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ORIGINAL ARTICLE

A CAD/CAE-integrated injection mold design system for plastic products

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Abstract Mold design is a knowledge-intensive process. This paper describes a knowledge-based oriented, parametric, modular and feature-based integrated computer-aided design/computer-aided engineering (CAD/CAE) system for mold design. Development of CAx systems for numerical simulation of plastic injection molding and mold design has opened new possibilities of product analysis during the mold design. The proposed system integrates Pro/ENGINEER system with the specially developed module for the calculation of injection molding parameters, mold design, and selection of mold elements. The system interface uses parametric and CAD/CAE feature-based database to streamline the process of design, editing, and reviewing. Also presented are general structure and part of output results from the proposed CAD/CAE-integrated injection mold design system.

Keywords Mold design · Numerical simulation · CAD · CAE

1 Introduction

Injection molding process is the most common molding process for making plastic parts. Generally, plastic injection molding design includes plastic product design, mold design, and injection molding process design, all of which contribute to the quality of the molded product as well as production efficiency [1]. This is process involving many design parameters that need to be considered in a concurrent manner. Mold design for plastic injection molding aided by computers has been focused by a number of authors worldwide for a long period. Various authors have developed program systems which help engineers to design part, mold, and selection parameters of injection molding. During the last decade, many authors have developed computer-aided design/computer-aided engineering (CAD/CAE) mold design systems for plastic injection molding. Jong et al. [2] developed a collaborative integrated design system for concurrent mold design within the CAD mold base on the web, using Pro/E. Low et al. [3] developed an application for standardization of initial design of plastic injection molds. The system enables choice and management of mold base of standard mold plates, but does not provide mold and injection molding calculations. The authors proposed a methodology of standardizing the cavity layout design system for plastic injection mold such that only standard cavity layouts are used. When standard layouts are used, their layout configurations can be easily stored in a database. Lin at al. [4, 5] describe a structural design system for 3D drawing mold based on functional features using a minimum set of initial information. In addition, it is also applicable to assign the functional features flexibly before accomplishing the design of a solid model for the main parts of a drawing mold. This design system includes modules for selection and calculation of mold components. It uses Pro/E modules Pro/Program and Pro/Toolkit, and consists of modules for mold selection, modification and design. Deng et al. [6, 7] analyzed development of the CAD/CAE integration. The authors also analyzed systems and problems of integration between CAD and CAE systems for numerical simulation of injection molding and mold design. Authors propose a feature ontology consisting of a number of CAD/CAE features. This feature represents not

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only the geometric information of plastic part, but also the design intent is oriented towards analysis. Part features contain the overall product information of a plastic part, wall features, development features (such as chamfer, ribs, boss, hole, etc.), treatment features which contain analysis-related design information and subwall/developed features. Wall and development features are so called "component features". Godec et al. [8, 9] developed a CAE system for mold design and injection molding parameters calculations. The system is based on morphology matrix and decision diagrams. The system is used for thermal, rheological and mechanical calculation, and material base management, but no integration with

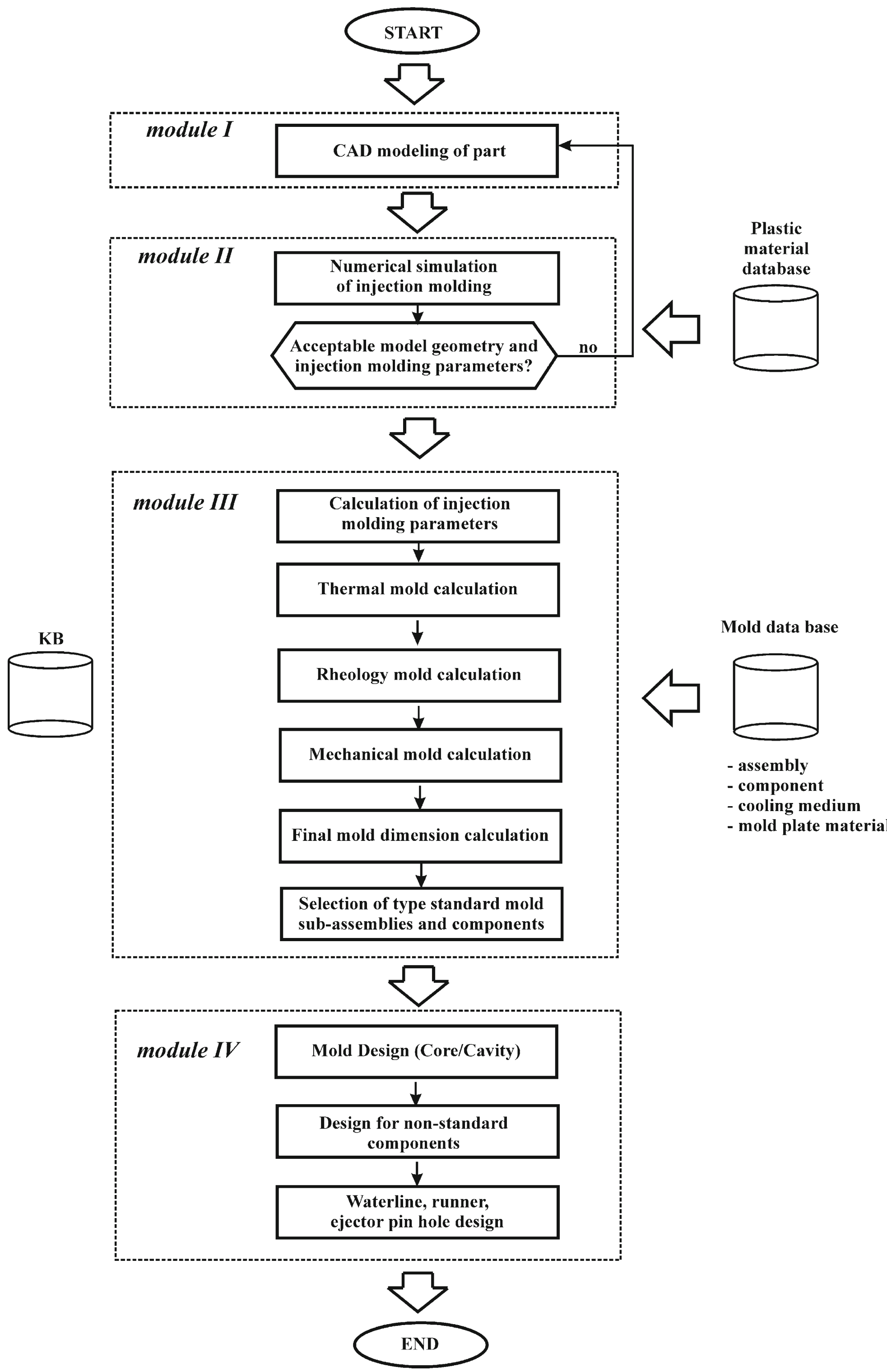


Fig. 1 General structure of integrated injection mold design system for plastic products

