# Computational Prediction of Defects During Injection Molding in a Complex Part

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*In this paper, a comparative study was conducted on the behaviour of three types of thermoplastic materials during the injection molding of a complex part using the Moldflow software. The numerical simulation is based on the Hele-Shaw flow model for the inelastic non-Newtonian fluids under non-isothermal conditions. Based on the numerical results accurate prediction of weld lines and air traps were carried out.*

*Keywords: injection molding, plastic materials, air trap, weld line*

Since the mid 1980s, polymer science and technology is not just on the periphery but at the center on numerous new developments. Due to their properties, polymer consumptions of developed and developing countries increased steadily such that the volume of synthetic polymers produced is greater than the volume of steel [1].

Manufacturing of polymers plays a major role in polymer research. The development of plastic process is considered to be as important as the development of plastic itself. Injection molding is the most important process used to manufacture plastic products. More than one third of all thermoplastic materials are processed by injection molding. The injection process has in fact one major disadvantage, namely the high cost of moulds, which is why manufacturing products by this process is ideally suited to manufacture mass-produced parts of complex shapes that require precise dimensions [2]. This disadvantage led to the development of the numerical simulation techniques that have great implications for the design of molds. During the last decade, there has been tremendous development in Computer Aided Engineering (CAE), which offers flexibility to determine the effect of different geometric futures and different molding and processing conditions on the moldability and quality of the final part [3]. Computer simulations offer the advantage of considering any molding option and to eliminate problems and optimize the part and mold before the first piece of steel is cut for the mold so that part quality will be higher and less expensive to produce.

Numerical simulation in the field of injection molding can be divided into the filling, packing, compensation and cooling phases, respectively. Since one of the major drawbacks with the simulation of the injection molding process is the transient free surface associated with the flow front [4], the way the plastic flows into the mold is of paramount importance in determining the quality of the part. Moreover, the visualization of the filling phase allows a very accurate prediction of the location of the welding lines and air-traps [2, 4]. This is very important in determination and removal of the causes leading to cracks in complex parts. The packing and the compensation phases are dominated by heat transfer, while the filling is dominated by fluid flow.

In this paper, in order to predict the possible defects that may appear during the injection molding, the behaviour of different thermoplastic materials (POM, PA66, and HDPE) during the injection of a ventilator part is investigated. The numerical simulations are carried out using Moldflow simulation technology which provides additional capability, specifically for automatic weld/meld line and air-trap prediction.

*Model description*

Numerical simulation of polymer melt flow in moulds requires a fully coupled solution of mechanical and thermal problems. Regardless of the complexity of the flow, it must satisfy the conservation of mass, conservation of momentul and conservation of energy laws, respectively,

The non-isothermal flow motion is mathematically described by the following partial differential equations [2, 3, 5, 6]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0; \qquad (1)$$

$$-\nabla p + \nabla \cdot \tau = 0 \qquad (2)$$

in the above equations, $\mathbf{u}$ is the velocity vector, ρ is the density, *p* is the pressure, The velocity vector in the Hele-Shaw flow model us assumed to be $u=(u_x, u_y, 0)$.

The heat transfer during the filling is modeled by the energy equation [6]

$$\rho C_P \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot \left( k \nabla T \right) + \eta \dot{\gamma}^2 , \qquad (3)$$

where *T* is the temperature, $C_p$ is the specific heat, *k* is the thermal conductivity, $\dot{\gamma}$ is the shear rate, and η is the viscosity.

The above equations are complemented by defining the constitutive equation that describes the behaviour of the polymer melt through its shear viscosity [7]. In the present paper, to consider the presence of the solidified layer along the mold walls, a Cross WLF model was used to describe the material behaviour as a function of processing and applied conditions. To describe the change of volume and shrinkage during the injection molding process a constitutive model for the pressure-volume-temperature for the polymer must be defined. In this paper, the 2-domanin Tai state equation is used [8].

