Journal of the Microelectronics & Packaging Society
Vol. 8, No. 3, p. 11-17. 2001

A Knowledge-based Design System for Injection Molding

Yong-Jeong Huh

School of mechatronics engineering, Korea University of Technology and Education, ChungNam, South Korea

Abstract: The design and manufacture of injection molded polymeric parts with desired properties is a costly process dominated by empiricism, including the repeated modification of actual tooling. This paper presents an expert design evaluation system which can predict the mechanical performance of a molded product and diagnose the design before the actual mold is machined. The knowledge-based system synergistically combines a rule-based expert system with CAE programs. Heuristic knowledge of injection molding is formalized as rules of an expert consultation system. The expert system interprets the analytical results of the process simulation, predicts the performance, evaluates the design and generates recommendations for optimal design alternatives.

Key words: Expert design evaluation system, Injection molding, Flow simulation, Mechanical performance,

1. Introduction

Design is, within the scope of engineering applications, a hierarchical series of transformation processes from a functional description of a product to a physical entity[1,2].

The design process involves creative, analytical, theoretical and experimental work in a complex, iterative and recursive manner. In this respect, the object of rational design is to make the specifications such that the designing, production and utilization of the product consume a minimum of resources and information[3]. A rational design strategy differs from an exhaustive generation-and-test problem-solving technique[4], in that it has criteria for evaluating design decisions and indices for generating design alternatives prior to the expensive and time-consuming prototype toolings.

Some of the major manufacturing processes often deteriorate the quality of the product significantly unless the manufacturability is not considered adequately in the part design. Injection molding, for example, generates a complicated distribution of the microstructure as determined by the choice of processing conditions, material, and configuration of the part and mold. Therefore, it requires the designer to have in-depth knowledge about the nature of the injection molding process to produce a successful injection molded product. An incomplete understanding of the process could result in product designs which have unacceptable properties or which cannot even be moldable.

The engineering tasks involved in injection molding are the creation of the geometry of parts and molds, and the choice of material and processing parameters. The current practice is highly empirical, since it has been difficult to predict the performance of the designed part analytically before it is actually made and tested. It requires the ad hoc use of expertise accumulated over the years and/or expensive time-consuming iterations involving prototype toolings. The short coming of empirical approaches to design and manufacture of injection molds is that the outcome is uncertain since the success of design can be confirmed only through time-consuming prototype testings (Fig. 1(a)). Furthermore, expertise can be acquired only through prolonged training and accumulation of experience.

The thermo-mechanical history of the molded part and the resulting microstructure must be predicted to evaluate the design analytically prior to actual prototype tooling and testing (Fig. 1(b)). Then the goal of rational design can be accomplished. In order to achieve this goal, a user-transparent, real time flow simulation program and mechanical performance prediction models

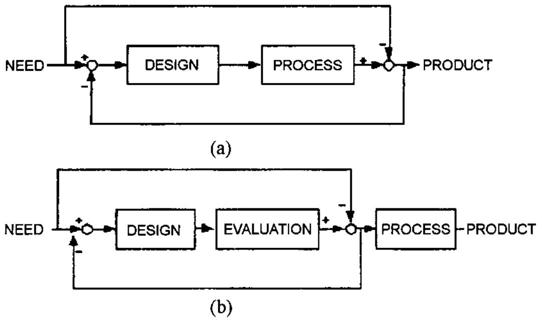


Fig. 1. Block diagrams of synthesis. (a) Conventional synthesis, (b) Computer-based rational synthesis.

need to be developed based on most convincing and efficient theoretical models.

2. Knowledge-based Design System

Since the mid of 1980's, CAE technologies for injection molding have made a big stride by the development of a few commercially applicable mold filling and cooling simulation programs[5]. The control volume method developed by the Cornell Injection Molding Program is the key development among them to transplant the computer graphics technology onto the flow simulation technology[6].The filling pattern of polymer melt, the distribution of the melt temperature, velocity, pressure and volumetric shrinkage can be visualized from the process simulation results. However, the result of the analysis cannot be quantitatively used for the mold design evaluation. The mechanical performance of the part, the strength of weldline defects, the occurrence of warpage and dimensional accuracy of the part can only be predicted with human experts' interpretation. Furthermore, the problem in an analytical simulation of the molding process has been the inevitable inclusion of simplifying assumptions in applying theoretical equations expediently to the actual molding process. This makes the accuracy of the analysis for the complex geometry of a mold degraded, notwithstanding the immense computational effort required, leading to a need to build physical prototypes. Therefore, the use of CAE analysis softwares in injection molding has been limited to a pre-visualization of the melt flow and a few simple qualitative assessments of the post-molding phenomena.