commercial CAx software is provided. Huang et al. [10] developed a mold-base design system for injection molding. The database they used was parametric and feature-based oriented. The system used Pro/E for modeling database components. Kong et al. [11] developed a parametric 3D plastic injection mold design system integrated with solid works. Other knowledge-based systems, such as IMOLD, ESMOLD, IKMOULD, and IKBMOULD, have been developed for injection mold design. IMOLD divides mold design into four major steps; parting surface design, impression design, runner system design, and mold-base design. The software uses a knowledge-based CAD system to provide an interactive environment, assist designers in the rapid completion of mold design, and promote the standardization of the mold design process. IKB-MOULD application consists of databases and knowledge bases for mold manufacturing. Lou et al. [12] developed an integrated knowledge-based system for mold-base design. The system has module for impression calculation, dimension calculation, calculation of the number of mold plates and selection of injection machine. The system uses Pro/Mold Base library. This paper describes KBS and key technologies, such as product modeling, the frame-rule method, CBS, and the neural networks. A multilayer neural network has been trained by back propagation BP. This neural network adopts length, width, height and the number of parts in the mold as input and nine parameters (length, width, and height of up and down set-in, mold bases side thickness, bottom thickness of the core, and cavity plates) as output. Mok et al. [13, 14] developed an intelligent collaborative KBS for injection molds. Mok at el. [15] has developed an effective reuse and retrieval system that can register modeled standard parts using a simple graphical user interface even though designers may not know the rules of registration for a database. The mold design system was developed using an Open API and commercial CAD/computer-aided manufacturing (CAM)/CAE solution. The system was applied to standardize mold bases and mold parts in Hyundai Heavy Industry. This system adopted the method of design editing, which implements the master model using features. The developed system provides methods whereby designers can register the master model, which is defined as a function of 3D CAD, as standard parts and effectively reuse standard parts even though they do not recognize the rules of the database.

Todic et al. [16] developed a software solution for automated process planning for manufacturing of plastic injection molds. This CAD/CAPP/CAM system does not provide CAE calculation of parameters of injection molding and mold design. Maican et al. [17] used CAE for mechanical, thermal, and rheological calculations. They analyzed physical, mechanical, and thermal properties of plastic materials. They defined the critical parameters of loaded part. Nardin et al. [18] tried to develop the system which would suit all the needs of the injection molding for selection of the part–mold–technology system. The simulation results consist of geometrical and manufacturing data. On the basis of the simulation results, part designers can optimize part geometry, while mold designers can optimize the running and the cooling system of the mold. The authors developed a program which helps the programmers of the injection molding machine to transfer simulation data directly to the machine. Zhou et al. [1] developed a virtual injection molding system based on numerical simulation. Ma et al. [19] developed standard component library for plastic injection mold design using an object-oriented approach. This is an object-oriented, library model for defining mechanical components parametrically. They developed an object-oriented mold component library model for incorporating different geometric topologies and non-geometric information. Over the years, many researchers have attempted to automate a whole

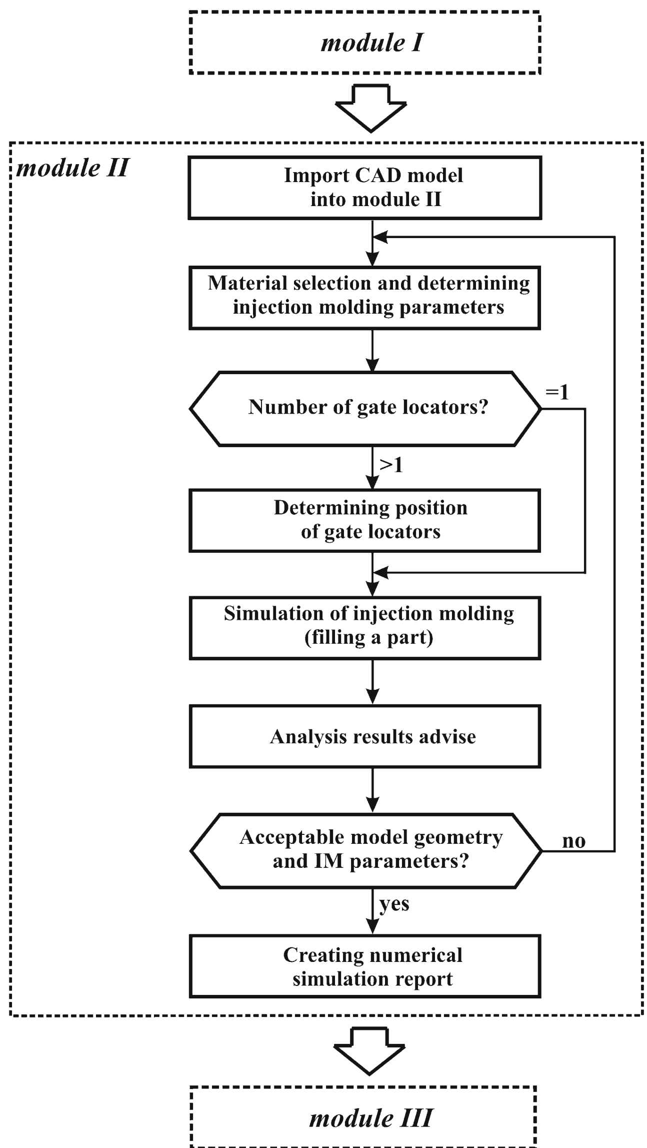


Fig. 2 Structure of module for numerical simulation of injection molding process

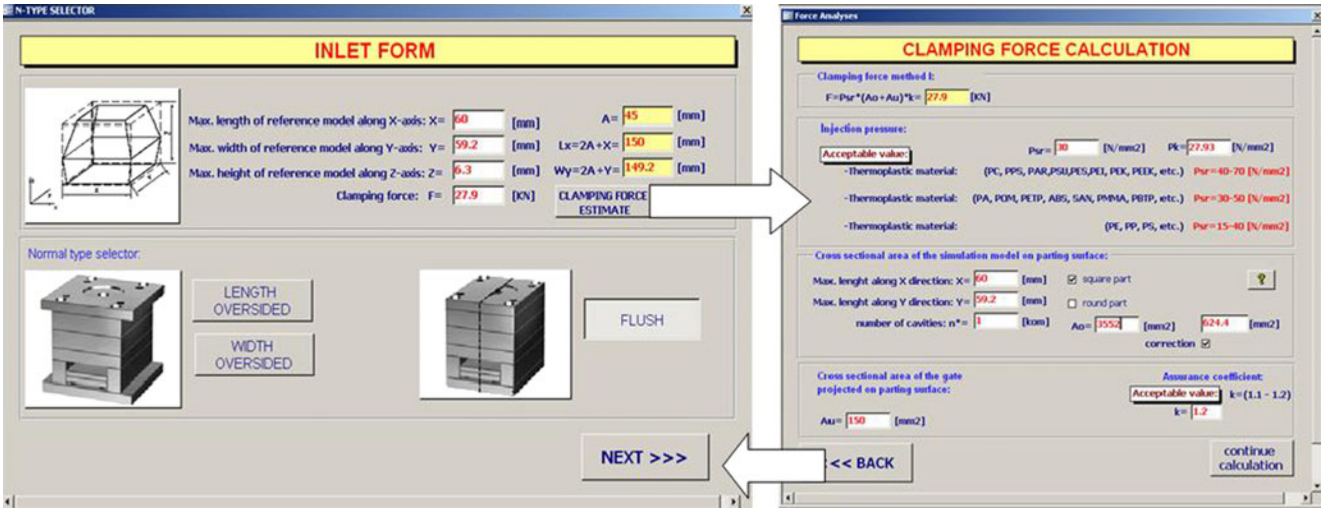


Fig. 3 Forms to define the mold geometry

mold design process using various knowledge-based engineering (KBE) approaches, such as rule-based reasoning (RBR), and case base (CBR) and parametric design template (PDT). Chan at al. [20] developed a 3D CAD knowledge-based-assisted injection mold design system (IKB mold). In their research, design rules and expert knowledge of mold design were obtained from experienced mold designers and handbooks through various traditional knowledge acquisition processes. The traditional KBE approaches, such as RBR, CBR, and simple PDT have been successfully applied to mold cavity and runner layout design automation of the one product mold.

