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EFFECT OF RUNNER DIMENSIONS ON CAVITY FILLING IN MICRO-INJECTION MOULDING FOR DEFECT-FREE PARTS

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ABSTRACT

Modelling and simulation of injection moulding process is an important technique that could shorten production cycle time with improved productivity for defect-free parts. This technique is more suitable for micro-injection moulding (μIM) process as likely defects during production can be predicted. Therefore, this study aims to investigate the effect of runner dimensions on quality of moulded parts. Solidworks plastic simulation software was used for mould cavity filling analysis of ASTM D638-10 Type V. The dimensions of the runner and the injection point investigated are 0.5 mm, 0.8 mm, 1 mm and 2 mm. The moulded part quality characteristics predicted are filling time, sink mark and air trap. In addition, analytical model for prediction of melt pressure as a function of both melt filled distance (x_o) and the temperature is developed. The theoretical model and simulation software are useful for investigations of defect-free parts in μIM process.

Keywords: melt flow analysis, micro-injection, micro-part, micro-feature, mould filling, simulation, viscosity model.

INTRODUCTION

Microinjection moulding (μIM) is a manufacturing method for producing microparts and components. It is found suitable for mass production of microparts for micro-machine and other micro devices. The micro device includes plastic optics, microfluidics, biochips, micromechanical components, micro-Total Analysis Systems, etc (Kim, Gang, Min, and Kim, 2014; Young, 2007). It is important to note that these products required high precision as well as quality part. Therefore, monitoring and control of quality part during production is necessity. Researcher applied optimisation to process condition of microinject to achieve a defect-free moulded parts. Some of the defects encountered during μIM are weldline, sink mark, voids from air trapped, incomplete cavity filling (short shot) etc.

According to Kim *et al*. (2014), many studies have been conducted to determine the critical factors for improving the filling performance in microinjection moulding. The relationship between the process parameters and the achievable filling length, the replication quality characteristics measured were reported. As a result, it has been found that injection speed, injection pressure, hold pressure and its duration, melt temperature, and mould temperature are competitive processes; however, the mould temperature appears to be the most critical factor in many studies (Lin & Young, 2009; Packianather, Griffiths, and Kadir, 2015). However, the performance of the μIM process is highly dependent on air evacuation as an important prerequisite for the production of quality parts and also for prolonging the tool life. Then process monitoring in μIM is most in order to understanding the effects of different parameter settings on moulded part quality characteristics and process consistency. This is related to the study of mold cavity air evacuation which can provide a useful information about the process dynamics as well as the cavity filling by the polymer melt (Griffiths, Dimov, Scholz, and Tosello, 2011). Shen, Chang, Shen, Hsu, and Wu (2008) studied the production process of microlens arrays and found that the filling of microstructure begins at the thick section. Likewise, the trapped air produces void, if it is not evacuated. As a result of the trapped air the polymer melt can exceed its critical temperature, and likely cooling variations which may lead to part warpage (Bendada, Derdouri, Lamontagne, and Simard, 2004).

Therefore, the focus of this study is to analyzed melt flow in micro channel of the μIM tooling. The investigation considered rectangular cross-sections of the runner for melt injection points during simulations in order to study the cavity filling.

MATERIALS AND METHOD

Material properties and simulation specification

The computer aided design (CAD) model of the ASTM D638-10 Type V, the feature and dimensions of this standard tensile specimen is presented in Figure-1. Solidworks plastic simulation software was used for the study. A generic material PP is selected from the database of the software to simulate cavity filling of a tensile specimen ASTM D638-10 Type V.

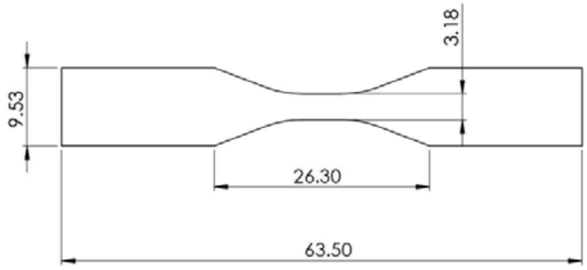

Figure-1. Sketch of the tensile specimen, all dimension is in mm.

