Strojniški vestnik - Journal of Mechanical Engineering 53(2007)7-8, 503-518
UDK - UDC 678.056:678.7
Izvirni znanstveni članek - Original scientific paper (1.01)

Optimiranje debeline brizganih plastičnih delov na podlagi simulacije Moldflow

Minimizing the Thicknesses of Injection-Molded Plastic Parts Based on a Moldflow Simulation

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Določitev debeline izdelka je pomembna naloga pri konstruiranju brizganih plastičnih izdelkov. Praviloma želimo čim tanjše debeline izdelkov, s čimer se prihrani material, toda pri tem mora izdelek še vedno zadostiti vsem zahtevam po kakovosti. Obstaja že množica metod za optimizacijo debeline na podlagi strukturne optimizacije, torej metode, ki temeljijo na trdnosti, stabilnosti, deformaciji itn. V nasprotju s tem pa je bilo narejenih zelo malo raziskav s področja optimizacije debeline izdelkov na podlagi brizganja ter drugih kakovostnih zahtev s področja brizganja. Konstruiranje plastičnih izdelkov brez optimizacije debeline, ki temelji na kakovosti brizganja vodi bodisi k odvečni uporabi materiala, bodisi k slabši kakovosti brizganja. Kot prvi korak k problemu je v prispevku prikazan poskus zmanjšanja debeline izdelka z uporabo simulacijske metode znotraj programskega paketa Moldflow®. V grobem je postopek sestavljen iz avtomatiziranega iterativnega postopka, ki spreminja debelino izdelka ter izvaja simulacijo brizganja plastike Moldflow, ter zajema rezultatov simulacije za oceno kakovosti brizganja, vse dokler niso dosežene postavljene zahteve konstrukcije. Predlagan je postopek za spreminjanje debeline izdelkov, ki je pod različnimi pogoji voden z omenjeno metodo. Predlagani so trije konvergenčni kriteriji za optimizacijo, prav tako pa je razvit in predstavljen prototip programske opreme, ki vključuje predstavljeno metodo. Z namenom predstavitve metode in izdelane programske opreme je v prispevku prikazan konstrukcijski študijski primer. Opisano delo je potrdilo, da je predlagana metoda primerna za minimalizacijo debeline izdelkov na podlagi kakovosti brizganja.

(Ključne besede: brizganje polimerov, optimiranje debeline, simuliranje, programski paketi, MOLDFLOW)

Determining the thickness of parts is an important task in injection-molded plastic-part design. In general, the thicknesses of parts should be minimized so that less material is used and at the same time the relevant quality requirements are also met. There are already a number of methods for thickness optimization in the area of structural optimization, where strength, stability, deformation, etc., are the primary concerns. In contrast to this, very little work has been done on thickness optimization that is oriented to part moldability and other molding-quality requirements. Without molding-quality-oriented thickness optimization, the plastic-part design will result in either a waste of material or poor molding qualities. As a first step to tackle this problem, this paper attempts to seek minimized part thicknesses by employing a Moldflow® simulation-based method. Briefly, it consists of an automated, iterative process of changing the part thicknesses, conducting a Moldflow simulation, retrieving the simulation results to assess the specified molding-quality criteria, until the design objectives are met. A route for part-thickness change is proposed, which is governed by the respective methods under several different situations. Three convergence criteria are proposed. A software prototype implementing the methodology was developed and presented. To illustrate the methodology as well as the software, a design case is also studied. The paper shows that the proposed methods are applicable to the molding-quality-oriented part-thickness minimization.

(Keywords: injection moulding, thickness optimization, simulations, software packages, MOLDFLOW)

0 INTRODUCTION

In injection-molded plastic-part design a number of requirements have to be taken into account, such as functionality, economy, moldability, ease of use, ease of service, and so on. Among other design tasks, the determination of the thicknesses of a plastic part has significant influences on the fulfillment of these requirements. In general, part thicknesses should be minimized so that less material is needed for the part, thus reducing its cost. This, however, is constrained not only by the requirements for mechanical, thermal and/or other aspects of performance of the part, such as strength and stiffness, but also the requirements on moldability and other molding-quality measures. A part that is too thin may cause defects in the molding process; or it may experience early failure in its usage. Hence, it is necessary to develop strategies and methods to minimize part thicknesses without violating any of these constraints.

There has been considerable work on thickness optimization from the perspective of structural optimization, concerning functional and performance requirements. However, the work on thickness optimization concerning molding-quality requirements is scarce. This has led to the problem that the parts are either unnecessarily thick or too thin to satisfy all the molding-quality requirements. As an initial step in achieving the molding-quality-oriented part-thickness optimization, this paper proposes a simulation-based method using the well-known injection-molding simulation software “Moldflow”. By “thickness minimization”, we mean that the target of optimality is fixed as the part thicknesses; and the molding qualities are not taken as the optimization objectives, but rather as the constraints of the problem. The method is based on the assumption that the preliminary design of a plastic part has already taken structural requirements into account, that is to say, the design problem may be initialized as consisting of a part structure (the geometry) and the relevant structural constraints relating to the part thicknesses. This initial structure and the constraints ensure that the design satisfies the functional and performance requirements. As a result, one of the subsequent design tasks, to be addressed in this paper, would be to determine the minimized part thicknesses, with which the part can further achieve the goal of moldability and satisfy other specified molding-quality requirements.

In the next section, a brief literature review will be given to further clarify the problem. Section 2 discusses the method in enabling the integration between injection-molding CAD and CAE, which works as a basis for the proposed simulation-based thickness minimization. Section 3 elaborates the relevant thickness-minimization methods, such as the iterative procedure, the thickness-change route, and so on. Section 4 studies a design case, whose results are discussed in Section 5. Section 6 concludes the study.

1 LITERATURE REVIEW

Thickness optimization has been well researched from the perspective of structural optimization. For example, McClung *et al.* [1] discussed the non-linear structural optimization of thickness in plastic-part design. Lam *et al.* [2] discussed the thickness optimization of plate and shell structures, where stress and stiffness are the optimality criteria. Rietz & Petersson [3] have studied the simultaneous optimization of both shape (topological structure) and thickness, where again the performance requirements are the objectives of the optimization.

As can be seen, all of the above work focuses on satisfying various functional and performance requirements. None has targeted the molding-quality requirements.

Among the few reports on molding-quality-oriented thickness optimization, Lee & Kim [4] studied the optimization of part thickness by employing a “Modified Complex Method” for its optimization algorithm, where a simulation-based approach was adopted using C-Mold software (which is now incorporated in the Moldflow package). Their work, however, is specifically for reducing warping, which is only one of the many molding quality measures. In another article of theirs, thickness optimization for a robust design against process variability was studied, where warping was once again selected as the target of optimization. By using FEM/ANN/GA (finite-element method, artificial neural network, genetic algorithms), Huang & Huang [5] discussed a thickness optimization method for blow-molded parts, yet the work was focused on a uniform part thickness after blow molding, without taking into account various other molding-quality requirements.

