Influence of Processing Parameters on Clamping Force During Injection Molding Process

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Abstract. Clamping force is needed during injection molding process to keep the injection mold closed. It is a crucial parameter that must be considered during the process of plastic part development, because high clamping forces can be achieved with stronger (and more expensive) injection molding machine. It is economically wise to use processing parameters that can allow manufacturing of parts with smaller machines. The clamping force is a variable strictly related to pressure present in the cavity of the injection mold. In this study two parameters that strongly influence injection pressure (plastic flow rate and volume-to-pressure switch-over point) were examined with numerical simulations performed in Autodesk Moldflow Insight software and validated with a experiment. According to obtained outcome the increase of melt flow speed results with significant (but linear) increase of injection pressure and for investigated part the switchover point has significant impact above 98%. The nonlinear behavior of clamping force during injection phase was observed because of the energy dissipation on polymer flow. The experiment validated the direction of changes whereas the differences in comparison to simulations were observed because of the limitations of measurement systems that were present in injection molding machine.

Keywords: Injection molding · Clamping force · V/P switchover · Thin-walled parts

1 Introduction

The British Plastic Federation ranks the injection molding technique as a prime process for manufacturing of plastic products. This cyclic process is known in industry as a fast method of yielding gross amounts of identical items [1]. The most basic process is composed of several steps; mold closing, filling, packing, cooling, mold opening and ejecting. Due to importance of this process in industry and wide range of application, particularly in household manufacturing, automotive industry, electronics and medical equipment it is constantly developed [2, 3].

Several goals are aimed at in orchestrating the injection molding process - the effectiveness of such process is dictated by proper regulation of the injection molding process parameters, material, mold design and the machine itself. Although the injection molding parameters are to some extent easily adjustable, the proper mold

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design remains the main challenge of the plastics engineers. Two main elements in mold design play a key role in regulating the flow and pressure distribution in the mold cavity; gate location, and runner systems [4]. By designing well functioning runner systems and by identification of the optimal gate location, most commonly occurring part defects such as warpage, flashing, weld lines, short shots, trapped gas pockets and uneven material density distribution can be resolved [5–7]. Furthermore this prioritizes the establishment of proper filling and packing phases and most importantly the switchover point between them. Switch-over filling-to-packing point (called further V/P switchover point) known otherwise as a mechanical switchover position related problem was elaborated by number of researchers, and is presented further [8].

1.1 Injection Molding Process

During injection molding process a certain preset volume of material is introduced into the mold cavity and additional melt from the barrel is provided by maintaining desired value of the melt pressure [9]. The diagram below (Fig. 1) depicts the V/P switchover point (marked C) and its significance in the control of mold-fill related imbalances, which will be further addressed. These undesired imbalances within parts features occur in the mold cavity. The most probable reason for such behavior is badly engineered gate positioning resulting in non-uniform filling of the mold extremities. However in regards to multi-cavity injection molds inaccurately designed, running system would be resulting unequal melt distribution in all the cavities. Imbalances resulting from the flow characteristics of molten polymer also have to be addressed. The liquid polymer resembles the shear-thinning characteristics, that is of non-Newtonian type fluids as the viscosity decreases with increased shear rate and temperature [8].

