Injection Moulding Simulation and Validation of Thin Wall Components for Precision Applications

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Abstract. This paper presents the results of the Moldex3D simulations and experimental validations carried on a complex 3D thin wall part, it critically analyzes the capability of Moldex3D and provides the guideline for more accurate simulation with the commercial softwareMoldex3D. The Boundary Layer Meshing (BLM) mode was adopted in this work to simulate the injection molding process of a hearing aid shell made of Polybutylene Terephthalate (PBT) with 30% glass fiber. Injection molding experiment was conducted to validate the prediction from Moldex3D. Injection time, injection pressure; pressure loss and warpage were treated as the main comparison criteria. Different parameters setting in Moldex3D were investigated to research their influence on the accuracy of the simulation. Results showed that the injection molding process prediction from the simulation was relatively precise when the nozzle geometry and the pressure effect on the material viscosity in the simulation model are considered. The determination of a proper heat transfer coefficient (HTC) is also vital for the simulation accuracy. The agreement between the warpage of the experiment molded parts and simulated parts was not good. Warpage was dominated by the fiber orientation. Predicted warpage was found to be extremely dependent on the filling HTC (Heat Transfer Coefficient) and the fiber orientation model used in Moldex3D, both of which had a significant influence on the fiber orientation.

Keywords: Moldex3D · Injection molding · Thin wall part · Simulations

1 Introduction

The thin wall part has a smaller wall thickness compared to the size of the part. For the plastic part, the injection moulding process becomes difficult as the wall thickness reduces. The size of a part determines how thin the wall thickness can be. The material flow behavior, the cooling behavior, and morphological characteristics are changed when parts are made with thin walls. These things influence the modulability of the

B. Gapiński et al. (Eds.): *Advances in Manufacturing II* - Volume 4, LNME, pp. 96–107, 2019.
https://doi.org/10.1007/978-3-030-16943-5_9

material as well as the simulation accuracies. One classic example of a thin wall part is the Hearing Aid (HA) shell.

The parts of the Hearing Aid are held together in a protective case consists usually of upper and lower shells which are assembled together at the final stage of the production [1]. Figure 1 shows the picture of an HA and its shells. The outer shells of Hearing Aids are made by injection molding. As they are usually thin wall structures, highly sophisticated molds and lot process optimizations by trial and errors are used to make the successful parts. So, the development time and expense of the hearing aid are increased significantly. To reduce the time and cost for developing a new hearing aid, Computer Aided Engineering (CAE) software like Moldex3D, can be employed to simulate the process of injection molding to optimize the part and mold design and to optimize injection molding process parameters in advance.

With the advances in the process simulation, it is highly likely that a lot of mold making efforts and many trial and errors can be reduced or even eliminated [2]. But this practice is not in vogue in the hearing aid industries due to the lack of validation of the simulation software for thin wall parts like hearing aid shells. The aim of this paper is validating and improving the prediction accuracy of one of the widely used injection moulding simulation software which is Moldex3D. Different parameters setting in Moldex3D were investigated to check their influence on the simulation accuracy. This paper will provide in-depth knowledge about the simulation process for highly demanding thin wall parts and show the way to improve the simulation accuracy.

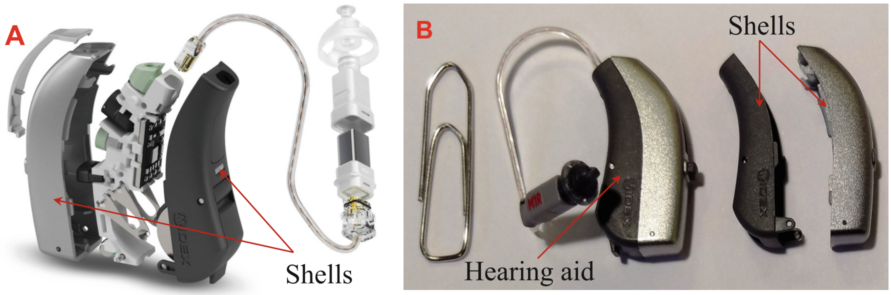

Fig. 1. Exploded view of a hearing aid showing shells (A); picture of a hearing aid and its shells (B). (Image courtesy: Widex A/S, Denmark).

