Effect of Packing Profile on Optimisation of Plastic Injection Moulding Process

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Abstract: - This study undertakes optimisation of a plastic injection moulded part using Autodesk Moldflow Insight. The focus of the study was optimisation of volumetric shrinkage, minimisation of sink marks, and reduction of part warpage. The top cover of an electric socket adaptor was modelled with Creo Parametric and the model imported into Moldflow where the feed system was defined. Processing parameters were set with Acrylonitrile Butadiene Styrene (ABS) chosen as the material. An initial analysis was carried out with the default packing profile. Further studies were carried out adjusting the pressure profile in each study till the recommended volumetric shrinkage was achieved. Volumetric shrinkage was successfully reduced from over 5% to 3.1% with variation in shrinkage reduced from 1.534% to 0.946%. Sink marks were reduced by 44.4% and uniform across points. Optimised packing pressure profile also reduced total warpage by 28.2%. The study established that differential shrinkage was the biggest contributor to part distortion.

Keywords: Optimisation, Volumetric Shrinkage, Sink Marks, Warpage, Packing Profile, Injection moulding.

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1 Introduction

Plastic materials and products cover the entire spectrum of the global economy and finds application in packaging, appliances, transportation, housing, automotive, and many other industries [1]. Injection moulding is considered as the most important plastic manufacturing process as more than a third of all thermoplastic materials are processed by injection moulding and more than half of all polymer processing equipment is for injection moulding [2].

As in other forming processes, mould design and the control of material flow in the mould cavities are very important factors in the quality of the product and thus in avoiding defects. Most of the defects in plastic injection moulding involves material flow and heat transfer process. Injection moulding operates at high temperatures and injects plasticised material into the mould cavity at high pressure, which could result in shrinkage and stress build-up problems. Shrinkage in turn could lead to warpage, cracking, and sink marks [3].

Volumetric shrinkage is dependent on melt temperature and pressure. Plastic injection moulders usually adjust process conditions to check shrinkage and ensure dimensional accuracy [4]. The effect of various critical processing conditions on shrinkage is presented in Fig. 1. Fig. 1a shows the percentage shrinkage initially reducing rapidly with increased packing time, but further increase in packing time has little effect on the shrinkage. Fig. 1b shows a near linear relationship between percentage shrinkage and packing pressure; as the packing pressure increases the shrinkage continues to decrease. Figs. 1c and 1d shows the effect of barrel and coolant temperatures respectively on the percentage shrinkage; as these parameters increase the shrinkage increases accordingly. Finally, in Figure 1e percentage shrinkage initially decreases with increase in cooling time but further increase results in shrinkage being unchanged. As shown the main parameters are related to pressure and temperature of the melt in the cavity. Although the time related parameters (packing and cooling time) are significant, they have a minimal effect on shrinkage when adequate parking and cooling times are used. The coolant temperature has a marginally greater effect than the barrel temperature, as it more directly controls the temperature of the moulding upon ejection.

Varying moulding process parameters provides considerably freedom in modifying the nominal shrinkage rate in the cavity. To influence the distribution of the shrinkage as a function of position in the mould cavity, it is possible to profile the packing pressure to control the melt pressure as it solidifies at different locations and times within the cavity. Implicitly, a higher packing pressure may be applied initially to reduce the shrinkage rate at locations farther from the gate, then reducing the packing pressure as the melt closer to the gate freezes to avoid over-packing or expansion of the part.

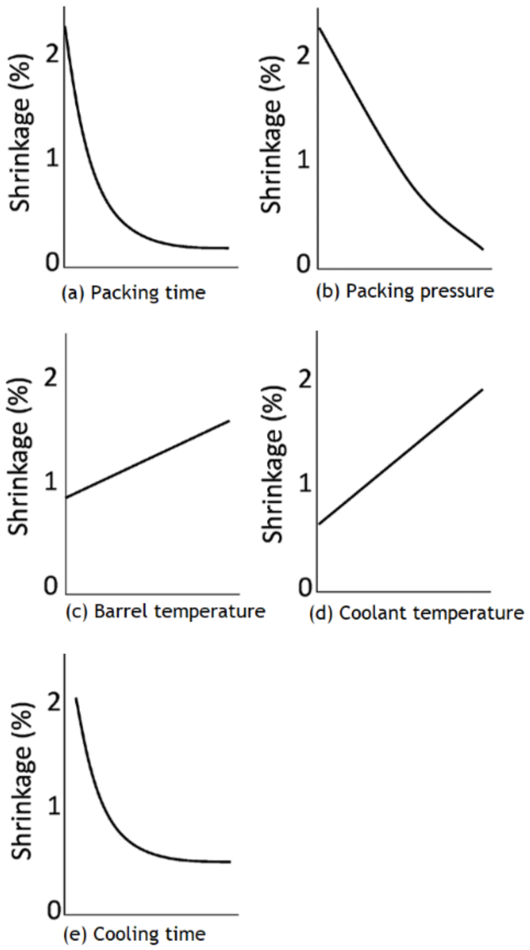

Fig. 1: Effect of processing conditions on shrinkage [4]

This work demonstrates the effect of a packing pressure profile on the optimisation of volumetric shrinkage, sink mark formation, and warpage, in an injection moulded part. This is significant as few moulders embraces the capabilities of profiling packing pressure in the enhancement of part quality [4].