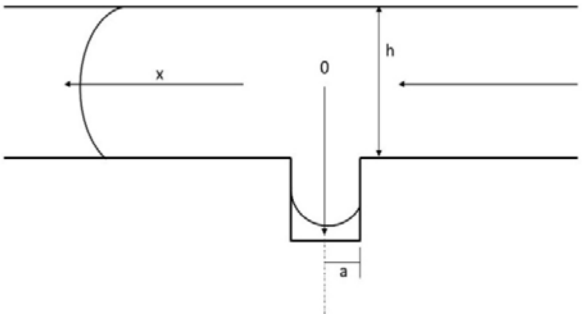

Figure-2. Schematics of the physical model for μIM flow channel.

The Machine specification and processing condition are presented in Table-1 as specified in the simulation. The configuration of a screw type "Allrounder" microinjection moulding machine by Arburg is specified.

Table-1. Machine specification and processing condition.

Parameters	**Value**
Maximum short volume (cm^3)	23
Screw diameter (mm)	18
Melt temperature(°C)	230
Mould wall temperature (°C)	40
Maximum injection pressure(Mpa)	250
Reference injection rate (cm^3/s)	53
Maximum injection (Machine) Flow Rate (cm^3/s)	76

Analytical modelling of μIM flow channel

This analysis considered a single point injection of melt through the flow channel to the mold cavity, the schematic representation is shown in Figure-2.

In addition, some assumption were made which include the following. The injection flow rate (*Q*) is considered to be constant during the filling process of the cavity and locally filled. Likewise, the volume in the part required is far small as compared to the main cavity. The amount of melt flow rate in the main cavity is assumed to be the same as the injection rate. For one-dimensional viscous flow, the momentum equation can be expressed as:

$$\frac{dp}{dx}=\frac{d}{dy}\left(\eta\frac{du}{dy}\right), \tag{1}$$

where η is the viscosity and, for a power law fluid, can be written as

$$\eta = m_x \dot{\gamma}^{n-1} \tag{2}$$

where $\dot{\gamma}$ represents is the shear rate, m_x is the flow consistency index, and n is the power law index. Since microinjection moulded cavity feature is filled within a short period of time. The temperature of the melt within the thickness (h) of the main flow path is assumed to be constant. Therefore, the m_x can be expressed as:

$$m_x = m_o e^{-a_0(T_m - T_0)} \tag{3}$$

where T_m is the melting temperature at the main cavity, and m_o, a_o and T_o are material constants. To solve for the velocity of the flow (u), equation (2) and (3) are substituted into equation (1) and evaluated as:

$$u=\left(\frac{1}{m_x}\right)^{\frac{1}{n}}\left(\frac{n}{n+1}\right)\left|\frac{dp}{dx}\right|^{\frac{1}{n}}\left[\left(\frac{h}{2}\right)^{\frac{n+1}{n}}-y^{\frac{n+1}{n}}\right] \tag{4}$$

and the Q across the cross section of the flow channel is given by

$$Q=\left(\frac{1}{m_x}\right)^{\frac{1}{n}}\left(\frac{2nw}{2n+1}\right)\left|\frac{dp}{dx}\right|^{\frac{1}{n}}\left(\frac{h}{2}\right)^{\frac{2n+1}{n}} \tag{5}$$

Also the pressure (P_o) at point o as indicated in Figure-2, depends on the filled distance (x_o), from the point to the flow front is assumed to be constant across the thickness of the main cavity and expressed as:

$$P_o=\frac{2^{n+1}\left(2n+1\right)^n}{n^n}\frac{m_x x_o}{w^n h^{2n+1}}Q^n \tag{6}$$

The melt velocity (V_x) along the flow path of the main cavity is expressed as:

$$V_x=\frac{dx}{dt}$$
$$\frac{dx}{dt}=\frac{Q_x}{wh}\approx\frac{Q}{wh} \tag{7}$$

It is assumed that the amount of melt into the channel is quite small and the flow rate at the main cavity (Q_x). Also, Q_x is about the same as the injection flow rate, Q. then evaluating equation (7) to estimate the flow front from point o is expressed as:

$$x_o = \frac{Qt}{wh} \tag{8}$$

From equation (5), pressure drop can be estimated and evaluate using:

$$\frac{dp}{dx} = m_x \left(\frac{2nw}{2n+1}\right)^{-n} \left(\frac{h}{2}\right)^{-(2n+1)} Q^n \tag{9}$$

Then substituting for m_x in equation (9), the pressure drop can be expressed as a function of both the melt flow filled distance x_0 and the temperature.