In order to alleviate these kind of difficulties, design evaluation using both the heuristic knowledge and the analytic CAE software has been introduced in this paper. A knowledge-based expert system is one that handles real-world, complex problems which require an expert's interpretation. Therefore, expert mold designers' knowledge can be encoded into production rules of an expert system which can then be used by experts as well as by non-experts in evaluating mold design. A hybrid structure of knowledge-base is constructed to combine the merits of heuristic and analytic knowledge for injection molding.

Hart[7] proposed the multi-level knowledge-base structure to enhance the performance and to eliminate the limits of expert systems. The multi-level structure incorporates heuristic reasonings of surface-level models combined with analytic deep-level models. The surface model is the production rule type system, whereas the deep model is a purely mathematical description of the physical system. The integration of the analysis programs and the rule-based expert system is the key characteristic of the multi-level knowledge-based system which enables a wide variety of non-expert users to use the sophisticated analysis programs effectively together with formalized heuristic rules.

An expert design evaluation system for injection molding is developed in this study, which has the following multi-level knowledge structure: flow simulation programs for rheological behavior of molten polymers and microstructure analysis programs for solidified polymers, both of which are developed as part of this research, form the deep reasoning model, while a classification model combined with the production system[8] forms the surface reasoning model of the system. Human experts' knowledge in the use of CAE programs and the interpretation of the result is formalized into production rules of the advisory system which also contains the heuristic rules of initial synthesis, evaluation and alternative generation (Fig. 2).

The knowledge-based system can diagnose designs based on both the heuristic rules developed from the expert designers' experience and the analytical results of the process simulation. It can also generate optimal alternative designs if the design is not acceptable. The

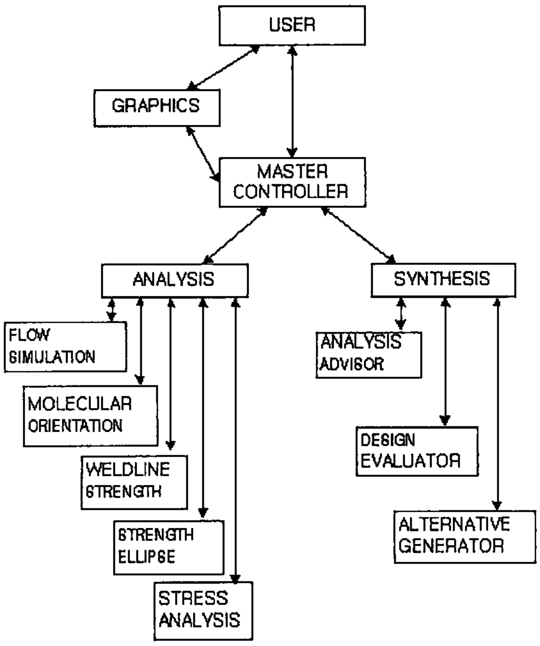


Fig. 2. Functional structure of the knowledge-based design system for injection molding.

multi-level reasoning structure of the knowledge-based system frees the designer from acquiring detailed knowledge of hydrodynamics, rheology, polymer science and numerical analysis which are necessary to run the analysis programs and to interpret the results of them, and provides human experts' knowledge which requires long time to acquire by non-experts.

3. Process Simulation

Injection molded parts have thin, quasi-three dimensional shapes, which can be unfolded to appropriate two dimensional layflats. A two dimensional flow simulation program was developed by Cornell Injection Molding Program for the non-isothermal filling of a thin cavity with variable thickness using generalized Hele-Shaw flow model[9]. It is assumed that inertial effects, streamwise heat conduction and gapwise heat convection are negligible. The fluid is taken to be inelastic, but non-Newtonian under nonisothermal conditions with the shear viscosity assumed to have a power-law shear rate dependence and an Arrhenius-type temperature dependence. The numerical computation is based on a finite element/finite difference scheme in which the planar coordinates are described in terms of finite elements and the gapwise and time derivatives are described in terms of finite difference.