2 Review of Related Works

Liao et al. (2004) investigated optimal process conditions for shrinkage and warpage of a thin-wall injection moulding of a mobile phone cover by considering the interaction effects between process parameters using Taguchi's method. The results established that packing pressure was the most important factor affecting shrinkage and warpage of the thin-wall part. It was also observed that the geometry of the part also affected the optimal process condition. The study then verified the optimal process conditions determined by Taguchi's method experimentally as the shrinkage and warpage of the part were successfully reduced [5].

Feng et al. (2006) examined multiple quality optimisation of injection moulding for Polyether Ether Ketone (PEEK). The study investigated the dimensional deviation and strength of screws produced by injection moulding by applying Taguchi method and Grey Relational Analysis. The process parameters that were consequential to the study were determined to include; mould temperature, pre-plasticity amount, injection pressure, injection speed, screw speed, pack pressure, and packing and cooling time. Taguchi method obtained the optimum processing combination for a single quality characteristic while grey relational analysis was applied for the optimisation of multiple quality characteristics. The study successful minimised dimensional deviation of the screw's outer diameter and obtained a deviation of 1.5748% between the predicted and target value of the dimension [6].

Mathivanan et al. (2009) developed a nonlinear mathematical model for injection moulding variables using Response Surface Methodology (RSM) [7]. The study involved minimisation of sink depth on injection moulded thermoplastic components. The injection moulding variables were represented as nonlinear mathematical model using response surface methodology based on central composite design (CCD) of experiments integrated with finite element flow simulation and genetic algorithm. Sink mark depth depends on both design and process variables such a rib-to-wall ratio, mould and melt temperature, and packing pressure. These variables were used for the modelling and optimisation of the system. To validate the model, 22 random test cases were observed and discrepancies between the control and expected results were within ±1.4% which shows the method is adequate in predicting and minimising sink mark defects. Though the focus of the study was on sink mark defects, adaptation to the study of other defects is highly attainable [8].

Stanek et al. (2011) studied optimisation of injection moulding process in determining ideal processing conditions with interest in the dimensions, shape, and properties of the parts produced using Moldflow Plastics Xpert (MPX). The MPX system achieved effective optimisation of the injection process with optimum process parameters resulting in elimination of possible product defects while reducing total cycle time [9].

Jiang et al. (2017) worked on warpage deformation by applying coupled finite element method as warpage usually results in degradation of appearance, quality, and assembly performance of products. Applying Computer-Aided Engineering (CAE), the residual stress, temperature, and anisotropic thermal and mechanical properties formed in injection moulding were used as initial conditions. Autodesk Moldflow software was used to solve pressure, temperature stress, and mechanical properties while Abaqus software was used to obtain the total warpage deformation in the moulded part with the stress and temperature distribution from Moldflow serving as initial conditions for Abaqus. The simulation warpage result was consistent with that obtained experimentally thereby providing a cost-effective means of predicting and minimising distortion of parts by varying process parameters [10].

Sreedharan et al. (2018) studied the prediction of moulding defects and achieving optimised process settings by applying Response Surface Methodology (RSM). Moldflow was used for flow simulation to ascertain possible moulding defects and initial process parameters, while RSM helped in identifying relationships between various process parameters and performance. The defects of interest were shrinkage and warpage in an injection moulded automobile component. Results obtained from the RSM analysis was evaluated through Analysis of Variance (ANOVA) table to determine an optimal cycle time that reduces or eliminates shrinkage and warpage. The study successfully reduced or eliminated defects while validating a repeatable method for optimising process parameters [11].

Mahesh et al. (2019) studied the prevention of defects by design and control of various injection moulding process parameters. The defects considered were flash, burn marks, short shot, shrinkage, weld lines, warpage, and sink marks. The manufacture of a ball point pen was undertaken for the study. It was inferred that the main process parameters key to part defects are clamping force, cooling time, pressure drop, and heat transfer rate. Analytical methods applying fundamental governing equations were used to determine initial values for the process parameters of interest, these parameters were then varied experimentally and their effects on mitigating the targeted defect observed. The study was able to select suitable design and process parameters to prevent product defects [12].