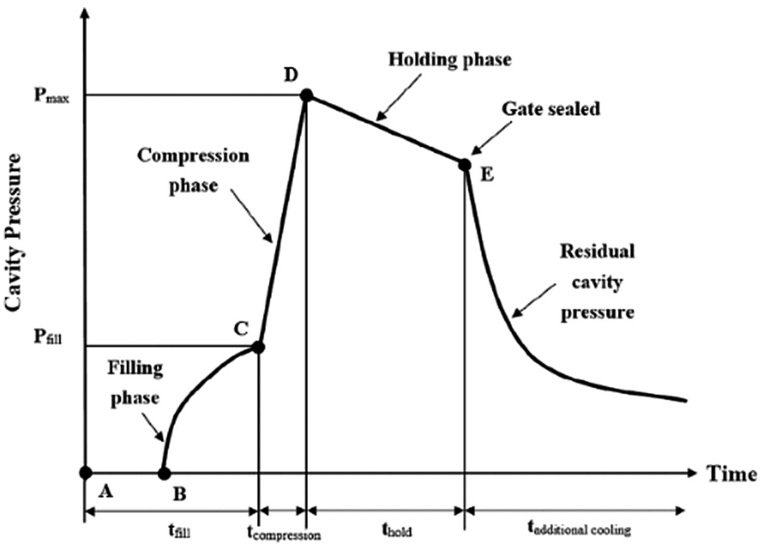

Fig. 1. Typical cavity pressure profile during injection molding process [10].

For typical process of injection molding four phases are presented on Fig. 1 above. It is important to point out that cavity pressure drop can also result in part deformation, this is where significance of the V/P switchover point emerges. Examining the diagram presented above, one can observe the beginning of the filling process at point B, the volumetric filling that slopes upward to point C representing, as previously mentioned, the V/P switchover point. At this moment the compression phase is initiated an a rapid rise in pressure to its maximum value at point D is observed. The linear pressure drop from D to E represents the packing phase, during this time additional melt is introduced to the mold cavity. This phase is completed upon sealing of the gate.

In other words the V/P switchover governs the additional volume of plastic melt that is forced to the mold cavity (beyond point C) so that it counteracts the shrinkage which occurs upon cooling.

The problem related with this particular point can be depicted by two instances; where the volume-to-pressure point is switched too early, and where it is switched to late. In the first case short shots would result, in the second, burn marks and flashing, even molten plastics obstructing mold opening and cavity wall extremities leading to further damages [11, 12].

Designing a proper mold for production of geometrical parts that require very tight tolerances is the most crucial step in obtaining high quality products. The mold cavity pressure in relation to V/P point is a single parameter that if well understood and controlled might certainly reduce the filling imbalances. These problems alone appear to consume much resources and time in the injection molding industry, indicating the necessity of further research of these phenomena.

1.2 Clamping Force

Clamping force must be applied by injection molding machine to the mold to counteract the pressure that is present in the mold during injection molding process. It's theoretical value F can be calculated from the multiplication of maximum pressure P that act on the mold and the area projected from the parting plane of the mold on a plane perpendicular to the direction of mold movement A:

$$F = P * A \tag{1}$$

This equation is used in the industrial practice for rough calculations of needed machine capabilities and profitability of the part manufacturing.

2 Experimental Setup

The analysis was conducted for a square shaped part (edge length was equal to 100 mm and the thickness was equal to 1 mm). The injection molding process parameters for this sample with its excess sprue material discarded is further described. Material used in the experiment was commercial grade isotactic polypropylene Moplen HP500N (Basell Orlen) which is commonly used in the industry. The experiment was carried out on fully electric injection molding machine Engel E-mac 50, with maximum clamping force of 500 kN and screw diameter Ø25 mm. The temperature on the nozzel was set to 240 °C and on the cylinder zones respectively: 230 °C, 220 °C, 210 °C. The mold temperature was preset to 35 °C (Fig. 2).

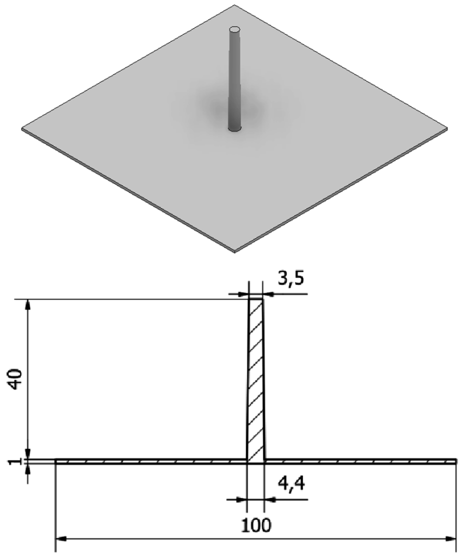

Fig. 2. Geometry of the investigated part along with the sprue.

