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Evaluation of Filling Conditions in Injection Moulding by Integrating Numerical Simulations

R. Hariharan and R.J. Golden Renjith Nimal

Mechanical Engineering, Bharath University, India

Abstract: The purpose of this topic is an integrated approach to evaluate gating system configurations to optimize the filling conditions of thermoplastic injection moulded parts. Through data integration between the finite element (FE) analysis and the Design of Experiment approach, the filling of parts with complex geometries was studied to optimize injection process parameters and improve the product quality. The numerical simulation of an injection moulding process allows the evaluation of the component manufacturability at the early stage of the development cycle, without fabricating prototypes and minimizing experimental tests. Normally, the FE analysis interests concerns filling, post-filling and cooling phases of the injection process. Using the FE system, a deeper investigation of stress and strain distributions can be performed to predict defect presence in the final product. However, this methodology is sensitive to existing differences between property of the real part and of its model (material, geometry, etc.).

Key words: Injection mold design · Weld lines · Fill time · Air traps · Tool design

INTRODUCTION

Companies have to produce high quality parts at lower costs in order to maintain competitiveness on the present market place. Plastic parts are commonly used in medical devices, telecommunications, computers, consumer electronics, domestic appliances and automotive fields. Demand is constantly increasing and plastic manufacturers must deal with several key challenges to improve product quality while lowering their costs. These important goals may be difficult to obtain if manufacturers do not carefully deal with crucial aspects and/or market perturbations such as: the continuous evolution of customer trends, compression of product life cycles, frequent requests for short-term volumes and shortage of skilled operators to work with sophisticated machine equipment. All these factors have a great influence on injection moulding because of the high initial capital costs connected to the expensive machines and moulds employed during fabrication. The achievement of high Quality parts requires information processing from several sources necessary to define, respect and improve product and mould features linked to design and manufacturing requirements. Significant time delays and increasing cost may appear if product design and manufacturing are not carefully evaluated and/or a deep understanding of the process is not available. Another aspect to consider is the strategic influence of moulds. Even if moulds require a small investment, they are very important during the evaluation of lead times, quality and costs of parts. The successful realization of new moulds and fast process start-up may be critical for the competitiveness of the entire production program.

The Injection Moulding Cycle: Injection molding is the most commonly used process to realize plastic parts with high production rates and good control on the product dimensions. This cyclical process is carried out in three phases: (i) filling, (ii) packing and (iii) cooling. During the first phase, a melted polymer fills the part cavity, moving through the sprue, runners and gates. In the packing phase, additional melted polymer enters the cavity to balance the part shrinkage caused by cooling. The cooling phase takes place concurrently with the filling and packing phases and considers polymer plasticization and the additional time required to obtain a more than 80% solidified product. This is necessary for the ejection of the part which together with mould opening completes the process. During these phases, interactions between material properties, machine parameters and process variables make fabrication complex.

Corresponding Author: R. Hariharan, Mechanical Engineering, Bharath University, India.

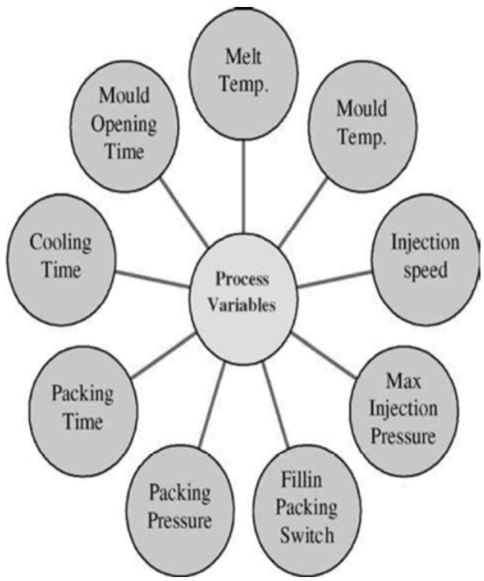


Fig. 1:

The quality of the final products, which may be characterized in terms of dimensional stability, appearance and mechanical properties, directly depends on these factors. During the manufacturing set-up, the process engineer performs all tasks necessary to optimize the process conditions and specify suitable machine requirements. The optimization process is realized by considering all or part of the main variables reported in Fig. 1. In fact the change of one process parameter influences the others, due to significant interactions between variables. Some researchers have carried out investigations on the analysis and control of injection moulding variables such as the polymer melt temperature, filling rate and packing pressure profiles. The melt temperature directly affects the polymer viscosity, filling flow rate, filling pressure and cavity pressure-time profile. The filling rate has a strong influence on the quality of the moulded part, especially on mechanical properties and dimensional stability. The optimal choice of the packing pressure profile reduces part residual stresses, reducing product shrinkage and warpage but increasing object weight.

