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RESEARCH ARTICLE

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Optimization of material and process parameters in the injection molding of piezoresistive card-type pressure sensors using the finite element method

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Abstract

The purpose of this study is to determine the most suitable material and process parameters for piezoresistive card-type pressure sensors during the injection molding process. Simulation analyzes done with different engineering plastics Polyamide (PA), Polybutylene Terephthalate (PBT) and Polycarbonate (PC) focus on the optimization of critical parameters such as fill time, injection pressure, volumetric shrinkage and cooling efficiency during the production process. Cooling channel diameter was 10 mm, cooling water temperature was 25°C and Reynolds number was 10,000 designed to provide the minimum time of delivery from the mold by using idle times. Results indicate that PA has the shortest filling time of 0.0548 sec, PC has a volume shrinkage of 6.63%, among the lowest ones and PBT shows the best thermal stability of 252.8°C PA, which operates at lower injection pressure (132.3 MPa), increases throughput, while PBT has exhibited a proper balance between mechanical and thermal performance and PC is the most suitable material for high-dimensional accuracy applications. This study serves as a guide for optimizing the material selection and molding parameters in the production of plastic-based pressure sensors.

Keywords: Piezoresistive pressure sensor; FEM; injection molding; process parameters

1. Introduction

Injection molding technology is a manufacturing method where critical parts are produced by shaping thermoplastics and the type of materials used is getting richer every day [1]. Nowadays, this technique, which is widely used to mold plastic materials into parts with complex geometries [2], plays a critical role in automotive [3-4], medical devices [5], electronics [6] and many other industries, especially by offering fast and high-precision production [7].

Plastic card type pressure sensors are widely used in critical applications such as tire pressure monitoring systems [8] and airbags, especially in the automotive industry [9]. Boris Adam et al. investigated in detail the performance of a pressure sensor developed with APSM (Advanced Porous Silicon Membrane) technology for use in airbag systems. The study focused on evaluating the effectiveness and application potential of the technology by analyzing the effects of this sensor on the pressure range and normalized differential pressure signal [10]. In the production of these sensors, material selection and optimization of process parameters are of great importance, since these parameters [11] directly affect the quality and performance of the final product [12-13].

Nan-Yang Zhao et al. conducted a study to reduce defects such as deformations and shrinkage encountered in injection molding processes. They explained how they are affected by process parameters such as injection rate, injection pressure, holding pressure, holding and cooling time. The paper comprehensively summarized recent progress on design of experiments approaches and four advanced methods (artificial neural networks, genetic algorithm, response surface methodology and Kriging model) [14].

Hsueh-Lin Wu and Ya-Hui Wang have conducted extensive studies to reduce the volumetric shrinkage in the injection molding process, especially in the chair bases, to solve this problem, which adversely affects the production quality and reduces the performance of the final product. These studies have enabled the optimization of various process parameters to minimize shrinkage and have made significant contributions to the improvement of production processes [15].

Modern simulation software offers effective tools to optimize various aspects of the injection molding process [16]. Using Moldflow software, heat transfer, injection pressure and filling times are optimized, resulting in significant improvements in product quality [17]. Fuat T. proposed a combined approach of Response Surface Methodology (RSM) and Grey Wolf Optimization (GWO) to optimize and model parameters such as polymer deformation, volumetric shrinkage and cycle time using Moldflow Insight software [18].

In their study, M.O.M Ali et al. used the Response Surface Method (RSM) to determine the optimum parameters on the filling time and explained that injection time is an important parameter that affects the filling time with 99% [19]. At the same time, the effects of cooling water temperature and Reynolds number on product quality were studied in detail by Fuat T. et al. using the Face Centered Cubic (FCC) experimental design approach [20].

Celio Fernandes et al. presented a comprehensive review of the mathematical modeling and optimization of the injection molding process, evaluating the effectiveness of artificial neural networks and evolutionary algorithms in this process. Their study highlighted the success of these methods in modeling and optimizing process parameters and made significant contributions to the development of injection molding technology [21].

Material selection is one of the most important aspects of the injection molding process. The viscoelastic properties and thermal behavior of different polymer materials significantly affect both the shape accuracy and mechanical strength of the final product. Markus Baum et al. studied various models involving the effects of temperature on viscosity and helped to systematically classify the models by creating mathematical structures that describe the complex viscous behavior of polymers in the filling stage of these models [22]. H.K. Lee et al. studied the residual stress distribution and surface replication performance in polymers in detail; while evaluating the residual stress state with photoelastic analysis methods, they verified the surface replication conditions with experimental findings [23].

The aim of this study is to investigate in detail the behavior of different plastic materials such as PC (Polycarbonate), PBT (Polybutylene Terephthalate) and PA (Polyamide) in the injection molding process through simulation and to identify the key factors affecting the quality of board type pressure sensors produced using these materials. The simulation process will help us understand the effects of critical parameters such as cooling water temperature and Reynolds number on filling times, injection pressure and surface deformation. The findings are intended to make significant contributions to both academic and industrial applications.

This paper demonstrates the potential of microinjection molding technology while presenting innovative methods that improve quality while reducing costs. The findings of the study will guide future research into optimizing material and process parameters to produce plastic board-type pressure sensors.

2. Method

Even if the desired product is standard, there may still be several production problems. These problems can be due to the size of the material and material characteristics. To remedy the problem, small changes in the production are employed. For example, optimization of the compressive force transfering the injection molding machine is one choice, while the design of sharp edges can be improved is another. These new features will make the production of hard-to-manufacture parts that have complex shapes simpler.

It is certainly important that there is a capability of the plastic to shrink dimensionally after the process of cooling in the mold, that adequate cooling is given to make the component trouble-free and the surface roughness is requested to be within the acceptable range of limits and in the meantime the design of the gating system should be the right one. These aspects play a major role in the productivity of the production process and the product cycle.

