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ORIGINAL ARTICLE

A reduction of protector cover warpage via topology optimization

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Abstract
Warpage is one of the most frequent issues facing the molding industry, especially for different wall thickness products. The aim of this study is to generate an optimization method in order to reduce warpage of a protector cover as much as possible. Topology optimization and deflection analysis were carried out to obtain a stiff design that resists warpage. The topology optimization results suggest a weak area/void in the product design. Then, a careful consideration in patterning the rib location and modification wall thickness based on topology data was introduced until it obtained an optimum wall deflection. Finally, the warpage conditions were found to optimize approximately 79.52% (left side), 76.12% (middle area), and 69.06% (right side) with respect to the reference model.

Keywords Warpage · Deflection · Topology · Optimization · Finite element · Plastic design

1 Introduction

Plastics are widely used and mostly preferred because of their nature of being lightweight, easily converted and economical. However, there are many challenges in processing plastic such as molding defects, warpage [1] and end use failures. Warpage occurs when the volumetric shrinkage is non-uniform [1–4] due to variation in temperature and pressure, and unequal in-residual stress formed within the molded product [1, 2, 5, 6]. In the filling/packing and warpage analysis, the model is assumed to be an orthotropic linear thermal elastic material that obeys the generalized Hele-Shaw flow model and the modified Duhamel-Neumann constitutive law [7], respectively. Hence, the model motion can be described by the following:

Filling/packing phase: Generalized Hele-Shaw Flow Model

$$\partial\rho/\partial t + \nabla\cdot(\rho u) = 0 \qquad (1)$$

$$\partial/\partial t\,(\eta\cdot\partial/\partial z)\text{-}\nabla\rho = 0 \qquad (2)$$

$$\rho C_p(\partial T/\partial z + u\cdot\nabla T) = \partial/\partial z(k\cdot\partial T/\partial z)\text{-}\eta y^2 \qquad (3)$$

Warpage analysis: Modified Duhamel-Neumann Constitutive Law

$$\nabla\cdot\sigma = 0 \qquad (4)$$

$$\sigma = C\cdot(\varepsilon - \alpha\Delta T) \qquad (5)$$

where ρ, C_p, k, η, and α denote the density, specific heat, thermal conductivity, viscosity and coefficient of linear thermal expansion of the plastic material, respectively. To run the analysis, filling/packing and warpage analysis are conducted to obtain deflection value of the molded product by using computer-aided software (CAE) [1, 6, 8], such as Moldflow, Moldex3D, and others. A warped product contributes to failure in assembly process, dimension instability due to displacement changes and appearance quality. But, with the proper techniques, a warped product can be controlled to acceptable limits [4].

A lot of plastic injection molding optimization techniques [6, 9, 16] have been introduced such as Taguchi technique, finite element analysis (FEA), and others to reduce molded product defects for manufacturing or during end use. In structural optimization, it can be divided into sizing, shape, and topology optimization. Finite

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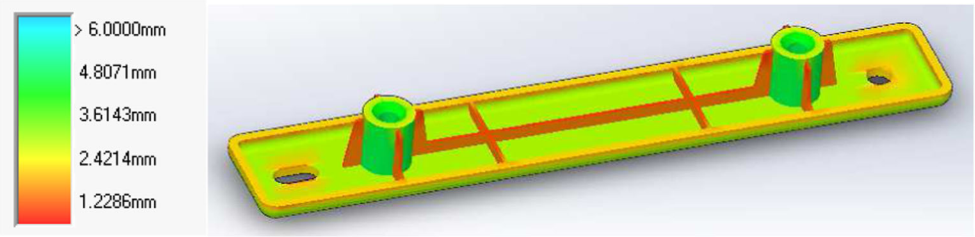


Fig. 1 Product design thickness analysis

element (FE) technique is one application of the optimization and evaluation of required design through topology optimization [8]. Topology optimization is a method to find the stiffest possible structure through a few strategies [8, 10] such as isotropic solid or empty element (ISE), evolution structural optimization (ESO), solid isotropic material with penaltization (SIMP), bi-directional evolution structural optimization (BESO), and others. In ISE and SIMP optimization, density method is used to determine the optimization process [13, 14], where the behavior of intermediate densities are higher compared to the relative stiffness. This process of creating the material density takes any value between 0 and 1 ($0 \leq \rho \leq 1$) density in order to find a minimum shape subject to either nodal displacement or eigenfrequency constraints [12]. In practice, density values are represented in a different color to indicate empty or solid element in order to reveal design area for the optimization. From a topological view, Chandana [11] was able to successfully conduct optimization by minimizing the mass and the costs of a refrigerator bed without sacrificing its physical properties. While, Gujicic [15] used the topology optimization in a polymer and metal hybrid material of body-in-white for lightweight structure, efficiency in stiffness and buckling performance.