In fact, simulation software such as Moldflow has now been widely used in industry. There are also many reports on injection-molding optimization, adopting a simulation-based approach. For example, Pandelidis & Zou ([6] and [7]) have proposed an optimization method based on Moldflow simulation by using an objective function to characterize a quality measure of the molded part, which was based on the criteria of temperature difference, overpacking and frictional heating. Both the gate location and the molding conditions were optimized.

Due to concern about the computation time incurred in the simulation-based approach, some AI (artificial intelligence) techniques have been attempted for injection-molding optimization, such as neural networks ([8] to [10]); fuzzy logic [11]; and case-based reasoning ([12] to [14]).

However, even these AI-based approaches are not completely free from simulation – many of them rely on simulation for knowledge acquisition and/or verification of the design outcome. Furthermore, with the rapid advances in computer technology and in the functionality of simulation packages, the simulation-based approach is becoming increasingly viable and affordable.

As such, it is legitimate to consider using a simulation approach in achieving the molding-quality-oriented part-thickness optimization.

However, to implement the Moldflow simulation-based approach, a problem must be solved first: Moldflow cannot be used to improve a design such as part-thicknesses minimization directly; it is just meant to provide a designer with an intuitive result, regarding whether a specific part and/or molding-process design is good or not. The designer has to find a suitable part thickness by trial-and-error, i.e., the designer must modify the part thicknesses after each execution of the simulation and evaluation of the simulation results. This is not only time consuming and error prone; more importantly, it is by no means possible to guarantee an optimized result with a finite number of trials.

To enable an iterative process of part-thickness change, Moldflow simulation, simulation-result retrieval and objective-function calculation to be carried out automatically using a computer program, so that a simulation-based thickness minimization can be implemented, the technology of the *injection-molding CAD-CAE integration model* may be leveraged. This is an object-oriented feature-based model that incorporates both design and analysis information about an injection-molded part [15]. The model consists of a number of hierarchically organized features, such as part feature, wall feature, hole feature, rib feature, boss feature and treatment feature. The part feature holds the overall information about the part, while all the other features are constituent components of the part.

These features are defined by both their geometrical and topological information from the part's CAD model, as well as the relevant CAE analysis data. They are thus referred to as the *CAD-CAE features*. For example, the part material, the boundary conditions, the processing conditions, *etc*., are the overall CAE analysis information, and thus are stored in the part feature. Suppressibility is a measure of whether or not a feature should be suppressed, so as to prevent it from being incorporated into the CAE analysis model. It is used to simplify the CAE model and thus applies to the features such as rib, boss, hole and treatment. Wall, rib and boss features all have an attribute of thickness, relevant to the topic of this paper.

The CAD-CAE features also hold constraints on their respective relevant attributes. For example, the desired molding quality criteria may be defined as a constraint of the part feature, while the constraint on the gate location on a wall feature may be defined as the constraint of the corresponding wall feature. For thickness minimization, the constraint on the thickness of a certain feature can be specified on that particular feature.

The model uses a CAD and a CAE system as its underlying platforms [16]. The part-geometry data is stored in the part CAD database, which is established by the CAD platform. ActiveX automation from the CAD system (*e.g.,* Solid Edge®) is employed for the model to access the part geometry data as well as the operations on these data. The model exploits the exposed functionalities of the CAD system through its automation server. Given that such an integration model is created and fully specified, the relevant routines of the underlying CAE system (*e.g.,* Moldflow) can then be activated to generate an analysis model (the mesh), which in turn can be used for the CAE analysis. As such, the integration model enables the automatic execution of part-geometry change and retrieval, such as the assignment of gate location on the part geometry (on the CAD side); and the execution of the relevant Moldflow modules and the retrieval of simulation results (on the CAE side), hence enabling an injection-molding CAD-CAE integration [17].

To conclude, the work on molding-quality-oriented part-thickness optimization is scarce and not comprehensive in terms of the number of molding qualities addressed. A simulation-based approach may be employed when addressing the problem of thickness minimization, for which the technology of the injection-molding CAD-CAE integration model may be leveraged.

2 CAD-CAE INTEGRATION FOR PART-THICKNESS MINIMIZATION

Before exploiting the existing CAD-CAE integration model in the part-thickness minimization, some enhancements to the integration model should be made first. These enhancements are used to enable the specification of the features whose thicknesses need be minimized, as well as the specification of molding-quality criteria to formulate the objective function.

2.1 Step variable for thickness change

A new attribute, i.e., a list of shape modification variables, is introduced for the CAD-CAE features. This is used to change the part geometry, including the part thicknesses. By specifying shape-modification variables, different types of shape modification problems, either positional or sizing of an individual feature, or modification to different features, can be handled in a unified manner. Hence, it benefits both model consistency and software-development efforts. In this paper, the shape-modification variable is used specifically for the step value of changing the part thicknesses, which is thus called the *step variable*, denoted as a “Step”.

The part thicknesses may be changed by increasing or decreasing a step value from the thicknesses of the relevant features bearing a thickness attribute, such as the wall feature (*e.g.,* the thin-wall feature and the extrusion feature in Solid Edge), and the rib feature (*e.g.* the rib and web-network feature in Solid Edge). By following the route of thickness change to be elaborated later, with the help of this step variable, the minimized part thicknesses can then be derived. (This is elaborated in Section 3.)

2.2 Formulation of the objective function

The designer should also specify the molding-quality measuring criteria, to be used for the formulation of the objective function for the intended thickness minimization. Some of these criteria are as follows [18]:

- The shear stress should not exceed the maximum recommended for the material type;
- The shear rate should not exceed the maximum recommended for the material type;
- The flow-front temperature should not be more than 20°C below the melt temperature;
- The cooling time should be uniform and minimized;
- The melt flow should be uniform, that is, the designer should try to make sure that all extremities are filled at the same time and at the same pressure.
- The designer may also have some specific quality requirements, such as minimizing the maximum shear stress, minimizing the maximum cavity pressure, uniform end-of-fill temperature, uniform volumetric shrinkage, and uniform warping. Some of these requirements may be imposed on a particular location or area of the plastic part, such as the shear stress requirement at the vicinity of snap fits, screw holes, occasional thin areas and where frequent bending may be necessary.

To enable the designer to specify these criteria rather than hardwire them in a computer program, the part feature is extended to include an attribute for storing a list of criteria construction variables, from which the objective function can be formulated. Some of these variables (the units are put inside the brackets) include the melt temperature (°C), the mold temperature (°C), the specified injection time (s), the actual injection time (s), the maximum shear stress (MPa), the maximum shear rate (1/s), the maximum pressure (MPa), the maximum flow-front temperature (°C), the minimum flow-front temperature (°C), the maximum end-of-fill temperature (°C), the minimum end-of-fill temperature (°C), the maximum cooling time (s), the minimum cooling time (s), the maximum volumetric shrinkage (%), the minimum volumetric shrinkage (%), the maximum clamp tonnage (tons), etc.