Ye et al. [21] proposed a feature-based and object-oriented hierarchical representation and simplified symbolic geometry approach for automation mold assembly modeling. The previously mentioned analysis of various systems shows that authors used different ways to solve the problems of mold design by reducing it to mold configurator (selector). They used CAD/CAE integration for creating precision rules for mold-base selection. Many authors used CAE system for numerical simulation of injection molding to define parameters of injection molding. Several also developed original CAE modules for mold and injection molding process calculation. However, common to all previously mentioned systems is the lack of module for calculation of mold and injection molding parameters which would allow integration with the results of numerical simulation. This leads to conclusion that there is a need to create a software system which integrates parameters of injection molding with the result obtained by numerical

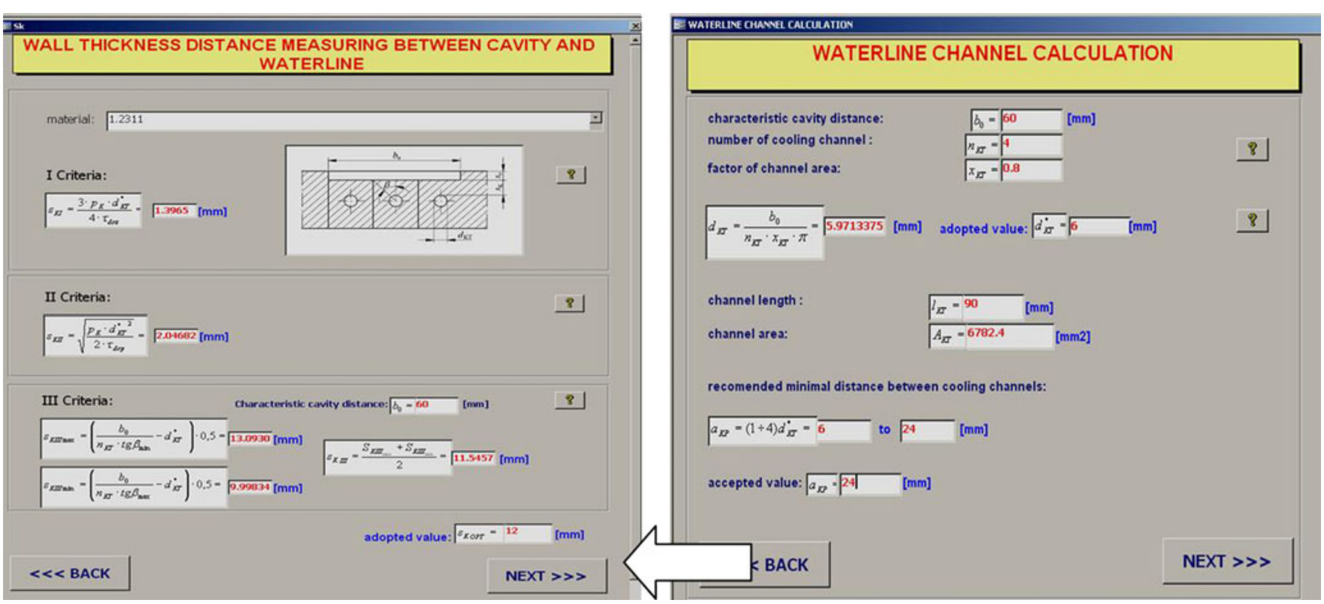


Fig. 4 Forms to determine the distance between the cooling channels and mold cavity

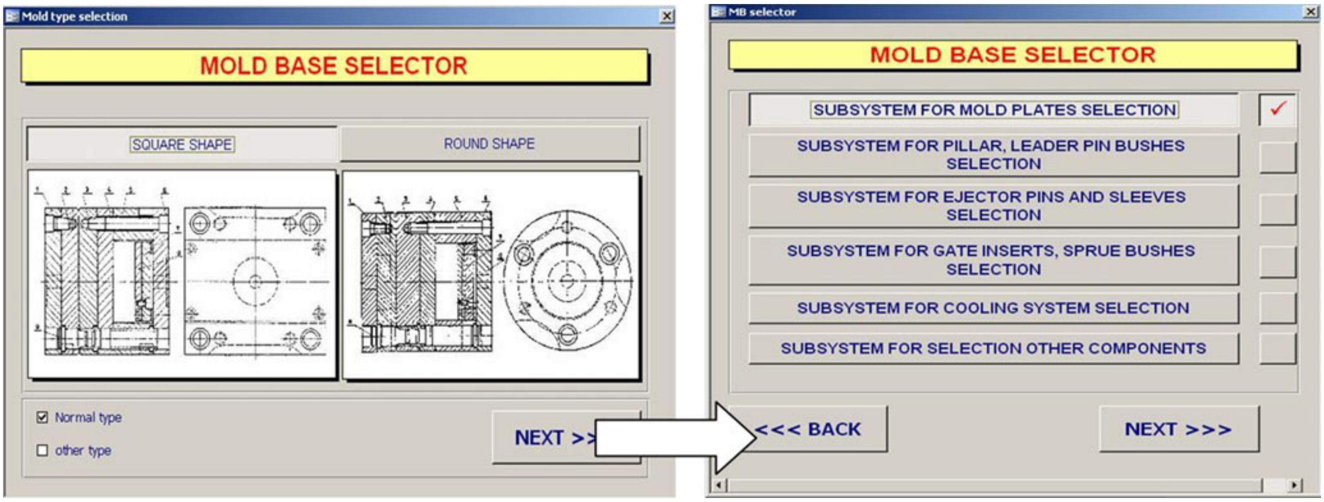


Fig. 5 Mold-base selector forms

simulation of injection molding, mold calculation, and selection. All this would be integrated into CAD/CAE-integrated injection mold design system for plastic products.