2 State-of-the-Art and Need for This Research

Computer modeling is revolutionizing manufacturing industries allowing optimizing product development process, improving resource management and enhancing the product quality to meet rising customer requirements and sustainability concerns. In the plastic industry, computer simulation aids the entire process starting from component design, mold design, and manufacturing, material selection, molding conditions enhancement and ending with cooling optimization (shrinkage and warpage analysis)

[3]. When all these tools are correctly and accurately used, the company can improve manufacturing efficiency and quality, which in today's competitive business world is crucial. Giving these facts real-life examples, by using computer modeling mold cost can be cut down by 10–40%, lead time can be decreased by 20–50%, molding time can be enhanced 10–50%, less material utilization by 5–30% and reduced product cycle time by 50–80% [4].

Molding parameters can be simulated and optimized for a given design and then tested and evaluated in the actual molding process after which further improvements can be made. To attain the most efficient process conditions, product requirements and material properties must be accounted for. Molding conditions are connected to the internal structure of the material and its rheological characteristics. The first phase, namely plasticization, is possible to optimize by adjusting the screw rotation speed and the pressure that the oil pump is exerting on it.

The injection time (injection speed) is a critical factor for pressure drop, a shear rate which is directly related to the molding type and the material selected for the process. Optimization can be performed based on pressure loss and temperature change [4]. The injection speed should be adjusted in the minimum pressure range and ensure constant melt temperature in the entire flow path to avoid a decrease in quality. During the packing phase, the optimized amount of pressure and time applied on the material allows avoiding sink marks or underweight.

Many researchers have studied, developed and published mathematical models that aim to provide with the accurate predictions and help to understand, develop and optimize the process of injection molding. Today it is possible to simulate the flow of polymer melt in extremely complex geometries by studying the nature of compressive viscous fluid flow under non-isothermal conditions and dividing the cavity geometry into layers (flow paths) that account for different type and speed of flow [5]. The Hele-Shaw model for inelastic, non-Newtonian fluid under non-isothermal conditions allow to successfully estimate shrinkage and warpage, fiber orientation and residual stresses inside the plastic parts. It is also possible to simulate process conditions for resin transfer molding, gas-assisted injection molding, micro moulding and injection/compression molding etc. [6, 7].

Today it is possible to solve 3D problems by FEM including crystallization models to account for the changes in morphology that occur when semi-crystalline thermoplastics solidify. Simulation tools are available to consider polymer blends that are non-uniform in microstructures having different molecule size and shape. Mathematical models are also developed for Fiber Reinforced Plastics (FRP) that focused molecular orientation and fiber orientation [8].

Over the years, researchers improved models for dedicated parts of the process, which combined together came as commercial software packages dedicated to injection molding simulations. Most widely known programs include AUTODESK Moldflow® and Moldex3D. CAE tools that can limit the time of trial-error period, but also some software tools are capable of suggesting the most favorable process set up by a model builder. The result came favoring the manual method delivering components with more accurate weight and higher dimensional stability.

Even after the significant improvements of models and simulations, it cannot be overlooked that the simulations have their limitations and no software is able to predict each real-life molding cycle with 100% accuracy. For time efficiency and possibility to simulate the process conditions, the software uses assumptions and approximations that the physical material and injection moulding unit cannot be accounted for.

With rising numbers of hearing problems and high customer requirements for small, light and esthetic hearing aids, the companies are facing many constraints in the process of fulfilling all demands while offering the final product at reasonable price. The hearing aids are built of two outer shells, fitted with a snap fit, that protect the electronics from mechanical damage and prevent body fluids and dirt from entering the inside.

The shells are manufactured by Injection Molding (IM). These small, thin wall components need complex molds and extensive process optimization to produce light-weight, geometrically accurate parts fulfilling the desired functionality. Due to high-quality products demand and very high initial cost of moulding equipment, companies must utilize various CAE tools to predict and enhance their product development to obtain efficiency and stay in the competition with other enterprises. Computer simulations are growing in importance in the plastic industry. As IM is a very complex process, utilization of such software simulations allows including all crucial factors – material properties, mold design, feeding system, cooling, shrinkage and so on. It should be noted that all available computer software packages are based on purely mathematical models that employ approximations and assumptions whereas the real-life conditions cannot be fully mimicked and there will always be some discrepancies between the simulation results and the final molded product.

