regions are connected where they share common boundaries. In addition to defining these boundaries, the topology editor is used to define *inner features*, such as holes, ribs, bosses, gate attachments, or interior regions that might have different attributes.
- the attributes editor is used to define or modify features that complete the definition of the model and, optionally, any associated loads. Included are standard features such as thickness and diameter, and coolant entrance and exit points. Special-purpose attributes include second mold material identification for mold cooling analysis, definition of mold surfaces for blow molding and thermoforming, and fixities and loads for structural analysis.
- the mesher discretizes the regions and surface regions into a three-dimensional, continuous, thin-shell, finite-element mesh appropriate for input into C-MOLD analyses [1].

The preparing consisted in defining the proper model for FEM analysis. After preparing the model FEM meshing was performed. Triangular 2D elements (for regions representing the dog bone and the gates) and beam 1D (for runners and cooling channels) were applied (Fig. 2). The plastic entrance point and the cooler entrance and exit point. The model previously prepared after FEM mesh verification was put to simulating program (Fig. 3. C-Mold Control Panel).

2.2. Materials properties

The analyses require accurate material-property data to generate the best predictions. Obtaining quality data is critical; simulation results can be only as good as the material-property data used.

Such models can be derived from scientific principles or from semi-empirical rules. The model constants can be determined from limited experiments, then used to describe material behavior under other conditions.

Modeling material behavior in the field of polymer processing has never been an easy task, for several reasons:

- material properties often vary from batch to batch (or from time to time),
- using regrind or recycled materials can affect behavior during processing,
- it is difficult to measure properties at the high temperatures,
- shear rates, pressures and cooling rates typical of actual processes,
- material behavior varies with changing conditions; for example, the temperature sensitivity of melt viscosity depends on shear rate as well as temperature.

Typical properties required for thermoplastics injection molding process simulation are:

- in the melt state: thermodynamic properties (density, heat capacity) and transport properties (rheological properties and thermal conductivity of the molten state).
- in the solid state: mechanical properties.

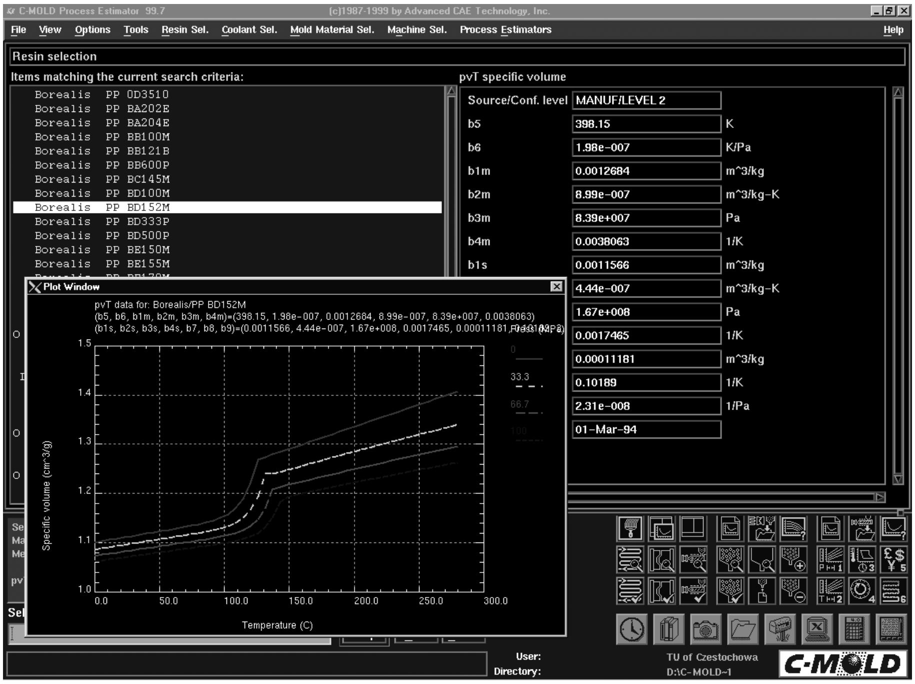

Fig. 4. Resin selection from C-Mold materials database

More sophisticated calculations might require additional properties. Polymer rheology is the most important property used in flow simulations. Most polymers exhibit two regimes of flow behavior, Newtonian and shear-thinning. Newtonian flow occurs at low shear rates, but with increasing shear, the viscosity tends to fall away in what is termed shear-thinning behavior. Viscosity also decreases with increasing temperature.