2 Structure of integrated CAD/CAE system

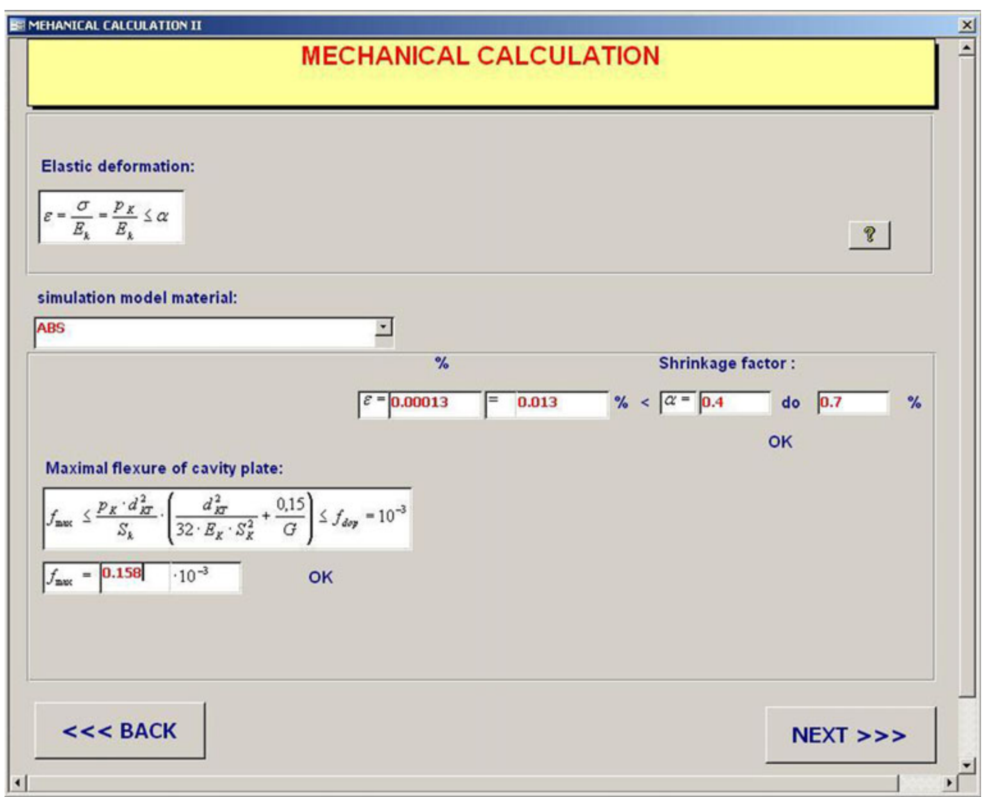
As is well known, various computational approaches for supporting mold design systems of various authors use design automation techniques such as KBE (RBR, CBR, PDT) or design optimisation techniques such as traditional (NLP,LP, BB, GBA, IR, HR) or metaheuristic search such as (TS, SA, GA) and other special techniques such as (SPA, AR, ED).

The developed interactive software system makes possible to perform: 3D modeling of the parts, analysis of part design and simulation model design, numerical simulation of injection molding, and mold design with required calculations.

The system consists of four basic modules:

- Module for CAD modeling of the part
- Module for numerical simulation of injection molding process

Fig. 6 Form for mechanical mold calculation



- Module for calculation of parameters of injection molding and mold design calculation and selection
- Module for mold modeling (core and cavity design and design all residual mold components)

The general structure of integrated injection mold design system for plastic products is shown in Fig. 1.

2.1 Module for CAD modeling of the part (module I)

The module for CAD modeling of the part is the first module within the integrated CAD/CAE system. This module is used for generating CAD model of the plastic product and appropriate simulation model. The result of this module is solid model of plastic part with all necessary geometrical and precision specifications. Precision specifications are: project name, number, feature ID, feature name, position of base point, code number of simulation annealing, trade material name, material grade, part tolerance, machine specification (name, clamping force, maximal pressure, dimensions of work piece), and number of cavity. If geometrical and precision specification is specified (given) with product model, the same are used as input to the next module, while this module is used only to generate the simulation model.

2.2 Module for numerical simulation of injection molding process (module II)

Module II is used for numerical simulation of injection molding process. User implements an iterative simulation process for determining the moldability parameters of injection molding and simulation model specification. The structure of this module is shown in Fig. 2.

After a product model is imported and a polymer is selected from the plastic material database, user selects the best location for gating subsystem. The database contains rheological, thermal, and mechanical properties of plastic materials. User defines parameters of injection molding and picks the location for the gating subsystem. Further analyses are carried out: the plastic flow, fill time, injection pressure, pressure drop, flow front temperature, presence of weld line, presence of air traps, cooling quality, etc.

The module offers four different types of mold flow analysis. Each analysis is aimed at solving specific problems:

- Part analysis—This analysis is used to test a known gate location, material, and part geometry to verify that a part will have acceptable processing conditions.
- Gate analysis—This analysis tests multiple gate locations and compares the analysis outputs to determine the optimal gate location.
- Sink mark analysis—This analysis detects sink mark locations and depths to resolve cosmetic problems before the mold is built eliminating quality disputes that could arise between the molder and the customer.

The most important parameters are the following: [22]

- Part thickness
- Flow length
- Radius and drafts,
- Thickness transitions
- Part material
- Location of gates
- Number of gates
- Mold temperature
- Melt temperature
- Injection pressure
- Maximal injection molding machine pressure

In addition to the previously mentioned parameters of injection molding, the module shows following simulation results: welding line position, distribution of air traps, the distribution of injection molding pressure, shear stress

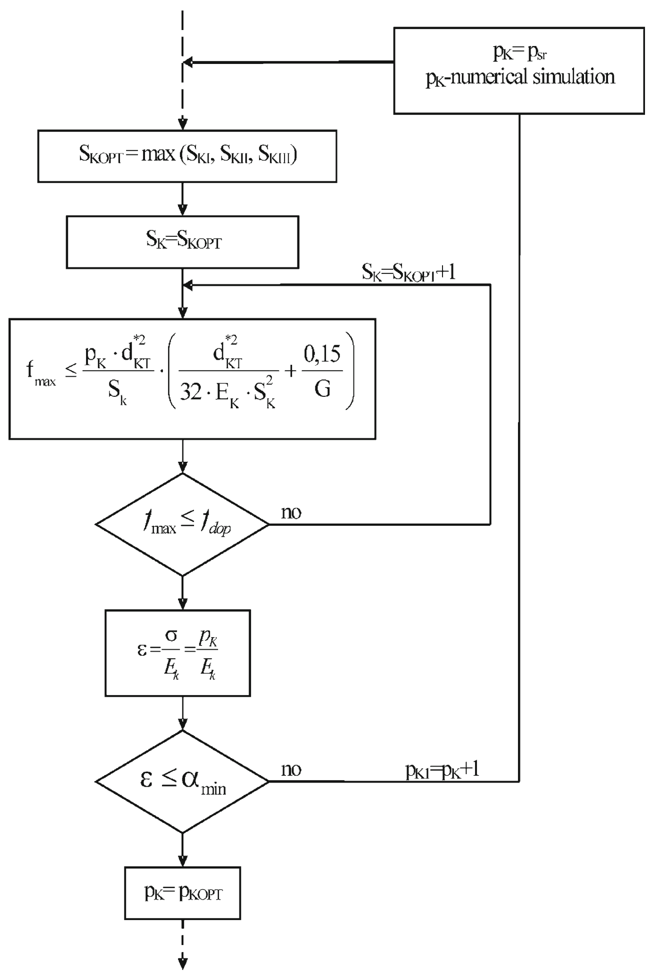


Fig. 7 Segment of the mechanical calculation algorithm

distribution, temperature distribution on the surface of the simulation model, the quality of filling of a simulation model, the quality of a simulation model from the standpoint of cooling, and time of injection molding [22, 23]. A part of output results from this module are the input data for the next module. These output results are: material grade and material supplier, modulus of elasticity in the flow direction, modulus of elasticity transverse direction, injection pressure, ejection temperature, mold temperature, melting temperature, highest melting temperature thermoplastic, thermoplastic density in liquid and solid state, and maximum pressure of injection molding machine. During implementation of iterative SA procedure, user defines the moldability simulation model and the parameters of injection molding. All results are represented by different colors in the regions of the simulation model.