Even though, information gained from the CAE tools is priceless for higher quality products, a better understanding of the processes and enhanced resources management. For the current work, Moldex3D simulation tool was chosen and the simulation results obtained from this tool is validated with an extensive experimental analysis. This work provides a guideline for the accurate simulation of a 3D thin wall part with the Moldex3D simulation package.

3 Materials and Methods

The test geometry was a simplified hearing aid shell. The part is shown in Fig. 2(A) which had outer dimensions of about 32 mm × 8 mm × 24 mm (length × width height) and a wall thickness of 0.8 mm. The material selected for the experiment was 30% glass fiber reinforced PBT (Arnite TV4 261), a semi-crystalline thermoplastic produced by DSM Engineering Plastics. This material is widely used for the production of hearing aid shells and other thin wall structures. The injection molding experiments were performed on a combined injection machine from two different systems. The clamping unit was from Arburg ALLROUNDER 270A and injection unit was from Arburg ALLROUNDER 170S, taking the advantages of small shot size but large clamping force.

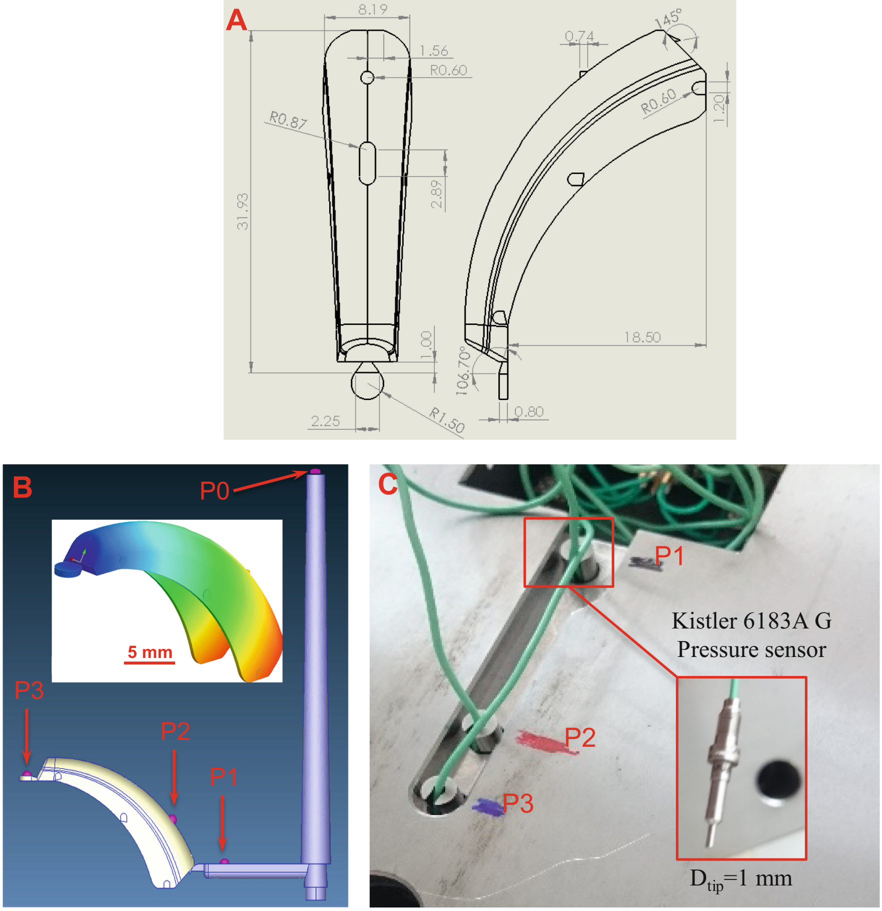

Fig. 2. Drawing of the hearing aid shell (A); simulated and CAD model of the shell (B) - CAD model showing the position of the sensors; assembly of the sensor in the mould (C).

3.1 Cavity Pressure Measurement System

Three pressure sensors (Type 6183A G) from Kistler were inserted inside the mold to record the cavity pressure during the injection molding process. As the sketch shown in Fig. 2(B), the first sensor denoted as P1 was located on the runner, the second one P2 was placed in the cavity, and the last one P3 was at the end of the cavity, on an overflow location. All of these sensors were embedded perpendicularly in the upper half of the mold and were fixed in the mold. The sensitivity of the sensors was 2.2 pC/psi. Pressure sensors were connected to CoMo Injection system for collecting data, which was then transferred to Como Data Center software installed on the laptop via a cable. By placing a magnet with inductive sensor near the mold, the Como injection system was triggered when mold was closing.