With these variables, the designer may select the relevant variables and then formulate the molding-quality criteria and objective function for the part-thickness minimization. For example, if the designer wishes to specify a constraint relating to the maximum shear stress, *e.g.,* the maximum shear stress should not exceed 0.2 MPa, he or she can select this variable (assuming it is denoted as "v1") and formulate the constrained objective function as follows:

$$\begin{cases} \text{Minimize:} \quad x = f\,(v1) \\ \text{Subject to:} \quad v1 < 0.2 \end{cases} \qquad (1),$$

where the variable x is the number of times of the "Step" is used to increase the minimized part thicknesses, *e.g.,* x = -1.5 means that the minimized part thicknesses would be the original thicknesses reduced by "1.5 Step" (the value of "Step" is previously specified by the designer). The relationship between the variable x and the variable v1, *i.e.,* the function f (v1), is implicitly determined by the Moldflow simulation results. Given a specified value for the variable x, which determines the part geometry, there would be the value for the variable v1 from the Moldflow simulation results. Since there is no explicit mathematical relationship between x and v1, the usual optimization procedure is not applicable. This is addressed in the next section.

It is worth noting that the optimization result should be examined against the requirements on thicknesses from the part's structural design, to ensure that the part can function properly in its application.

3 PROCEDURE FOR PART-THICKNESS MINIMIZATION

By not taking the usual steps of optimization, this paper proposes a specific way for part-thickness minimization, in that the minimization is achieved by directly changing the part thicknesses until an optimality is eventually arrived at. To make the elaboration of the methodology easy and clear, we will be introducing a software prototype first. This software was developed to implement the proposed thickness-minimization approach. It was developed using Microsoft Visual C++® as the programming language, where Solid Edge is used as the underlying CAD system, and Moldflow is used as the underlying CAE system. Fig. 1 shows the graphical user interface (GUI) of the software, where the Solid Edge environment is shown, while

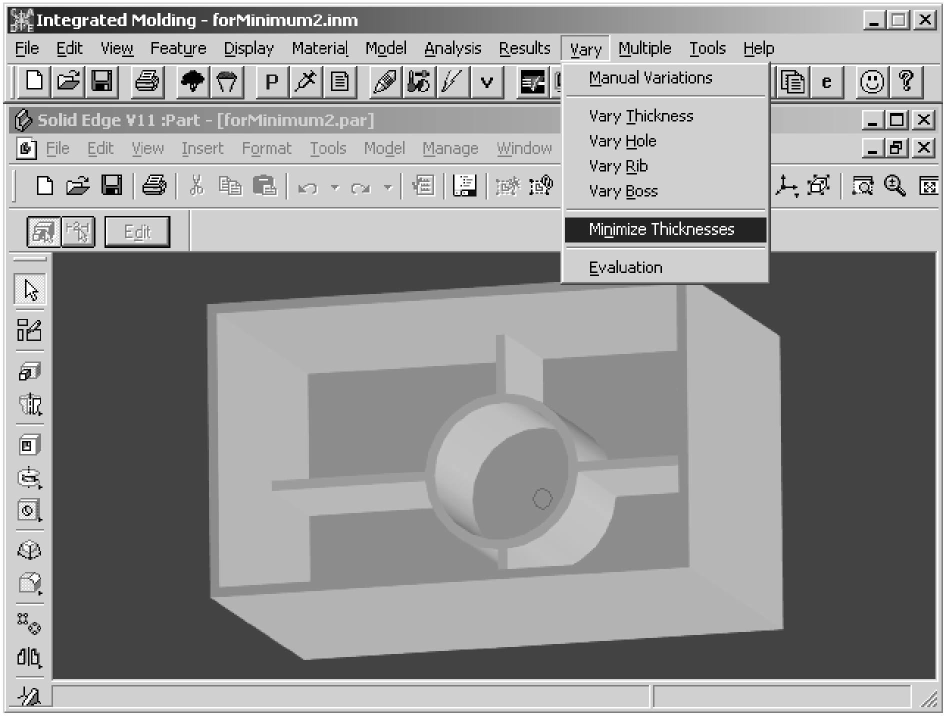


Fig. 1. *User interface of the developed software for minimizing part thicknesses*

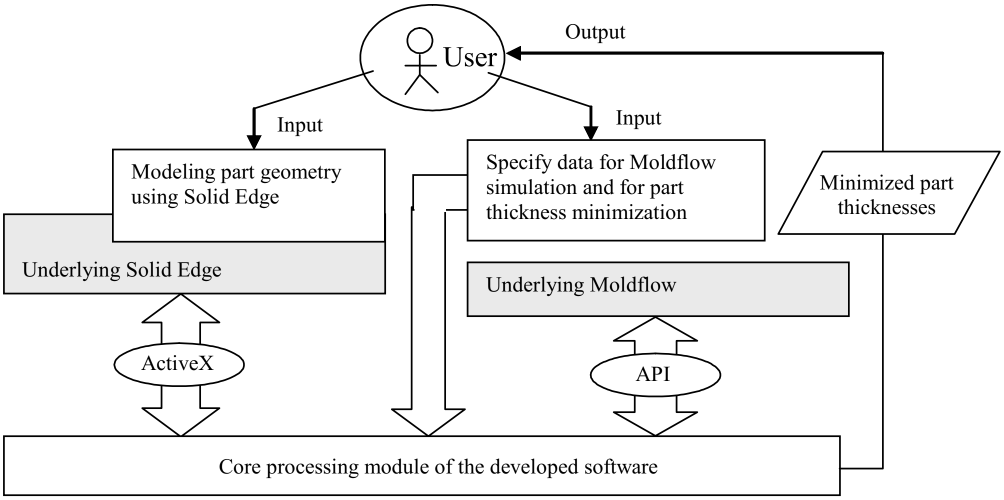


Fig. 2. *System framework of the developed software*

the Moldflow module is not shown because it only appears when its relevant routines are activated by the software. The screen snapshot also captured a part geometry, which will be used later as the case study.