Hence, this paper deals with the topology optimization for structural analysis and the plastic product simulation for warpage reduction in injection molding field. The aim of this study is to generate an optimization method in order to reduce warpage of a protector cover as much as possible. Topology optimization and deflection analysis are carried out to obtain a stiff design that resists warpage. The topology optimization results suggest a weak area/void in the product design. Then, a novel consideration in patterning the rib location and modification wall thickness based on topology data were introduced until it obtained an optimum wall deflection.

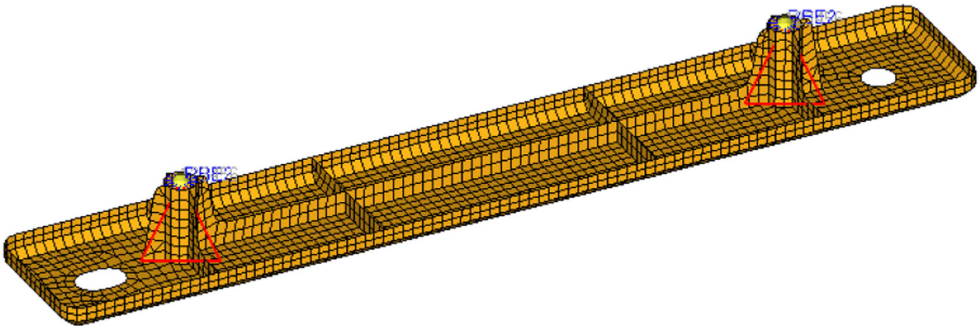


Fig. 2 Protector cover in FE model

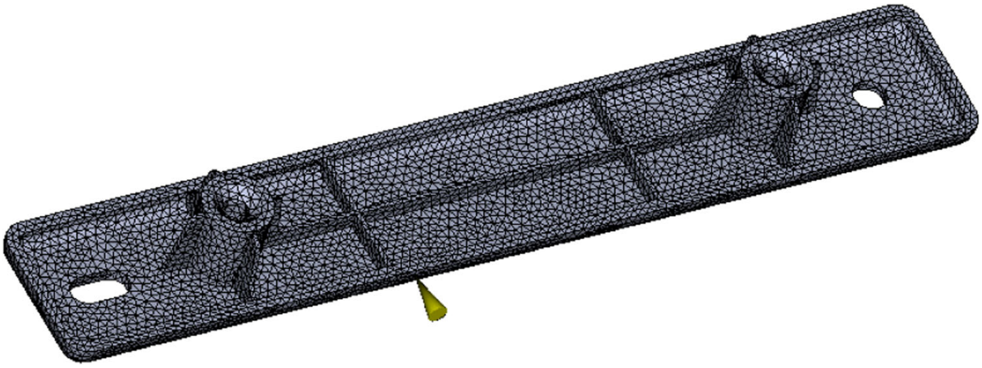


Fig. 3 Protector cover in dual domain model

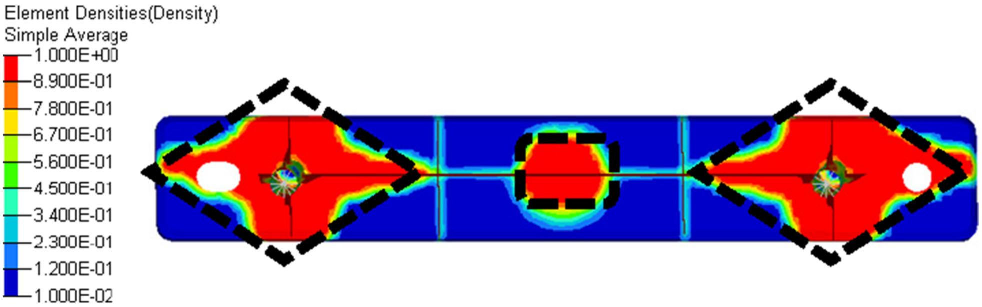


Fig. 4 Topology result and dashed line box indicate area for optimization

2 Materials and methods

2.1 Product design

With two bosses, ribs and variations in wall thickness, the thickness analysis of the product is shown in Fig. 1. The thicknesses for bosses, ribs, and wall thickness were designed with sizes of 2.3, 1, and 2.5 mm, respectively, with the mass of the product recorded at about 20.81 g. As sequenced in the molding process, a non-conductive melt is provided to flow into the cavity since there are variations in the wall thickness especially the melt flow from thick to thin wall or vice versa. Thus, the high degree in differential volumetric shrinkage is expected upon completion in molding process and lead to high warpage condition.