The main characteristics of an injection moulding machine are reported in terms of: the mould clamping force, calculated injection volume, injection flow rate, heating input power, screw rotating speed, maximum pressure on material and distance between tie bars. The mould external dimensions and the part projected area represent the primary factors to consider during the machine choice. The mould dimensions affect the size of machine platens while the part projected area determines the injection pressure and the size of the injection unit. The other machine characteristics are strictly related to the process conditions chosen to produce Moulded parts.

Approaches to the Process Evaluation: The design and the optimization process of a plastic molded part and of its related tooling system are crucial tasks in order to obtain high-quality products. Aesthetical and functional requirements represent only two factors influencing the product design while analyses of product manufacturability and mouldability are very important for mould fabrication. Moreover interactions between the process variables of injection moulding require particular attention when setting-up the machine. Several approaches can be used to deal with these aspects, roughly classified into: (i) design by experience, (ii) by experiment and (iii) by numerical simulation. Design by experience, widely used in the past, is strictly related to decisions, both good and bad, taken by skilled personnel basing on previous production information. Company experience can be re-used for all products but it is not shared between different operators, also representing an approximate knowledge. In fact each design is highly dependent on the individual experience of the designer, who decides the appropriate configuration to realize a product. This approach is efficient when materials are well- known and new products are only variations of previous ones. However design by experience becomes inadequate in cases of completely new products, materials and/or processes. Moreover company knowledge can be drastically reduced due to designer turn-over, a very probable condition in the actual market situation. In addition design is not always optimized. Design by experiments is more useful than design by experience to analyse processes through measurements of the effects of one or more experimental factors on some specific sets of responses. The necessary knowledge to improve or repair processes is provided by experimental activity. Using the experimental results, designers and process engineers can: identify modifications to improve product realization, isolate sources of defects, test methods for defect elimination or reduction, optimize procedures and acquire sufficient knowledge on new machines, methods or materials. A well-structured investigation plan must be employed in order to speed-up experimental analysis while concurrently reducing experiment costs and increasing experimental reliability. In addition, this well- designed plan can decrease risks of experimentation within reasonable bounds. The limitations of this approach are mainly connected to the need for physical prototypes to test different process conditions. Several moulds are required to the test design solutions and identify the optimal process variables for each of them, with a consequent increment of product development costs. Design by numerical simulations represents a powerful alternative to speed-up the product development cycle, reducing activities linked to experimental tests and mould fabrication. The computer industry has provided higher levels of sophistication in the hardware available. The new hardware, coupled to new software development, allows more enhanced computer-aided systems and finite element analysis software packages to be implemented, providing more information to designers and mould-makers in the manufacturability analysis while further compressing the design/fabrication process. The numerical models of part and mould designs give accurate solutions and reliable predictions for a specific set of process parameters because they include the physical law formulation of the process itself. Using numerical simulation software, the physical prototypes are replaced with digital ones, reducing effort and costs connected to the experimental activity. However the experimental design continues to be used because engineers must completely understand the manufacturing process in order to create proper simulation-oriented models.

In this way, the results of the numerical models are more reliable, thanks to detailed data of the process characteristics, representation of material properties, etc.

Product Development Environment: The proposed approach is realized by integrating data coming from: the computer-aided design (CAD) system, finite element (FE) methodology, statistical methods and experimentation (Fig. 2).