To incorporate the dependence of melt viscosity on shear rate, temperature, and pressure, the following 5-constant (n, τ^*, B, T_b, β), Cross-exp model is adequate for simulating the filling stage in injection molding [2,3, 5-17]:

$$\eta(T,\dot{\gamma},p)=\frac{\eta_0(T,p)}{1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{1}$$

with:

$$\eta_0(T,p)=B\exp\left(\frac{T_b}{T}\right)\exp(\beta\cdot p) \tag{2}$$

The Cross-exp model treats polymer viscosity as a function of temperature T, and shear rate $\dot{\gamma}$. It handles both the newtonian and the shear-thinning flow regions found in polymer rheology. Unlike many other models in present use, the constants of the Cross-exp model do have a physical significance. The transition between the two regimes is characterized by τ^*, the shear stress at which shear thinning behavior begins to manifest itself. The slope of the shear-thinning curve is characterized by (1 - n). Depending on the material, it might not be possible to generate the complete curve. However, the best rheology data spans both of these regions. If there are insufficient points in the shear-thinning region, the value of n might be erroneous. Similarly, if the data set lies almost entirely in the power-law region, the values of the zero-shear viscosity, η_0 and τ^*, will tend to be ill-defined, even though the product, $\eta_0^{\,n} \times (\tau^*)^{(1-n)}$, will be well-defined, corresponding to the multiplicative factor in the power-law region.

The remaining three constants of the Cross-exp model are used to model the zero-shear-rate viscosity. Concerning T_b, which characterizes the temperature sensitivity of η_0, note that this quantity tends to depend on temperature, especially in the vicinity of the glass transition. As such, this modeling is adequate for the filling stage, where the bulk of the polymer is in the vicinity of the processing temperature, usually more than 100 °C away from the glass transition, where T_b is relatively constant. A more sophisticated model is adopted for post-filling simulations.

To extend the modeling into the post-filling stage, it is more appropriate to employ the following 7-constant (n, τ^*, D_1, D_2, D_3, A_1, $\tilde{A}_2$), Cross-WLF model, which still represents the shear-thinning behavior according to equation (1), but replaces equation (2) with a more extensive model based on the WLF [4, 18, 19] functional form:

$$\eta_0(T,p) = D_1 \exp\left[-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right] \qquad (3)$$

where:

$$T^* = D_2 + D_3 p \qquad (4)$$

and:

$$A_2 = \tilde{A}_2 + D_3 p \qquad (5)$$

T^* is a reference temperature and is typically taken as the glass-transition temperature of the material. That is D_2 corresponds to the glass-transition temperature at low pressure (such as 1 atm), whereas D_3 characterizes the linear pressure dependence of $T^*(p)$.

In addition to the shear viscosity, the simulation of polymer flow dynamics during the filling and post-filling stages requires other properties: mass density ρ, or specific volume $\upsilon = \frac{1}{\rho}$; specific heat C_p, thermal conductivity k, and transition temperature T_{trans}. To complete warpage analysis, mechanical properties are also required. The fill time in injection molding processes is typically very short compared to the characteristic cooling time associated with the given cavity thickness. However, a more accurate representation for the thermal properties is essential for C-MOLD Post-Filling. In particular, the compressibility of the polymer becomes a critical ingredient in modeling the material behavior during the post-filling stage, when additional material is packed into the cavity under high holding pressure to compensate for shrinkage due to continuous cooling.

Specific volume (pvT diagram) is used to obtain information about the compressibility and volumetric expansion of polymeric materials. If the data are obtained under equilibrium, they are fundamental thermodynamic properties of the material. The data are seen to reflect transitions as the material moves from one physical state to another.