Mukras (2020) worked on a framework for optimising injection moulding process parameters to reduce product cycle time within the constraints of acceptable product defects. Two product defects; volumetric shrinkage and warpage, as well as seven process parameters; injection speed, injection pressure, packing pressure, packing time, cooling time, mould temperature, and melt temperature, were considered. Test points, indicative of various processing parameters, were chosen and injection moulding experiments carried out on these test points. The results from the experiments were used to compute volumetric shrinkage and warpage at each test points with kriging technique used to construct the relationships between product cycle time, volumetric shrinkage, and warpage, as well as the seven injection moulding parameters. Experimental results revealed acceptable close agreement with simulation optimisation results with deviation in the cycle time, warpage, and volumetric shrinkage being 6.7%, 3.2%, and 8% respectively [13].

3 Materials, Equipment and Methods

3.1 Materials

The main materials used in this study can be broadly categorised into software, measuring instruments and raw material.

3.1.1 Software

PTC Creo Parametric 7.0 was used to develop and convert the CAD model to an interchangeable format. Autodesk Moldflow 2019 was used to define and configure the mould layout, feed system, and carryout the analysis.

3.1.2 Measuring Instrument

A digital calliper was used for linear measurement of the part to be moulded while a radius template was used to gauge curved edges.

3.1.3 Raw Material

The raw material chosen for this study was Acrylonitrile Butadiene Styrene (ABS) due to its favourable properties with respect to an electric socket adaptor. The acrylonitrile in ABS provides chemical and thermal stability, while the butadiene adds toughness and strength. Styrene gives the finished polymer a nice, glossy finish. ABS has a low melting point, which enables its easy use in the injection moulding process [14].

3.2 Equipment

A capable computer with the necessary hardware is required for creating 3D CAD models and carrying out analysis and simulation. Processor, graphics card, and memory are usually the key hardware for numerical studies. However, Moldflow 2019 does not utilise dedicated graphics card even when available. Computer aided design and computer aided engineering normally require workstation grade computers with a professional graphics card capable of handling three-dimensional models and carrying out complex mathematical calculations as required during simulation. Moldflow Insight 2019 recommends a minimum of 8 GB of memory, so for this study a mobile workstation (laptop) was used; Lenovo ThinkPad P1 Gen 2, with intel core i7 processor, 32 GB memory, 750 GB solid state drive storage, and a professional graphic processor – Nvidia Quadro T1000, with 4 GB dedicated memory.

3.3 Methods

3.3.1 Creating Part Geometry

Simulation study begins with a CAD model of the part. PTC Creo Parametric 7.0 was used to develop the model of an electric socket adaptor top cover. The 3D model captured the details of the part such as openings for plugs and indication LED, screw bosses, and ribs as shown in Fig 2. The part was converted to a STEP file so it can be imported into Moldflow.

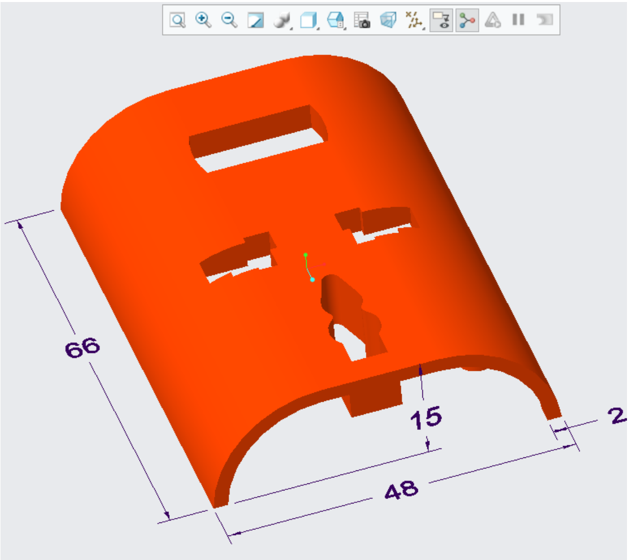

Fig 2: Three-Dimensional Model of Electric Socket Adaptor

3.3.2 Fill and Pack Analysis

Autodesk Moldflow Insight was used for the fill and pack study to determine the optimal packing pressure. A new project was created and the CAD file imported and oriented to specify the parting plane. Injection point was specified and feed system created by specifying its position with respect to the gate location. The orifice, length, and include angle of the sprue were specified. The runner diameter, gate orifice, and length of the runner were also specified. Fill + Pack was selected as the analysis sequence, generic ABS as the material while process settings were specified by setting mould temperature to 60 ºC and melt temperature to 230 ºC. A flow rate of 15 cm^3/s was chosen. The default packing profile; where the packing pressure is held at 80% of the injection pressure for 10 seconds, was used. After the initial analysis, packing profile was adjusted and the simulation carried out for different profiles till an optimised volumetric shrinkage was achieved. An optimum was found by increasing the packing pressure to 200% of the injection pressure at the start of the packing phase, then steadily reducing the pressure to 180% in 10 seconds, finally to 80% of the injection pressure within another 10 seconds. Fig 3 represents the default packing profile plot while Fig 4 shows the optimised packing profile plot.