The main objectives of the proposed environment were the definition, identification and validation of the optimal filling conditions of an injection moulded part. The framework consists of several modules, necessary to: (i) model the part and mould using a general-purpose CAD system, (ii) transform the CAD models into FE meshes to perform numerical analyses, (iii) identify the main parameters influencing processability and mouldability of the part using design of experiments approaches and (iv) verify predicted results with the real manufacturing conditions through well designed experimental plans. Particular attention has been paid to critical aspects related to the definition of information flows and to the search for the optimal process conditions. The information flow was defined in terms of received and transferred data between framework modules in order to implement a concurrent engineering approach. For this reason, the level of details of each module was accurately chosen to support successive activities and allow data evaluation. The design by numerical simulations and by experiments were the methodologies used to evaluate and identify the optimal process conditions. The different modules of the proposed environment and their data flows are described in more detail in the following sections.

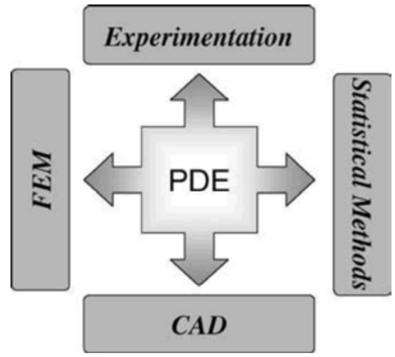


Fig. 2: Product development environment

Product Representation and FE Analyses: The CAD system supported all activities related to modeling of the part and mould. The part was designed using feature-based methodology. This approach allowed the robust design of part components because the main geometrical parameters and extra data (e.g. material properties and/ or attributes) are directly associated to each feature. This association was also useful during injection moulding analyses in order to identify the parting plane and define cavity layouts. The mould design was carried out using both feature-based and parametric approaches. The type and structure of the mould were initially defined while values associated to main parameters were specified in order to specialize mould geometry. At the same time, the feature based design allowed the assembly of mould plates and associated components to be performed using automatic operations. These operations were implemented for standard and three-plate moulds only. The design of feeding and cooling systems was postponed until after filling analysis. The mould configuration was also adapted to the injection machine used for the part production, so integrating manufacturing process knowledge into the CAD system. Several advantages were obtained using the feature-based and parametric design of the mould such as: the evaluation of several mould configurations with a

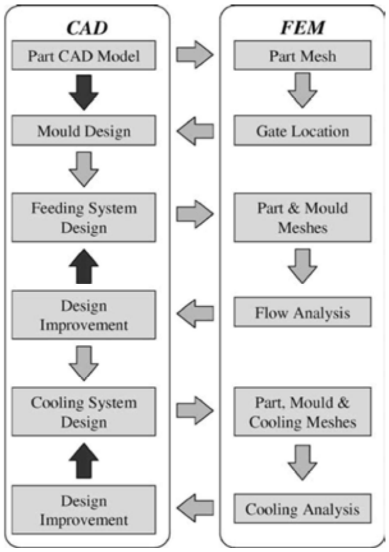


Fig. 3: CAD/FEM data exchange.

limited parameter management, structure definition of larger and more complex moulds, improvement of accuracy for an easy up-date process and speeding-up of the overall project realization. The data exchange between the CAD and FE simulation systems was realized into several steps (Fig. 3).

The CAD model of the part was initially transferred into the FE system using the IGES file format. The part mesh was generated by specifying the mesh type (double-skin or tetrahedral). A pre-processing operation was necessary to correct mesh problems such as: overlapping elements, high aspect ratios, connectivity regions and non-manifold edges. The mid-plane representation was not used because of its limitations connected to the computational effort required in generating mid-plane meshes from 3D CAD solid models and the lower speed and accuracy for all model analyses than those of other representations. On the contrary, the solution time was lower than that of double-skin and tetrahedral meshes because of the reduced number of elements required. The choice between the double-skin and tetrahedral meshes as well as the demand for accuracy for filling and packing analyses depend on the wall thickness and the computation time. Thin and thick-walled parts are respectively modelled using double- skin and tetrahedral meshes. A tetrahedral mesh is also used when great thickness variations occur in the part. The computation time is directly related to the number of elements and their typology. As a consequence, analyses on tetrahedral meshes are more time consuming than those on double-skin. Based on these conditions and some limitations of the FE system employed (warpage analysis cannot be performed on a tetrahedral mesh), the methodology used in proposed framework was to identify the main variables influencing the process only using double- skin meshes and then refine process conditions by coupling warpage results on double-skin model with filling, packing and cooling results on a tetrahedral model. Several FE analyses were carried out, consisting of:

- Identification of the best gate position, (ii) study of polymer flow advancement, (iii) evaluation of thermal fluxes and (iv) analysis of part warpage (Fig. 3).