2.3 Module for calculation of parameters of injection molding and mold design calculation and selection (module III)

This module is used for analytical calculations, mold sizing, and its selection. Two of the more forms for determining the dimensions of core and cavity mold plates are shown in Fig. 3.

Based on the dimensions of the simulation model and clamping force (Fig. 3) user selects the mold material and system calculates the width and length of core and cavity plates. Wall thickness between the mold cavity to the cooling channel can be calculated with the following three criteria: criterion allowable shear stress, allowable bending stress criterion, and the criterion of allowable angle isotherms are shown in Fig. 4 [22, 24]. The system adopts the maximum value of comparing the values of wall thickness calculated by previously mentioned criteria.

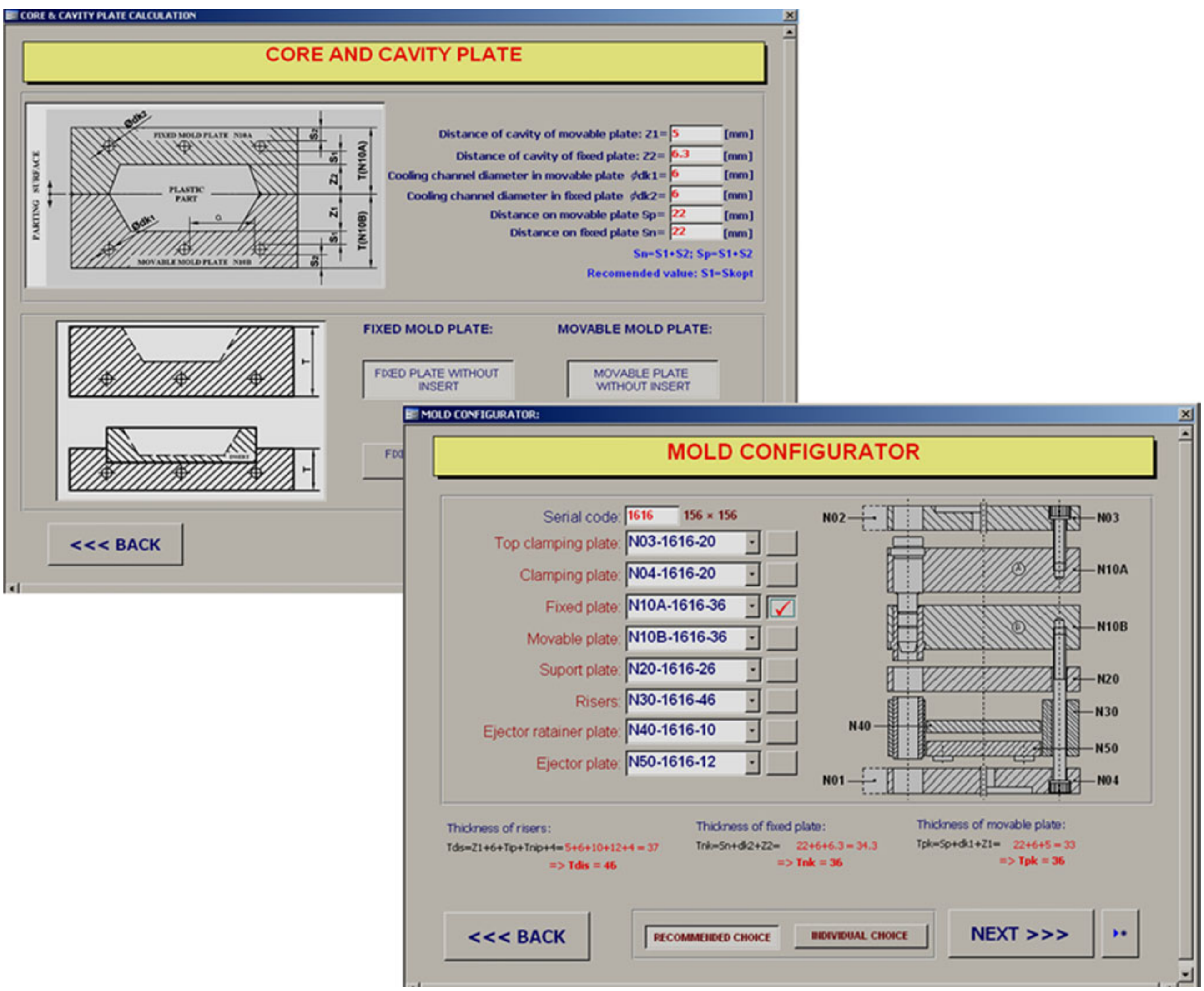


Fig. 8 Forms for standard mold plates selection

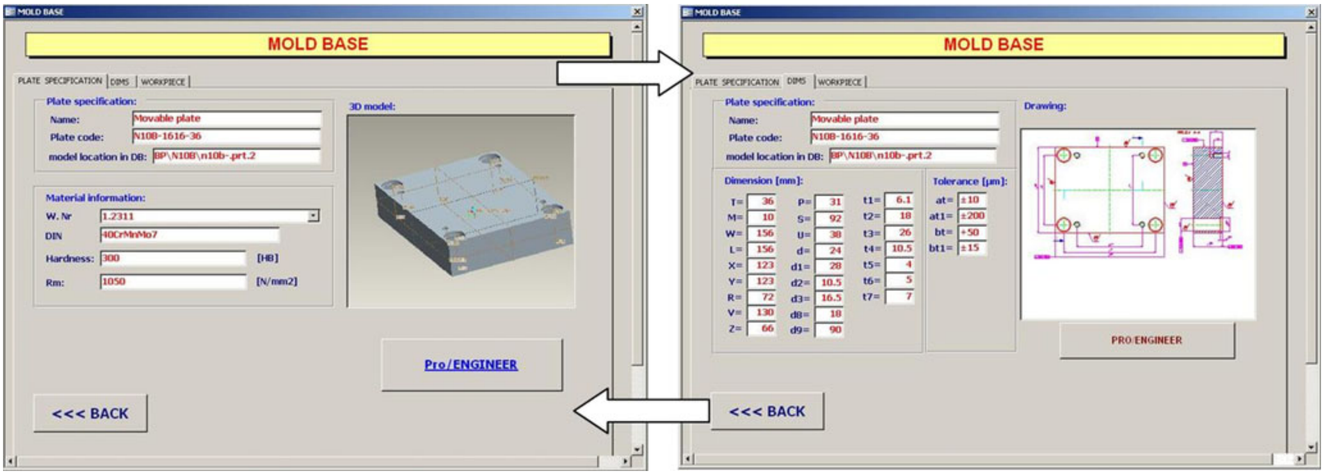


Fig. 9 Forms for mold plate model generation

Based on the geometry of the simulation model, user select shape and mold type. Forms for the selection mold shape, type, and subsystems are shown in Fig. 5. Once these steps are completed, user implements the thermal, rheological, and mechanical calculation of mold specifications. An example of one of the several forms for mechanical mold calculation is shown in Fig. 6.

Segment of the algorithm of mechanical calculations is shown in Fig. 7.