2.2 Topology optimization model

Altair HyperMesh® was used as the finite element meshing utility in preparing for the topology optimization. The design created in the CAD program was imported as an Initial Graphics Exchange Specification (IGES) file. The geometry was converted to midplane surface in preparation of the meshing process. The surface was meshed in mixed elements by using the auto-mesh features with a nominal minimum size of 2 mm. Total nodes and element created were found to be 2488 nodes and 2421 elements respectively. The boss holes were filled with rigid RBE2 elements and the Degree of Freedom (dof) for each holes were set to a value of 0.0 with selected constraints dof1, dof2, dof3, dof4, dof5, and dof6 to act as bolt and to ensure that the material stress limit was not violated [14]. Then, the finite element model was created by changing the user profile to Optistruct. This created a design space as shown in Fig. 2, where the entire space of the model was set to be optimized. The load collectors and load steps were created to set a subcase for the initial job. Radioss was selected as the solver and the analysis was run. Upon obtaining the initial result, the Hyperview was used to view the first mode shape result of the model.

For the topology optimization, Hypermesh was used again to create design variables such as element density and deformation energy. These steps are significant in order to obtain the pseudo-density contour of 0 to 1 density, where the high-density element region requires design modification. Then, the model was submitted to run the Optistruct analysis. Hyperview was used to view a static plot of the density result. The last iteration was selected to obtain the pseudo-density contour result.

2.3 Deflection analysis

Moldflow was used to analyze the deflection index of the model to show warpage condition. The CAD model was initially imported and converted to STL (STereoLithography) file using the CAD program. In Moldflow, the model was converted into Dual Domain and meshed as shown in Fig. 3 with the global edge length on surface set at 2 mm. The injection location was set at a straight wall along the length of the base.

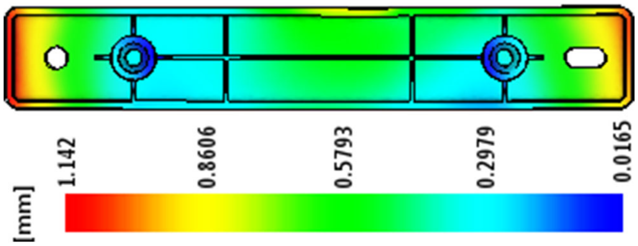


Fig. 5 Total (XYZ direction) deflection

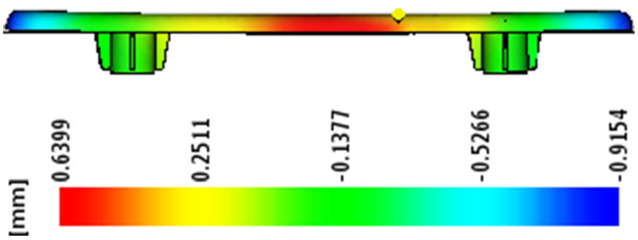
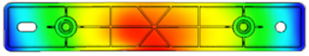
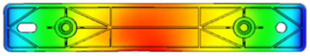
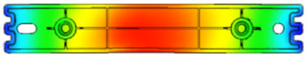
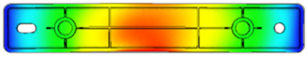
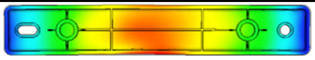


Fig. 6 Y direction deflection

Table 1 First protector cover modifications

No.	Modification	Deflection (mm) Left side	Middle	Right side
1.		-0.8862 (-7.26%)	0.5981 (-7.26%)	-0.903 (1.35%)
2.		-1.069 (-29.39%)	0.7545 (-17.91%)	-1.234 (-34.8%)
3.		-0.9779 (-18.36%)	0.6476(-1.2%)	-1.028 (-12.3%)
4.		-0.7803 (5.56%)	0.6202 (3.08%)	-0.8194 (10.49%)
5.		-0.6074 (26.48%)	0.4813 (24.79%)	-0.6592 (27.99%)

The material used was polypropylenes (PP) manufactured by TOTAL Chemicals under the name Finally HXN-1220 and their grade code is CM8614. The PP was filled with 20% talc. The physical property values for Young's modulus, density, yield strength, and Poisson's ratio of the PP are 1677 MPa, 1E-9 kg/m^3, 24.2 Mpa, and 0.33, respectively. The recommended machine tonnage was 100 tonnes. Meanwhile, the processing condition for the melt temperature, cooling time, packing profile, and molded temperature was set at 240 °C, automatic, 80% and 35 °C, respectively. Lastly, the analyses of filling/packing/warped were run.