The identification of the gate position of each part was very important due to its beneficial effects on part warpage and material orientation. The main goals of the gate location analysis were to: balance flows between mould cavities (all cavities must be completely filled at the same time), reduce weld lines and air traps, prevent hesitation, avoid orientation effects, etc. In addition, the selection of this analysis was very useful to detect problems associated with over-packing such as: non-uniform shrinkage, product sticking, flashing, excessive cycle time and part weight. Part over-packing occurs when extra material is compressed into one flow path while other flow paths are still filling. Once the gate location analysis had been completed, the design of the feeding system and cooling systems was performed. Some of the main functions demanded for an efficient design of the feeding system are: to assure mould cavity filling with a minimum of knit lines, facilitate part de-moulding at the completion of the process cycle, keep looses in pressure, temperature and material small and produce little or no effect on the total cycle time. These technical requirements are sometimes in conflict with the cost-effective demand for rapid product solidification and short process cycles. For this reason, a compromise between cost and quality of the product must be usually found. In addition, some product functions during service and/or use as well as aesthetic features may limit available configurations for the feeding system. The main characteristics demanded of the cooling system are the efficient heat removal, the uniform temperature distribution between mould cavities and the minimization of the cycle time. Concurrently to these, undesired effects such as sink marks, differential shrinkage and cold spot must be avoided. The design of the cooling system is more complicated than the feeding system for a multi-cavity mould. The heat conduction rate is mainly affected by the product shape and the distance between cavities. As a consequence, the cooling design could not be performed until the mould design and the flow analysis have been completed. On the other hand, the filling analysis is influenced by the heat fluxes along cavities. For this reason, the flow and cooling analyses were performed using a step-by step procedure and then coupled to represent the entire injection moulding process. Several evaluations were carried out to identify possible modifications to the mould design in order to improve part fabrication. The flow induced and/or thermal-induced residual stresses were calculated at each step. In the first step of the simulation stage, the polymer flow (filling and packing) was studied under specific constraints on material properties, gating system and moulding machine. This step was important to evaluate the filling process parameters, final part characteristics and flow-induced stresses. In the cooling step, the meshes of the mould and first configuration of the cooling system were joined to the part to perform the thermal analysis. The simultaneous investigation of the part and mould during this step allowed the estimation of the effects of each process parameter on the global performance of the final product. This permitted the appraisal of the thermal residual stresses of the injection moulding process. The filling/packing and cooling steps were re-iterated until thermal flow stability between cavity, mould and cooling system were reached. At the end of this simulation stage, a model containing the warped surfaces was achieved and useful information was obtained to optimize the cooling system design.

FE optimization and experimentation The optimization of process parameters of injection moulding requires a great effort. The interactions between geometrical part dimensions, material properties and machine characteristics make it difficult to identify the parameters which most influence the fabrication process. One possible approach is to vary one parameter at time, holding others fixed and realize both FE simulation and experimental tasks for each parameter set. As a result, numerical results are always compared with experimental ones and a reliable FE model is obtained. The limitation of this trial and error methodology is related to the large number of cases to be produced and analysed in a wide range of process conditions, obtaining a poor parameter ranking as a result. A different methodology was instead used in this study (Fig. 4). Statistical approaches were used to support FE analyses and obtain the improvement of the part and mould designs. The statistical approaches are mainly based on two design of experiment techniques: Taguchi parametric design (TPD) and response surface (RS). The creation of a reliable FE model was performed by