$$\frac{dp}{dx} = \left(\frac{2n+1}{nw}\right)^{n} \left(\frac{h}{2}\right)^{-(2n+1)} Q^n m_o e^{-a_0(T_m - T_0)} \tag{10}$$

Integrating equation (10) or substituting for m_x in equation (6) yield expression for pressure in term of the material properties and as a function of the temperature.

$$p(x_0, T_0) = \left(\frac{2n+1}{nw}\right)^{n} \left(\frac{h}{2}\right)^{-(2n+1)} Q^n x_0 m_o e^{-a_0(T_m - T_0)} \tag{11}$$

Numerical modelling and simulation of µIM

The filling phase of injection molding is a very complex process. Though the analysis is based on generalized Hele-Shaw (GHS) model by many researchers and simulations software (such as moldflow, Solidworks plastics, mold3D etc). However, the melt is assumed to be incompressible and as non-Newtonian fluid under non-isothermal conditions. The continuity equation (12) and momentum equation (13) of the melt are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{12}$$

$$\frac{\partial p}{\partial x} = \frac{\partial}{\partial x}\left(\eta \frac{\partial u}{\partial z}\right), \tag{13}$$

$$\frac{\partial p}{\partial y} = \frac{\partial}{\partial y}\left(\eta \frac{\partial v}{\partial z}\right), \tag{14}$$

$$\frac{\partial p}{\partial z} = 0 \tag{15}$$

From equation (12) *u, v* and *w* represent velocity function along the x, y and z axis respectively; while *p* is the pressure and η is the viscosity. The energy equation of the melt is express as:

$$\rho C_p \left(\frac{\partial T}{\partial t} + V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial x}\right) = K \frac{\partial^2 T}{\partial x^2} + \eta \dot{\gamma}^2 \tag{16}$$

Using dimensional analysis, the 2.5D approximation of the shear rate is expressed as:

$$\dot{\gamma} = \sqrt{\left[\left(\frac{\partial v_x}{\partial z}\right)^2 + \left(\frac{\partial v_y}{\partial z}\right)^2\right]} \tag{17}$$

where $\dot{\gamma}$ represents the shear rate in both equation (16) and (17), *T* is the absolute temperature and other quantities are time (*t*), melt density (ρ), specific heat (C_p) and *K* represents thermal conductivity of melt feedstock. The energy equation for the solid phase is expressed as:

$$\rho_s C_{p_s} \frac{\partial T_s}{\partial t} = K \frac{\partial^2 T_s}{\partial {z_s}^2} \tag{18}$$

As stated earlier, these equations are used for the simulation of melt flow. The procedure adopted for the implementation of simulation using Solidworks plastics are outlined below:

i. developed CAD model
ii. mesh
iii. specification of processing conditions
iv. solution
v. results

RESULTS AND DISCUSSIONS

The results of mould cavity filling for an ASTM D638-10 Type V specimen is carried out and presented in the following Figures. Figure-3 (a), (b), (c) and (d) shows filling time of the cavity specimen for 0.5 mm, 0.8 mm, 1.0 mm, 2 mm respectively. The simulation results indicates that the cavity is completely filled in 2 seconds expect for the case of Figure 3(b) required 4 s. This is due to the gate location and operating setting error.