3.2 Injection Molding Process Parameters

Injection molding experiments were performed with the molding parameters listed in Table 1. The same moulding parameters were used both for the simulation and experiment. Experiments consisted of a batch of full shots with packing, a batch of shots stopping at V/P switch over time without packing and 3 batches of short shots. Molding of each production batch included a temperature stabilization period of about 10 min, then a molding series of 20 parts followed by an actual series of 20 parts for analysis.

Table 1. Injection molding and Meshing parameters for the experiments.

Moulding parameters	Values	Simulation parameters	Setting
Melt temperature [^{o}C]	270	Cavity mesh type	2 layer BLM offset ratio 0.3
Mold temperature [^{o}C]	90.5	Runner mesh type	2 washer layers
Back pressure [MPa]	12.5	Global mesh size	0.4
Injection speed [mm/s]	37.5	Refinements base	Curvature and proximity
V/P switch over time [s]	0.4	Mesh size on the gate	0.2
Packing pressure [MPa]	99.0	Cavity mesh element	59432
Packing time [s]	2.8	Runner mesh element	695832
Cooling time [s]	8	Project settings	Machine mode-1

3.3 Simulation Experiment

The real geometries of the hearing aid shell cavity, gate, cold runner as well as the cooling channels were directly imported into the Moldex3D Designer to build the model. In addition, three sensor nodes, i.e. the pink points in Fig. 3(A), with the same location as in the real mold were constructed to record the pressure change and then compare with the sensor pressure profiles in the experiment. In the simulation, the hot runner was also included in the model to resemble the machine geometry which consisted of a nozzle and used part of the barrel. The internal geometry of the real nozzle was obtained by measuring the real nozzle part. The model constructed can be seen in Fig. 3(B). The models were meshed with the settings listed in Table 1.

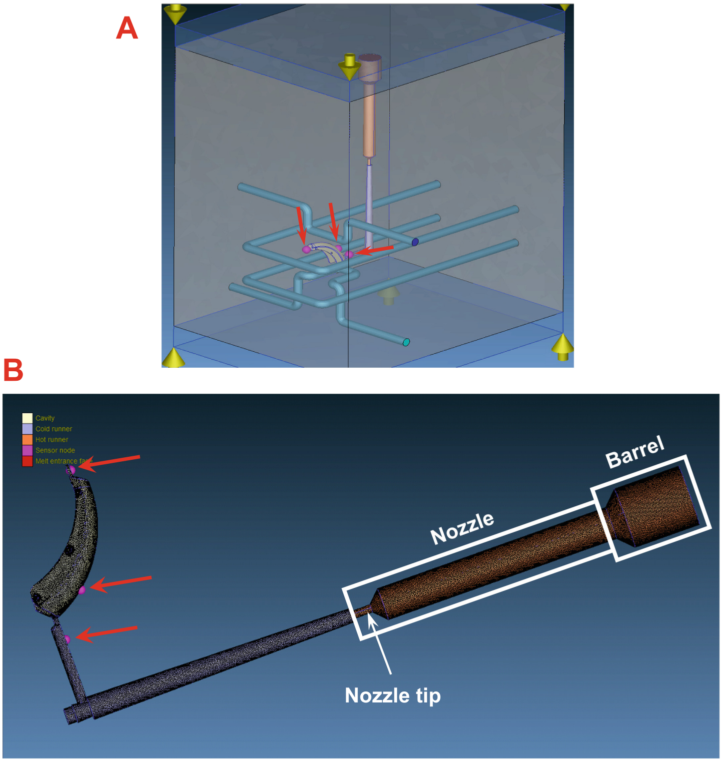

Fig. 3. The simulation model in Moldex3D Designer (A); modeling of the machine geometry (B). (Sensor locations are indicated by the red arrow).

4 Results and Discussion

Figure 4 shows the short shots comparison from the experiment with the simulation. The shape of the short shot and profile of the flow front have good agreement between the experiment and simulation.