The Moldflow solver is based on the Hele-Shaw flow model for the inelastic non-Newtonian fluids under non-isothermal condition [8]. The Hele-Shaw model is derived from averaged measures of the equivalent shear strain rate and viscosity over the channel cross-section. The principle of Hele-Shaw flow is based on the following assumptions:

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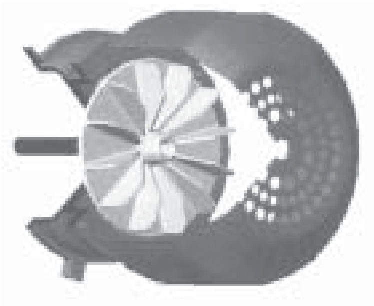


Fig.1. 3D view of the injected part “Ventilator” assembled on the axle of an electrical engine

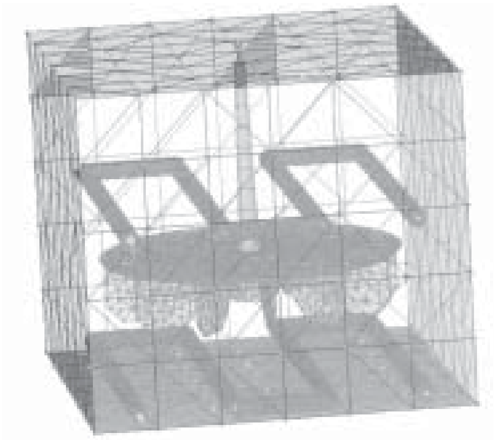


Fig.2. The descretisation mesh of the “Ventilator” and a cooling channels incorporated into the mould surface wizard

laminar flow of a generalized Newton fluid, inertia and gravity effects can be ignored, in-plane heat conduction is negligible compared to conduction in the thickness direction, thermal convection in the thickness direction is neglected, heat loss from edge can be ignored for the triangular element type [7, 8].

*Numerical simulation*

Figure 1 shows the geometry of the part considered in this paper. In order to run a Moldflow analysis, the model part is discretized into finite elements. Generally, the more elements are, the more precise the analysis is. Moldflow uses three mesh types: midplane, fusion, and 3D mesh [8]. In this paper, the ventilator part is modeld using a fusion mesh (or a modiffied 2.5D mesh) which simulates a 3D part with boundary or skin mesh on the outside surfaces of the model part (fig. 2). The ventilator was discretized using 10 744 triangular elements and 5374 nodes, the average aspect ratio of triangle elements being 2.433. In the fusion mesh, elements across the thickness are alined and matched. The distance between the elements on the opposite sides of the wall defines the part thickness. The percentage of matched elements should be at least 85% in order to achieve a mesh density that can provide good quality of the mesh [8]. In our simulation we have obtained a match ratio of 88%. To account for extra heat transfer along the edge parts (called edge effect) element on the edge are set to 75% of the thickness of face elements touching the edge. The feed system and cooling channels were discretized using beam elements (fig. 2). The calculated volume for the fusion mesh is more accurate that the midplane due to the surface used with fusion. The correct estimation of the volume is very important since it is needed to define the flow rate. Also, the volume will influence the flow rate and the pressure calculation in the runner system.

**Results and discussions**

The numerical comparative study has been carried out for three different thermoplastic materials. Table 1 shows the material properties used in this paper. The material properties are chosen from the Moldflow database [8].

The molding conditions include filling/packing time, mold temperature, pressure profile and injection rate profile, melt temperature. These conditions are the fundamental parameters needed for a fill or flow analysis. The values of the molding conditions, considering the temperature of the environment T = 25° C are presented in table 2. The time variations of the specific volume for different pressures are presented in figure 3.