The finite element method has a good and wise way of separating the production part into more fine parts so the study of its behavior could be done. The part was processed through the finite element method to simulate in-mold flow analysis. In this investigation, the in-mold flow simulation has been carried out by the use of Autodesk Moldflow Insight Synergy 2016 version software and the injection analysis was worked with the help of the Cool-Fill-Pack-Warpage module, designed for mold cooling and filling time. Fluid behavior was determined in these studies by the use of the following formulas:

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \tag{1}$$

Momentum Conservation Equation

$$\frac{\partial^2}{\partial t} \nabla^2 \cdot (\rho V)^{\frac{1}{2}} = 0 + V^{\frac{1}{2}} \cdot \frac{\nabla^2}{\partial t} \rho + \rho V . V^{\frac{1}{2}} = 0 \tag{2}$$

Conservation of Energy Equation

$$P_c \frac{dt}{v_{dt}} = k \nabla^2 T + \emptyset \tag{3}$$

3. Material

We can find that by the literature review, the engineering plastics applied to the production of plastic board-type piezoresistive pressure sensors in the last ten years have attracted considerable attention for their high structural strength and stiffness as well as for their low cost and resistance to fatigue [24]. PA, PBT and PC materials were the predominantly used materials in the manufacture of piezoresistive pressure sensors using the card-type technology. Table 1 shows the thermophysical properties of the materials designated for injection analysis namely, the three engineering plastics used in the Moldflow Synergy Material Database and the trade names are Novarex PC, Valox PBT, Amoled PA.

Table 1. Physical characteristics table.

Material	**PA**	**PBT**	**PC**	
Physical Properties	**Value**	**Value**	**Value**	**Unit**
Melt Density	0.95273	1.0451	1.0579	g/cm^3
Melt Temperature	335	248	300	°C
Solid Density	1.2473	1.2585	1.397	g/cm^3
Surface Temperature	80	60	95	°C
Modulus of Elasticity E1	2410	2600	2280	MPa
Maximum Shear Stress	0.5	0.41	0.5	MPa

3.1. Model

The board type sensor is depicted in Figure 1 as a 2D technical drawing and 3D model. The piezoresistive film model is 6.85 mm, 10.00 mm and 1.78 mm, respectively, having its X, Y and Z bases of piezoresistive card type pressure sensor solid model in a Cartesian coordinate system. Two inlets on the model are 3 mm apart and the internal hole diameter is 1.14 mm.

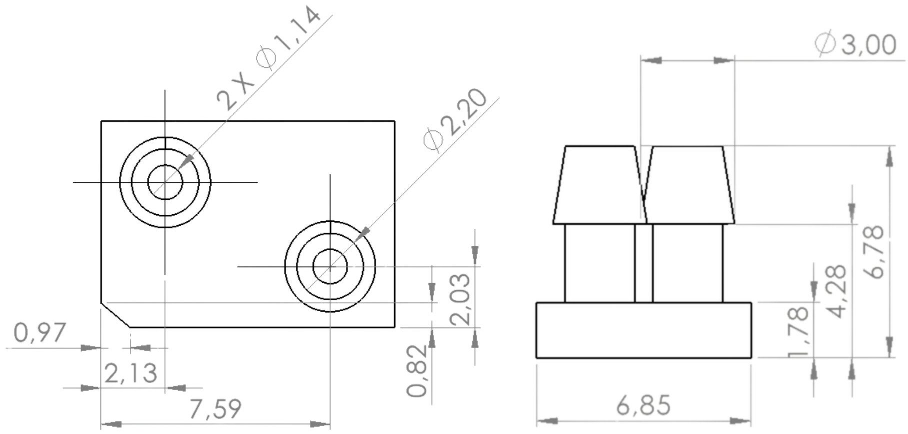


Fig. 1. Technical drawing dimensions of the model.

3.2 Mesh

The piezoresistive pressure gauge is designed with a flat structure when the triangular mesh lattice is used to cover the surface. The total number of the triangular mesh is 10798. This embodiment is designed to represent the geometric complexity of the model with high precision and to give a suitable mesh density for finite element analysis. The mesh element choice and the uniform mesh structure became efficient for the model's physical behavior simulation. The parameter specific to the proportion of the length-height width of a triangle to one of its angles (aspect ratio) which is an important one for the mesh and thus for the quality of the mesh structure, is maximum 3.69. Mesh representation of the model is shown in Figure 2.

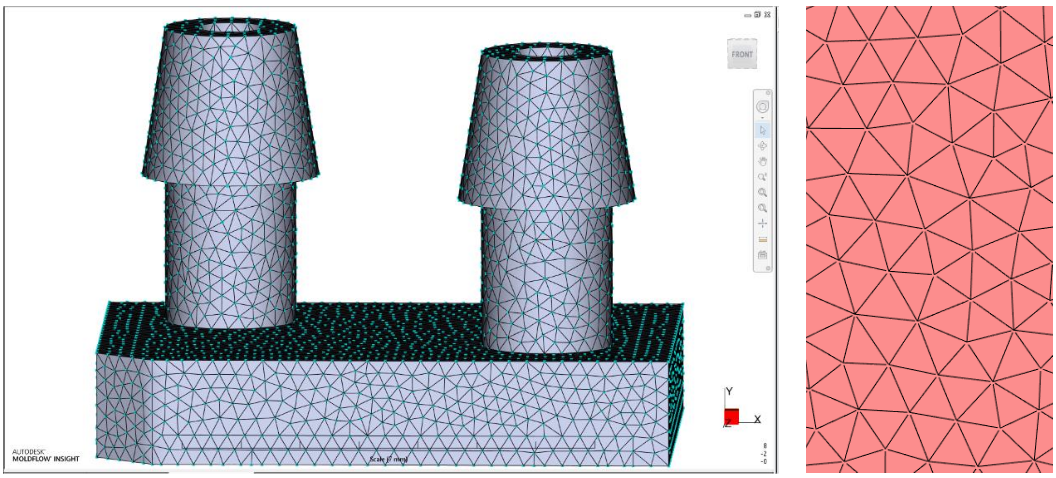


Fig. 2. Meshed model.