The measurement of clamping force in the injection phase of the process was executed with melt flow rates: 40, 60, 80 and 100 cm^3/s and the V/P switchover points for the investigation were set: 100, 98, 96, 90% consecutively. For measurement of clamping force in the packing phase there was chosen one melt flow rate (60 cm^3/s) and one V/P switchover point (96%). At those parameters the peak of injection pressure was around 40 MPa, therefore the packing pressure values were chosen as a percentage of this value: 25% (10 MPa), 50% (20 MPa), 75% (30 MPa), 100% (40 MPa), 125% (50 MPa).

The injection process took place at four different melt flow rate values. In each case the injection volume of the material needed to be set differently, so in the filling stage the cavity was filled exactly in 100%. After obtaining the V/P switchover point, mass of the part was measured and noted as a reference in setting other switch over points for cavity filling of 98%, 96%, 90% respectively.

The experiment was executed in one approach. Before starting the measurement plan injection process was carried out for at least 20 cycles. After that the mass of the part and the peak injection pressure through 5 cycles was measured as a control of stability of the process. The overall cycle time was set to 60 s, giving time for mass measurements, notes, parameter changes and minor troubleshooting. All those precautions where necessary to stabilize the mold and the material temperature in the cylinder, ensuring uniform conditions for all measurements.

For every set of conditions were injected at least 5 mold and the clamping force and injection pressure at the front of the screw was recorded spontaneously be the machine with resolution of 0,01 s. The results were tabularized and depicted on graphs. The obtained results were compiled and compared with the simulation data.

Numerical simulations of the injection and packing phase were performed with Autodesk Moldflow Insight 2019 software. Analyses were made with processing parameters used in the experiment mentioned above. At the injection location (top of the sprue) contact diameter was set to 5 mm to ensure the situation that the beginning of the sprue will not solidify.

3 Results

3.1 Injection Phase

First part of the study was the investigation of the injection phase with different processing parameters. The relation of the injection pressure to V/P switchover points for different melt flow rates is depicted below at Fig. 3. According to the simulation result there is a linear increase of maximum injection pressure with the increase of melt flow rate (no change of the diagram shape is observed). Significant increase of maximum pressure was observed between 98 and 100%.

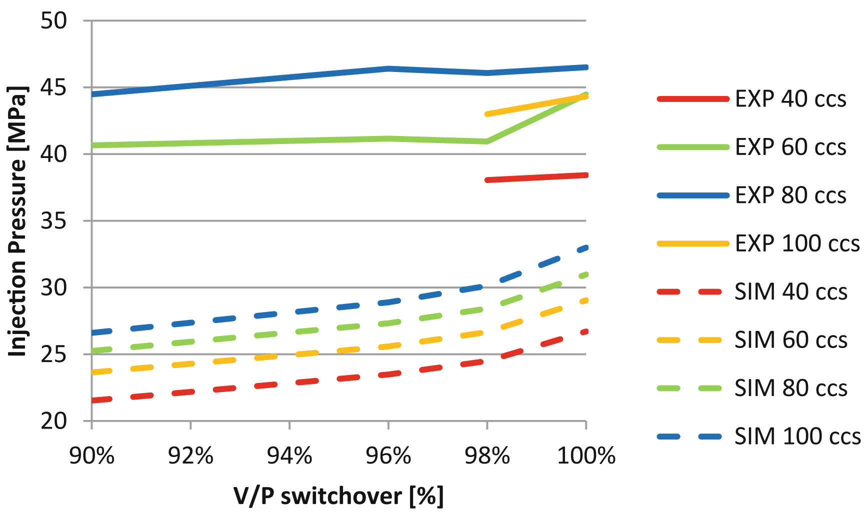

Fig. 3. Maximum injection pressure in function of V/P switchover point for different melt flow rates.