**Table 1**

MATERIALS PROPERTIES

| Materials / Properties | Ultraform H4320 | Celanese Nylon 1200 | Fortiflex T50-4400-1 |
|---|---|---|---|
| Family Abbreviation | POM | PA 66 | HDPE |
| Modulus of elasticity (MPa) | 2600 | 2690 | 911 |
| Poisson’s ratio | 0.42 | 0.398 | 0.426 |
| Shear modulus (MPa) | 910 | 962 | 319 |
| Melt density (g/cm$^3$) | 1.1571 | 0.9543 | 0.7381 |
| Solid density (g/cm$^3$) | 1.407 | 1.1509 | 0.9516 |
| Transition temperature (°C) | 145 | 213 | 112 |
| Melt temperature (°C) | 200 | 295 | 220 |
| Thermal conductivity (W/m °C) | 0.14 | 0.246 | 0.211 |
| Heating/cooling rate (°C/s) | -0.667 | -0.333 | -0.333 |

**Table 2**
PROCESS CONDITIONS

| Properties \ Materials | Ultraform H4320 | Celanese Nylon 1200 | Fortiflex T50-4400-1 |
|---|---|---|---|
| Mold surface temperature (°C) | 90 | 80 | 40 |
| Melt temperature range (°C) | | | |
| Minimum<br>Maximum | 190<br>220 | 280<br>310 | 180<br>280 |
| Mold temperature range (°C) | | | |
| Minimum<br>Maximum | 60<br>100 | 60<br>100 | 20<br>95 |
| Ejection temperature (°C) | 110 | 190 | 100 |
| Maximum shear stress (MPa) | 0.45 | 0.5 | 0.22 |
| Maximum shear rate (1/s) | 40000 | 60000 | 65000 |
| Switch-over Pressure (MPa) | 54.4231 | 35.6161 | 15.7610 |
| Maximum clamp force required (tons) | 2.9436 | 1.3555 | 0.6336 |

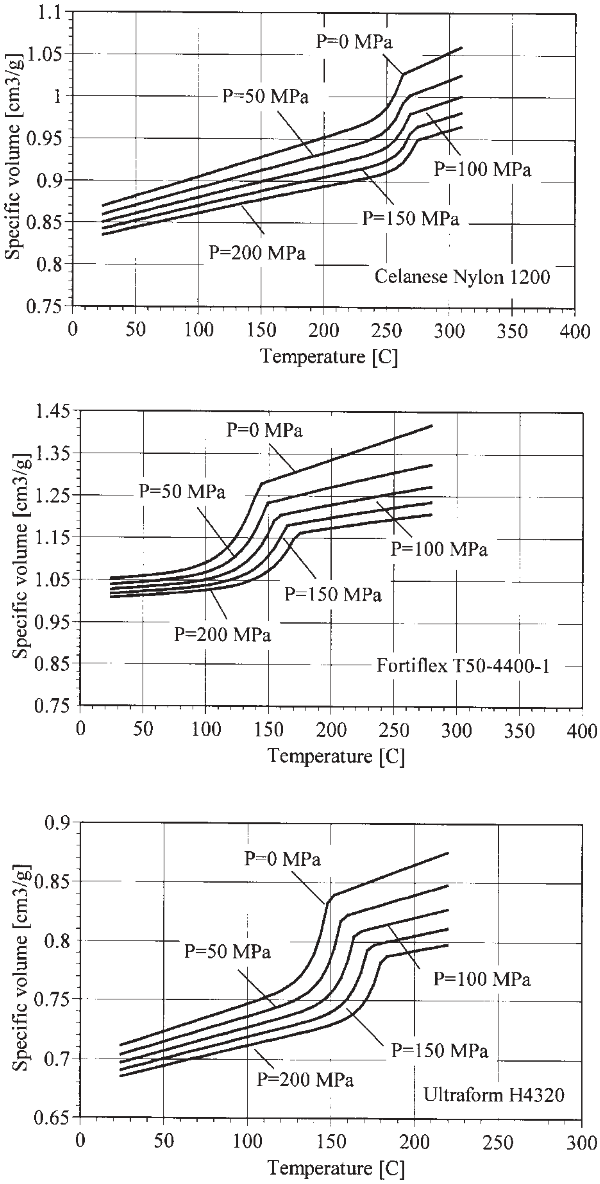


Fig. 3. Specific volume as a function of temperature

In order to run an analysis, some basic information about the molding machine must be defined, i.e. the injection pressure and clam tonnage capacities, respectively. Every analysis has a default molding machine that can be used. Moldflow also has an extensive database of molding