To improve the extent of precision within the simulation, localized mesh refinement was undertaken surrounding the important segments like injection gates, edges that are sharp and parts of the model that are thin. This method allowed for a better representation of flow behavior and temperature distribution in the critical areas where disturbances are expected in the molding operations.

4. Modeling and analysis

The piezoresistive card type pressure sensor analyzed was simulated with SolidWorks commercial software program. It is crucial to simulate the appropriate mold design to create it. The mold designing of the model was done in the Moldflow Insight software.

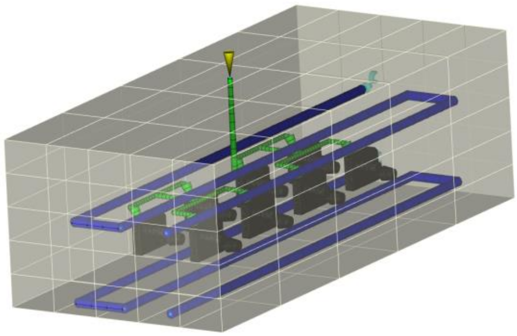


Fig. 3. Mold dimensions in Cartesian coordinates.

According to this 3D animation, the size of the mold measures 216, 50 and 200 mm for the X, Y and Z axes. The 3D representation of the mold is demonstrated in Figure 3. Tol steel P-20 was the used mold material. In this study, the Cool-Fill-Pack-Warpage analysis was completed and the recommended program values were input as the process settings.

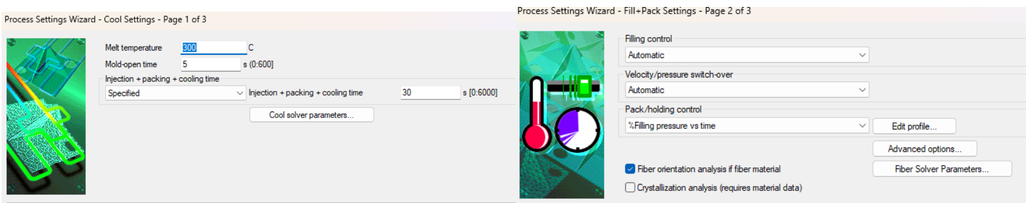


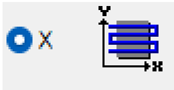
Fig. 4. Process settings view.

A process adjustment with adequate filling pressure was performed for 10 seconds and was limited to a maximum of 80% of the scope. The process controller was configured with the temperature control tab, the mold temperature control set as Uniform and 95°C was the criterion for the mold surface temperature. Besides this, the melt temperature reading was changed to 300°C as shown in Figure 4, while the room temperature was kept at 25°C. Summing up, the right time to fill the empty space (the open mold time) for starting is 5 seconds, the best cooling time is 20 seconds and a total of 30 seconds have been set as the enhanced time (injection + packing + cooling time) which was found to be the most effective configuration for the process.

4.1 Cooling circuit design

The vertical channels used for the cooling system were chosen to allow for the efficient design of the cooling system and the quality improvement of the product. From the sample of 8 pieces, it is possible to determine which heat channels have diameters and positions cooled by the dart. The rapid and uniform distribution of the heat and essential temperature balancing were done by the diameters and positions of the cooling channels. By carrying out a uniform cooling process, the system runs at the highest efficiency and having the temperature profiles in the same position as the product. The cooling channels table is provided in Table 2.

Table 2. Cooling Duct Dimensions.

Part Size (X Axis) (mm)	68.04
Part Size (Y Axis) (mm)	20.34
Part Size (Z Axis) (mm)	6.85
Channel Diameter (mm)	10
Distance of the circuit to part (mm)	25
Channel Type	

These design features are shown in detail on the Figure 5 where the duct layout is. The picture is very evident of the way the optimization and the fixing of the ducts are to be made so that there is no one spot that is cooler than the others and thus ensured, the temperature control is done effectively.

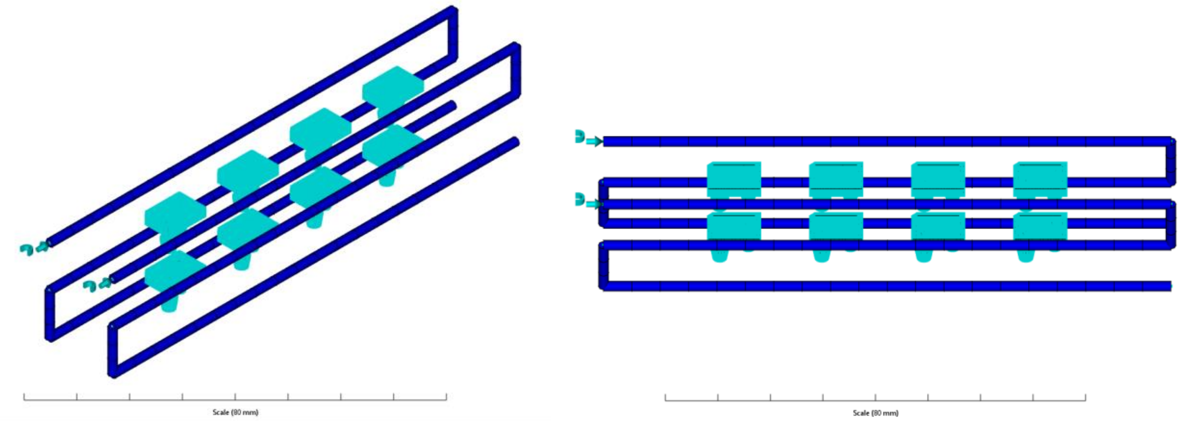


Fig. 5. Cooling circuit model.