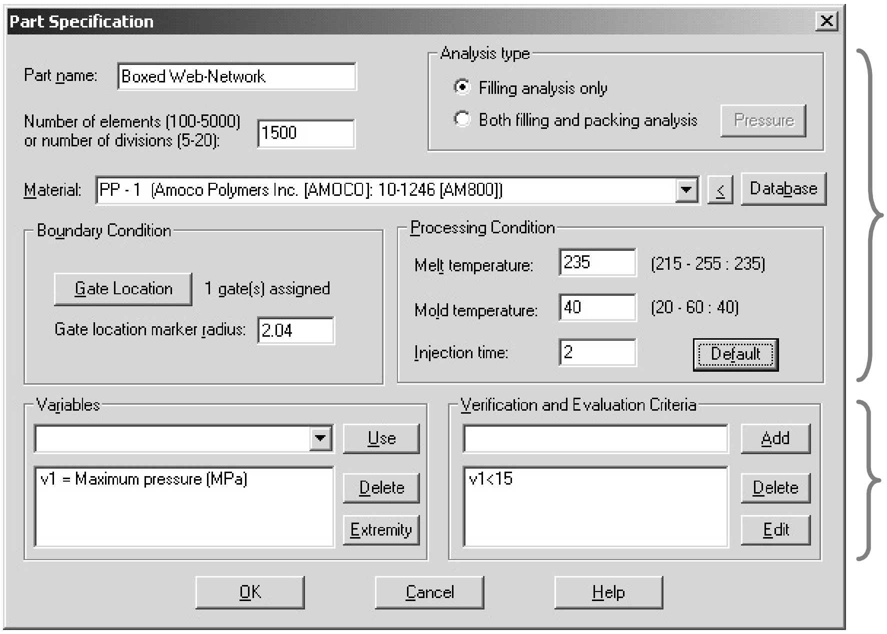
It should be noted that the software has been developed over the past several years, addressing a number of injection-molding optimization problems. This paper only deals with the newly added function module of part-thickness minimization, which can be activated by using the highlighted (mouse-selected) menu item: "Minimize Thicknesses". The system framework of the developed software is shown in Fig. 2. Basically, it consists of two input modules, a core processing module and an output module, in addition to the two underlying systems (*i.e.,* Solid Edge and Moldflow). The communication between the core processing module and Solid Edge is through the ActiveX automation of Solid Edge. By ActiveX automation, Solid Edge exposes its functionalities to the outside world (*i.e.*, the other applications). The communication between the core processing module and Moldflow is through the APIs (Application Program Interfaces) provided by Moldflow. The following sections will introduce these modules, which form the proposed procedure for minimizing the part thicknesses.

3.1 Step 1: to create the initial integration model using the first input module

According to the existing CAD-CAE integration model, the designer first creates a part geometric model by using the underlying CAD system, *i.e.,* Solid Edge. After that the Moldflow simulation analysis information should be specified, including the part material, the gate location (as a boundary condition), the melt temperature, the mold temperature, the injection time, *etc.* (See references [15] to [17] for details.) For the mesh generation, the designer should also specify the mesh-density data, such as the number of elements or the number of divisions of unit length. Fig. 3 shows a screen snapshot, where the upper section is the user interface for specifying such information.

The specified data are used for the Moldflow simulation, which in turn is used for calculating the molding-quality criteria. As such, the designer should also specify or formulate quality criteria by first selecting criteria-construction variables. The lower section of Fig. 3 shows the user interface for selecting the relevant variables, as well as for formulating the quality criteria. For the variable selection, as is shown in the lower left corner, the combo-box stored all the aforementioned variables. By clicking the "Use" button, the selected variables will be listed in the list-box below the combo-box. For the criteria formulation, as is shown in the lower-right corner, the designer can use the "Add" button to put the formulated criteria into the lower list-box. For brevity, the use of the other buttons ("Edit", "Delete", "Extremity") is not elaborated. The detailed procedure for formulating the quality criteria from the criteria construction variables can be found in [17].

By using this input module, the initial integration model will be created, which contains all the data shown in Fig. 3.



Part name: Boxed Web-Network

Number of elements (100-5000) or number of divisions (5-20): 1500

● Filling analysis only

○ Both filling and packing analysis

Material: PP - 1 (Amoco Polymers Inc. [AMOCO]: 10-1246 [AM800])

1 gate(s) assigned

Gate location marker radius: 2.04

Melt temperature: 235 (215 - 255 : 235)

Mold temperature: 40 (20 - 60 : 40)

Injection time: 2

v1 = Maximum pressure (MPa)

v1<15

Specify data for Moldflow simulation

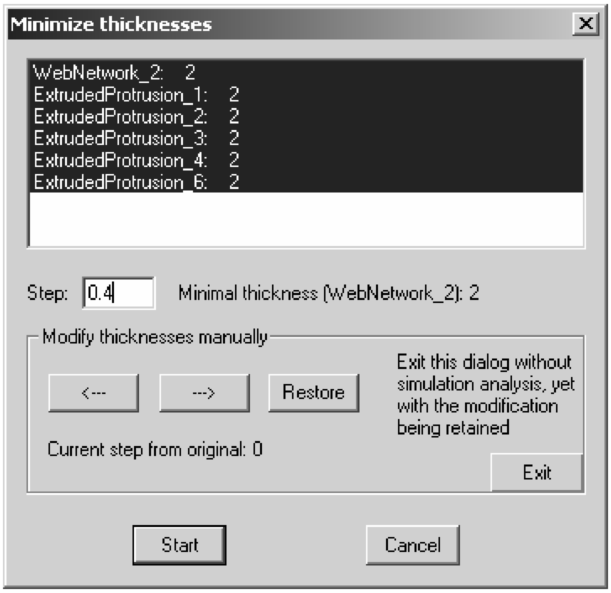
Select variables & specify criteria

Fig. 3. *Specify the data for the Moldflow simulation and the quality criteria*

3.2 Step 2: to specify the features whose thicknesses need be minimized by using the second input module

By exploiting the ActiveX automation of Solid Edge, the software automatically examines all the features of the part geometry, and lists those features bearing thickness attributes. The designer can then select which of these features will be used for the thickness minimization. Fig. 4 shows the user interface for selecting these features, as well as other relevant data for the part-thickness minimization. This is the second input module of the software.

The upper list-box lists the features and their corresponding initial thicknesses. The designer also needs to specify the step value of the thickness



WebNetwork_2: 2
ExtrudedProtrusion_1: 2
ExtrudedProtrusion_2: 2
ExtrudedProtrusion_3: 2
ExtrudedProtrusion_4: 2
ExtrudedProtrusion_6: 2

Step: 0.4

Minimal thickness (WebNetwork_2): 2

Current step from original: 0

Exit this dialog without simulation analysis, yet with the modification being retained

Fig. 4. *User interface for specifying the features whose thicknesses should be minimized*

change with which the thicknesses of the selected features will increase or decrease each time the part geometry is modified during the iterative part-thickness minimization process. The user interface also shows the minimal thickness of the selected features, which is used to help the designer in specifying the step value.

There is an additional functionality within this user interface, in that the designer can also manually change the initial thicknesses of the selected features. The user can dynamically reduce or increase the selected feature thicknesses by pushing the buttons “⟵” and “⟶” respectively, with each push changing the step value.

After all the intended features are selected and the step value is assigned, the designer can push the “Start” button to start the thickness minimization process.