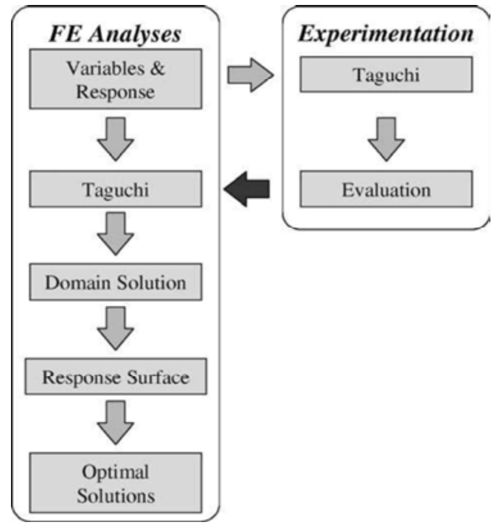


Fig. 4: FEM/experimentation data exchange

validating it on a small set of experimental data. The planning and analysis of both experimental data and numerical simulations were carried out using the TPD approach. The primary goal of the approach was to find factor settings that minimize response variation, while adjusting (or keeping) the process on target. In this way, the reduction of variation was obtained by tuning the levels of influencing factors and controlling the variation of other factors. An L8 orthogonal array, consisting of five factors with two levels for each of them, was employed to analyse the product. The factors considered were: the melt temperature, mould temperature, injection time, packing time and pressure. The TPD approach was useful to evaluate the influence of parameter variation on product quality but it was not efficient at identifying the optimal parameter set.

As a consequence, a response surface methodology was used to plan the subsequent numerical simulation phase. This approach allowed the examination of the relationship between one or more response variables and a set of quantitative experimental variables or factors. Some conditions were expected to obtain an efficient data analysis:(i) a number of factors less than 5; (ii) quadratic models were employed; and (ii) at least three levels of every factor were used in the design. Starting from the Taguchi analysis results, a new process variable domain was defined by selecting al least three main factors influencing part fabrication. For each factor, three levels were specified (min-medium-max) in order to obtain a exhaustive design plan. The RS approach was only applied to the optimization of FE simulation responses thanks to the reliability of the FE predicted results.

RESULTS

The research activity was carried out in collaboration with a company producing plastic products. The investigated product consisted of an aluminium trolley covered by a plastic component. The functional requirements for the plastic component were related to respecting strict tolerances for final assembly with the trolley and other elements of the complete product, while obtaining a good surface appearance. Table 1 reports some characteristics of the part polymer used. BASF Ultramid1 A3EG6, a glass fibre reinforced PA66 polymer (30% in weight), is normally employed in machinery components and housings of high stiffness and dimensional stability such as lamp socket housings, cooling fans and insulating profile for aluminium window frames. This polymer easily flows due to its low viscosity, allowing the realization of thin components, but the viscosity is very sensitive to the operative temperature. Shrinkage is between 0.2 and 1% because of the presence of the glass fibre reinforcement. However differential shrinkages in the flow and cross-flow directions are quite high.

Gate Location: The part was modelled using the CAD\CAM system CATIA1 v5 of Dassault Systemes and then transferred tothe FE modelling environment of MOLDFLOW1 Plastic Insight. The mesh was realized using the double-skin representation and consisted of 874 elements for each part. The injection machine used was NEGRIBOSSI CANBIO V110, the characteristics of which respect the EUROMAP standard. The gate location analysis is very important because of fast freeze-off times of the polymer. The analysis was Fig. 4. FEM/experimentation data exchange.

Runner Design and Filling Analysis: Definitions of the parting plane and number of mould cavities are pre-requisites to be satisfied before the filling analysis can be carried out. The parting plane was located at the same z-level at lower faces of the part side wings. The number of cavities was equal to four in order to obtain the highest production throughput while respecting the maximum occupied frontal areas for the possible mould dimensions. The feeding system for the two selected location points are shown in Fig. 7, considering that any type of gate may be used for the feeding design. These systems employed cold sprue, runners and gates.

Fig. 5: Part mesh.