**Table 3**
MACHINE PARAMETERS

| | |
|---|---|
| Maximum machine clamp force (tonne) | 7000 |
| Maximum injection pressure (MPa) | 180 |
| Maximum machine injection rate ($cm^3/s$) | 5000 |
| Machine hydraulic response time (s) | 0.01 |

machine so the machine can be used. For both cases, all the parameters can be customized. In our simulation we have chosen a molding machine from the Moldflow database. The parameters of the molding machine are presented in table 3.

The filling phase is the phase of the cycle where most problems occur. The results of this analysis are reviewed in the following. Mold filling is used to predict cycle times, to ensure complete filling of the mold, and to predict weld lines and air traps.

Figure 4 presents the clamping force history curves during the filling and packing phases. The clamp force is calculated automatically for a flow analysis in Moldflow. It can be observed from this figure that, in the case of the Ultraform H4320, the clamp force is 2.72 higher than the clamp force of the Celanese Nylon 1200 and 6.25 higher than Fortiflex T50-4400-1, respectively. The maximum value of the clamp force can change radically depending when the velocity/pressure switchover is done and the injection and packing profile that is used.

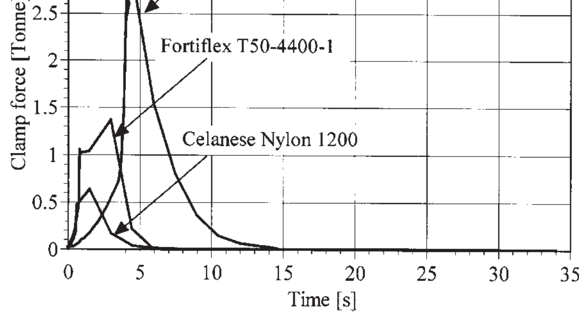


Fig. 4. Variation of the calm force during the filling and packing phases

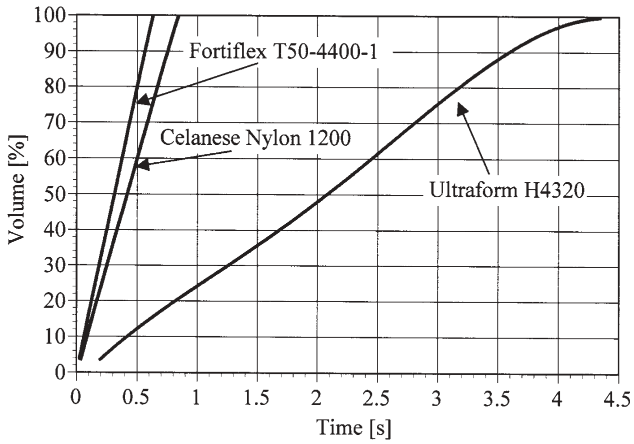



Fig. 5. Variation of the melt volume during the filling phase

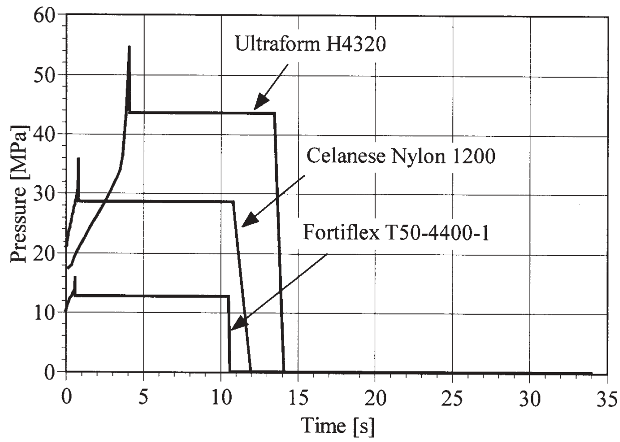



Fig. 7. Pressure at injection location during the filling and packing phases

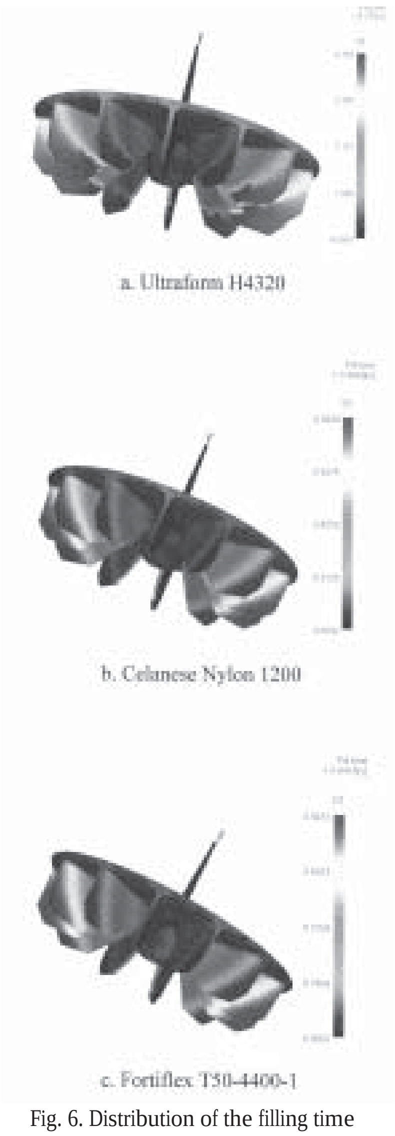
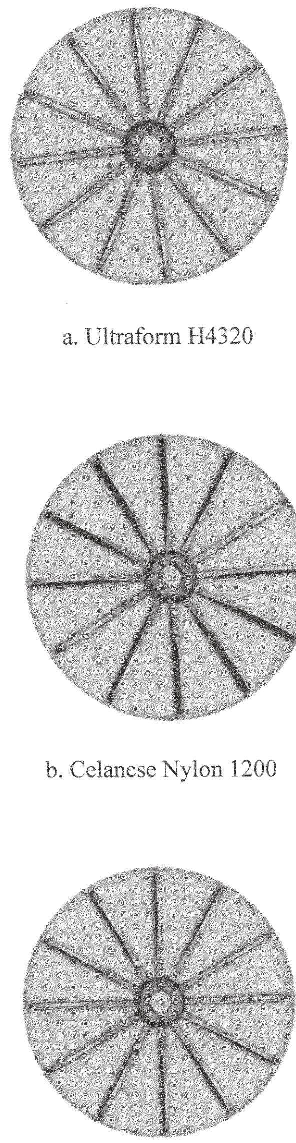