Firstly the experimental results for 100% filling of the mold cavity had to be discarded, because it does not coincide with the theory and rest of the result. This might arise from the fact that it was difficult to achieve repeatable results (significant error was measured and is presented at Fig. 4). In the experiment the increase of injection pressure with the increase of V/P switchover point is mostly negligible, what can be explained with previously mentioned problems of precise injection for this thin-walled part. This effect would be easier to examine if the flow length would be larger, polymer melt would have higher viscosity or part would have higher volume. Because of the limitation of the clamping force measurement system such thin-walled geometry was chosen.

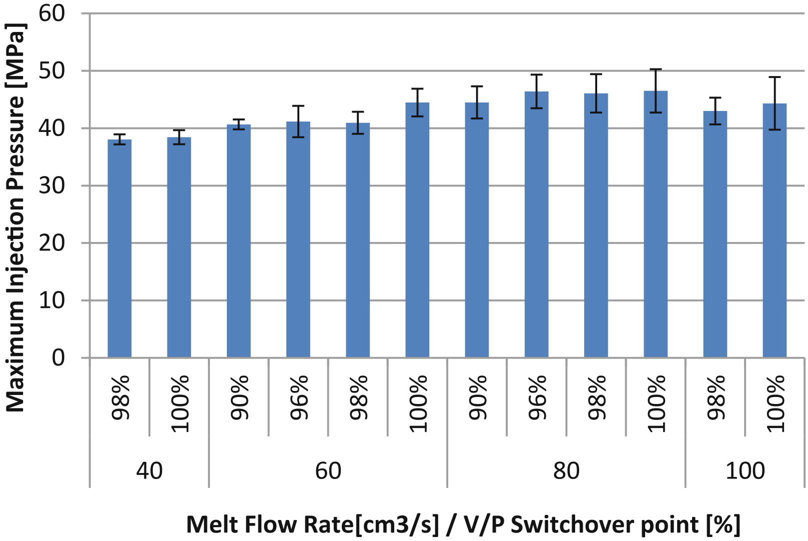

Fig. 4. Maximum injection pressure at the front of the screw for different melt flow rate and V/P Switchover points.

The values of injection pressure obtained for 60 and 80 cm^3/s were twice as high as the values obtained in a simulation. It can be explained with the difference between injection pressure at the front of the screw and injection pressure in the cavity of the mold. There is a significant pressure drop when polymer is moved from the injection unit to the mold. To prove this fact the injection molding process with withdrawn injection molding unit was performed for melt flow rate equal to 10 cm^3/s (other values were blocked by the manufacturer of injection molding machine). The relation between pressure drop, volume at the front of the screw and time is presented at Fig. 5 and is equal to about 8 MPa. With shorter injection time (higher melt flow rates) this value should rise. It means that its subtraction from maximum injection pressure value presented at Fig. 3 should give the results much closer to the simulation.

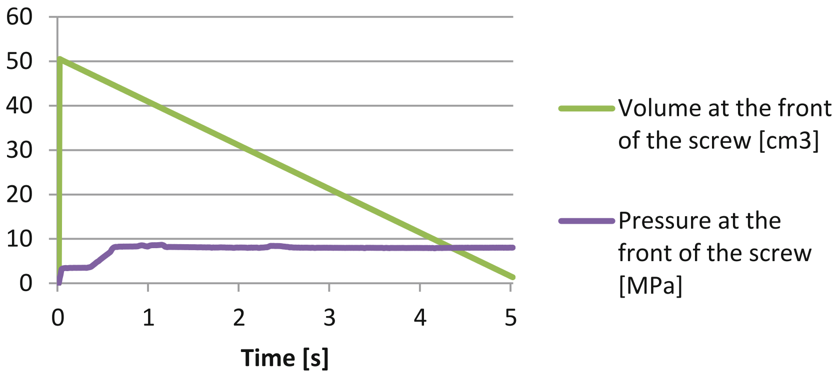

Fig. 5. Injection pressure and volume at the front of the screw at the screw during injection molding process with withdrawn injection molding unit at melt flow rate equal to 10 cm^3/s.

The simulation predicts the increase of clamping force as the melt flow rate rises from 40 to 100 cm^3/s what was not observed in the experiment (Fig. 6). For each case the value of clamping force rises insignificantly up to the V/P switchover value of 96% (significant rise is observed for melt flow rate equal to 100 cm^3/s). Above 96% higher rise of clamping force is observed.