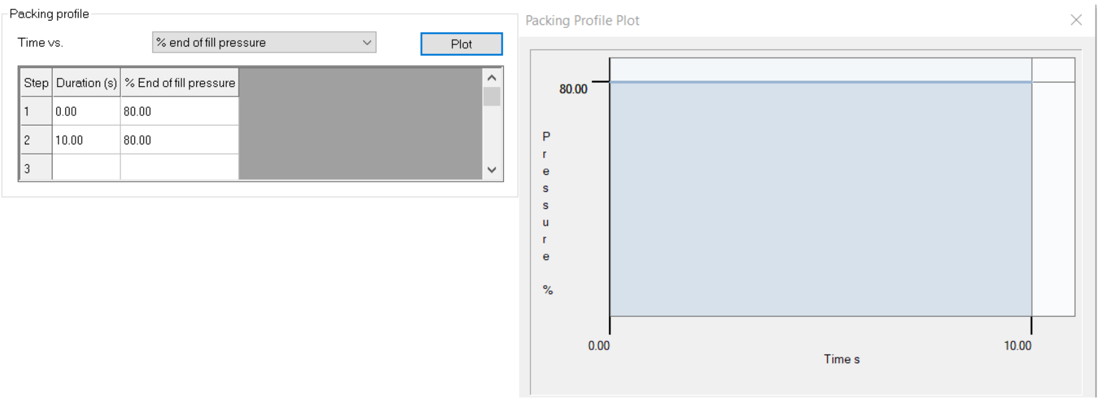

Fig 3: Initial Packing Profile and Plot

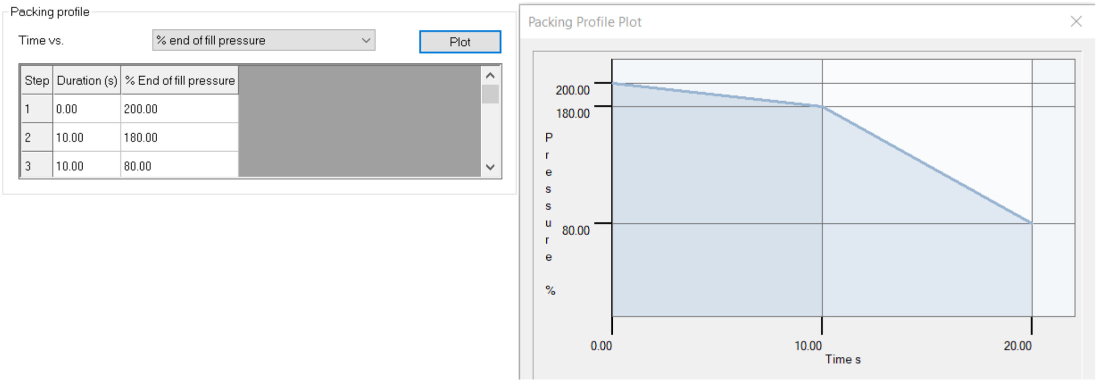

Fig 4: Optimised Packing Profile and Plot for desirable Volumetric Shrinkage

3.3.3 Warp Analysis

A warp analysis was used to study the degree of deformation on the part, isolate the causes of warpage, and optimise for minimum warpage. For this study, the sequence was set to Cool (FEM) + Fill + Pack + Warp and the option to isolate cause of warpage selected to provide insight into the analysis. As the analysis sequence implies, a cooling, packing, and filling analysis would be carried to determine part warpage. The study for the fill and pack study was imported as it already contains the feed system and process settings such as materials as well as mould and melt temperatures. The cooling system was then setup by first creating cooling channels using the Cooling Circuit Wizard of Moldflow Insight 2019. The cooling channel diameter and the distance of the cooling circuit below and above the part was set to 10 mm and the number of channels set to 2. With the cooling channels in place, the mould boundary was then defined as 108, 129, and 75 mm for the x, y, and z dimensions respectively, to accommodate the core and cavity plates with the cooling channels in place.

As expected with FEM studies, meshing of the mould was required. Creating mesh for the mould involves 2 steps; meshing all surfaces (mould, mould boundary, cooling channels, and inserts) with triangular elements, then meshing the volume of the mould with 3D elements based on the triangular elements. Fig. 5 shows the meshed mould with the cooling channels and feed system in place. After generating the mesh, the cooling process settings were defined. The coolant temperature was set to 40 ^{o}C and mould opening time 5 seconds.

With the packing and cooling parameters defined, the set up was analysed and the results viewed. To view the results, a split window was used displaying four different results; three causes of deflection (differential cooling, differential shrinkage, and orientation effect) and the aggregate deflection which is the combined effect of all three causes of deflection. The optimised packing pressure obtained from the fill and pack analysis was then applied and the analysis repeated to ascertain the effect of the optimised packing profile on warpage.