Where,

f_{max} maximal flexure of cavity plate
f_{dop} allowed displacement of cavity plate
ε elastic deformation
α_{min} minimal value of shrinkage factor
E_k modulus of elasticity of cavity plate
G shear modulus
S_k wall thickness distance measuring between cavity and waterline
d_{KT} cooling channel diameter

After the thermal, rheological, and mechanical calculations, user selects mold plates from the mold base. Form for the selection of standard mold plates is shown in Fig. 8. The system calculates the value of thickness of risers, fixed, and movable mold plates (Fig. 8). Based on the calculated dimensions, the system automatically adopts the first major standard value for the thickness of risers, movable, and fixed mold plate. Calculation of the thickness and the adoption of standard values are presented in the form as shown in Fig. 8.

The interactive system recommends the required mold plates. The module loads dimensions from the database and generates a solid model of the plate. After the plate selection, the plate is automatically dimensioned, material plate is

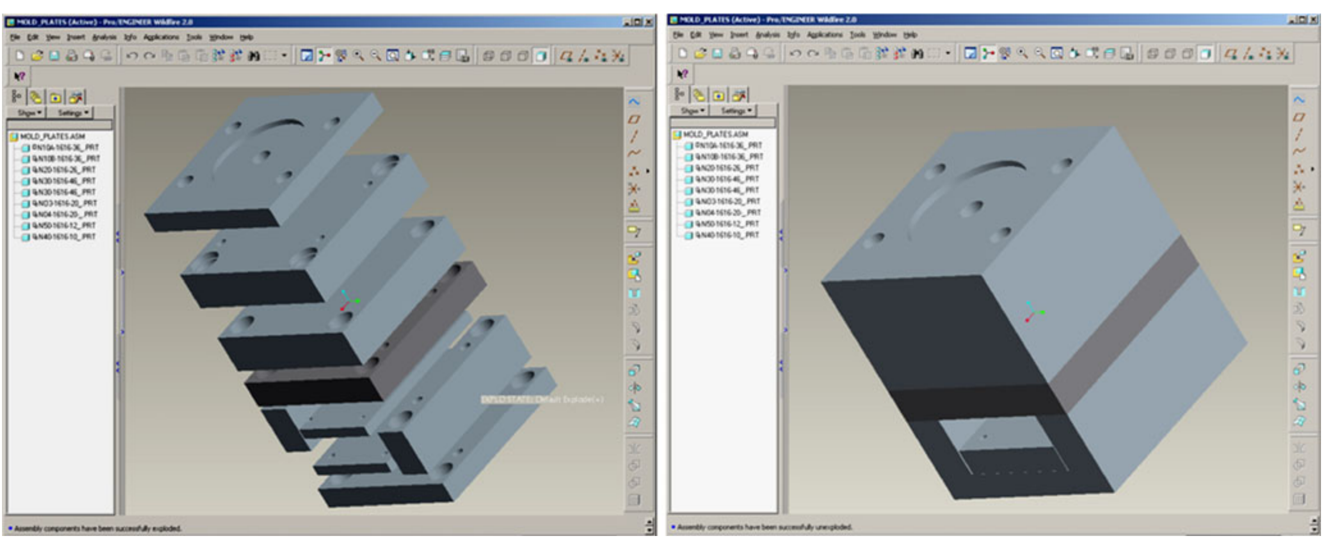


Fig. 10 Structure of module IV

assigned, and 3D model and 2D technical drawing are generated on demand. Dimensions of mold component (e.g., fixed plate) are shown in the form for mold plate mode generation, as shown in Fig. 9.

The system loads the plate size required from the mold base. In this way, load up any other necessary standard mold plates that make up the mold subassembly. Subassembly mold model made up of instance plates are shown in Fig. 10

Then get loaded other components of subsystems as shown in Fig. 5. Subsystem for selection other components include bolts and washers. The way of components selection are based on a production rules by authors and by company "D-M-E" [25, 26].

2.4 Module for mold modeling (core and cavity design and design all residual mold components; module IV)

This module is used for CAD modeling of the mold (core and cavity design). This module uses additional software tools for automation creating core and cavity from simulation (reference) model including shrinkage factor of plastics material and automation splitting mold volumes of the fixed and movable plates. The structure of this module is shown in Fig. 11.

Additional capability of this module consists of software tools for:

- Applying a shrinkage that corresponds to design plastic part, geometry, and molding conditions, which are computed in module for numerical simulation
- Make conceptual CAD model for nonstandard plates and mold components
- Design impression, inserts, sand cores, sliders and other components that define a shape of molded part
- Populate a mold assembly with standard components such as new developed mold base which consists of D-M-E mold base and mold base of enterprises which use this system, and CAD modeling ejector pins, screws, and other components creating corresponding clearance holes
- Create runners and waterlines, which dimensions was calculated in module for calculating of parameters of injection molding and mold design calculation and selection
- Check interference of components during mold opening, and check the draft surfaces

After applied dimensions and selection mold components, user loads 3D model of the fixed (core) and movable (cavity) plate. Geometry mold specifications, calculated in the previous module, are automatically integrated into this module, allowing it to generate the final mold assembly. Output from this module receives the complete mold model of the assembly as shown in Fig. 15. This module allows

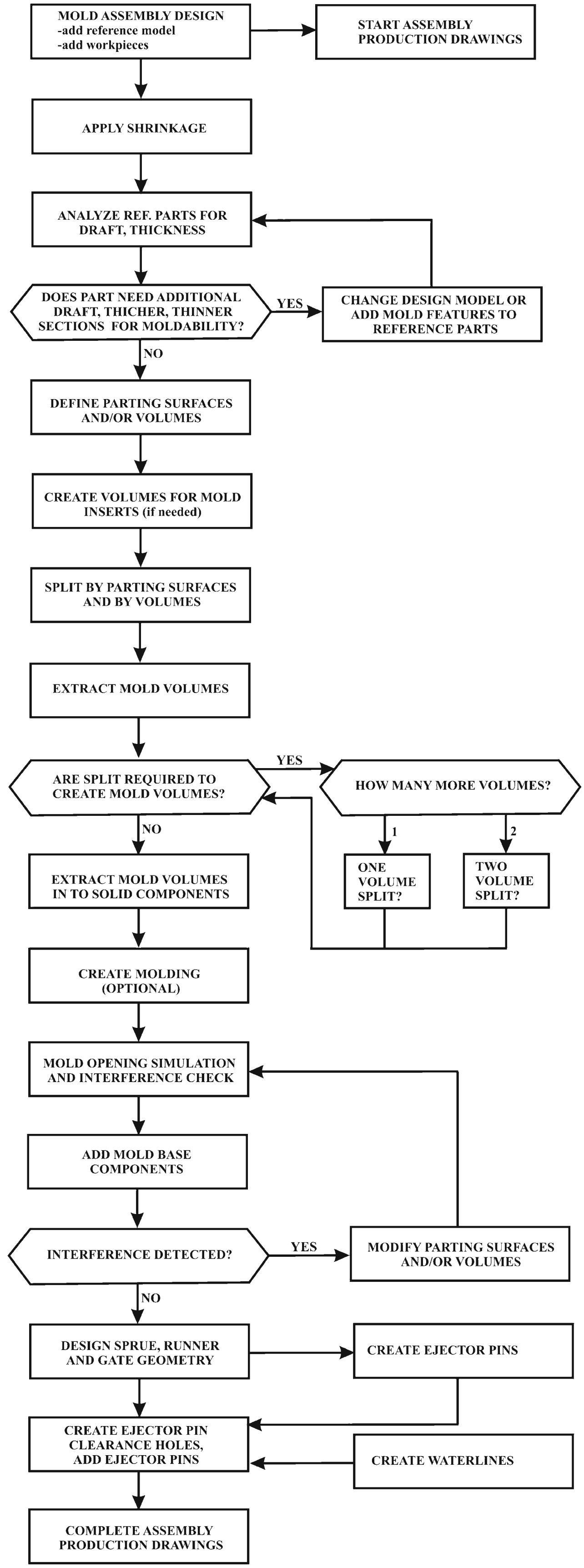


Fig. 11 Subassembly model of mold

Fig. 12 CAD model of the test product

modeling of nonstandard and standard mold components that are not contained in the mold base.