Governing Equations

The Hele-Shaw flow model in a thin cavity has been generalized for an inelastic non-Newtonian fluid under non-isothermal conditions. In the model, the equations of continuity and momentum can be respectively reduced to

$$\nabla \cdot (S\Delta P) = 0 \tag{1}$$

$$u = -\frac{1}{b}\frac{\partial P}{\partial x}S, \quad u = -\frac{1}{b}\frac{\partial P}{\partial y}S \tag{2}$$

where

$$S = \int_0^b \frac{z^2}{\eta}dz \tag{3}$$

Also, the energy equation becomes

$$rC_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial z^2} + \eta\gamma^2 \tag{4}$$

where

$$\eta = m(T)\gamma^{n-1} = A\exp\left(\frac{T_a}{T}\right)\gamma^{n-1} \tag{5}$$

$$\gamma = \left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]^{1/2} \tag{6}$$

Finite Element Formulation

Using the divergence theorem, the Galerkin weighted residual equation corresponding to Eq. 1 is written as

$$\int_\Omega \Psi_i \Delta \cdot (S\Delta P)d\Omega$$

$$= \int_\Omega \Delta\Psi_i \cdot (S\Delta P)d\Omega + \int_\Omega \left[Y_i S\frac{\partial P}{\partial n}\right]dS = 0 \tag{7}$$

Interpolating the pressure P, we obtain the following algebraic equation associated with each element in the flow field

$$A_{ij}P_j = R_i \tag{8}$$

The nonlinear equation (Eq. 8) can be rewritten in the following form

$$A_{ij}dP_j = R_i - A_{ij}P_j^I \tag{9}$$

$$P_j^{I+1} = P_j^I + dP_j \tag{10}$$

where

$$A_{ij} = \int_{\Omega} S\Psi_{j,x}\Psi_{i,x}d\Omega + \int_{\Omega} S\Psi_{j,y}\Psi_{i,y}d\Omega \tag{11}$$

$$R_i = \int_{C} \Psi_i S\frac{\partial P}{\partial n}ds \tag{12}$$

Here, I denotes the number of iteration.

The moldability of the design can be readily predicted from the flow simulation by observing a necessary injection pressure during the filling simulation. When the necessary injection pressure does not exceed the limit of the machine's capacity, the design and associated toolings are thought to be adequate to produce the designed part. When the designed part is predicted to be moldable, it is then necessary to predict the mechanical behavior of the molded part. It is done by establishing a thermomechanical data base during the cavity filling simulation.

4. Knowledge Formalization

EXSYS is a general purpose expert system which provides a basic framework for designing a specific expert system developed by EXSYS incorporation. It is one of the simpler systems and is specialized for classification type applications. It is written in C, which makes communication between the expert system and the external analysis programs relatively straightforward. Heuristic rules of design for injection molding are formalized and implemented as production rules according to the EXSYS' language structure. They are based not only on human experts' experience but also on the result from analysis programs.

Design Evaluation

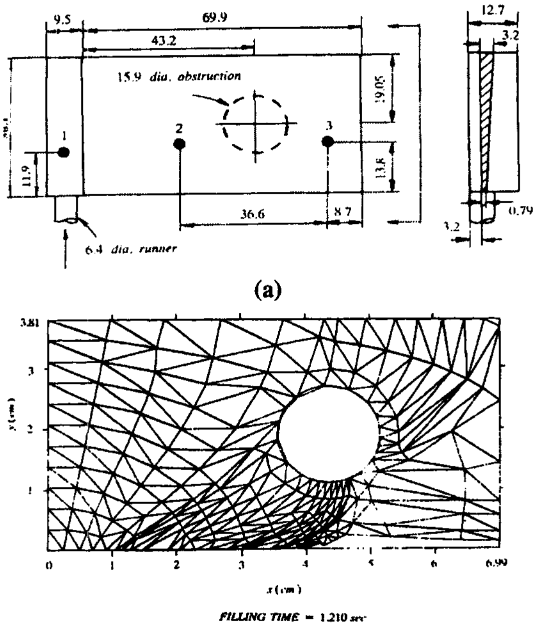
Moldability of a designed part can be readily determined from the result of the flow simulation. When the necessary injection power during the flow simulation exceeds the limit of the employed injection molding machine, it can be concluded that the flow path is blocked by the pre-solidification of polymer melt. This results in a short shot of the part and the designed part is not moldable. Therefore, the first criterion for design evaluation is set as follows:

- **Moldability**

When the required injection power exceeds the limit of the machine's capacity, short shot occurs and the designed part is not moldable.