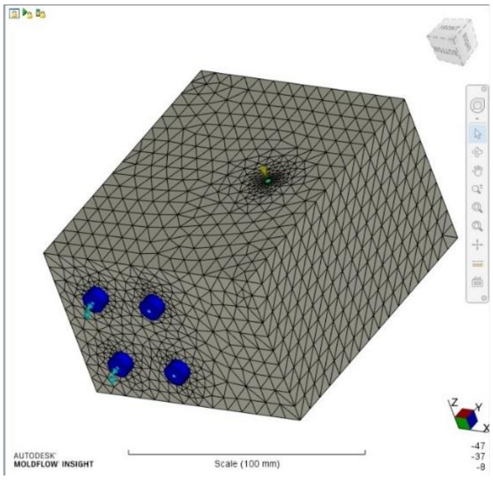

Fig. 5: Meshed Mould Volume with Cooling and Feed System

4 Results and Discussion

4.1 Result of Volumetric Shrinkage and Sink Mark Estimate

Fig. 6 presents the result of volumetric shrinkage at ejection with the default packing profile and the optimised packing profile. The recommended shrinkage for ABS plastic of this thickness is between 1% to 3% while the variation in shrinkage is best if within 2% [15].

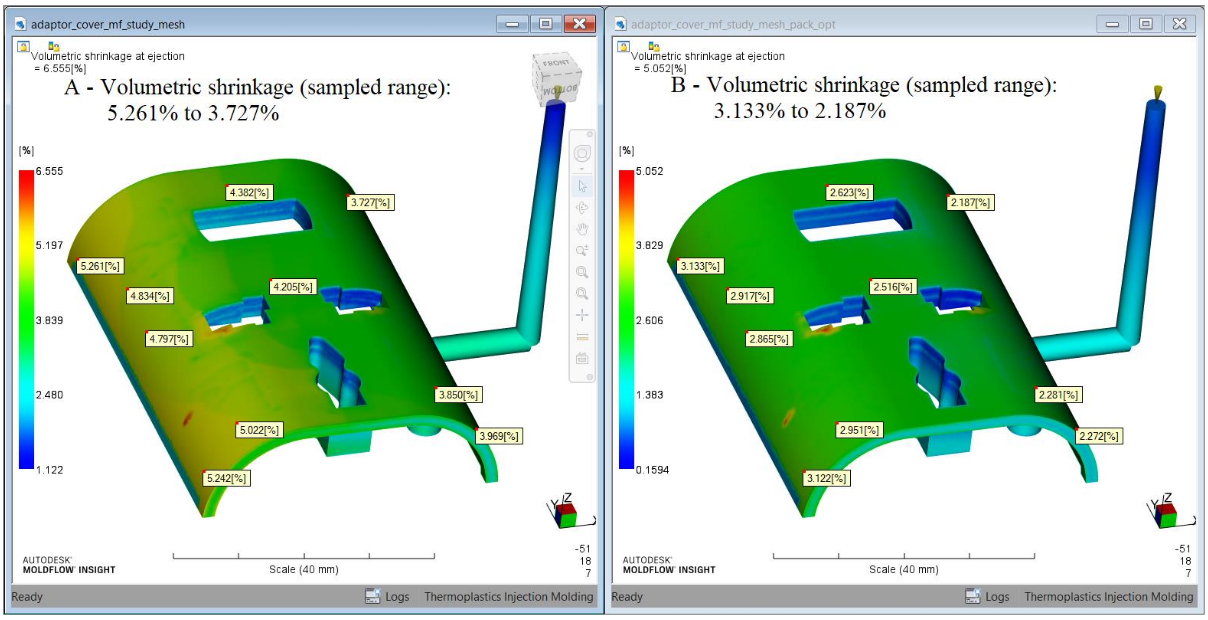

Fig. 6: Result of Volumetric Shrinkage at Ejection with default Packing Profile (left) and Optimised Packing Profile (right)

Fig. 6 presents the result for volumetric shrinkage with the default and optimised packing profile. Visually, the uniformity of the colour shades on that of the optimised packing profile suggests uniform shrinkage on the top face of the part. The value of the volumetric shrinkage at corresponding points have also been displayed for both studies. It can be seen that the shrinkage at some points for the default packing profile is above 5% which is way more than the recommended 3% while the maximum shrinkage for the optimised profile it is about 3.1%.

Fig. 7 compares the estimated sink marks from the default and optimised packing profile, once more it is also visually evident that the sink marks from the default profile were more intense, examination of sink marks on corresponding points also show a marked improvement with the optimised packing profile, whereas the sink mark depth varies (0.0376mm and 0.0326mm) with the default packing pressure, it is uniform (0.012mm) with the optimised packing pressure, thereby significantly reducing visual defects on the moulding.