The injection pressure of the experiment and the simulation were 99.0 and 81.5 MPa respectively as shown in Fig. 5(A). Figure 5(B) and (C) show the cavity pressure profiles from three pressure sensors from experiment and simulation respectively, where the pressure reached the peak point at the transition from the end of filling to the packing stage. It can be observed that the simulated pressure curves during the holding stage have more fluctuation compared with the experiment.

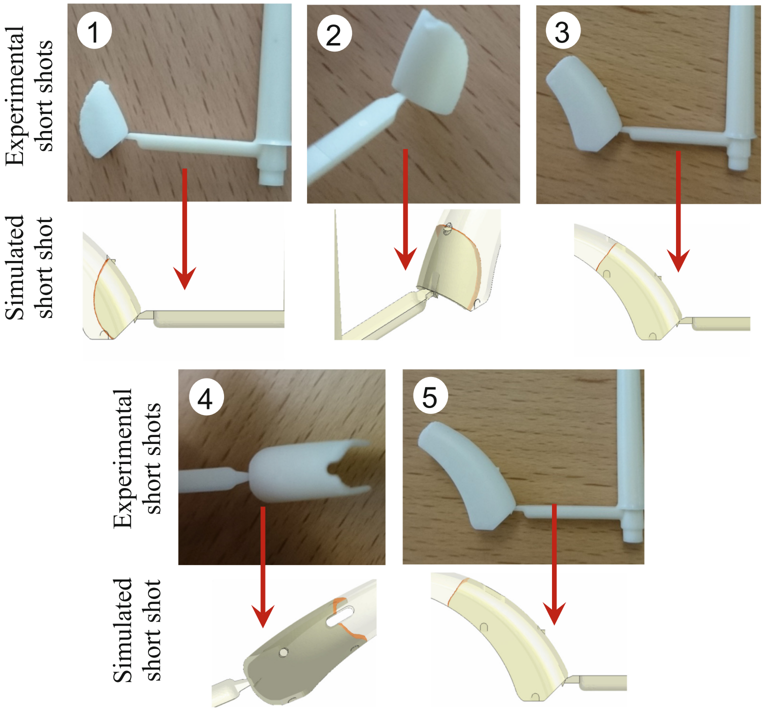

Fig. 4. Short shot comparison between the experiment and simulation showing good agreements.

From the comparison between the experiment and simulation, the following points can be observed:

- Melt front shapes are in good agreement between simulation and experiment. From the perspective of filling behavior, injection time and pressure distribution, Moldex3D R13 with BLM meshing mode has the ability to predict the injection molding process of a thin wall part correctly, even though it can't be 100% identical.
- Injection time, ram stroke, injection pressure, and cavity pressure loss in the simulation are all smaller than the experimental values. Different factors are responsible for this and will be discussed later.
- The deformation modes of the simulated part and the molded part are different, simulated part shrank in the flow direction while molded part extended in this direction. By observing the displacement caused by fiber orientation effect and random fiber orientation effect in the simulation, speculation can be made that the difference of warpage is perhaps caused by the underestimation of fiber orientation effect in the simulation.