The global mechanical behavior of the designed part can be determined by comparing the result of analysis for stress distribution due to an externally applied load and its effect on the mechanical anisotropies predicted for the entire geometry. However, this requires an immense amount of computation time and data storage. This problem can be alleviated by using a heuristic method to avoid the brute force analysis in evaluating mechanical acceptability of the design.

It has been observed by experts that mechanical fail-



(a)

(b)

Fig. 3. (a) Plane view and side view for the cavity including of three pressure transducers: indicated dimensions are in units of mm, (b) Mesh configuration during the filling-simulation (Filling time=1.210 sec).

ures start where stresses are concentrated at the weakest directions of mechanical anisotropies. For arbitrary loading situations, stress concentrations occur at holes, corners, edges and thin sections. Therefore the distribution of microstructural anisotropies at these regions are critical in determining the critical mechanical behavior of the part. Form the above observation, the second criterion is deduced for evaluation the mechanical performance of molded parts as follows:

- **Mechanical Acceptability**

An adverse combination of microstructure and geometry is the principal cause of the mechanical failure of an injection molded part.

A local prediction scheme which checks the microstructure only at critical locations of the designed part is developed based on this rule. The microstructures and accompanying an isotropic properties are predicted at regions pre-selected based on possible occurrence

of stress concentration. Then the acceptability of the design is judged using production rules.

Design Alternative Generation

Human experts have developed simple and intuitive design rules based on years of trial-and error testing experience. As an effort to formalize the empirically acquired remedies as production rules, the causal relationship between the design variables, thermomechanical properties, and the resulting microstructural anisotropies are studied.

- **General Causality**[10-12)]

The direction of the anisotropy is mainly dependent on the geometrical variables, such as, the primary part shape, the secondary part shape, type and location of the gate.

- The magnitude of the anisotropy and the molda-bility is mainly dependent on thermal and temporal variables of the process, such as, melt and mold tempera-ture, and injection rate.

Although the general causality is not a theoretically induced fact, it can be effectively used in generating design alternatives together with the evaluation criteria established above. By integrating the heuristic observations and the analytical predictions, decision rules for design diagnosis and redesign is formulated in Fig. 4.

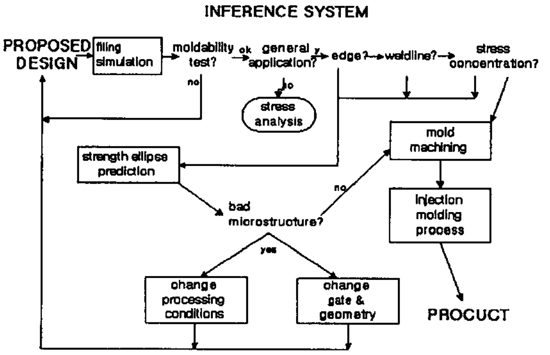


Fig. 4. Decision rules for design diagnosis and redesign. Both the analytical results and empirical findings are integrated into this inference engine.

5. Evaluation System

A prototype knowledge-based design system (Fig. 5) is built based on performance prediction programs and the production rules which are formalized in previous section (Fig. 4).

The use interacts with the synthesis system via the master controller. The master controller receives initial design information from the user and triggers the expert system to request an advice for the next action. Depending upon the decision from the expert system, the controller either executes the analysis programs or returns the decision of the expert system to the designer for

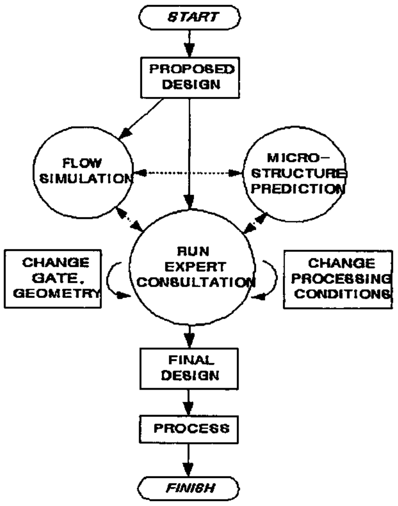


Fig. 5. The prototype expert design system for injection molding.

additional questioning or conclusions.

The expert system has three major functional blocks: data retrieval and synthesis control, design evaluation, and redesign advice. Based on the information supplied by the master controller, it interprets the data and decides the necessary actions for the controller. If the supplied information is not sufficient to evaluate the design or to confirm the conclusion, the expert system requests the controller to take relevant action to obtain more data either from the user or from the analysis programs. After retrieving sufficient information to evaluate the design. It diagnoses the design and generates proper alternatives.

