Study on Filling Patterns of Engineering Polymers in Geometrically Balanced Injection Molds

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Filling patterns and imbalances which occur during injection molding of engineering plastics, e.g. Polyoxymethylene (POM), have been studied. Four different geometries of runner systems have been applied for experimentation. Autodesk Moldflow software has been used for finite element method (FEM) simulations of imbalance phenomenon. Evolution strategies have been suggested for optimization of runner systems in multi-cavity injection molds.
Key words: Injection Molding, Filling Imbalance, FEM Simulations

Introduction

Multi-cavity injection molding has been regarded as a low cost mass-production method for producing plastic parts. However, the flow imbalance during filling a multi-cavity mold using symmetrical runner system is a serious problem [1]. It causes non-fills, dimensional variations, warp, flash, and many more product inconsistences. The filling imbalance in geometrically balanced molds is always difficult to handle in injection molding. Previous studies have shown that the most common filling pattern in geometrically balanced feeding systems is faster filling of inner cavities, and slower filling of outer cavities which is presented in Fig.1. There is a little literature concerning the filling imbalance phenomenon. Recently, an extensive study has been performed for several commodity plastics using various runner systems [1]. In this paper, the phenomenon has been carefully studied for engineering material Polyoxymethylene POM with totally different thermo-rheological characteristics and high requirements for processing.

The greatest effort in explaining the phenomenon of filling imbalance in multi-cavity injection molds has been taken by Beaumont [1]. He revealed that the flow imbalance is closely related to the three-dimensional thermo-mechanical history of the material melt flow in the runners, and he proposed a novel apparatus called MeltFlipper to overturn the melt stream to avoid the imbalance problem. Various configurations of the MeltFlipper system are shown in Fig.2.

The polymer melt flow in the injection molds is a complex fluid mechanics problem. This is a three-dimensional, unsteady, compressible, and non-newtonian as well as non-

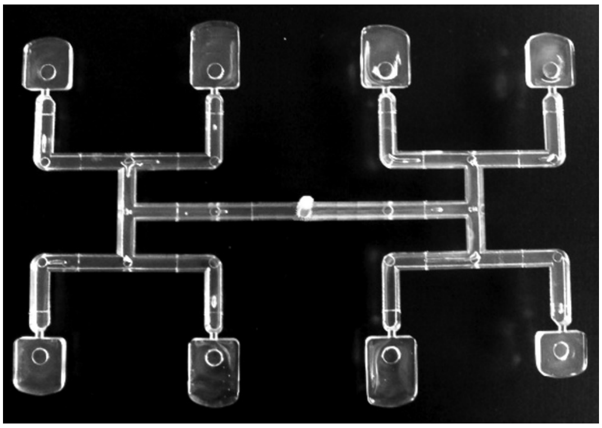

Figure 1: Example of mold filling imbalance (Polystyrene)

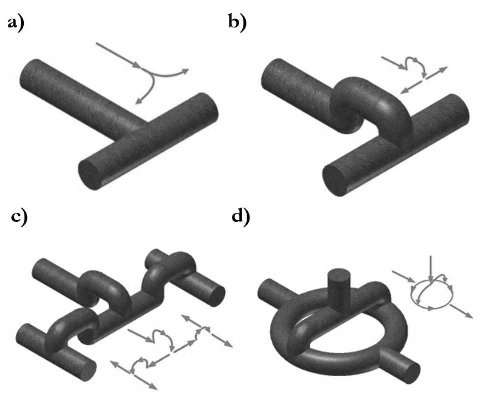

Figure 2: Runners configurations: a) standard - G_S, b) "single" MeltFlipper - G_1, c) "double" Melt Flipper – G_2, d) "peripheral" MeltFlipper - G_3

isothermal flow, and sometimes even viscoelastic flow. Molten polymers are the pseudoplastic fluids, and their viscosity is strongly dependent on the shear rate and temperature. The viscosity decreases with an increase of the shear rate and temperature.

Filling imbalance results from a non-linear velocity profile in the runners which generates a non-linear shear rate profile, and finally a non-linear temperature profile, which strongly influence the polymer melt viscosity. And, shear rate and viscosity determine the heat amount produced during the flow.

It can be written [3] that

$$Q = \eta(\dot{\gamma}, T)\dot{\gamma}^2 \quad (1)$$

where is the heat amount produced in an elemental volume of the flowing material, W/m^3, is the apparent shear viscosity of the material, Pa·s, is the temperature, °C, and is the shear rate, 1/s.