3 Results

3.1 Topology optimization result

Figure 4 shows the pseudo-density contour results for the last iteration of the protector cover model. These results indicate the optimized material distribution of element densities in order to justify the lower and higher density inside the elements. The optimization solution was converged after the seventh time. Based on the optimization results in Fig. 4, blue represents a lower density (0.01) element which suggests

Table 2 Second protector cover modifications

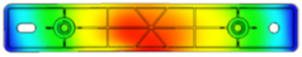
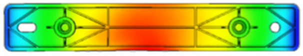
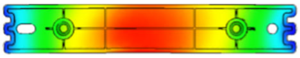
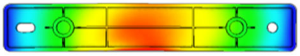
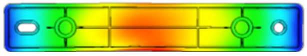
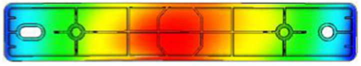
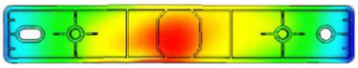
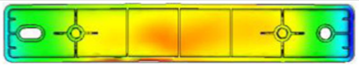
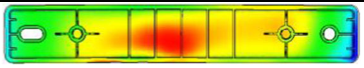
No.	Modification	Deflection (mm) Left side	Middle	Right side
1.		-0.8862 (-7.26%)	0.5981 (-7.26%)	-0.903 (1.35%)
2.		-1.069 (-29.39%)	0.7545 (-17.91%)	-1.234 (-34.8%)
3.		-0.9779 (-18.36%)	0.6476(-1.2%)	-1.028 (-12.3%)
4.		-0.7803 (5.56%)	0.6202 (3.08%)	-0.8194 (10.49%)
5.		-0.6074 (26.48%)	0.4813 (24.79%)	-0.6592 (27.99%)

Table 3 Third protector cover modifications

No.	Modification	Deflection (mm) Left side	Middle	Right side
1.		-0.7196 (12.9%)	0.5136 (19.74%)	-0.7966 (12.98%)
2.		-0.3898 (52.82%)	0.3314 (48.21%)	-0.469 (48.77%)
3.		-0.2681 (67.55%)	0.228 (64.37%)	-0.4897 (46.5%)
4.		-0.1692 (79.52%)	0.1528 (76.12%)	-0.2832 (69.06%)

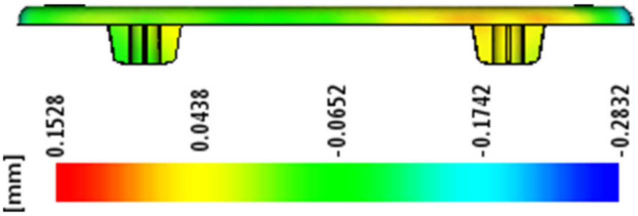


Fig. 7 Y direction deflection

unnecessary design changes. Meanwhile, red represents the high density (1) elements. The red contour elements on the model require the design to be changed either by adjusting the wall thickness or ribs. The higher densities were found to emerge at the constraint areas and at the middle of the design as shown by the dashed line box in Fig. 4. It is because there is less material to increase product stiffness. Therefore, the topology optimization results are found significant to identify design changes on the model, where the modifications need to be done on the red contour area.

3.2 Warpage optimization

Through the first warpage analysis, the maximum deformation of the model in X, Y, and Z directions ranged from 0.0165 to − 1.142 mm as shown in Fig. 5. Meanwhile, in anisotropic X, Y, and Z direction, the maximum deformations ranged from 0.6797 to − 0.7238 mm, 0.6399 to − 0.9154 mm, and 0.4185 to − 0.6302 mm, respectively. Thus, this data suggests that Y direction plays a main role in the warpage condition as shown in Fig. 6 and becomes the reference model for the design changes. Therefore, the control of Y direction is the key to reduce warping value. On the other hand, if failure occurs, a high warpage value will lead to assembly problems with another part.