Thermal conductivity is one of the most important properties that influence the injection molding pressure prediction. Thermal conductivity for semi-crystalline polymers, however, shows an abrupt increase when temperature drops below the crystallization temperature T_c. This is because of the appearance of the crystalline phase, which creates regions of high thermal conductivity.

The transition temperature is used by C-MOLD analyses as the polymer freeze temperature. This temperature corresponds to the glass-transition temperature T_g, for amorphous polymers and to the crystallization temperature T_c, for crystalline polymers. In theory, the transition points determined from pvT, specific heat, thermal conductivity, and viscosity measurements should be identical. However, typical data for these transition points are not so close, due to the limitations of today's measurement techniques. Particularly for semi-crystalline materials, rate dependence tends to create a significant spread in the transitions measured by the various instruments. At this moment, the best way to determine transition temperature is by a DSC cooling scan.

Polypropylene of Polish made (Petrochemia Plock) which trade name is Malen P J-400 was used for the tests. It should be underlined that the knowledge of all properties of the material used for simulation is the necessary condition for obtaining the accurate results of the simulation. There are two ways of introducing the input data (resins, cooler and form material properties) to the simulator. The first one is to search the built-in materials database (Fig.4). The database contains about 11 000 materials. If the search fails the materials data must be added to the existing database which was done with Malen P J-400. If the search fails the materials data must be added to the existing database which was done with Malen P J-400.

2.3. Process conditions

The injection was performed on Kraus Maffei KM 65/160/C1. This is the injection machine equipped with modern control system that guarantees high accuracy and reparability of the process. The rich instrumentation of the machine allowed for precise recording and storing the injection parameters. Additional sensor placed inside the form (Fig. 5) allowed for monitoring the pressure run in the runner. Technical data of KM 65/160/C1 were found in C-Mold database allowing quick introducing them into the simulator.

The parameters of the process identical to the real ones were introduced:

- inlet temperature 220 °C,
- injection rate 50 cm^3/s,
- filling time 1 s,
- holding time 20 s,
- cooling time 20 s,
- form temperature 32 °C.

3. The simulation process

After introducing all the necessary data into the simulator the simulation of the mould filling itself was performed. Several variants of FEM model were examined in order to determine how its accuracy affects the simulation results.

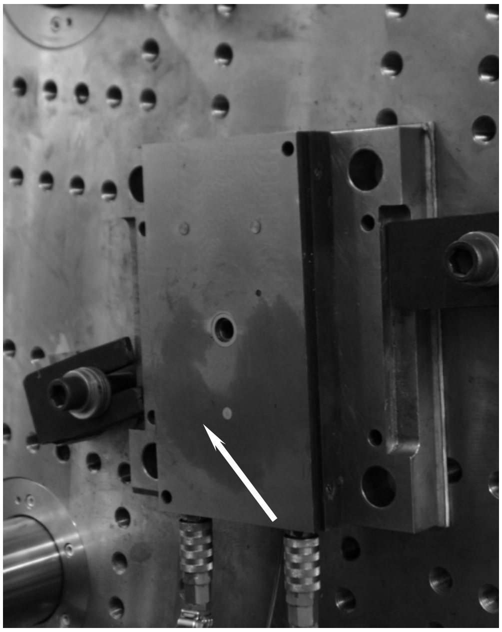

Fig. 5. The view to the stationary part of moulding form with the pressure sensor

C-Mold program requires introducing, among other things, the temperature in plastic entrance point. The temperature measurement of melt resin is usually conducted with use of thermocouples placed in successive heating zones of the injection barrel. Assuming in the simulation plastic temperature in the nozzle closest zone (fig. 6) leads to very serious error in the numerical analysis results (what will be proved). In order to eliminate such an error the region between the end of nozzle and the last thermocouple in barrel was modelled as a part of runner (fig. 7a). A point at the level of thermocouple was assumed to be the plastic entrance point. This "additional" part of runner was modelled both as a cold and hot runner.

The process of introducing the data and running the simulations illustrated by the arrows in fig. 3. After making the calculations and balancing the runners (what was not necessary in the present simulation) the visualisation of the results could started with use of C Mold Visualizer.