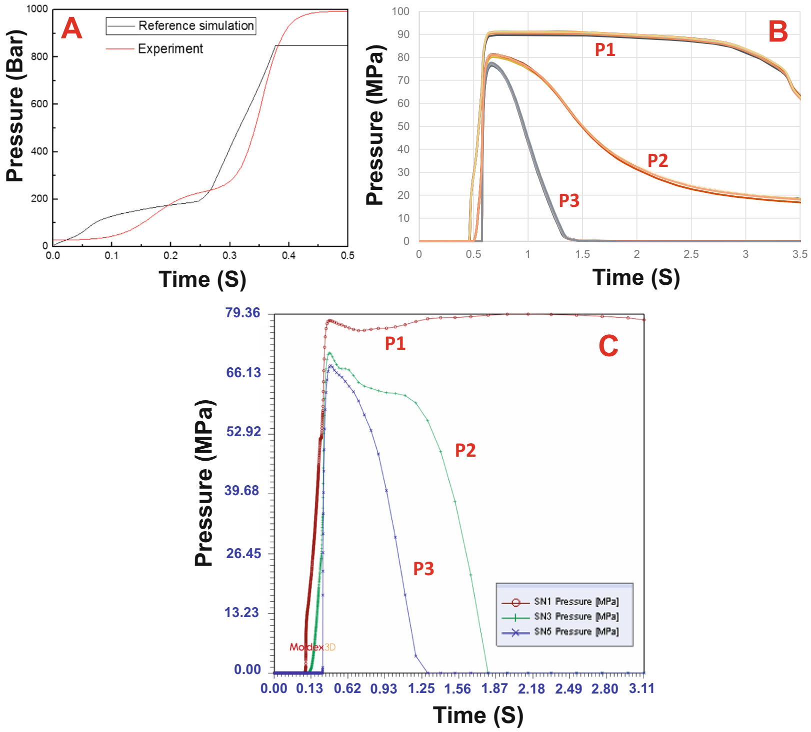

Fig. 5. Simulated and experimental injection pressure profiles (A); Cavity pressure curves of 20 injection cycles recorded by three sensors inserted in the mold (B); Cavity pressure curves from simulation (C).

4.1 Paragraphs and Indents Effects of the Factors Influencing the Accuracy of the Simulation

Based on the discrepancy of the reference simulation and experiment results, a detail investigation of the influence of following factors in the simulation software was made to improve the accuracy of simulation prediction:

- Flow solver efficiency factor
- Pressure-dependent viscosity
- Machine geometry
- Heat transfer coefficient (HTC)
- Fiber parameters settings (RPR)
- Crystalline effect
- Geometry boundary
- Viscoelasticity
- The flow rate of coolant

The investigation showed that the higher efficiency factor increased the time from V/P switchover point to the end of filling greatly, i.e. filling time minus injection time.