3.3 Step 3: an iterative process following a route of thickness change by using the core processing module

Generally, for a thin-walled plastic part, increasing the part thicknesses will enhance the molding-quality results. (These should of course be within certain limits, because if the thicknesses are too large, the part will not be thin-walled, and then even the Moldflow simulation results will not be trustworthy.) The thickness minimization process is in effect a process of how the part thicknesses should be changed, *i.e.,* a route of thickness change should be identified. At first, the initial part (without thickness change) should be used to conduct a Moldflow simulation analysis. This is denoted as the first simulation. The implementation software will make use of the specified data discussed in Section 3.1 to activate the necessary Moldflow routines to fulfill the task. Upon completion, the software will extract relevant data from the simulation results and calculate the specified quality-measuring criteria to determine whether any of them is violated. Depending on the results from the first simulation, there will be two situations for the next step of action (*i.e.,* how the thicknesses should be changed):

(1) If all the criteria are met (we say the simulation has “passed”), the part thicknesses may be reduced. Hence the thicknesses of all the selected features will be reduced by a step value, denoted as “- Step”.
(2) If one or more of the criteria are not met (we say the simulation has “failed”), the part thicknesses will have to be increased. Hence, the thicknesses will be increased by a step value, denoted as “+ Step”.

The changed part geometry will then be used to activate another round of Moldflow simulation and criteria calculations; this is called the second simulation.

After the first two simulations, there will be four situations for the next step of action (*i.e.,* how the third simulation is going to be activated), depending on their results:

(1) If the first simulation passed and the second simulation passed again, then the next step will be reducing the thicknesses by another step value, *i.e.,* “- Step”.
(2) If the first simulation failed, and the second simulation failed again, then the next step will be increasing the thicknesses by another step value, *i.e.,* “+ Step”.
(3) If the first simulation passed, while the second simulation failed, then the next step will be increasing the thicknesses for ½ Step, denoted as “+ ½ Step”. This is because, from the first to the second simulation, see Fig. 5 (a), the change

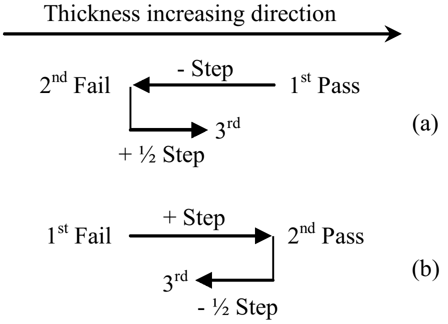


Fig. 5. *Situations involving "± ½ Step" of thickness change: (a) "+ ½ Step"; (b) "- ½ Step"*

of thickness was "- Step"; now from the second to the third, the part thickness increase should obviously be less than one "Step". As such, "+ ½ Step" is used.

(4) If the first simulation failed, while the second simulation passed, then the next step will be reducing the thicknesses by ½ Step, denoted as "- ½ Step". The reason for this situation is the same as situation No.3. See Fig. 5 (b) for an illustration.

The fourth simulation will depend on the results from the second and the third simulations. Like with the above four situations, the change in the part thicknesses will be "± Step", or "± ½ Step", or "± ¼ Step". The first two are easy to understand. The situations of "± ¼ Step" occur when "± ½ Step" were used from the second to the third simulation, and there were Pass/Fail swaps between these two proceeding simulations. For example, in Fig. 5 (a), there was "+ ½ Step" thickness change from the second (Failed) to the third (assuming Passed). Since the third simulation has passed, the next step will be changing the thicknesses by "- ¼ Step". In Fig. 5 (b), there was "- ½ Step" thickness change from the second (Passed) to the third (assuming Failed). Since the third simulation has failed, the next step will be changing the thicknesses by "+ ¼ Step".

However, if there was no Pass/Fail swap, the next step will arrive at a part geometry that has thicknesses already encountered before. For example, in Fig. 5 (a), from the second simulation (Failed) to the third simulation (assuming Failed again), the change of "+ ½ Step" again will lead to the part geometry for the fourth simulation be the same as that for the first simulation. In Fig. 5 (b), from the second simulation (Passed) to the third simulation (assuming Passed again), the change of "- ½ Step" again will lead to the part geometry for the fourth simulation also being the same as that for the first simulation. To avoid repetition of the same Moldflow simulation, thus saving computation time and other resources, the implementation software stores the results of each simulation and automatically retrieves them once a past record is encountered.

The subsequent steps will follow the above route of the thickness-minimization process. The process stops once any of the following situations occur (called the convergence criteria):

(1) If the thickness change from the previous simulation to the current is in between "± ¼ Step" and "± 1/16 Step" inclusive, and the current simulation has passed the specified criteria, the process will stop and the part thicknesses corresponding to the current simulation will be the thickness minimization result. If the thickness change has already arrived at "± 1/16 Step" and the simulation has always failed since after the thickness change of "± ¼ Step", then there is no need for the process to proceed further, and the part thickness corresponding to the last passed simulation (which should be before the "± ¼ Step" was encountered) will be the thickness minimization result. The latter is necessary because there is no practical usefulness in getting an extremely small thickness change.

(2) If the total number of simulations has exceeded 30, the process stops, and the part thicknesses corresponding to the last passed simulation will be the thickness minimization result. If, however, there has been no successful simulation, then the work for thickness minimization is considered unsuccessful. In such a case the designer may consider increasing the specified step value, and executing the implementation software again. For example, if the specified "Step" value is 0.01mm, then after 30 times of "± Step" thickness change, the total thickness change is only 0.3 mm, which may not be significant enough to affect the simulation results effectively.

(3) If the minimal thickness was less than 0.1 mm, which is too small to be practically applicable, then the process stops, and the part thicknesses corresponding to the last passed simulation will be the thickness minimization result. The work for thickness minimization is considered unsuccessful if there was no successful simulation previously. Of course, this situation is very unlikely to occur, unless the specified criteria are extremely loose. This is because such small thicknesses shall definitely lead to a very low level of molding quality.

4 CASE STUDY

4.1 Problem assignment

The design case is a plastic box with a web-network inside (a cylinder and four plates), as shown in Fig. 6. It consists of several wall features (called extruded protrusions in Solid Edge), and a web-network feature. This part structure was chosen because it comprises most commonly used features where the thicknesses of the features might be changed. The web-network feature is representative of rib features because they are all used for the enforcement of the part strength. The initial thicknesses are all 2 mm. The part geometric model was created interactively by using the modeling tools provided by Solid Edge. A circle sketch was also created, which is used by the CAD-CAE integration model to indicate the gate location. The analysis information specified includes:

- Part material:
  Type: PP (Polypropylene);
  Manufacturer: Amoco Polymers Inc. [AMOCO];
  Trade name: 10-1246 [AM800].
- Boundary condition: the gate location is defined by the centre of the circle sketch, which is at the outer side of the part's bottom surface, as is shown in Fig. 6;
- Molding conditions (the melt temperature and mold temperature are suggested by the Moldflow material database):
  Melt temperature: 235°C;
  Mold temperature: 40°C;
  Injection time: 2 s.
- Criteria construction variable:
  $v1$ = maximum cavity pressure (MPa).
- The molding quality criterion for the thickness minimization:
  $v1 < 15$.