Pure water was used as a coolant at 25° and the flow Reynolds number for the circulation was 10000. The fluid properties of the coolant in the analysis are given in Table 3.

Table 3. Fluid properties of the coolant.

Properties	**Value**	**Unit**
Coolant density	0.988	g/cm^3
Coolant specific heat	4180	J/kg-C
Coolant thermal conductivity	0.643	W/m-C

4.2 Gate location

The conformity issues resulted in a lack of and a very poor replication of the mold resulting in substantial flow defects like long gating systems and as such, were main sources of defects in the parts molded by that system. Therefore, part failure caused by shrinkage-induced warpage is a commonly known phenomenon. The detailed results of the flow resistance indicator and gate suitability analyses are visualized and presented in Figure 6. This approach is indispensable to the procedure of production optimization and the increase in the product's quality. The most suitable injection point was decided upon after the molding window and the gate location were determined through the use of a computer program which the results, in turn, are indicated in Figure 6.

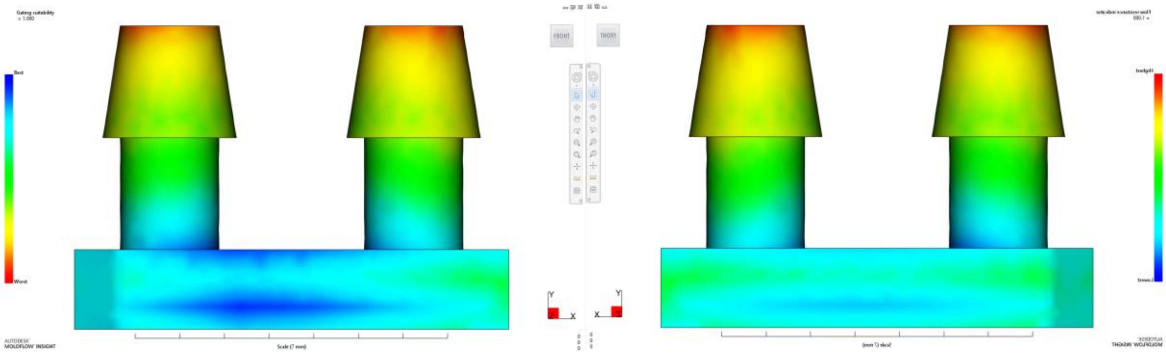


Fig. 6. a) Gating suitability. b) Flow resistance indicator analysis results.

Figure 6 illustrates the flow path system design for the piezoresistive card-type pressure sensor model. In Figure 6a, the overall layout of the runner system is depicted, pointing out the fact that the melt is driven uniformly to the eight identical cavities through the main and secondary runners. In Figure 6b, the material flow behavior within the runner system is presented through a simulation based analysis. The texture in Figure 6b symbolizes the distance and the progress of the melt moving as well as the distribution of the flow velocity, where warmer colors mainly red and orange indicate the speed of the flow and cooler colors, mainly blue and green, indicate no flow or regions with potential flow hesitation respectively.

4.3 Runner system

Injection molding flow path design depends not only on the filling time but also on the surface quality. The mold provided for the technological program has been carefully designed to provide and control the flow path that has thus resulted in eight piezoresistive solid models being manufactured at the same time. Additionally, this leads to the optimized flow pattern design and the flow path system layout that Figure 7 displays based on these design features.

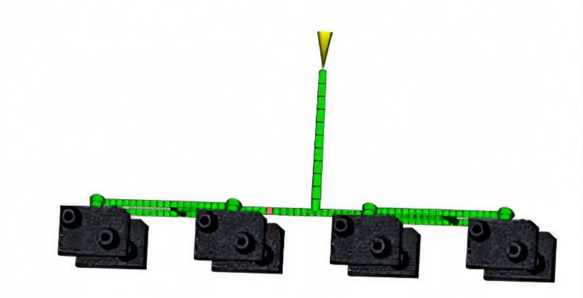


Fig. 7. Flow path system design.

To ensure all cavities were filled evenly and to minimize the internal stresses and the defects in the flow the design of the runner system was according to the rules of symmetry and balance. In the arrangement of eight sensor bodies simultaneously the manufacturing efficiency was notably increased.

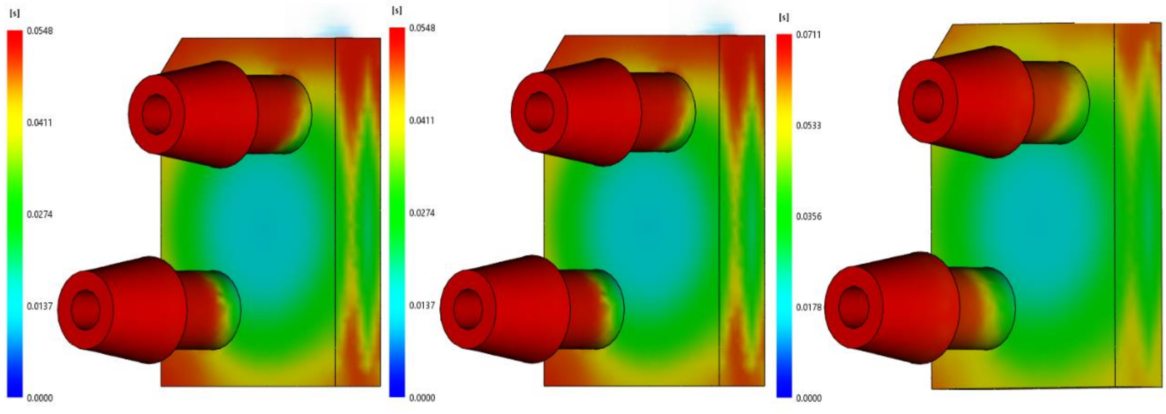
The design of the runner system was well balanced and symmetrical for the even distribution of molten plastic within all cavities. This configuration made it possible to produce eight piezoresistive sensor bodies at the same time and without any defects which considerably increased manufacturing efficiency. The flow path optimization avoided the unfavorable occurrence of turbulence, air entrapment and surface defects during the filling operation. The simulation analyses indicated that material was smoothly directed to all the cavities via the main and secondary runners. This runner plan improved part quality while minimizing cycle time as a result of the optimization of production costs.