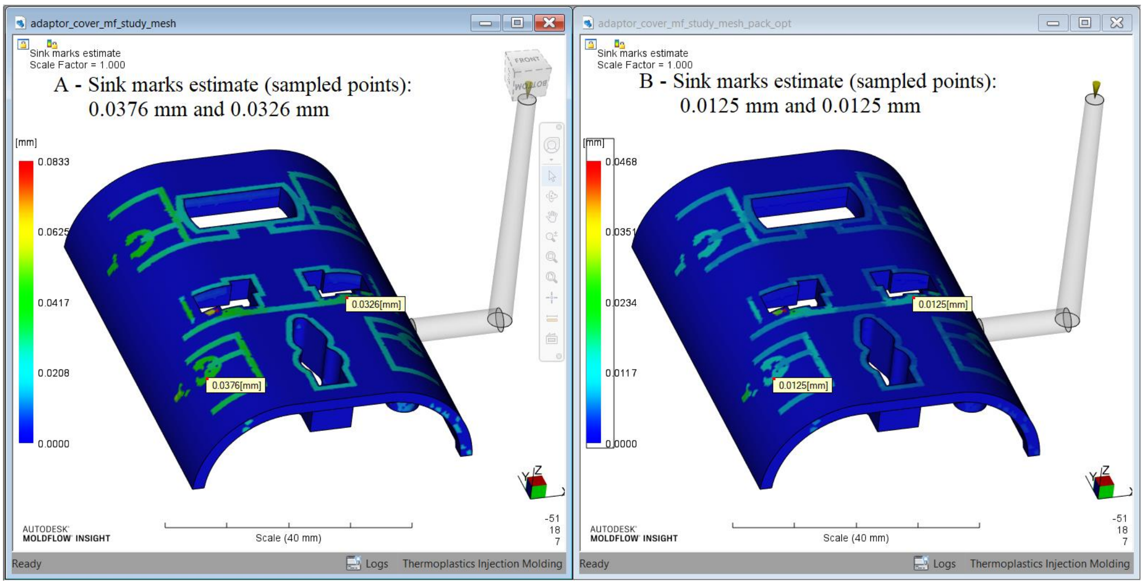

Fig. 7: Comparison of Sink Marks Estimate with default Packing Profile (left) and Optimised Packing Profile (right)

4.2 Result of Warp Analysis

Warpage is due of internal stresses as the part cool down and shrink and results in visual distortion of the part and making moulded parts difficult to fit together in an assembly. Result of the incorporation of different variants to the determination of the causes of warpage is presented in Fig. 8; clockwise from upper left: A) aggregate deflection, B) contribution of differential cooling, C) contribution of differential shrinkage, and D) contribution of orientation effect.

The contribution of different factors to total warpage is represented as the pie chart in Fig. 9, as shown a whole 92% of the shrinkage is as a result of differential shrinkage which is by far the largest contributor to warpage.