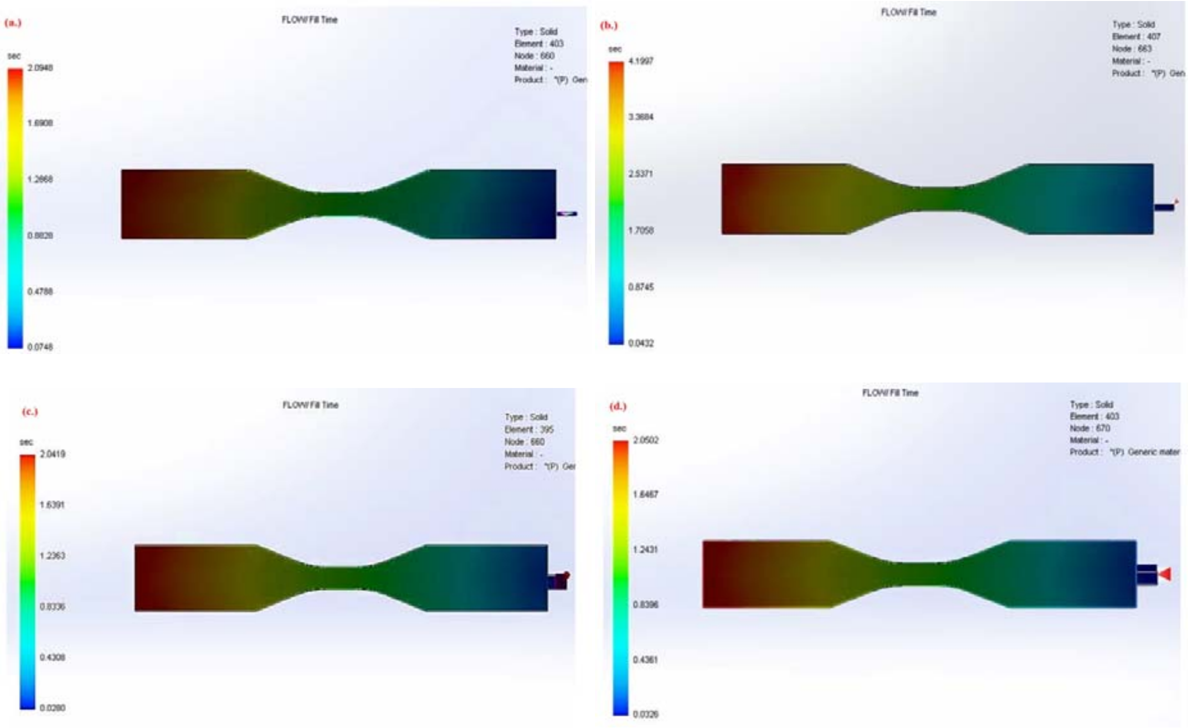

Figure-3. Filling time (s) for various runner dimensions: (a) 0.5 mm, (b) 0.8 mm, (c) 1.0 mm, (d) 2 mm.

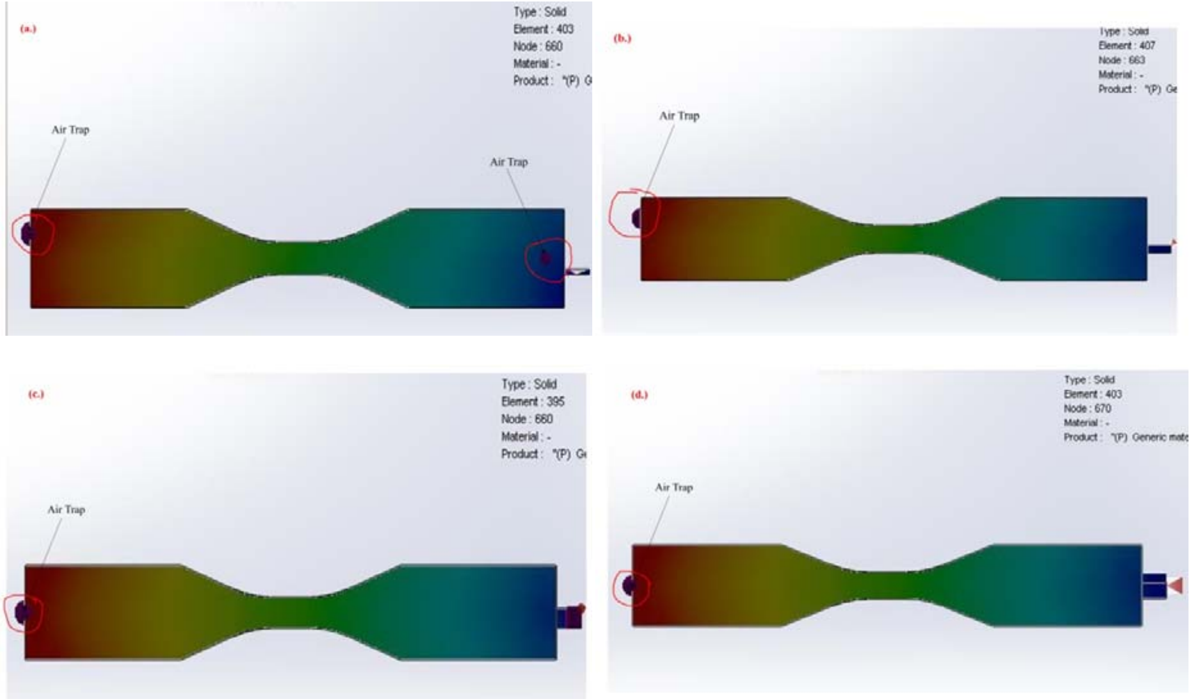

Figure-4. Air trap for various runner dimensions: (a) 0.5 mm, (b) 0.8 mm, (c) 1.0 mm, (d) 2 mm.