The goal of the current design problem is to seek the minimized part thicknesses, including the thicknesses of the wall features and the web-network feature, on the condition that the specified criterion can be met. The objective function is thus formulated as:

$$\begin{cases} \text{Minimize:} & x = f(v1) \\ \text{Subject to:} & v1 < 15 \end{cases} \quad (2),$$

where the variable x has the same meaning as in Equation (1), mentioned in Section 2.2. Fig. 4 shows the selected features and the specified step value (0.4 mm).

4.2 Solution

After the specification of the above data, the software will automatically generate a mesh model from the part geometry, conduct the Moldflow simulation, extract the analysis results, evaluate the molding-quality criteria, and then change the part thicknesses, following the route of the thickness change. The process is iterative, until one of the convergence criteria is met. Fig. 7 shows a screen snapshot of the final results of this design case.

A close look at the results summary (Fig. 7) will reveal the route of the thickness change, as is illustrated in Fig. 8. The first two simulations all

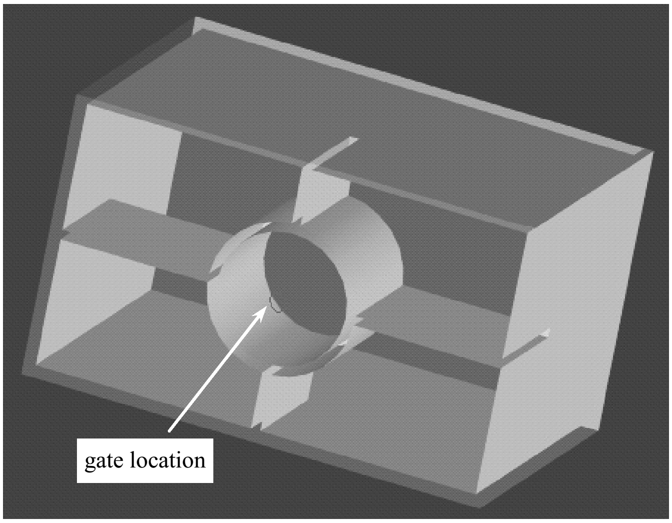
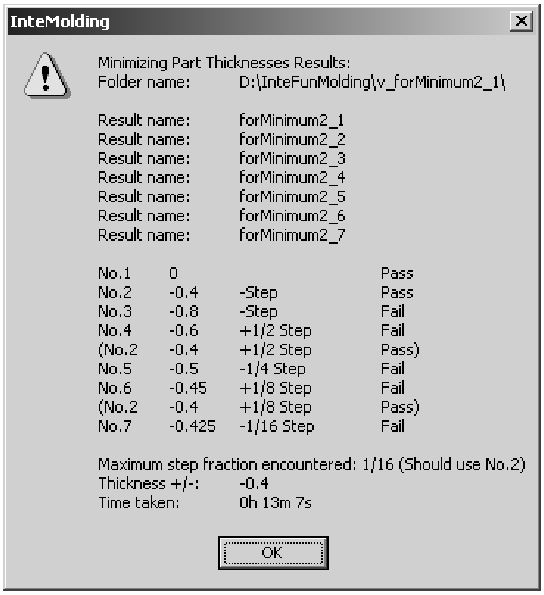


Fig. 6. *Initial part geometry (the small circle in the sketch indicates the gate location). Remarks: (1) the box and the interior web-network feature were displayed in different colors just for viewing purposes; (2) the wall with the circle sketch, i.e., the bottom wall of the box, was intentionally displayed in a transparent color to allow its inside to be seen.*



```
InteMolding

Minimizing Part Thicknesses Results:
Folder name:        D:\InteFunMolding\v_forMinimum2_1\

Result name:        forMinimum2_1
Result name:        forMinimum2_2
Result name:        forMinimum2_3
Result name:        forMinimum2_4
Result name:        forMinimum2_5
Result name:        forMinimum2_6
Result name:        forMinimum2_7

No.1     0                          Pass
No.2     -0.4     -Step             Pass
No.3     -0.8     -Step             Fail
No.4     -0.6     +1/2 Step         Fail
(No.2    -0.4     +1/2 Step         Pass)
No.5     -0.5     -1/4 Step         Fail
No.6     -0.45    +1/8 Step         Fail
(No.2    -0.4     +1/8 Step         Pass)
No.7     -0.425   -1/16 Step        Fail

Maximum step fraction encountered: 1/16 (Should use No.2)
Thickness +/-:      -0.4
Time taken:         0h 13m 7s
```

Fig. 7. *Thickness-minimization results for the studied design case*

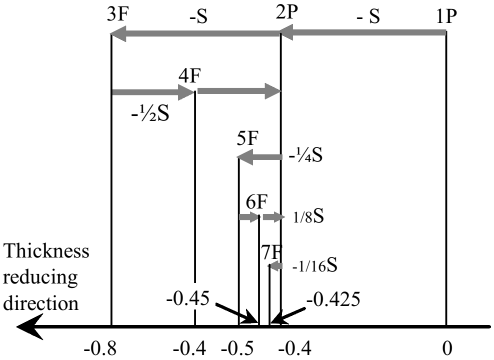


Fig. 8. *Route of thickness change for the design case. Remarks: P-Pass, F-Fail, S-Step, e.g., "1P" means simulation No.1 passed, "3F" means simulation No.3 failed*

result with "Pass", that is, No. 1 (using the initial part geometry without the thickness change) and No.2. The thickness change after each of the two simulations was "- Step", trying to reduce the part thicknesses. Simulation No. 3 failed, hence a "+ ½ Step" change of thickness was applied to generate the part geometry for simulation No. 4. Simulation No. 4 failed again, hence a continuous change of thickness, *i.e.,* "+ ½ Step" was applied. Now, the part geometry coincided with that of simulation No. 2, thus there was no need to conduct the Moldflow simulation again. Since simulation No.2 passed, the thickness change for the next simulation (No. 5) will be "- ¼ Step". This procedure went on until the convergence criterion No.1 was triggered (*i.e.,* the thickness change is between "¼ Step" and "1/16 Step" inclusive, and there is no simulation that passed the molding-quality criteria within this range. In this situation the last simulation with "Pass" will be retrieved as the final result). The simulation No.2 was the immediate last one with a "Pass", thus its thickness change corresponds to the thickness-minimization result.

Hence, for this design case, the sought x = -1, and the total change of thicknesses is -Step = -0.4 mm. The results can be summarized as:

- The sought: x = -1;
- Thickness change: -Step = -0.4 mm;
  (from 2.0 mm to 1.6 mm)
- Thickness reduction percentage: 0.4/2 = 20%.