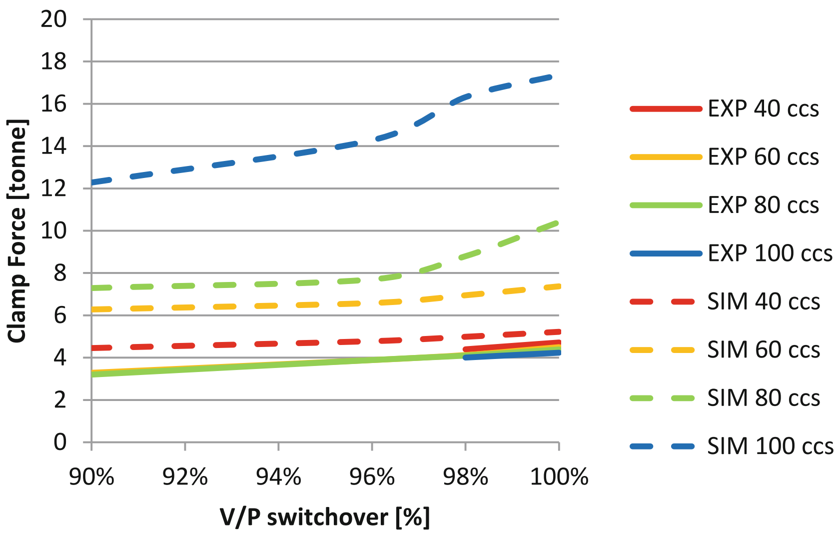

Fig. 6. Maximum clamping force in function of V/P switchover point for different melt flow rates.

In the experiment the differences for used processing parameters are negligible in comparison to differences observed for numerical simulations. It was found that there is some inertia present in injection pressure measurement system, so increase of clamping force was not registered because of short injection time. It is presented in further part of this article (Fig. 11), where clamping force starts to rise after 0,2 s. Because of short injection step this rise was not measured. This is the explanation of the decrease of maximum clamping force with the increase of melt flow rate (shorter injection time) which is presented at the Fig. 7.

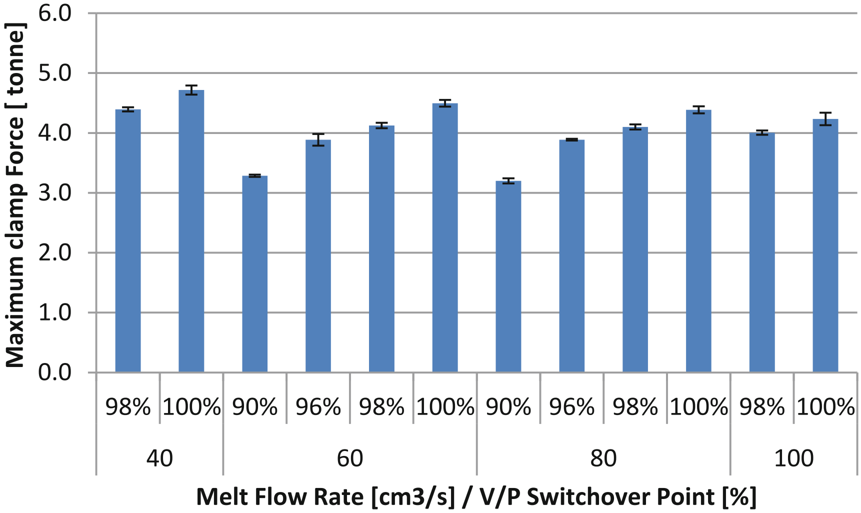

Fig. 7. Maximum clamping force at the front of the screw for different melt flow rate and V/P Switchover points.

The significant difference between theoretical clamping force during injection phase was obtained with Eq. (1) and observed clamping force. The theoretical values was substantially lower, because during injection phase some of the energy is dissipated through of polymer flow. It should be noted that maximum clamping force rise is nonlinear – the increase of the value is higher for higher melt flow rates in contrast to maximum injection pressure.