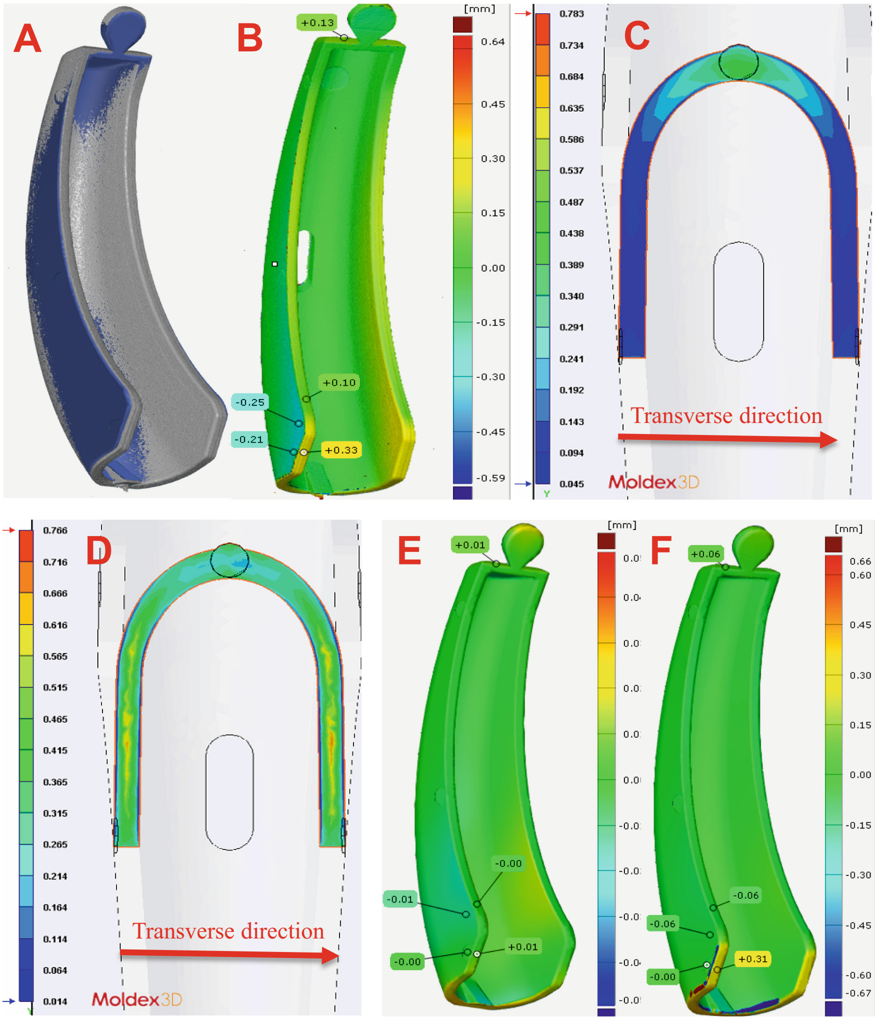

Fig. 6. Geometrical comparison of CT scanned part (grey) and simulated part (blue)-(A), color mapping inspection of the CT scan part showing its deviation from the simulated part (B); Fiber orientation in transverse direction of part with packing HTC 1500 (C) and with packing HTC 6000 (D); Simulated part geometry comparison with α = 0.1 and 0.7 (E); α = 0.1 and 0.99 (F).

For example, the simulation with efficiency factor 5, showed an increased time difference of 45.45% compared with the simulation done with efficiency factor 1. The pressure dependent viscosity parameter D has a large influence on injection time and the pressure. The injection time, injection pressures, as well as the pressure loss, were all increased with rising pressure dependent viscosity parameter D. It was frequently reported that the modeling of nozzle and the barrel of injection machine as hot runner in the simulation increases the filling time and injection pressure, making the simulation more accurate and closer to the experiment result [6, 9]. But according to the current investigation, the hot runner in the simulation model didn't make much difference on warpage compared with those without a hot runner. As the Moldex3D machine mode-1 already considers the compressibility in the barrel, the model only with nozzle geometry as hot runner in the simulation is suggested, which increases the V/P switchover time by 9.6%, ram stroke length by 9.4% and pressure loss from machine to the first sensor (P0–P1) by 76.7%.

Higher filling HTC can increase the injection time, injection pressure as well as the pressure loss in the cavity. But it also has the tendency to cause more shrinkage in the flow direction but less shrinkage in the transverse direction. The warpage in the part is dominated by the fiber orientation. The fiber orientation calculation is done at the filling phase in Moldex3D, so different filling HTC can cause different fiber orientation as well as warpage. The automatically determined HTC suggested by Moldex3D is not reliable; it seems to overestimate the HTC values. Due to the larger surface-to-volume ratio and the smaller thickness, the cooling and heat loss happens faster for micro and thin wall parts, which indicates a better heat transfer condition for the parts with small dimension and thin wall structures. So from this perspective, HTC value should not be too small. And from the aspect of warpage, HTC should not be too large. For the hearing aid shell, a filling/packing/detached HTC of 3000/2500/1500 is recommended. When the material, geometry and process conditions change, HTC values should be optimized.

Retarding Principal Rate (RPR) model parameter- α influences the warpage (see picture E and F of Fig. 6) by changing the fiber orientation. Too large α will decrease the effect of fiber orientation, and thus cause a more isotropic deformation in the flow in transverse direction. The investigation shows that the α-value smaller or higher than 0.7, doesn't make any big effect. So the filler parameter values of short fibers, i.e. $Ci = 0.005$, $Cm = 0$ and $\alpha = 0.7$, suggested by Moldex3D, are fine for thin walled structure. The crystallization effect of the material is not recommended to consider for thin wall part due to the faster cooling, even for semi-crystalline material like PBT. When the part is thick enough, the crystalline effect should be considered and the packing HTC should be decreased to reflect the worse thermal contact between the mold and part due to the high shrinkage (coming from the crystallization effect).

5 Conclusion

With proper parameter settings, Moldex3D is able to predict the injection molding process in a relatively precise way. It is necessary to consider the effect of pressure on the viscosity in the simulation as it has a large influence on injection time, pressure and pressure loss. Larger filling HTC can increase the injection time, pressure as well as the pressure loss. Larger packing HTC can increase the pressure loss but also bring more fluctuation to the pressure curves. To make an accurate prediction, it is necessary to consider the effect of pressure on viscosity, use proper heat transfer coefficient and include the nozzle geometry but not consider crystallization effect for small and thin wall part in the simulation. Currently, Moldex3D can't accurately predict the warpage for a complex part made of fiber filled plastics. Predicted warpage of part made of the fiber filled plastics relies a lot on the fiber orientation [10], which is influenced significantly by the filling HTC and RPR fiber orientation model in Moldex3D.

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