Fig. 6. Distribution of the filling time



a. Ultraform H4320

b. Celanese Nylon 1200

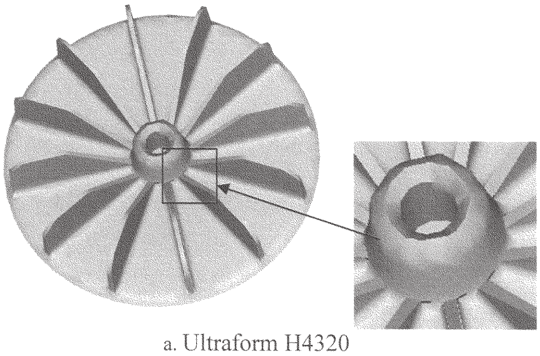
c. Fortiflex T50-4400-1

Fig. 8. Prediction of the air traps

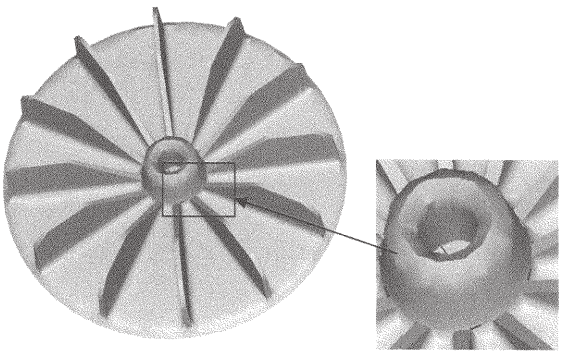
Figure 5 presents the variation of the volume of the molten material injected during the cavity filling. For Celanese and Fortiflex the variation is linear and the material volume injected during the same time is 5.2 and respectively 6.9 times higher than for Ultraform. The distribution of the predicted fill time is presented in figure 6. In all cases, the filling has been carried out correctly.

The pressure at injection location during the filling and packing phases of the analysis is presented in figure 7. The pressure at injection location result is very useful for checking whether there are any pressure spikes. This result can also be used to determine the pressure distribution in the cavity at the change-over point in the analysis.

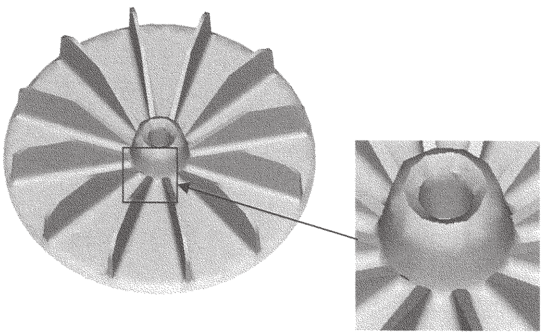
Within the Moldflow simulation several types of defects can be predicted. The most important are the air traps and weld/meld lines [8]. An air trap is air caught inside the mold cavity. Air trap locations are usually in areas that fill last. Trapped air will result in voids and bubbles inside the



a. Ultraform H4320



b. Celanese Nylon 1200



c. Fortiflex T50-4400-1

Fig. 9. Prediction of the welding lines

molded part, a short shot, or surface defects such as blemishes or burn marks. In order to avoid air traps, the vents must be placed in the areas that fill last. Also, it is recommended to re-design the gate and delivery system in such a way that the last to fill areas are located at the proper venting location [9].

A weld line is formed when separate melt fronts traveling in opposite directions meet. A meld line occurs if two emerging melt fronts flow parallel to each other and create a bond between them. Weld and meld lines are caused by holes or inserts in the part, multiple gates, or variable wall thickness where hesitation or race tracking occurs. Weld lines are undesirable when part strength is important. The strength of the weld line area can be from 10 to 90% as strong as the pure material [10]. In order to increase the strength of the weld lines it is recommended to increase the wall thickness that will improve the transmission of pressure and maintain a higher melt temperature, to adjust the gate position, increase the size gate and runners [9]. If the vents are placed in the area of the weld line the air traps will be eliminated.

Welds lines are formed at nodes. When a weld line is predicted at two or more connected nodes, a line is drawn between the nodes [8]. Weld lines prediction is very sensitive to mesh density. Also, a fine mesh does allow an air trap to be predicted. Figure 8 shows the air traps predicted at the end of packing phase. An air trap is shown by a colored line around a node on the mesh. In figure 9, the formation of the weld lines is presented.

## Conclusion

In this paper, a comparative study was carried out on the behaviour of three types of thermoplastic materials during the injection molding of a complex part using the Moldflow software. The numerical comparative study has pointed out that Fortiflex T50-4400-1 has very good filling behaviour. Even the thin channels of the part are filled very well.

The simulation results can be used to predict the defects and to test the effect of different materials and processing conditions on the final shape of the injected part. Furthermore, the simulation results can be successfully used to find the optimal configuration of the part, and to design the mold and the injection molding process to avoid the defects.

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