3.2 Packing Phase

In the second part of study the injection phase along with the packing phase was investigated. In this part experimental data for higher pressures (40 and 50 MPa) sudden drop of packing pressure and clamping force was observed during packing phase (between 0,5 and 1 s). This drop was caused because so-called cushion (certain volume of polymer at the front of the screw that is used to transfer pressure from the screw to the polymer inside the mold) was reduced to 0 and the pressure from the screw was not transferred properly to the mold.

For lower packing pressures strong correlation in packing phase was observed between simulation and experiment. Noticeable is the fact that rise of clamping force is instant, were in the experiment the force rise gradually. The difference can be observed during first 0,5 s of the packing phase, where the change of the packing pressure is significantly longer for real process in comparison to simulation. The explanation of this phenomenon is the inertia and reaction time of the injection molding unit. In the simulation these aspects were not considered so almost instant change of pressure in the mold is observed.

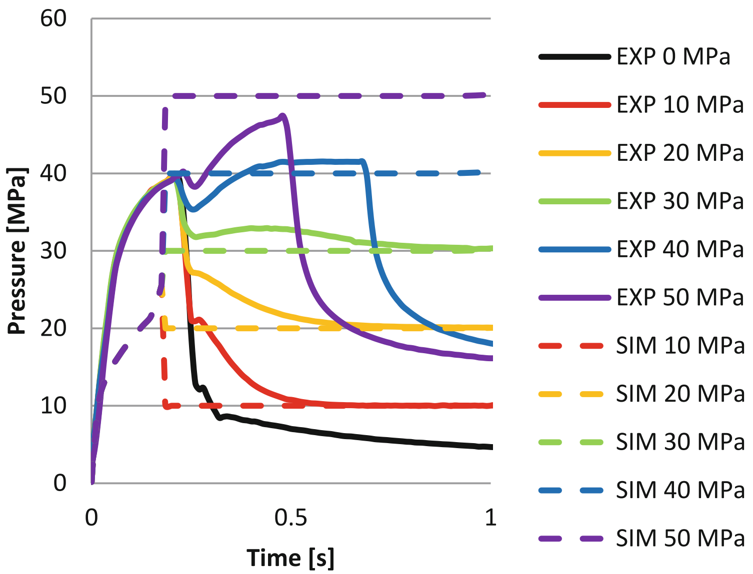

Fig. 8. Pressure at the front of the screw (EXP) and injection pressure in the mold (SIM) during injection molding process for different packing pressures.

To analyze the injection phase additional diagram with shorter time range was presented (Fig. 9). According to presented results the injection pressure measurement system cannot measure injection pressure lower than about 5 MPa. The difference between simulation and experiments arise from different measurement locations. Injection pressure diagram obtained from simulation was manually fit to the experimental result (right upper corner of Fig. 9). Very good correlation was obtained, what means that it is possible to obtain information about pressure drop.

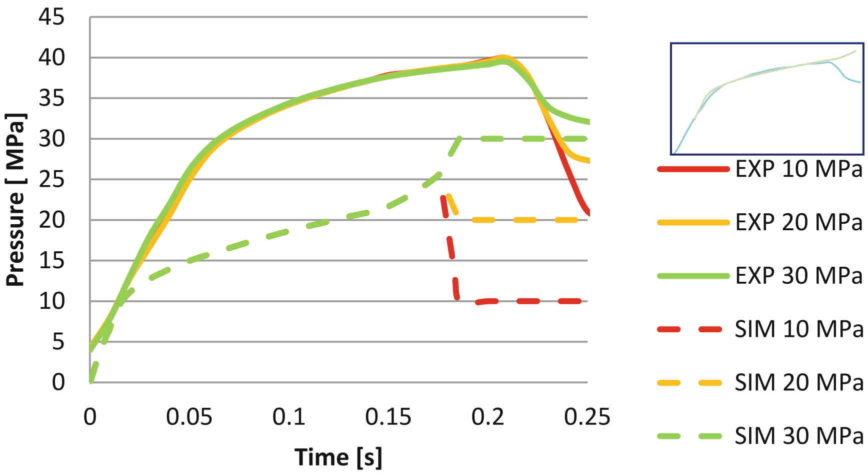

Fig. 9. Pressure at the front of the screw (EXP) and injection pressure in the mold (SIM) during injection molding process for different packing pressures. In this diagram results with improper pressure transfer were removed and the time was set to present the injection phase.