5. Results

The results achieved in this research are in line with the conclusions presented in the literature. One good case in point is that M.A.M. Ali et al. pointed out that filling time is the most important parameter that is affected by the injection process and if this parameter is optimized, then other factors that contribute to the production cycle time are not significant [19]. The analysis of this study revealed that PA had the shortest filling time (0.0548 s), thus confirming the idea that less viscous materials are more favorable for the process of mold filling. On the same note, Hsueh-Lin Wu and Ya-Hui Wang gave the proof of the fact that proper selection of materials and process conditions could potentially decrease volumetric shrinkage [15]. The result of our simulation also agreed with this, since PC material experienced the smallest volumetric shrinkage (6.63%) among all tested materials.

5.1 Fill time

Filling the time in the process is defined by the process of changing the material into the form of a product. According to the literature review, the study concluded that the time spent on the injection of the molds is the main parameter affecting the flow time [19]. The network model is set up by the operator who sets the proper gate location, material type and analysis parameters and the filling time analysis is executed. Figure 8 presents the details of the process when the material fills the model and the lines are the gameplay. The analysis result showed that PA is the material that best absorbs the filling time which gives the smaller time variant.



PA Time:0.0548s PBT Time:0.0987s PC Time:0.0711s

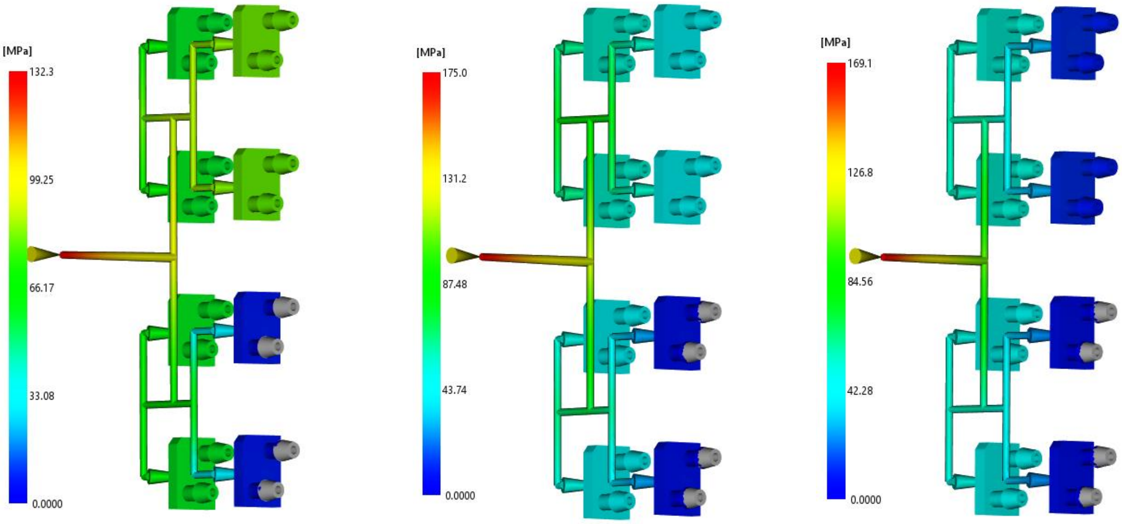
Fig. 8. Fill time results.

5.2 Pressure at v/p switchover

V/P switchover is a process that describes the point when the powders are transitioned from Speed control (injection process) to Pressure control (pressure holding process) at the moment at which the material is injected into the mold [25].

All raw material (PA, PBT and PC) were considered within a triad that was subjected to simulation. Based on the results of the Pressure at V/P Switchover procedure, PA is concluded as the material that seems to give the best results in production. The results of the analysis are presented in Figure 9.

The V/P switchover pressure is the key point of transition from filling to packing during the injection process, so it affects the surface quality and structural strength inside. In this research, PA was found to be the one with the least amount of V/P switchover pressure, efficient control of the in-mold pressure was also achieved and thus the energy consumption was minimized. Conversely, PBT and PC were found to have higher switchover pressures, which indicated that they had greater filling resistance. This parameter is a critical selection criterion for the material especially one required to achieve high precision. An internal mold stress reduction that's lower thresholded switchover pressure also aids in an easier and more uniform material flow.