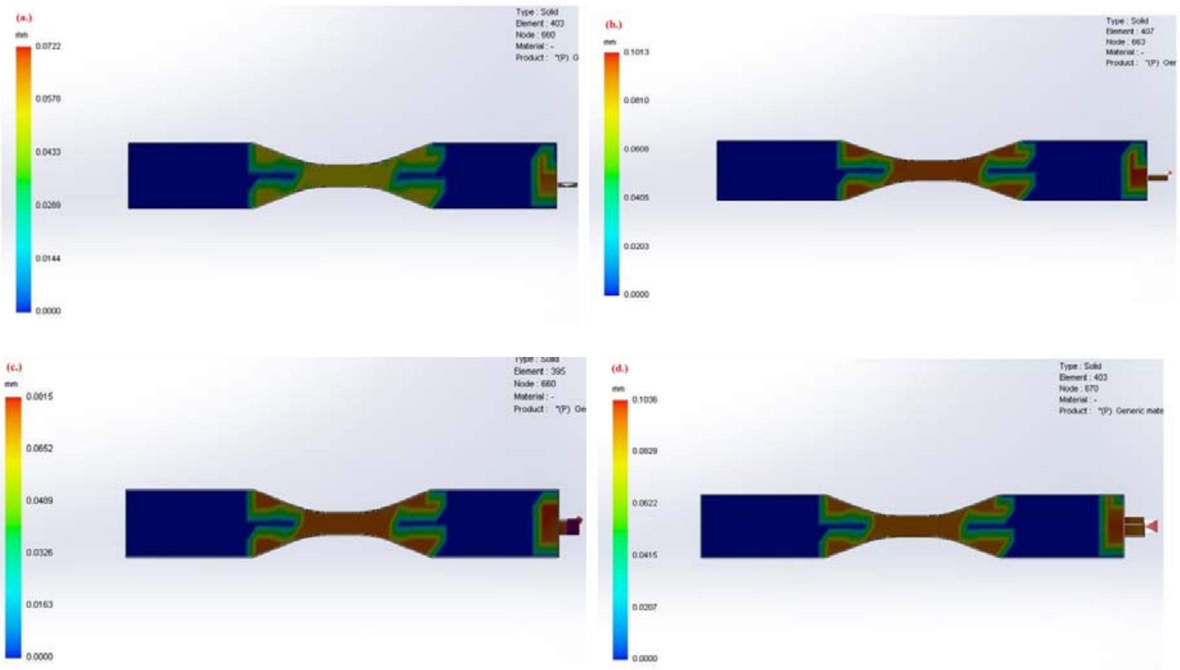

Figure-5. Sink mark for various runner dimensions: (a) 0.5 mm, (b) 0.8 mm, (c) 1.0 mm, (d) 2 mm.