Table 1 shows deflection results for the initial model modifications. The results show the comparison of deflection value and their percentage deflection with the reference sample. It was found that the addition of the ribs at the middle and slanted ribs at side walls are not significant to improve the deflection value as shown in the first and second modifications. Therefore, the design changes started at the side walls with corrugated design as shown in the third modification. However, the results show that the deflection value was still not reduced. Next, for the fourth modification, the thickness of the bosses was reduced by removing 1 mm inside the bosses. The result shows a reduction in controlling warpage. The fourth design was maintained and circle ribs were added at the circle holes as shown in fifth modification. It was found that the deflection increases in average of 5 to 25%. Therefore, it is suggested that the modification of ribs to circle holes and boss thickness are important features to optimize warpage.

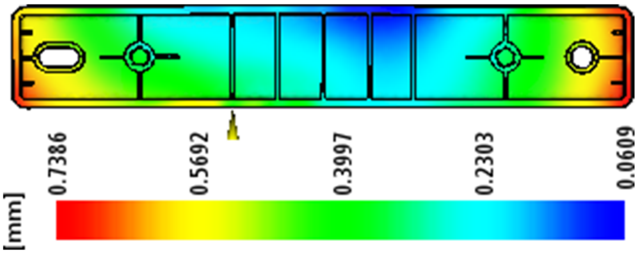


Fig. 8 Total (XYZ direction) deflection

Table 2 shows the succeeding modification for the modified model. The first modification was carried out with the origin boss shape. The results were found to be − 2.94, 15.16, and − 1.44% for left, middle, and right side respectively. For second modification, 1 mm of outside bosses thickness was cut to include screw function. The results show an improvement for both sides of approximately 26%. However, the middle remained (15%). For third and fourth modification, ribs were added from circle ribs at the holes to the side wall. However, the deflection value was lower and not significant for the modification process. Next, the ribs in fifth modification were cut into half at the circle ribs holes side and other half ribs were maintained at the side wall in order to create gussets. The results show that the deflection values at the both side walls were recorded at approximately 29%, while that at the middle region was found to be 23%. Thus, the findings suggest that the deflection values of the model can be optimized by adding the gussets and reducing the outside of the boss thickness.

Table 3 shows the final modification for the model. The final modification showed a significant improvement where the final deflection value reduced until 80%. It started with the addition of center rib and the deflection value increased to