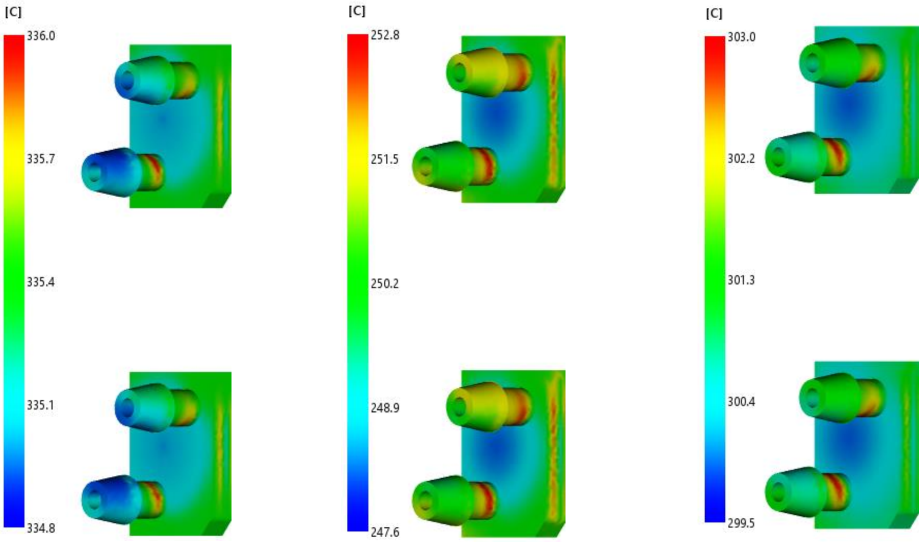


PA Pressure: 132.3 MPa   PBT Pressure: 175 MPa   PC Pressure: 169.1 MPa

Fig. 9. Pressure at v/p switchover results.

5.3 Temperature at front flow

In the analysis of cooling, in general, mold is put at a lower temperature than the melting material and the material temperature reduces during the filling process. The research found that PBT is the most suitable material for the selection of the optimum Temperature at Front Flow value. The results of the study are shown in Figure 10.



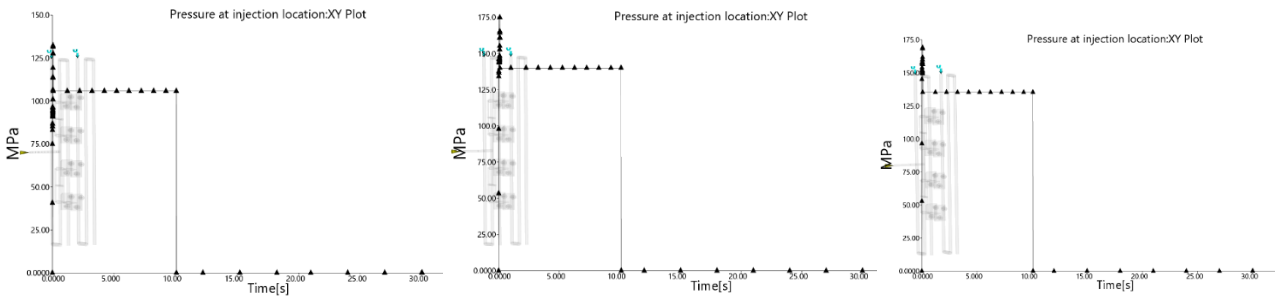
PA Temperature: 336°C PBT Temperature: 252.8°C PC Temperature:303°C

Fig. 10. Temperature at front flow analysis results.

The term "front flow temperature" denotes the temperature of the liquid polymer when it first reaches the cavity of the mold and acts as a major parameter for the control of surface quality, flow stability and thus for the prevention of filling defects. The results of this study show that PBT was characterized by the lowest front flow temperature as a result of its excellent thermal stability and its technical ability to minimize such trouble as burning, surface deformation and flash formation, which are the common problems in the molding of plastics. The temperature control was more effective, the filling process was smoother and more controlled and thus the overall product quality was improved. Therefore, PBT would remain the most suitable material for heat-sensitive components in particular.

5.4 Pressure at injection location: xy plot

The control of injection point pressure analysis, where three different materials were used for the produced parts in order to guarantee the optimum pressure control, is presented. These are PA, PBT and PC respectively. The results of the analysis are shown in Figure 11.



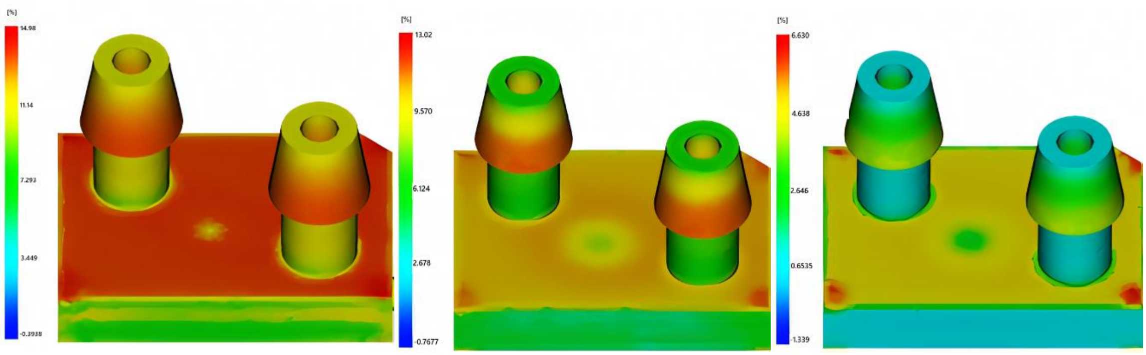
PA PBT PC

Fig. 11. Pressure at injection location: xy plot results.

When the injected material enters the mold, the pressure at the injection site is proportional to the resistance met by the material through the mold and it is the prime factor in flow balance and distribution of internal stress. The analysis showed that the PA had the least amount of the injection pressure, meaning a more stable filling process, which is less energy consuming. On the other hand, PBT and PC received more pressure readings, which indicated the increased resistance of flow, primarily in narrow geometries and a more uneven pressure distribution in the mold. This finding emphasizes that adjusting the injection pressure not only rids the product of quality defects but also increases the efficiency of the whole process.

5.5 Volumetric shrinkage at ejection

The literature review has revealed that the process parameters have been optimized in respect of the volumetric shrinkage [26]. The study results noted that material that provides optimal volumetric shrinkage value was PC -6.63%. The analysis results are given in Figure 12 as PA, PBT and PC respectively.