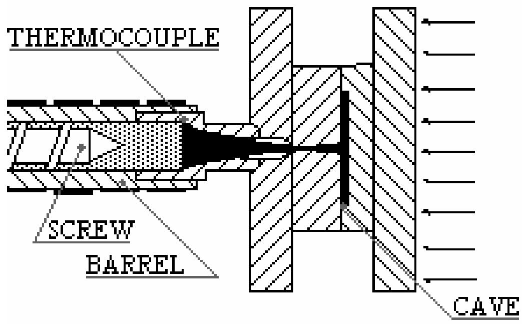

Fig. 6. Temperature sensor localisation (the one closest to the nozzle)

4. The results and discussion

The tests delivered comparative material that allowed for estimating the correctness of the simulations performed. In fig. 9 the results of the numerical analysis and real process were correlated.

The runs illustrate the change of pressure value in the form for individual models vs time. The filling and the beginning of postfilling stages were considered. The results analysis proved the insignificant influence of the modelling of additional runner as a hot one. The simulation results of the above model were identical. The figure 9 shows the significant influence of the model modifications on numerical analysis results. The discussed above model modification gave the results about 30% better then these for the standard model.

5. Conclusions

The tests carried out lest us to draw the following conclusions:

- The results of the numerical simulations depend mostly on input data accuracy. Accuracy means here the knowledge of detailed description of the real materials with use of FEM model as well as the material and process parameters.

- The bad name on a lack of practical use of simulation software arises mainly from insufficient knowledge of processes occurring during injecting and the technique of creating the FEM models.
- Inaccuracy of the described simulations (despite model modification) results from the fact that the authors did not have full range of plastic properties data and the tests of the resin properties were performed under slightly different conditions than these recommended by the C-Mold laboratory.

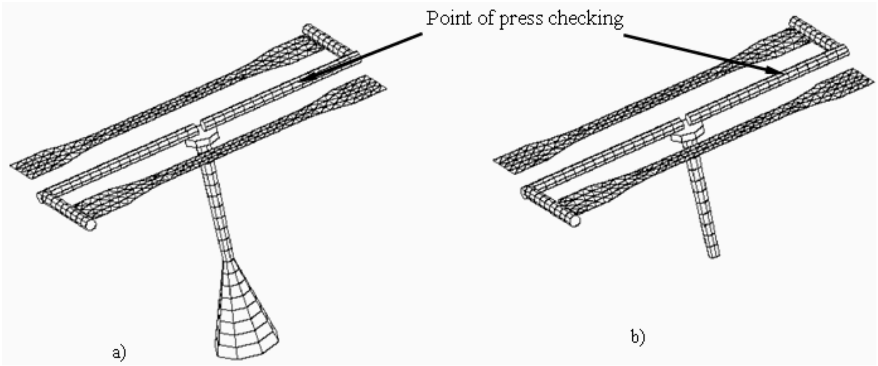

Fig. 7. FEM models used for the simulation (without cooling channels):
a) model with runner correction,
b) standard model

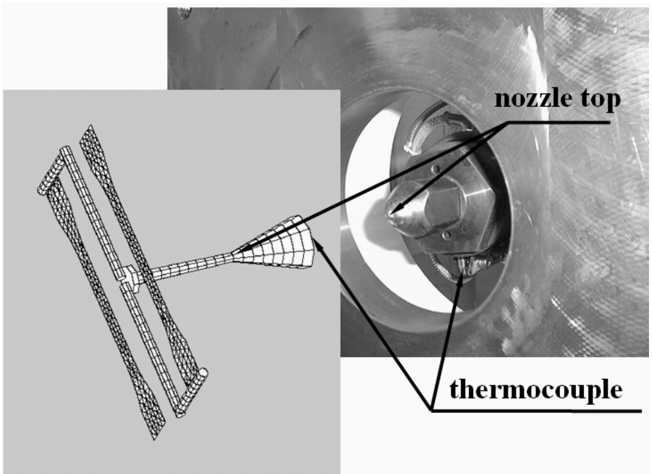

Fig. 8. Illustration the region between the end of the nozzle and the last thermocouple in barrel (a point at the level of thermocouple was assumed to be the plastic entrance)

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