Clamping force diagram in relation to time of packing phase was presented at Fig. 10. Similarly to the injection pressure results, for high packing pressures the cushion reached zero, leading to sudden drop of polymer pressure and clamping force.

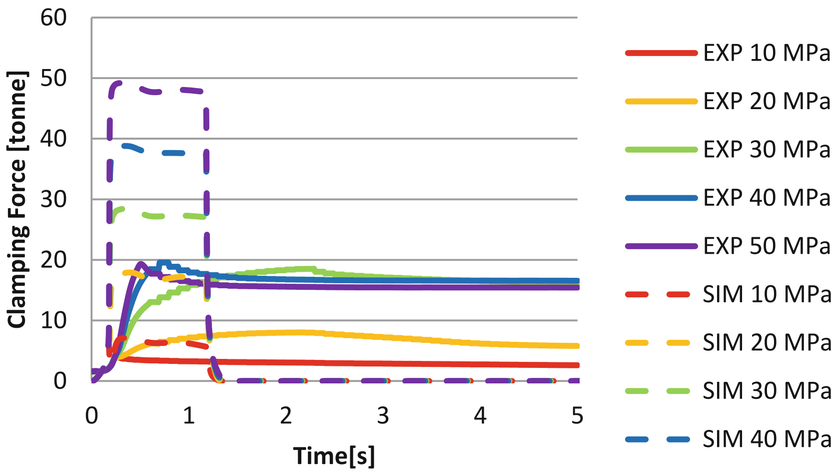

Fig. 10. Clamping force results for experiment (EXP) and simulations (SIM) during injection molding process for different packing pressures.

Simulations results of clamping forces are slightly lower than theoretical values of clamping forces calculated with assumed packing pressure. Experimental clamping forces are significantly lower than theoretical values of clamping forces estimated. Experimental clamping forces were registered by injection molding machine with small inertia (about 0,1 s), what is presented at Fig. 11. Smaller values of clamping forces are related to the process setup. In this experiment minimal clamping force equal to 1 tonne was set (experimental diagram starts from 1 tonne). Unfortunately, this setup lead to a small deflection of the mold. This movement could reduce the value of clamping force. Applying higher value of clamping force prevented deflection of the mold but caused the machine to measure preset force, not force created by the injected polymer.