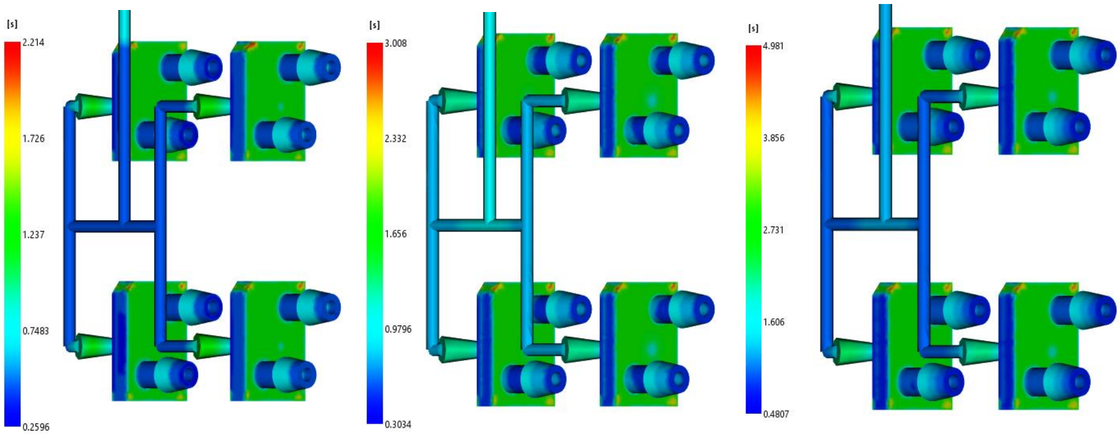
PA: 14.98% PBT: 13.02% PC: 6.63%

Fig. 12. Volumetric shrinkage values.

From the study it has been established that the lowest shrinkage rate is obtained with PC, thus making it the most suitable material for high precision applications. Conversely, chemicals such as PA and PBT were shown to have the highest shrinkage values which must be carefully taken into consideration in respect of warpage and dimensional deviations.

5.6 Time to reach ejection temperature

It is recognized that melt, mold and ejection temperature really influence the reduction of demolding time [27]. Based on the analytical results of Figure 13, it is clear that the material with the best demolding time is PA by time value of 2.214s.



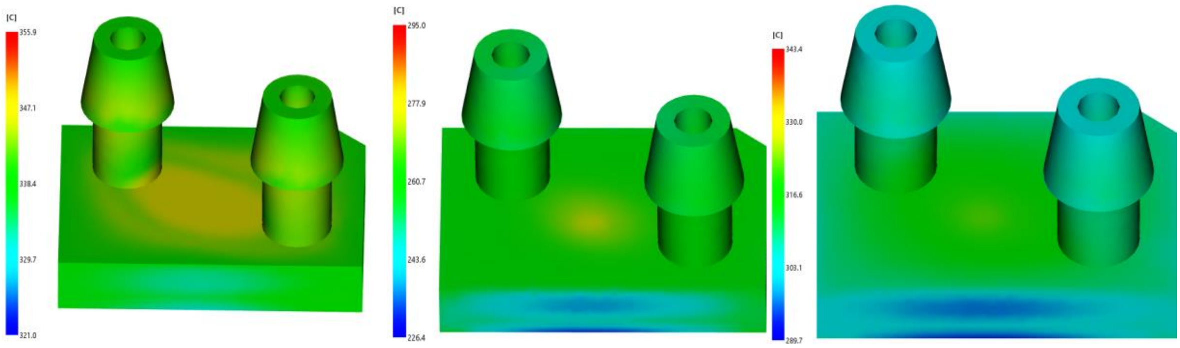
PA: 2.214s PBT: 3.008s PC: 4.981s

Fig. 13. Time to reach ejection temperature results.

The part needs to be cooled enough before, so we can remove it, the removal of the part must be safe. A comparative study of PA, PBT and PC materials was conducted with respect to the ejection temperature profile as the time taken by each to reach the ejection temperature was measured. The time took PA the least time, 2.214 seconds, faster than others, thus leading to the leading advantage of this type of material in rapid manufacturing processes. On the other hand, PBT and PC took much longer to reach this temperature hence leading to a possible elongation of the production cycle.

5.7 Bulk temperature at end of fill

As a part of bulk temperature analysis at the end of fill, the part temperature was monitored after the filling stage during injection. The material which was found to have the highest value was PBT which was 295 according to the analysis. The record is shown in Figure 14.



PA:355.9°C PBT: 295°C PC:343.4 °C

Fig. 14. Bulk temperature at end of fill results.

The bulk temperature measured at the end of the fill is a significant factor for evaluating the homogenous distribution and cooling of the molten material inside the mold. In this study, PBT which is the material we used reached the lowest average temperature of 295°C most likely due to better control of heating during the molding process. This property permits the choice of PBT in exact molding applications where the balance of heat is imperative.

5.8 Circuit pressure

Pressure Circuit analysis was done for determining the pressure on the cooling circuit and the results got from this analysis are shown in Figure 15. The molding process is strongly influenced by circuit pressure because it is a very important aspect of effective heat removal. Ensuring that the circuit pressure is well managed ensures that the coolant flows uniformly through the mold and that temperature variations and local shrinkage are minimal. The findings of this study's analysis show that the cooling circuit's pressure distribution was correctly designed and guaranteed effective heat transfer. The low pressure deviations indicate the thermal stability of the system and the good state of the overall part quality are achieved.