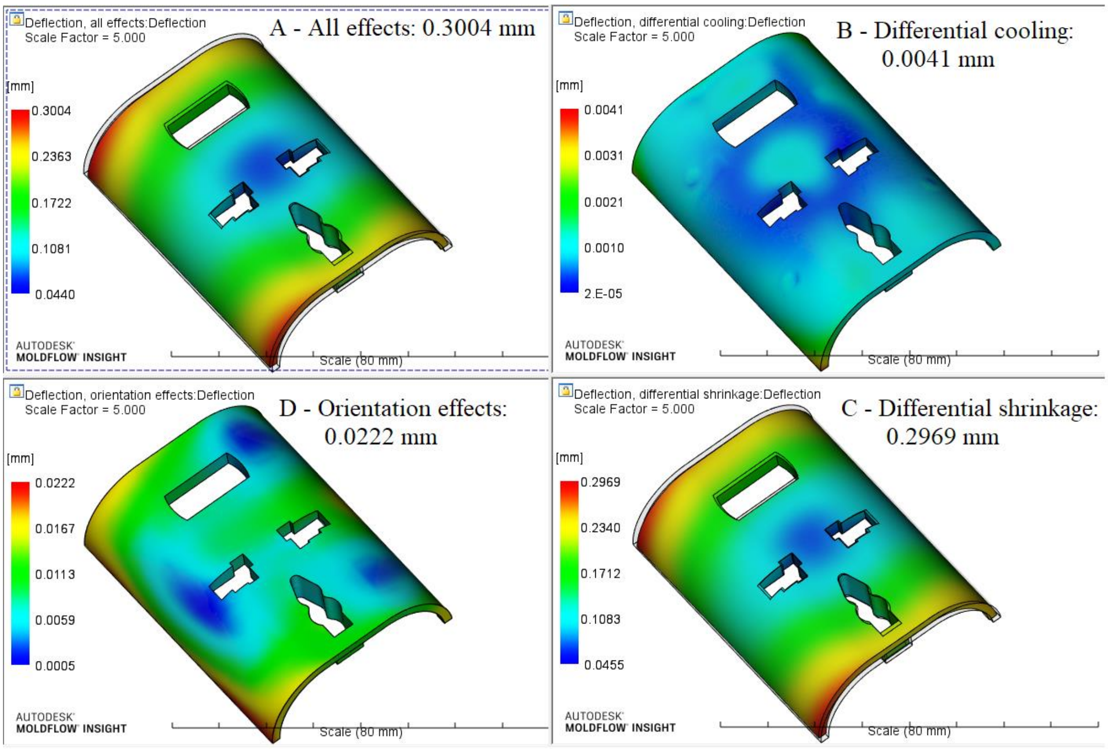

Fig. 8: Investigation of causes of warpage with initial study

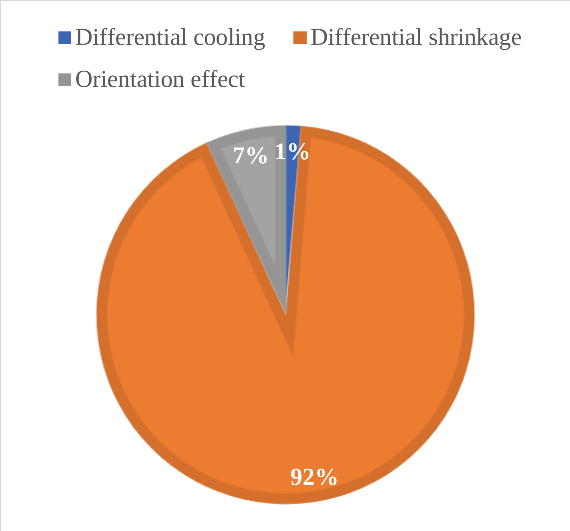

Fig. 9: Causes of Warpage – Initial Study

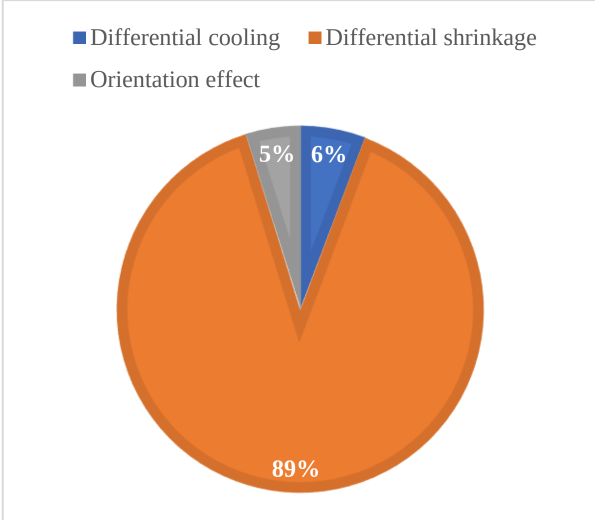

Fig. 10: Causes of Warpage - Optimised Study

The result of the warpage analysis after applying the optimised packing pressure is shown in Fig. 11 while Fig. 10 is a pie chart showing the contribution of different factors to the total warpage. As observed from both figures the packing pressure reduced the total deflection from a maximum of 0.3004mm to 0.2408mm while reducing the contribution of differential shrinkage, from 92% to 89%, to total distortion.