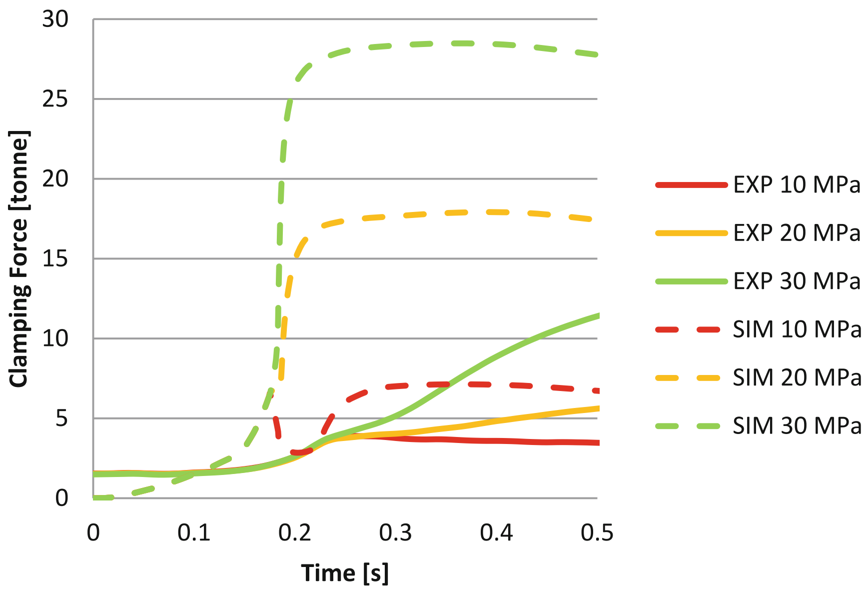

Fig. 11. Clamping force results for experiment (EXP) and simulations (SIM) during injection molding process for different packing pressures. In this diagram results with improper pressure transfer were removed and the time was set to present the injection phase.

4 Conclusions

In this paper the influence of parameters such as melt flow rate, volume-to-pressure (V/P) switchover point value, injection time on the clamping force and the injection pressure during the injection molding process was investigated. The results obtained in the investigation of the molded 1 mm square-shaped plate shows the significant changes in pressure at higher V/P switchover points.

The purpose of the experiment was to validate the simulation with obtained experimental results, especially in situation where only pressure at the front of screw could be measured along with clamping force. Several limitations of measurement systems of injection molding machines should be denoted: minimum packing pressure and clamping force that must be reached to be registered, inertia of clamping force measurement.

In previous research [4] it was shown how fill imbalance lead to significant increase of pressure drop during filling of the mold cavity and the effect was most prominent above 98% V/P point value. Similar situation was observed in this study. In the previous analysis the packing pressure nor melt flow rate was not investigated in regards to the clamping force and maximum injection pressure.

The numerical results showed that during injection phase the linear change of injection pressure was observed in reference to melt flow rate. The clamping force during injection stage had nonlinear behavior – with higher melt flow rates the higher growth of clamping force was observed.

Significant difference was observed between experimental and simulation results in registered injection pressure. To compare the injection pressure at the front of the screw (experiment) with injection pressure at the entrance of the mold (numerical simulation) additional measurement with withdrawn injection molding unit was performed to obtain the information about pressure losses at the injection molding unit. Further analysis showed that it is possible to fit the diagram of injection pressure in the mold with the diagram of the injection pressure at the entrance of the mold. This kind of diagram (and the information about shift of fitted diagram) can be used for future extrapolations of to obtain real injection pressure based on numerical simulation.

The paradox occurred in relation between maximum clamping force and melt flow rate in the filling phase. It would be expected to that the clamping force would increase with the melt flow rate and simulation show that exact relation, but the experiment conducted on the machine shown that the peak clamping force slowly decrease with the melt flow rate. This phenomena could be explained trough analyzing relation of injection pressure and clamping force in time (Figs. 8, 9, 10 and 11). The response of clamping force is delayed in relation to injection pressure. It is a consequence of filling the sprue and the distance between sensor on the screw and in the clamping mechanism. Force between those two systems is transmitted through a compressive polymer liquid which acts as a damper and releases the accumulated energy with some delay. During slower filling of the cavity the time to release the energy is longer, therefore it could reach higher value in the clamping force. In higher melt flow rates the filling stage is shorter and instant release of the pressure on the screw causes the cut of the clamping force on a value to which it managed to rise. This situation was observed for a thin plate with central sprue. It would need further investigation does this phenomena would occur with more complicated part or in a multi-cavity mold with runner system.

It should be noted that the differences in previously described phenomenon are very small. The experimental relation between maximum clamping force and V/P switch-over point in the filling phase had proper direction despite the differences in measured values. The difference between simulation and experiment was present because of the process setting (minimal clamping force) and inertia of clamping force measurement system.

According to presented results the numerical simulations serves as an important tool in prediction of the maximal pressure and maximal clamping force needed in the injection molding unit before the mold is constructed and can lead to more optimal process planning. The information can be easily obtained (in comparison to experimental results, where many limitations appears during realization of experimental setup) and can be used as a basis for further pre-setting of the packing pressure. Obtaining specific curves for different melt flow rates and polymeric grades can be used for precise prediction of real injection pressure in injection molding process.

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