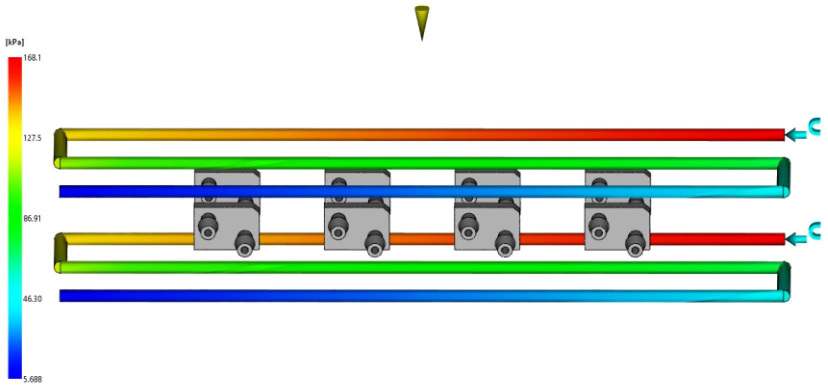


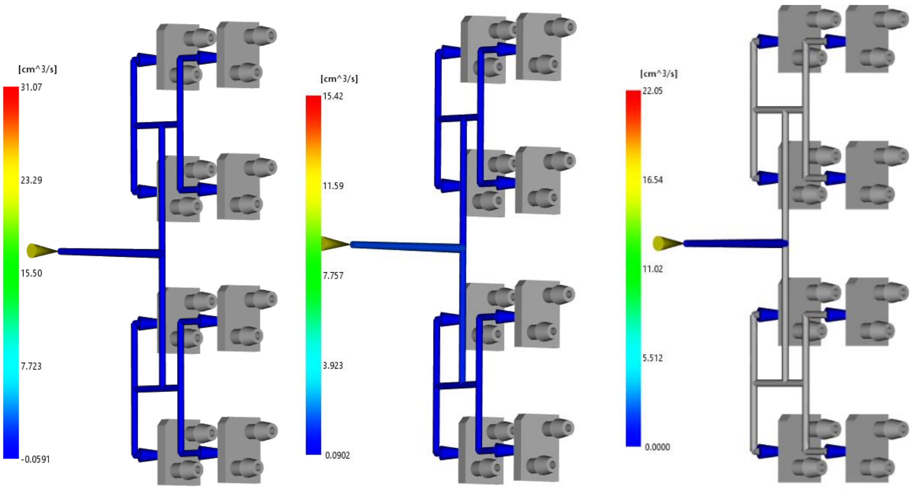
Fig. 15. Circuit pressure results.

5.9 Flow rate beams

The flow rate beams analysis included 3 different material types, considering the safe and stable flow control. These were PBT, PA and PC materials. The consequence of the study made it clear that of the three, PBT was able to satisfy production requirements in a more optimal way. Defining flow rate values is critical in determining whether or not the molten material penetrates the mold properly and evenly. As far as this research is concerned, PBT has proved to be the most effective in the control of filling process so that it becomes an even and uninterrupted process. Figure 16 displays the findings of the study.

The low and steady flow rate value (15.42 cm^3/s) of PBT ensured that rapid directional shifts that could cause turbulence in convoluted geometries were prevented. However, the higher flow rates of PA and PC materials at some locations indicated some regions were overpack and some potential surface defects were present. Thus, these defects may lead to increased cooling differentials and stress accumulations. The use of PBT caused a uniform flow pattern, which led to a more balanced temperature and pressure distribution in the full mold. This further proves that PBT is the best material in applications such as the one described above where precision is essential and high surface quality is a must.

A review of these analyses indicates that in the selection of materials, the characteristics of flow must be weighed equally with mechanical and thermal properties. The technique of flow rate control is the most crucial one in multi-cavity molds in achieving the equal filling of all cavities. The filling might be quicker at higher flow rates; however, such filling rates would also lead to a greater chance of defects such as air entrapment. The flow rate that was controlled by PBT was able to minimize such problems leading to the greater reliability of the molding process. The conclusions derived from these studies confirm that it is necessary that flow rate analysis must be a part of the design stage of injection molding operations.



PA: 31.07[cm^3/s] PBT: 15.42[cm^3/s] PC: 22.05[cm^3/s]

Fig. 16. Flow rate beams results.

6. Conclusion

To determine the most suitable material and process parameters for the piezoresistive card type pressure sensors in the injection molding process, a comprehensive analysis has been carried out in this work. Three different engineering plastics, namely, PA, PBT and PC, have been evaluated and the impact of each material on the production process has been studied.

The simulation analysis results demonstrated that PA had the shortest filling time of 0.0548 s and the lowest mold disconnect time of 2.214 s, PC was the one with the lowest volumetric shrinkage of 6.63% and the one with the best thermal stability of 252.8°C was PBT. In addition, PA showed the lowest injection pressure value of 132.3 MPa whereas PBT showed optimum flow control leading to a balanced production process.

Accordingly, it is concluded that PA is advantageous in the rapid production of devices such as quick charging and energy efficient function whereas PC is useful in the applications where dimensional accuracy is critical and PBT is the best production choice if both mechanical and thermal stabilities are important. The study also identified that both mechanical as well as thermal stabilities are important factors in the production process and thus, PBT is a balanced solution. This proves its suitability and flexibility by further adding a product's market advantages.

The study is a comprehensive guide for the material selection and optimization of the injection molding parameters for the production of piezoresistive pressure sensors. The findings will contribute to the development of low cost, efficient and quality production processes that can be implemented in both academic and industrial applications. Although the study’s findings significantly enlighten the understanding of the behavior of various engineering plastics in the process of injection molding, it would be advisable for the research in the future to be more focused on the verification of these findings of simulation with the help of experiments. The physical molding of PA, PBT and PC as well as the same process conditions of this study would enable one to conduct a direct comparison with the data gotten from the simulation. In addition to drawing the line between the simulations and the real injections, the findings would help to detect any kind of discrepancy due to the data feed into the machine, differences in the materials or the environment. Also, the part may need to undergo long term trials and mechanical tests to determine the service life and the fitness for pressure sensor applications. The co-use of the data from the experiments with the outputs of the simulation will, beyond a doubt, lift the method up to the stage of full reliability and industrial practicability.

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Author Contributions

F.T. and B.B. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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