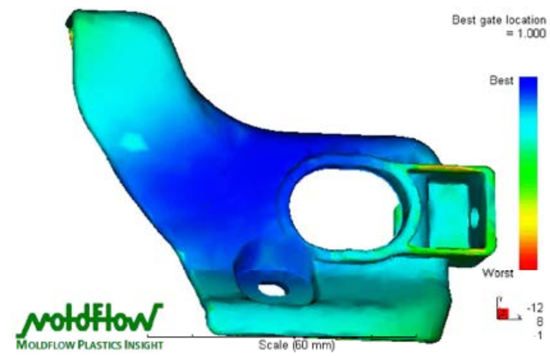
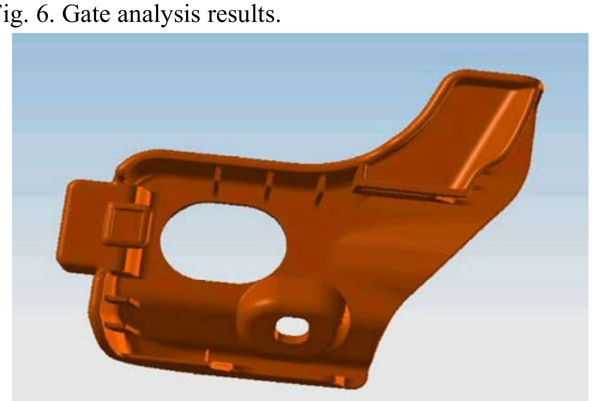
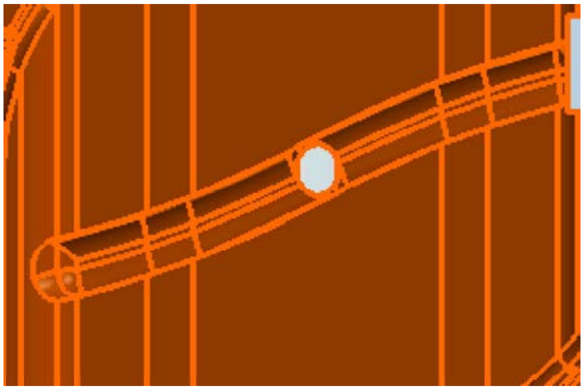


Fig. 6. Gate analysis results.



Injection Machine Technical Data:

- Screw diameter (mm) 28
- Screw length-to-diameter ratio 20
- Distance between tie bars 310*310mm
- Maximum flow rate (cm3/s) 122
- Minimum mold height 2 00
- Maximum mold height 300
- Mould clamping force (kN) 60
- Shot weight 48gms



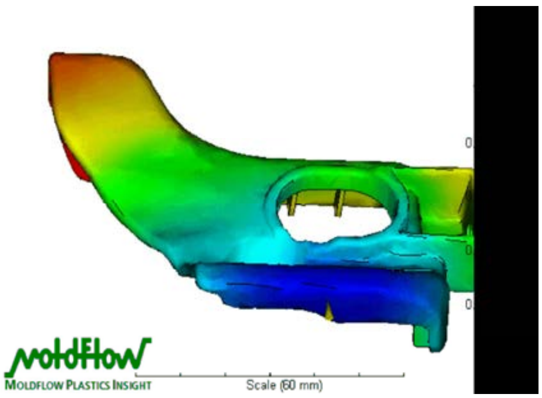


Table 1: Properties of polypropylene : Physical properties

Density (g/cm3)	1.36
Water absorption (%)	5.5
Moisture absorption at equilibrium (%)	0.01
Linear mould shrinkage, flow direction	0.0025
Linear mould shrinkage, traverse	0.011
Melt flow(in min)	40 g/10
Maximum shear stress (Mpa)	0.5
Thermal properties CTE, linear 20 8C-parallel (mm/m 8C)	17
CTE, linear 20 8C-transverse to flow (mm/m 8C)	65
Melting point (8C)	260
VICAT softening point (50 h/50 N) (8C)	250
Oxygen index (%)	24

CONCLUSIONS

Considering the results obtained by integrating FE and DOE approaches, the proposed framework can be enhanced by: (i) promoting more extensive data integration between CAD, FE and experimental activities, (ii) standardizing the DOE-FEM procedures in order to support non-skilled operators in the identification of stable processing zone, (iii) training artificial intelligence systems (e.g. neural networks) that embed optimization tasks in a real-time system for process control. Further research could lead to the use of specialized sensors for on-line measurements of the cavity pressure to make the FE predictions of product fabrication more accurate.

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