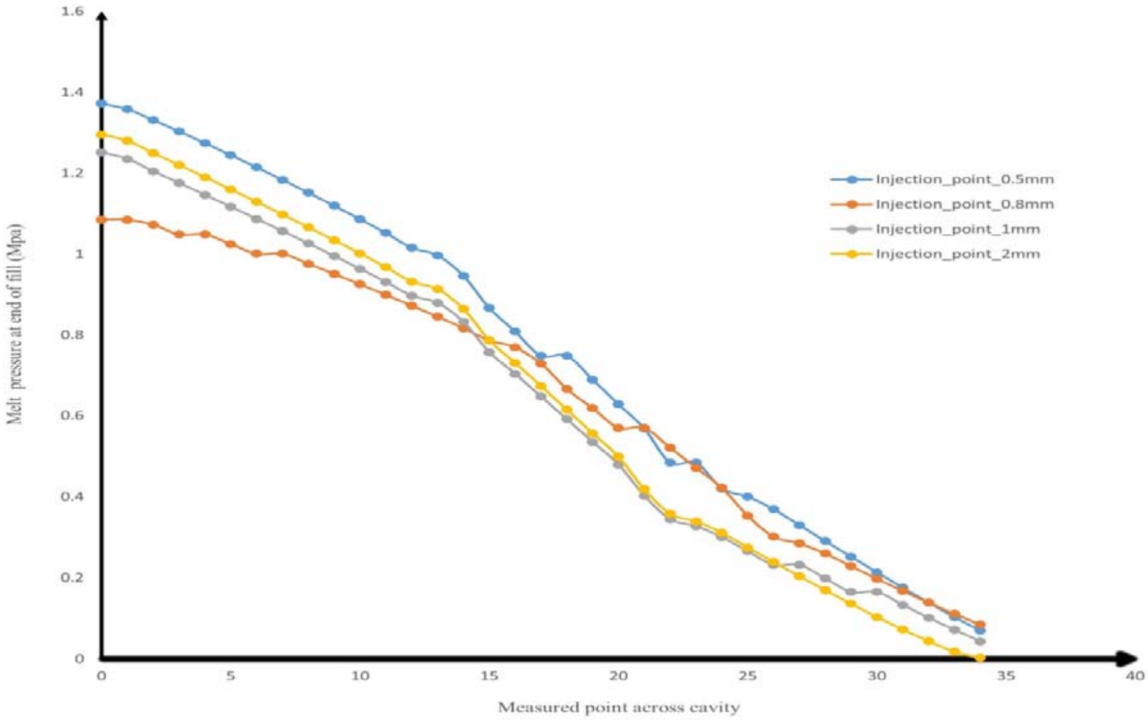

Figure-6. Melt pressure along the mould cavity for the considered runner dimensions.

Meanwhile, Lin and Young (2009) states that the Commercial software does not adequately predict the filling behaviour of the microstructure in a micro-injection moulding. However a theoretical model was developed to complement for the pressure prediction as other useful information is achieved from the software.

Figure-4 (a), (b), (c) and (d) depicts the air trap of the ASTM D638-10 Type V specimen with runner dimensions of 0.5 mm, 0.8 mm, 1.0 mm, 2 mm respectively. When the air is caught inside the mould cavity, it becomes trapped by converging melt flow fronts during filling process. In practice, air-trap locations are usually in areas that fill last and caused by lack/ inadequate presence of vents or undersized vents. Another common cause is that the tendency of polymer melt fills preferentially in thicker sections (race-tracking). It is better avoided since its presences results in part defects. To avoid air trap and its effects on moulded part, the following design rules could adopted:

i. avoid a large thickness ratio in part, to minimize the race tracking effect of melt.
ii. make adequate provison for vent in the areas of mould that fill last.

Figures 5 (a), (b), (c) and (d) illustrates the prediction of the sink mark, is more concentrated at the centre of the ASTM D638-10 Type V specimen. Sink marks are depressions on the surface of injection moulded parts caused during the cooling process. Thicker sections of moulded part will cool at a slower rate than others. In addition, a high percentage value of shrinkage is expected in such location of the part. Meanwhile, after the material on the outside has cooled and solidified, the core material starts to cool. Its shrinkage pulls the surface of the main wall inward and results in a sink mark. The following design rules which are adopted to avoid or minimized sink mark in moulded parts:

i. part thickness should be uniform, if possible.
ii. the thickness of rib or bosses should be 50% ~ 80% of the attached wall thickness.
iii. avoid using gates that are too small since which can prevent full packing of the cavity.

In practice the mould cavity filling analysis indicates that the pressure profile presents a decreasing from the inlet gates to downstream position since the flow length is increasing in flow direction. The very high pressure is required for part with thin cavity since the flow resistance is enlarge and the solidification may be occurred during filling process, therefore, if the injection pressure is not enough, short shot may be occurred. The maximum pressure occurs at gate location and gets decreasing from the gate location to downstream position, as shown in Figure-6.

CONCLUSIONS

Filling of mould cavity by the melt during microinjection moulding process was investigated using Solidworks plastic simulation software. The support of theoretical modelling and experimental investigation is required for the cavity filling analysis of µIM process. This is because the available commercial software results are sometime not correct. This situation is experienced either due to over assumptions and or limited user know-how for the use of the software. Therefore, the following conclusions are drawn:

- Predictions of filling time sink mark and air trap for the moulded part is carried out for various runner dimensions.
- Effect of runner dimension on filling of mould cavity is investigated. The results shows that high pressure is required as runner dimension get smaller and prone to more defect as more trapped air is noticed during the simulation.
- Simulation predictions are useful for improved productivity and cycle time of defect-free parts by µIM.

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