Fig. 9 shows the part from the thickness minimization, with the Moldflow simulation results

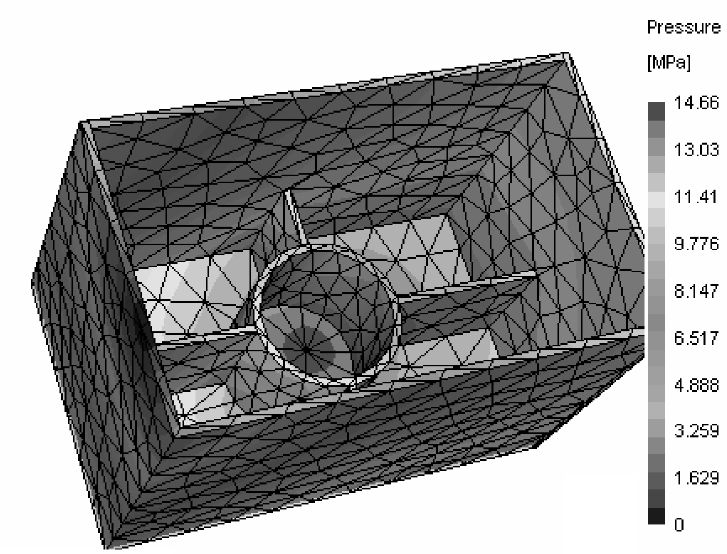


Fig. 9. *Pressure distribution for the design case at the end of the fill*

showing the pressure distribution at the end of the fill.

The above example shows that the part thicknesses were indeed reduced after the thickness minimization. However, if the molding criteria were set tighter, the minimization results might be quite different. For example, if we change the criterion to the following:

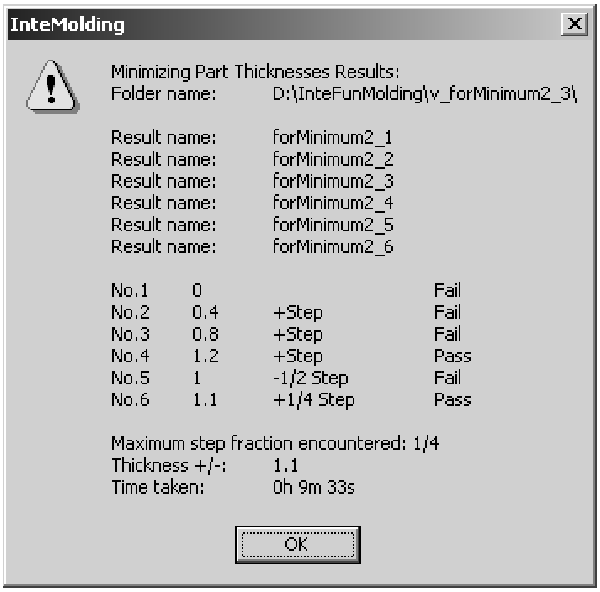
$$v1 < 5$$

The minimization result based on this new criterion is shown in Fig. 10.

As can be seen, for the modified molding criteria:

- the sought: x = 3 –1/2 +1/4 = 2.75;
- thicknesses change: 2.75 Step = 1.1 mm; (from 2 mm to 3.1 mm)
- thickness increase percentage: 1.1/2 = 55%.

This time the route of the thickness change is quite clear. The first convergence criterion was again triggered (*i.e.,* the thickness change is between the "¼ Step" and the "1/16 Step" inclusive, and there is one simulation that passed the molding-quality criteria. In this situation, this one will be



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InteMolding

Minimizing Part Thicknesses Results:
Folder name:      D:\InteFunMolding\v_forMinimum2_3\

Result name:      forMinimum2_1
Result name:      forMinimum2_2
Result name:      forMinimum2_3
Result name:      forMinimum2_4
Result name:      forMinimum2_5
Result name:      forMinimum2_6

No.1    0                          Fail
No.2    0.4       +Step            Fail
No.3    0.8       +Step            Fail
No.4    1.2       +Step            Pass
No.5    1         -1/2 Step        Fail
No.6    1.1       +1/4 Step        Pass

Maximum step fraction encountered: 1/4
Thickness +/-:    1.1
Time taken:       0h 9m 33s
```

Fig. 10. *Thickness minimization results after the changed molding-quality criteria*

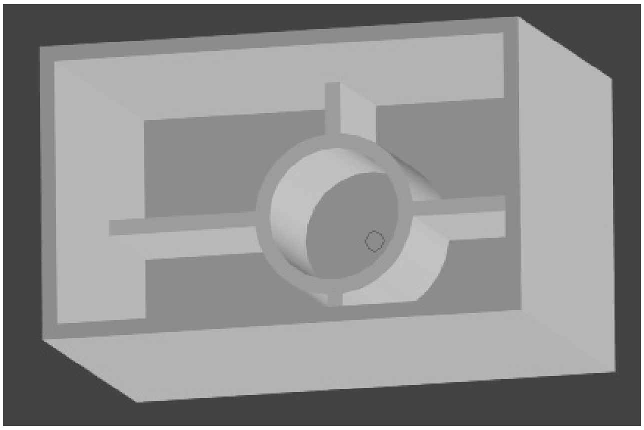


Fig. 11. *Part geometry as a result of the thickness minimization after the changed molding-quality criteria*

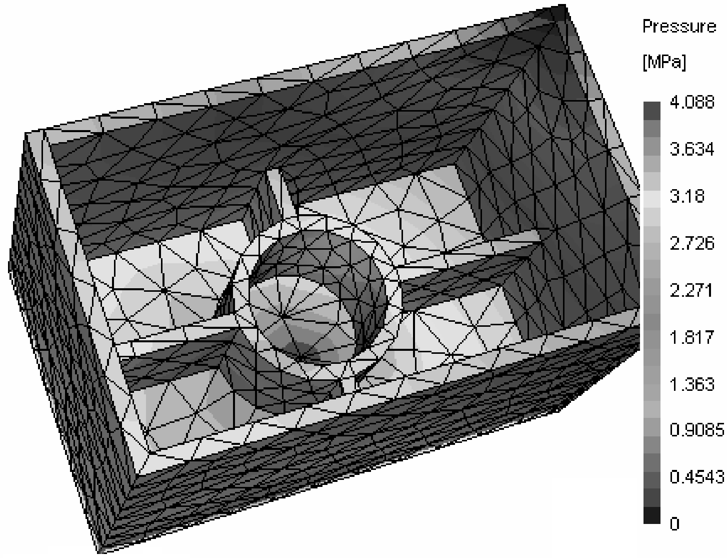


Fig. 12. *Pressure distribution after the changed molding-quality criteria*

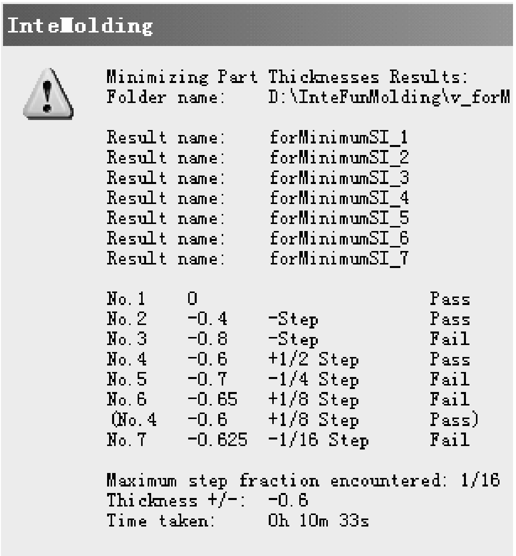
regarded as the final result, i.e., simulation No. 6). Fig. 11 shows the part geometry as a result of the thickness minimization, and Fig. 12 shows the corresponding pressure distribution from the Moldflow simulation. By comparing Fig. 11 and 12 with Fig. 6, it is easy to see the difference resulting from the different molding-quality requirements.

Now let us change the design case by using multiple quality criteria. Assume that this time the designer is more concerned about the clamp tonnage and maximum shear rate. He or she can then specify the following two criteria:

- Criteria construction variables:
  v1 = maximum clamp tonnages (tonne),
  v2 = maximum shear rate (1/s).
- The corresponding molding-quality criteria for the thickness minimization:
  v1 < 10,
  v2 < 50000.

The requirement on clamp tonnage is easy to understand. The second quality criterion is actually a more stringent material requirement that was mentioned previously: “Shear rate should not exceed the maximum recommended for the material type”, which, for the current material, is 10^5 (1/s).

All the other molding conditions remain unchanged. The minimization results were shown in Fig. 13, which show that the total change of thicknesses is –0.6 mm. Hence, the part thicknesses can be reduced by 0.6/2 = 30%.



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Minimizing Part Thicknesses Results:
Folder name:     D:\InteFunMolding\v_forM

Result name:     forMinimumSI_1
Result name:     forMinimumSI_2
Result name:     forMinimumSI_3
Result name:     forMinimumSI_4
Result name:     forMinimumSI_5
Result name:     forMinimumSI_6
Result name:     forMinimumSI_7

No.1    0                       Pass
No.2    -0.4    -Step           Pass
No.3    -0.8    -Step           Fail
No.4    -0.6    +1/2 Step       Pass
No.5    -0.7    -1/4 Step       Fail
No.6    -0.65   +1/8 Step       Fail
 (No.4  -0.6    +1/8 Step       Pass)
No.7    -0.625  -1/16 Step      Fail

Maximum step fraction encountered: 1/16
Thickness +/-:  -0.6
Time taken:      0h 10m 33s
```