3 Case study

The complete theoretical framework of the CAD/CAE-integrated injection mold design system for plastic products was presented in the previous sections. In order to complete this review, the system was entirely tested on a real case study. The system was tested on few examples of similar plastic parts. Based on the general structure of the model of integrated CAD/CAE design system shown in Fig. 1, the authors tested the system on some concrete examples. One of the examples used for verification of the test model of the plastic part is shown in Fig. 12.

The module for the numerical simulation of injection molding process defines the optimal location for setting gating subsystem. Dark blue regions indicate the optimal position for setting gating subsystem as shown in Fig. 13.

Based on dimensions, shape, material of the case study product (Fig. 11), optimal gating subsystem location (Fig. 13), and injection molding parameters (Table 1), the simulation model shown in Fig. 14 was generated.

One of the rules for defining simulation model gate for numerical simulation:

> IF (tunnel, plastic material, mass) THEN prediction dimension (upper tunnel, length, diameter1, diameter2, radius, angle, etc.)

Part of the output results from module II, which are used in module III are shown in Table 1.

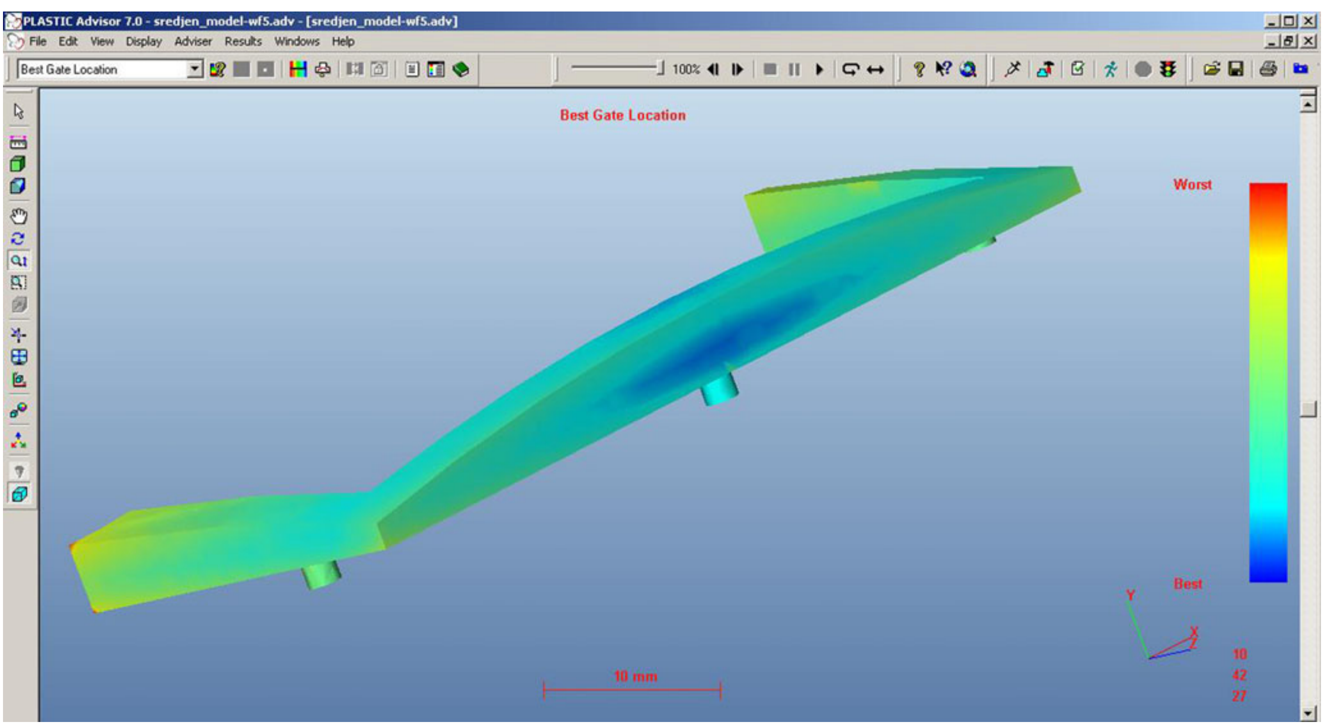


Fig. 13 Optimal gating subsystem location in the part

Table 1 Part of the output results from the module for the numerical simulation of injection molding process

Material grade and material supplier	Acrylonitrile butadiene styrene 780 (ABS 780), Kumho Chemicals Inc.
Max injection pressure	100 MPa
Mold temperature	60°C ili 40
Melt Temperature	230°C
Injection Time	0,39 s 0,2 s
Injection Pressure	27,93 MPa
Recommended ejection temperature	79°C
Modulus of elasticity, flow direction for ABS 780	2,600 MPa
Modulus of elasticity, transverse direction for ABS 780	2,600 MPa
Poision ratio in all directions for ABS 780	0.38
Shear modulus for ABS 780	942 MPa
Density in liquid state	0.94032 g/cm^3
Density in solid state	1.047 g/cm^3

In module III, the system calculates clamping force F= 27.9 kN (Fig. 3), cooling channel diameter d_{KT}=6 mm, cooling channel length l_{KT}=90 mm (Fig. 4). Given the shape and dimensions of the simulation model, square shape of mold with normal performance was selected as shown in Fig. 5. Selected mold assembly standard series: 1,616, length and width of mold housing 156×156 mm as shown in Fig. 8. In the segment of calculation shown in Fig. 8, mold design system panel recommends the following mold plates:

- Top clamping plate N03-1616-20
- Bottom clamping plate N04-1616-20
- Fixed mold plate (core plate) N10A-1616-36
- Movable plate (cavity plate) N10B-1616-36
- Support plate N20-1616-26
- Risers N30-1616-46
- Ejector retainer plate N40-1616-10
- Ejector plate N50-1616-12

After finishing the fixed and movable mold plates from the standpoint of CAD modeling core and cavity plates, cooling channel, followed by manual selection of other mold standard components such as sprue bush, locating ring, guide pins, guide bush, leading bushing guide, spacer plates, screws (M4×10, M10×100, M10×30, M6×16, M10×30, etc.) and modeling nonstandard mold components (if any) ejector pins, ejector holes, inserts etc. A complete model of the mold assembly with tested simulation model is shown in Fig. 15.