Such a complex phenomenon can be studied using sophisticated numerical methods, and/or advanced specifically oriented software, like Moldflow, Cadmould and Moldex3D [3-6]. This software is specially dedicated to simulate the injection molding process.

FEM Simulations

In order to study the filling imbalance in multi-cavity injection molds FEM simulations have been made using an advanced injection molding system Autodesk Moldflow [5]. Polybutylene Terephthalate (PBT) Valox 337 has been used in the study. The Cross-WLF rheological model of the material has been applied for simulations.

The Cross-WLF viscosity model describes the temperature, shear rate, and pressure dependency of the viscosity of flowing material. The model is given by the following equation:

$$\eta = \frac{\eta_0}{1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}} \quad (2)$$

where:
η is the melt viscosity, Pa·s,
η_0 is the zero shear viscosity or the "Newtonian limit" the viscosity approaches at a very low shear rate,
is the shear rate, 1/s,
$\dot{\gamma}$ τ^* is the critical stress level, Pa, at the transition to shear thinning behaviour, determined by curve fitting, and
n is the power law index in the high shear rate polymer flow region, determined by curve fitting.
The parameters of the model we used in the study were the following:
the power-law flow index n=0,2139,
the zero viscosity $\eta_0 = D_1 \exp\left[\frac{-A_1(T-T_g)}{A_2+(T-T_g)}\right]$,
the critical stress τ^* = 353100 Pa,
the glass transition point T_g = 323K, and data-fitted coefficients
D_1=5.32·10^{23} Pa·s,
A_1=59.833,
A_2=51.6 K.

The effect of using of an overturn apparatus (MeltFlipper) on the mold filling pattern has been presented in Fig.3. For a standard runner system (Fig.2a) the material of high viscosity flows into outer cavities, and the material of low viscosity flows into inner cavities. These lead to faster filling of inner cavities and slower filling of outer cavities (Fig.3a). For a MeltFlipper system (Fig.2b) the filling pattern changes, and faster filling of outer cavities is observed which results from lower viscosity of the material as well as slower filling of inner cavities is seen which results from higher viscosity of the material (Fig.3b).

Experimental

An extensive experimentation has been made to study the filling imbalance problem and investigate an effect of using of the MeltFlipper apparatus on the phenomenon. Eight-cavity mold with changeable runner inserts has been designed to this aim.

Four different runner layouts have been tested:
- the geometrically balanced standard runner system G_S (Fig.2a), and three MeltFlipper systems:
- the classical "single" system G_1 (Fig.2b),
- the "double" system G_2 (Fig.2c), and
- the "peripheral" system G_3 (Fig.2d).

Each system has been tested for Polyoxymethylene (POM) Hostaform C 9021. The material properties have been presented in Tabl.1.

Three injection rates have been applied, 20%, 50%, and 80% of the maximum available injection rate equal to V_{max} = 100 mm/s. The processing parameters have been shown in Tabl.2.

Table 1. Material properties

Resin type	POM
Trade name	Hostaform C 9021
Producer	Ticona
Melt volume-flow rate MFR [cm^3/10 min]	8
Temperature [°C]	190
Load [kg]	2,16
Vicat softening temperature [°C] B50	150

Table.2. Processing parameters

Nozzle temperature [°C]	230		
Injection rate [%]	20	50	80
Holding pressure [MPa]	0		
Holding time[s]	0		
Cooling time [s]	20		
Screw rotation speed [1/min]	140		
Back pressure [MPa]	0,2		
Mold temperature [°C]	30		

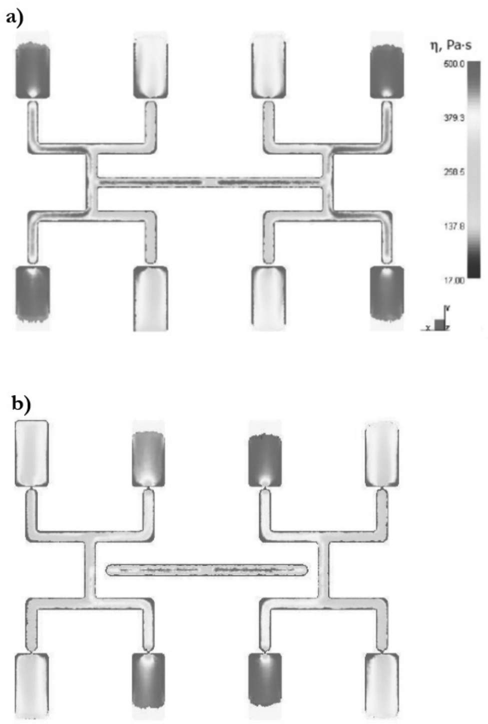

Figure 3. PBT simulations – viscosity plots: a) Standard configuration, b) MeltFlipper configuration