Fig. 13. *Thickness-minimization results when multiple molding-quality criteria are used*

5 DISCUSSION

The results from the above case study show that, apart from the initial part geometry and molding conditions (gate location, melt temperature, mold temperature, injection time, *etc.*), the part-thickness-minimization results are predominantly determined by the specified molding-quality requirements. Different molding-quality requirements for the same design problem might result in quite opposite results: the part thicknesses may be reduced or they may have to be increased.

In the studied design case the pressure distribution is selected as a molding-quality measure. As discussed in Section 2.2, there are many molding qualities that may be used as the injection-molding optimization criteria. Among these criteria, some are more sensitive to part thicknesses, such as pressure, shear stress, clamp tonnage, and volumetric shrinkage. For the case of the pressure distribution, the "maximum end-of-fill pressure" may be used to characterize the molding quality partially. This variable should generally not exceed a certain value, because the maximum hydraulic pressure of an injection-molding machine ram is determined by the injection-molding machine, which is related to the maximum pressure at the nozzle, which in turn is related to the pressure in the molding cavity. Setting a threshold for the maximum end-of-fill cavity pressure will ensure that the injection molding machine can provide the necessary ram pressure for the molding process, reducing the possibility of molding defects caused by flow hesitation and short-shot.

The case study shows that if the threshold for the cavity pressure is set high (15 MPa), the part thicknesses may be reduced; if it is set low (5 MPa), the part thicknesses may have to be increased. This is true because if the part walls are too thin, the melt flow will face more resistance in the cavity, leading to a higher cavity pressure. In contrast, if the wall thicknesses are large, the plastic melt will flow more easily in the cavity, hence the cavity pressure will be lower. However, regarding how much the part thicknesses can be reduced or increased, there has to be a certain algorithm and some calculation. This is where the work described in this paper has made its contribution.

The case was then further explored when multiple molding-quality criteria were used. The results show that multiple quality criteria can be specified and used for the thickness minimization as well.

6 CONCLUSIONS

The design of an injection-molded plastic part should take both functional and performance requirements, as well as injection-molding requirements into account. Optimization of part thicknesses is an important design task. One of the problems in part-thickness optimization is that most of the existing works are only oriented to the functional and performance requirements. To tackle this problem, the above sections have presented a simulation-based methodology for minimizing the part thicknesses. This is basically an iterative process of changing the thicknesses of the selected part features, executing a Moldflow simulation, assessing the molding-quality criteria, and based on the results, determining the next change (following the route of the change) of part thicknesses. The thickness change can be in both directions, *i.e.,* "+/-" the specified step value; and it can be a full step value, or a fraction of a step value, including 1/2, 1/4, 1/8, 1/16 step values.

The methodology was implemented in a software prototype, with which the part-thickness change and the Moldflow simulation can be made automatically by the computer programs. The design case study has further demonstrated the usefulness of the proposed methodology.

The presented paper provides a novel method for injection-molding designers to obtain minimized part thicknesses related to the part-molding quality requirements. The innovation has three aspects: first, a route of thickness change towards meeting the specified quality criteria was proposed; second, the existing injection-molding CAD-CAE integration model was enhanced to allow a part-thickness change to be specified and executed; and third, several convergence criteria were proposed for the thickness-minimization search process.

However, the problem of part-thickness optimization is complex, due to the complex nature of the injection molding process itself. This paper has only addressed the problem of "thickness minimization", where the objective for optimality is the thicknesses, while the molding-quality requirements are only treated as the constraints; rather than that of "thickness optimization", where both the thicknesses and the molding qualities should be the optimization objectives. Hence, it was only an initial effort in tackling the problem thoroughly. Future work will involve taking the molding qualities as part of the optimization objectives, so that the part thicknesses can be optimized in such a way that, not only the plastic material requirement is low, but also the part molding-qualities are high.

Acknowledgments

This paper is based on work funded by Zhejiang Provincial Natural Science Foundation of China under Grant No. R104247 (the talent-nurturing program).

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Prejeto:
Received: 2.5.2007

Sprejeto:
Accepted: 27.6.2007

Odprto za diskusijo: 1 leto
Open for discussion: 1 year