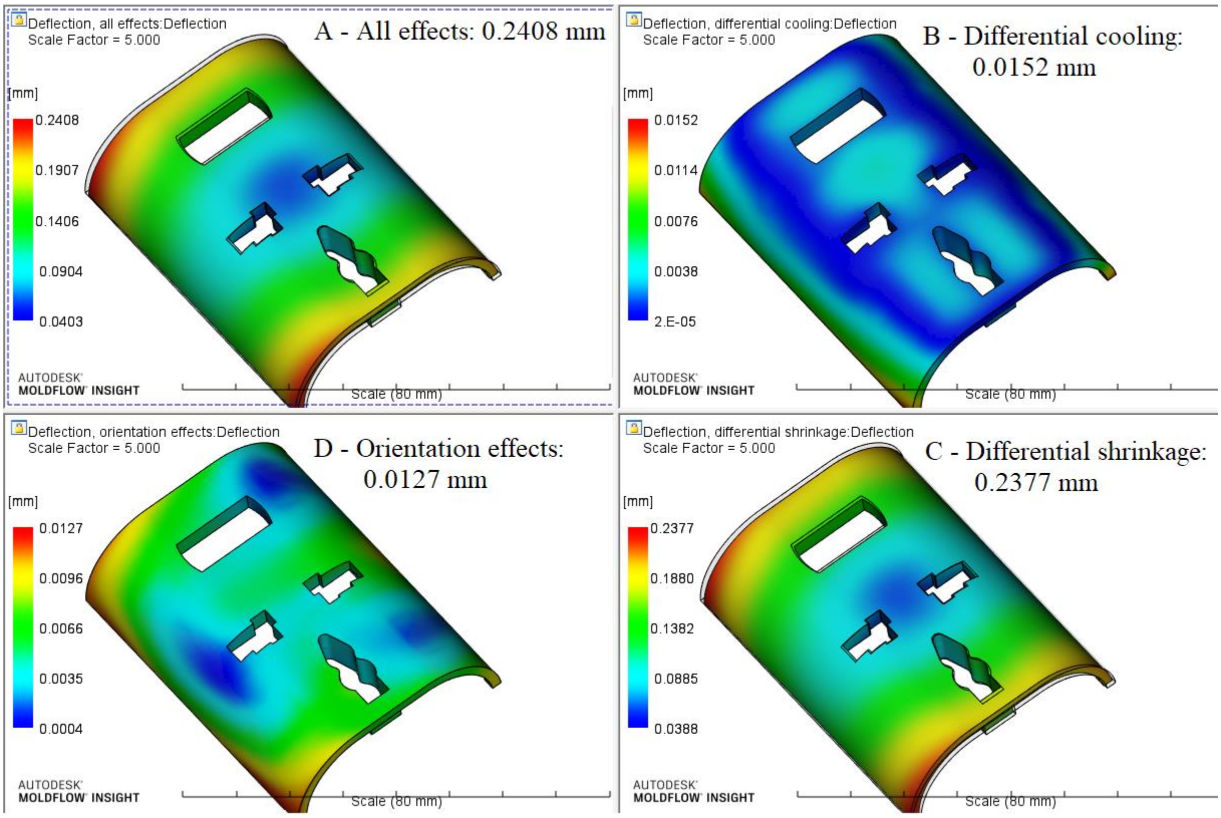

Fig. 11: Result of Optimisation of Part Warpage

Table 1: Comparison of warpage results for initial and optimised study

	Initial	Optimised	Difference	% Reduction	Total % Reduction
Total deflection					
Minimum	0.0440mm	0.0403mm	0.0037mm	8.4%	28.2%
Maximum	0.3004mm	0.2408mm	0.0596mm	19.8%	
Due to differential cooling					
Minimum	0.00002mm	0.00002mm	0mm	0%	-270.7%
Maximum	0.0041mm	0.0152mm	-0.0111mm	-270.7%	
Due to differential shrinkage					
Minimum	0.0455mm	0.0388mm	0.0067mm	14.7%	34.6%
Maximum	0.2969mm	0.2377mm	0.0592mm	19.9%	
Due to orientation effect					
Minimum	0.0005mm	0.0004mm	0.0001mm	20%	62.8%
Maximum	0.0222mm	0.0127mm	0.0095mm	42.8%	

Table 1 compares part deflection highlighting the contribution of various factors to the total deflection for the initial and optimised study. The maximum and minimum values in the table represents the maximum and minimum deflection due to differential cooling, differential shrinkage, orientation effects, as well as the aggregate deflection. The difference in the deflection due to the optimised study was obtained by subtracting corresponding deflection values of the initial study from that of the optimised study. The percentage reduction in warpage due to the optimised study was then computed from the difference in distortion and the corresponding initial values. Finally, the total reduction in deflection was obtained from the sum of the maximum and minimum reduction in distortion. The optimisation thus reduced the total deflection by 28.8% where the maximum deflection was less than a quarter of a millimetre. However, applying the packing profile significantly increased the deflection from differential cooling by over 270%, this demonstrates the complexity in optimising process parameters in plastic injection moulding. Optimising an aspect, such as shrinkage, could be detrimental to the cooling aspect hence a form of balance needs to the achieved depending on the requirements. Application of the optimised packing profile results in a reduction in distortion coming from differential shrinkage and orientation effect as well as reducing overall distortion of the part.

5 Conclusions

This study successfully optimised a plastic injection moulded part by obtaining an effective packing profile to achieve optimum volumetric shrinkage and reduction of visual defect such as sink marks.

The following conclusions were drawn from the study:

(i) Uneven shrinkage of moulded part is the biggest contributor to defects such as warpage and sink marks and a packing pressure profile is an effective means of minimising uneven shrinkage. Application of packing pressure reduced shrinkage from 5% to 3.1% while the variation in shrinkage was reduced from 1.534% to 0.946%, representing a reasonably uniform shrinkage thereby minimising internal stresses.

(ii) The optimised reduction in internal stresses is evident in the control of warpage as total deflection was reduced by 28.2%.

(iii) Optimised packing profile also reduced visual defects as sink marks were reduced from a maximum value of 0.0833 mm to 0.0463 mm (44.4% reduction) with uniform sink marks of 0.0125mm across the sampled points as compared to a variation of 0.0376 mm to 0.0326 mm from point to point with the default packing profile.

6 Recommendations

For future study, it is recommended that further studies be carried out to reduce the effect of deferential cooling on the total distortion as a means of further reducing the warpage of the part.

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