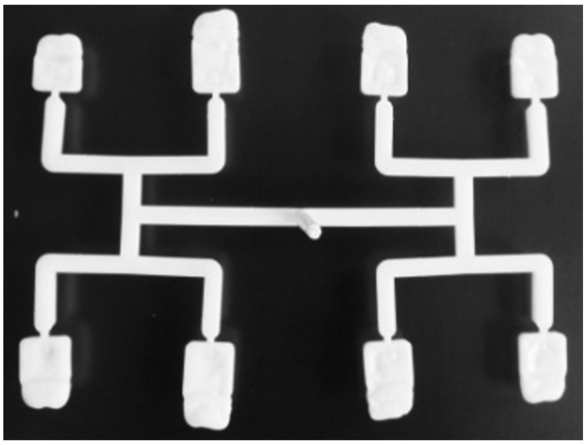

Figure 4. POM molding with standard runners (Geometry_S)

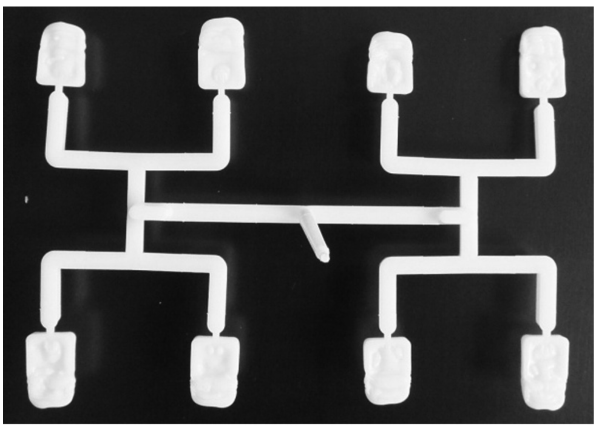

Figure 5: POM molding with “single” Melt Flipper (Geometry_1)

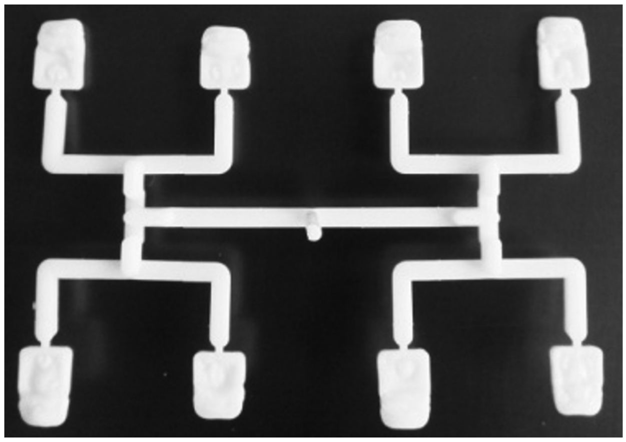

Figure 6. POM molding with “double” MeltFlipper (Geometry_2)

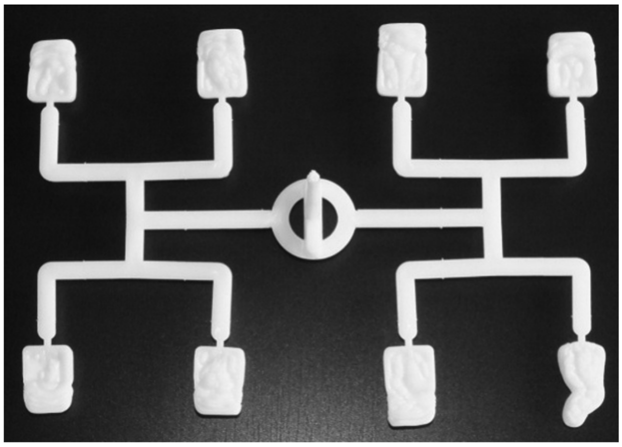

Figure 7. POM molding with “peripheral” MeltFlipper (Geometry_3)

Some results of experimentations have been presented in Figs.4-7. It is clearly seen that standard runner geometry causes faster filling of inner cavities (Fig. 4), and “single” as well as “double” MeltFlipper geometries noticeably balance the filling pattern (Figs. 5-6). Using of a “peripheral” MeltFlipper geometry leads to the filling pattern similar to that one specific for standard geometry (Fig. 7).