The analysis system has five functional blocks as shown in Fig. 2. Flow simulation is the core of the analysis system because it generates a necessary thermomechanical data base for further analyses. Therefore, it is executed whenever a design change is made. Moldability is readily predicted from the result of the flow simulation. Mechanical performance prediction programs are executed only when the expert system requests the running of the specific program among them.

For a more realistic case study, an L-shaped cavity with an insert at the center and varying thickness is designed as shown in Fig. 3(a). The part is then unfolded as a lay-flat and the two dimensional cavity filling simulation is carried out with the assumption the melt is injected through a fan gate. Processing parameters and constants are as follows:

Melt Temperature: 493 K
Mold Wall Temperature: 303 K
Injection Rate: 10.0 cm^3/sec(whole cavity)
Material: polystyrene

For a given design task, the flow simulation program is first executed to build a thermomechanical data base. Advanced melt fronts are generated automatically at each time step as shown in Fig. 3(b).

Then the expert consultation program is initiated. Based on the decision from the expert system, a part or the whole of the microstructure analysis programs is executed. The expert system's request with relevant data for a specific analysis program is transmitted to the microstructure analysis system via communication programs between the expert system and the microstructure analysis program. The result of the analysis, then, automatically returns to the expert system to diagnose the design. If the design is not acceptable, the user generates an alternative solution based on expert system's advice. the design cycle is repeated until the acceptable design is made.

6. Conclusion

A knowledge-based design system is built to embody the goal of a rational design by integrating two domains of knowledge of injection molding. Heuristic knowledge of design is formalized as production rules and combined with analytical knowledge from the process simulation. Theoretical models for predicting the moldability of the design and the mechanical performance of the molded part have been formulated.

The overall structure of the expert system, as designed, is based on EXSYS, which is an expert system designing tool, and linked together with analysis programs to have a multi-level reasoning structure. The synthesis system can diagnose the design and direct the designer to reach the optimum design based on the accumulated human experts' knowledge and the most convincing theoretical models of the process which are hard to acquire by non-expert designers.

By employing a reasonable approximation with convincing mathematical models of one dimensional shear and two dimensional elongational flow, the spatial variations of molecular orientation and accompanying mechanical strength are successfully predicted.

The current knowledge base contains decision rules and mathematical models only with respect to moldability and mechanical acceptability of the design. More knowledge about the injection molding process must supplement the current knowledge base in order to evaluate and modify designs in every aspect of injection molding, such as, sinkmarks, jetting, warpage, and mold design, among others.

References

1. Suh, N.P., "Manufacturing and Productivity," Key note paper at the Sagamoer Conference, (1984).

2. Rinderle, J.R., "Measures of Functional Coupling in Design," Ph D Thesis, MIT, (1982).
3. Suh, N.P., Bell, A.C. and Gossard, D.C., "On An Axiomatic Approach to Manufacturing Systems," Journal of Engineering for Industry, Trans. ASME Vol.100, No.2, May, (1978).
4. Winston, P.H., "Artificial Intelligence," Addison Wesley, (1984).
5. Manzione, L.T., "Applications of Computer Aided Engineering in Injection Molding," Hanser Publishers, (1987).
6. Wang, V.W., *et al.*, "Dynamic Simulation and Graphics for the Injection Molding of Three Dimensional Parts," Journal of Polymer Engineering, pp. 21-45, (1986).
7. Hart, P., "Directions for Artificial Intelligence in the Eighties," SIGNART News letter 79:11-16, (1982).
8. Weiss, S.M. and Kern, K.B., *et al.*, "A Guide to the Expert Consultation System," Technical Report CBM-TR-94 Rutgers University, December, (1984).
9. Hieber, C.A. and Shen, S.F., "A Finite-Element, Finite-Difference Simulation of the Injection-Molding Filling Process," Journal of Non-Newtonian Fluid Mechanics 7, pp. 1-32, (1980).
10. Kim, S.G., "Knowledge-based Synthesis System for Injection Molding," Ph D thesis MIT, (1985).
11. Kim, S.G. and Suh, N.P., "Performance Prediction of Weldline Strength in Amorphous Polymers," SPE 42th ANTEC Technical Papers, New Orleans, May, (1984).
12. Hull, D., "An Introduction to Composite Materials," Cambridge Univ. Press, (1981).