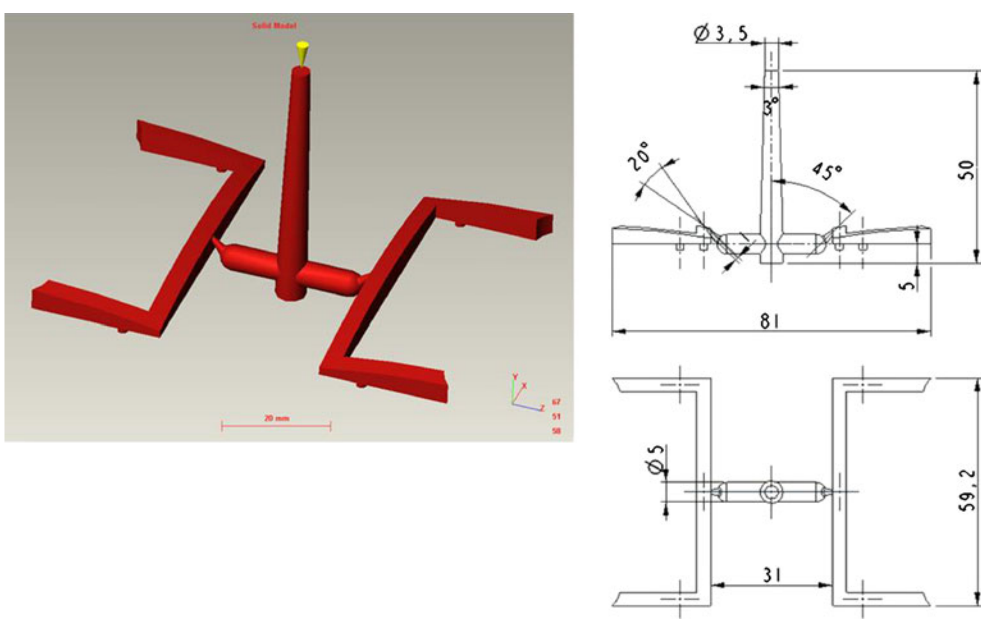


Fig. 14 Simulation model of plastic part

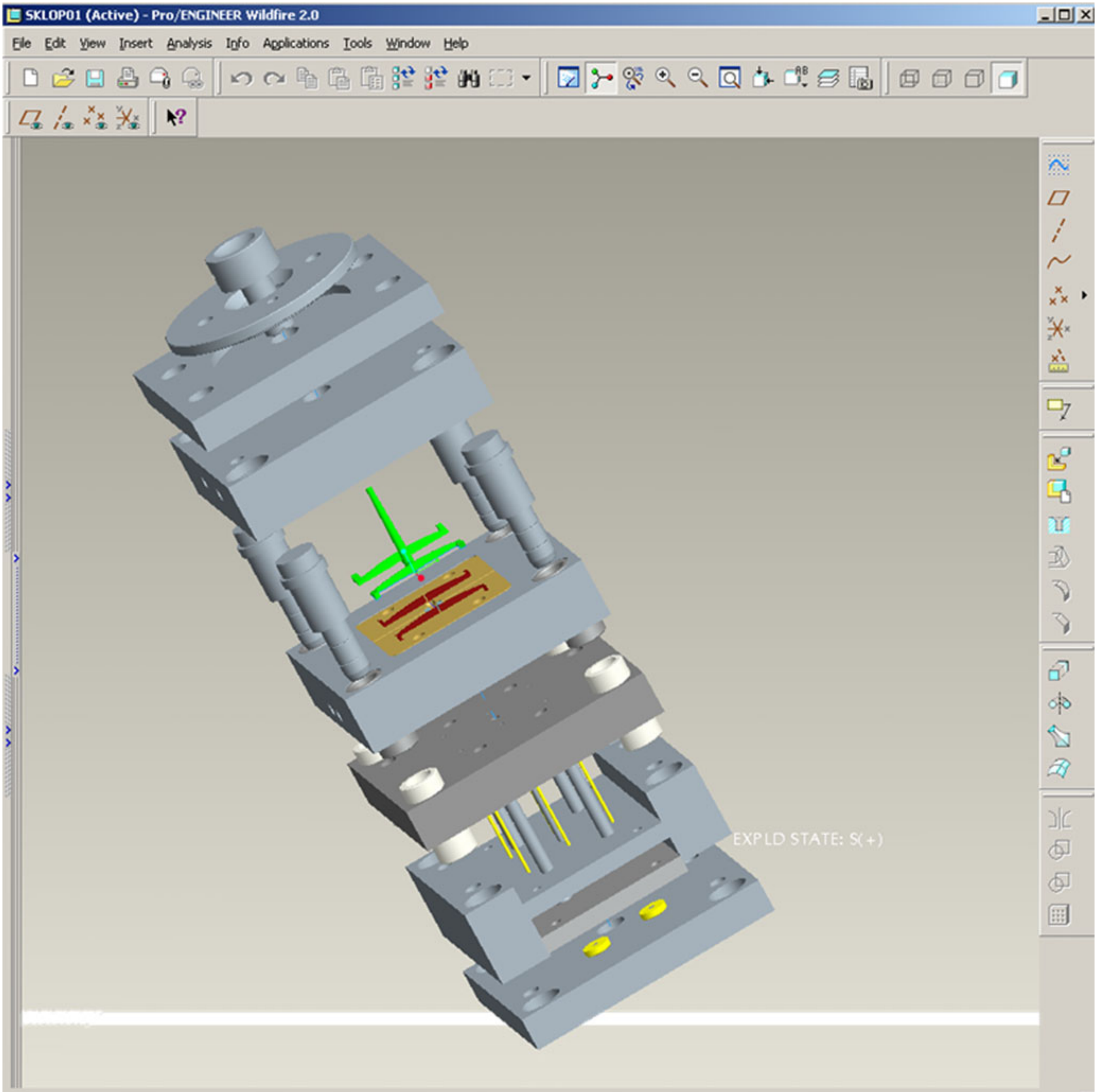


Fig. 15 Model of the mold assembly with tested simulation model

4 Conclusion

The objective of this research was to develop a CAD/CAE integrated system for mold design which is based on Pro/ENGINEER system and uses specially designed and developed modules for mold design. This paper presents a software solution for multiple cavity mold of identical molding parts, the so-called one product mold. The system is dedicated to design of normal types of molds for products whose length and width are substantially greater than product height, i.e., the system is customized for special requirements of mold manufacturers. The proposed system allows full control over CAD/CAE feature parameters which enables convenient and rapid mold modification. The described CAD/CAE modules are feature-based, parametric, based on solid models, and object oriented. The module for numerical simulation of injection molding allows the determination selection of injection molding parameters. The module for calculation of parameters of injection molding process and mold design calculation and selection improves design faster, reduces mold design errors, and provides geometric and precision information necessary for complete mold design. The knowledge base of the system can be accessed by mold designers through interactive modules so that their own intelligence and experience can also be incorporated into the total mold design. Manufacture of the part confirms that the developed CAD/CAE system provides correct results and proves to be a confident software tool.

Future research will be directed towards three main goals. The first is to develop a system for automation of family mold design. Another line of research is the integration with CAPP system for plastic injection molds manufacturing developed at the Faculty of Technical Sciences. Finally, following current trends in this area, a collaborative system using web technologies and blackboard architecture shall be designed and implemented.

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