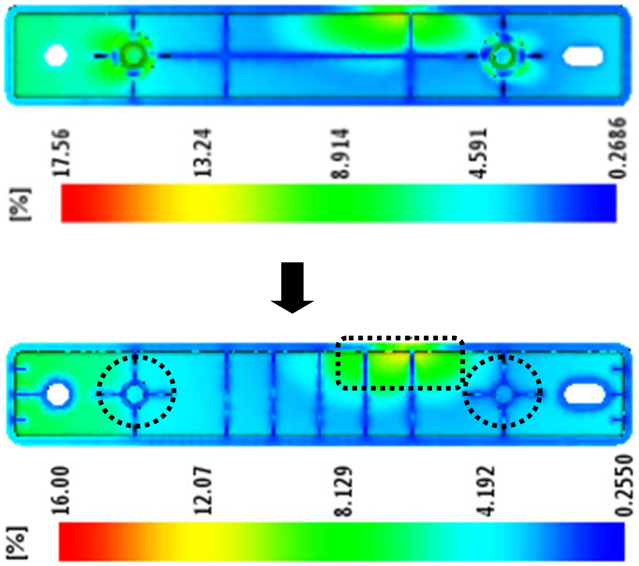


Fig. 9 Volumetric shrinkage result before (top) and after (bottom) modification

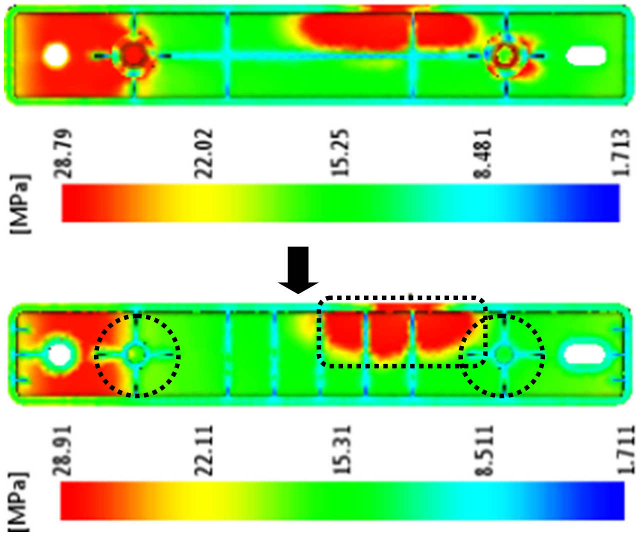


Fig. 10 In-residual stress result before (top) and after (bottom) modification

12.9% (left), 19.74% (middle), and 12.98% (right). For second modification, the horizontal rib was removed. The results show that a major reduction in the deflection value with an average deflection percentage was found to be 50%. As the horizontal rib positions have parallel lines with the side wall, it is expected to worsen the warpage when the part starts to cool. Thus, it is clearly shown that the horizontal rib position and thickness of the bosses will cause the part to warp. This supports the previous topology study where warpage happens at the high density region. Therefore, to optimize this warpage, it is advised to remove all the horizontal ribs and reduce boss thickness. Next, in order to continue optimizing warpage, the processes began with the modification at the middle region. Firstly, a vertical rib was added and a deflection index was increased to approximately 65% excluding the right side. This was because the right side would be the last part to be filled, thus warping was not easy to be controlled compared to the other area. Secondly, 2 additional vertical ribs were added at the middle. This led to ultimate optimization where the deflection for the left, middle, and right sides of the protector cover were found to be 80, 76, and 70% respectively.

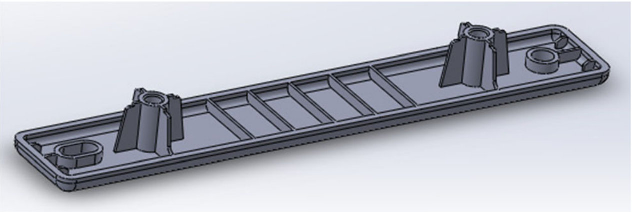


Fig. 11 Final design

4 Discussion

Figure 7 shows the final modification with maximum 80% optimization for the Y direction. The side area of protector cover shows a significant improvement of the deflection value. Meanwhile, Fig. 8 shows the total deflection value for XYZ direction, where there is an average 35% increase with respect to the reference sample. Based on the moldflow results, there were three major reasons which affect the warpage condition: (1) elimination of the horizontal rib, (2) volumetric shrinkage, and (3) in-residual stress.

Upon the final optimization, the warping of the protector cover had been greatly improved. The main effects of warpage came from the elimination of the horizontal rib in the middle of the product. It was because the thinner rib tends to solidify earlier than the other parts and shrink less than the long side wall, thus higher shrinkage values can be expected at the thin wall compared with thick wall [8, 17], which lead to higher warpage. In this case, the horizontal rib warped first towards the opposite wall which resulted in increase of the deflection value. By removing this rib, the deflection value was decreased to at least 28 to 40% of the deflection index for Y direction.

Secondly, the warpage was affected by the uneven distribution of the volumetric shrinkage [8] due to differences in wall thickness and cooling rate [1]. The main areas affected are at gate location and at the bosses as shown in Fig. 9. Through the analysis, reduction of boss thickness, addition of the gussets and circle rib at the holes contributed to an even volumetric shrinkage distribution as shown in the black dashed circle in Fig. 9. Meanwhile, the additions of the ribs in the middle of product segregated the volumetric shrinkage into three portions and thus optimized the warpage in the middle region. Thirdly, a similar trend is found in the residual stress result, as shown in Fig. 10, as a major cause of warpage [6], where reduction of boss thickness, addition of circle ribs at the holes and gussets, and the segregation of residual stress by planting the vertical ribs in three portions optimized the warpage condition (Fig. 11).

5 Conclusion

In conclusion, the new combinations of topology and moldflow technique have been developed to optimize warpage condition for the protector cover. By comparing the deflection value, the results show a successfully warpage optimization of up to 79.53% (left), 76.12% (middle), and 69.06% (right) with respect to the reference sample. Therefore, product warpage is expected to be below than 0.3 mm in Y direction and gives a favorable condition for easy assembly process. Furthermore, the results obtained are highly recommended for the modification process, where it shows a lot of enhanced design changes in order to make a stiff design that resists warpage and this is greatly significant as it will lead to improvement of product quality.

For future work, it is suggested that a real product analysis is conducted through coordinate measuring machine (CMM) to measure the displacement changes with respect to CAE optimization. Secondly, the product is proposed to undergo a thermal analysis in order to study the durability under a cool, hot and humid temperature.

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