Mold filling imbalance has been evaluated using a mass filling imbalance factor defined by the following relation

$$I_m = 100\% \left(1 - \frac{m_2}{m_1}\right) \quad (3)$$

where:
I_m is the mass filling imbalance factor,
m_1 is an average mass of the material from inner cavities, and
m_2 is an average mass of the material from outer cavities.

Mass filling imbalance factors I_m have been plotted against injection rate for all the geometries used in the study (Fig. 8). These show the differences in mold filling patterns. Geometry_S and Geometry_3 cause positive imbalance which means that inner cavities are filling faster,

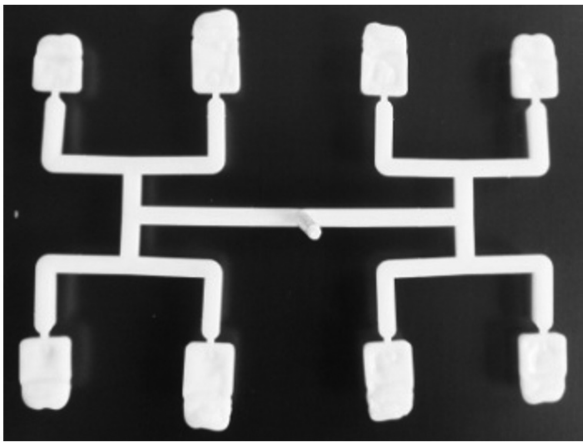

Figure 8: Flow imbalance for POM

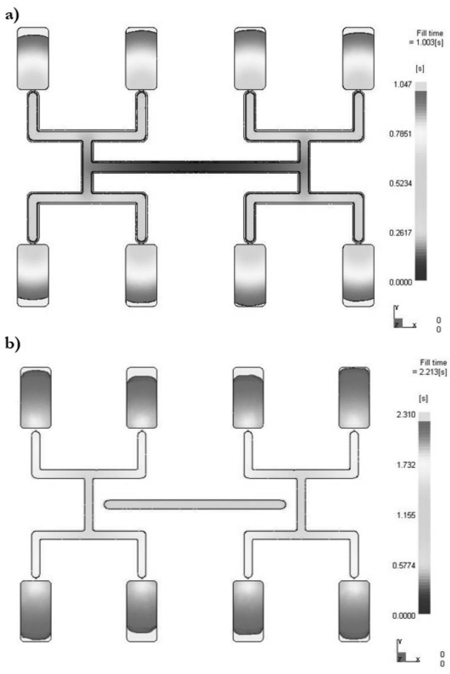

Figure 9. POM simulations – filling time plots: a) standard configuration, b) MeltFlipper configuration

and it is opposite to Geometry_1 and Geometry_2 which induce negative mass filling imbalance which results in faster filling of outer cavities.

Numerical simulations for mold filling have been depicted in Fig.9. Faster filling of inner cavities is clearly seen for standard geometry (Fig.9a) which is consistent with experimental data (Fig.4). MeltFlipper geometry obviously balances the filling pattern and faster filling of outer cavities is observed (Fig.9b) which is comparable with experimental data (Fig.5).

Conclusions

Filling imbalance in multi-cavity geometrically balanced injection molds has been studied using several feeding systems. It can be stated that any clear regularities in filling have not been noticed when changing the system, and obviously there is no universal design for the runner system. The individual simulation has to be applied for each case. Meshing, cooling conditions, material characteristics are of high importance for these simulations. Evolution strategies (Genetic Algorithms) are suggested for optimization of runner systems in multi-cavity injection molds to solve the problem.

Genetic Algorithms are search and optimization methods that imitate the natural evolution process. They start from a set of randomly generated points and apply genetic operators like crossover and mutation to confine the region where the optimum is located. It prevents the algorithm from being trapped in a local minimum. And, this does not require any derivatives and does not impose any restrictions on the convexity of the search space. It is a very powerfool tool for optimization in polymer processing [7].

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