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Design and thermal analysis of plastic injection mould

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Abstract

This paper presents the design of a plastic injection mould for producing warpage testing specimen and performing thermal analysis for the mould to access on the effect of thermal residual stress in the mould. The technique, theory, methods as well as consideration needed in designing of plastic injection mould are presented. Design of mould was carried out using commercial computer aided design software Unigraphics, Version 13.0. The model for thermal residual stress analysis due to uneven cooling of the specimen was developed and solved using a commercial finite element analysis software called LUSAS Analyst, Version 13.5. The software provides contour plot of temperature distribution for the model and also temperature variation through the plastic injection molding cycle by plotting time response curves. The results show that shrinkage is likely to occur in the region near the cooling channels as compared to other regions. This uneven cooling effect at different regions of mould contributed to warpage.

Keywords: Plastic Injection mould; Design; Thermal analysis

1. Introduction

Plastic industry is one of the world's fastest growing industries, ranked as one of the few billion-dollar industries. Almost every product that is used in daily life involves the usage of plastic and most of these products can be produced by plastic injection molding method [1]. Plastic injection molding process is well known as the manufacturing process to create products with various shapes and complex geometry at low cost [2].

The plastic injection molding process is a cyclic process. There are four significant stages in the process. These stages are filling, packing, cooling and ejection. The plastic injection molding process begins with feeding the resin and the appropriate additives from the hopper to the heating/injection system of the injection plastic injection molding machine [3]. This is the "filling stage" in which the mould cavity is filled with hot polymer melt at injection temperature. After the cavity is filled, in the "packing stage", additional polymer melt is packed into the cavity at a higher pressure to compensate the expected shrinkage as the polymer solidifies. This is followed by "cooling stage" where the mould is cooled until the part is sufficiently rigid to be ejected. The last step is the "ejection stage" in which the mould is opened and the part is ejected, after which the mould is closed again to begin the next cycle [4].

The design and manufacture of injection molded polymeric parts with desired properties is a costly process dominated by empiricism, including the repeated modification of actual tooling. Among the task of mould design, designing the mould specific supplementary geometry, usually on the core side, is quite complicated by the inclusion of projection and depression [5].

In order to design a mould, many important designing factors must be taken into consideration. These factors are mould size, number of cavity, cavity layouts, runner systems, gating systems, shrinkage and ejection system [6].

In thermal analysis of the mould, the main objective is to analyze the effect of thermal residual stress or molded-in stresses on product dimension. Thermally induced stresses develop principally during the cooling stage of an injection molded part, mainly as a consequence of its low thermal conductivity and the difference in temperature between the molten resin and the mould. An uneven temperature field exists around product cavity during cooling [7].

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During cooling, location near the cooling channel experiences more cooling than location far away from the cooling channel. This different temperature causes the material to experience differential shrinkage causing thermal stresses. Significant thermal stress can cause warpage problem. Therefore, it is important to simulate the thermal residual stress field of the injection-molded part during the cooling stage [8]. By understanding the characteristics of thermal stress distribution, deformation caused by the thermal residual stress can be predicted.

In this paper the design of a plastic injection mould for producing warpage testing specimen and for performing thermal analysis for the mould to access on the effect of thermal residual stress in the mould is presented.

2. Methodology

2.1. Design of warpage testing specimen

This section illustrates the design of the warpage testing specimen to be used in plastic injection mould. It is clear that warpage is the main problem that exists in product with thin shell feature. Therefore, the main purpose of the product development is to design a plastic part for determining the effective factors in the warpage problem of an injection-moulded part with a thin shell.

The warpage testing specimen is developed from thin shell plastics. The overall dimensions of the specimen were 120 mm in length, 50 mm in width and 1 mm in thickness. The material used for producing the warpage testing specimen was acrylonitrile butadiene stylene (ABS) and the injection temperature, time and pressure were 210 °C, 3 s and 60 MPa, respectively. Fig. 1 shows the warpage testing specimen produced.

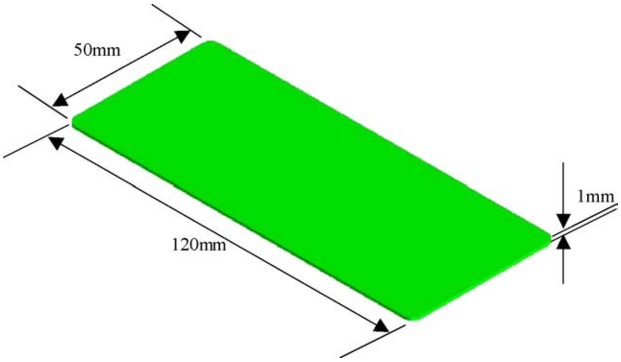


Fig. 1. Warpage testing specimen produced.

2.2. Design of plastic injection mould for warpage testing specimen

This section describes the design aspects and other considerations involved in designing the mould to produce warpage testing specimen. The material used for producing the plastic injection mould for warpage testing specimen was AISI 1050 carbon steel.

Four design concepts had been considered in designing of the mould including:

i. Three-plate mould (Concept 1) having two parting line with single cavity. Not applicable due to high cost.
ii. Two-plate mould (Concept 2) having one parting line with single cavity without gating system. Not applicable due to low production quantity per injection.
iii. Two-plate mould (Concept 3) having one parting line with double cavities with gating and ejection system. Not applicable as ejector pins might damage the product as the product is too thin.
iv. Two-plate mould (Concept 4) having one parting line with double cavities with gating system, only used sprue puller act as ejector to avoid product damage during ejection.

In designing of the mould for the warpage testing specimen, the fourth design concept had been applied. Various design considerations had been applied in the design.

Firstly, the mould was designed based on the platen dimension of the plastic injection machine used (BOY 22D). There is a limitation of the machine, which is the maximum area of machine platen is given by the distance between two tie bars. The distance between tie bars of the machine is 254 mm. Therefore, the maximum width of the mould plate should not exceed this distance. Furthermore, 4 mm space had been reserved between the two tie bars and the mould for mould setting-up and handling purposes. This gives the final maximum width of the mould as 250 mm. The standard mould base with 250 mm × 250 mm is employed. The mould base is fitted to the machine using Matex clamp at the upper right and lower left corner of the mould base or mould platen. Dimensions of other related mould plates are shown in Table 1.

The mould had been designed with clamping pressure having clamping force higher than the internal cavity force (reaction force) to avoid flashing from happening.

Based on the dimensions provided by standard mould set, the width and the height of the core plate are 200 and 250 mm, respectively. These dimensions enabled design of two cavities on core plate to be placed horizontally as there is enough space while the cavity plate is left empty and it is only fixed with sprue bushing for the purpose of feeding molten plastics. Therefore, it is only one standard parting line was designed at

Table 1
Mould plates dimensions.

Components	Size (mm) – width × height × thickness
Top clamping plate	250 × 250 × 25
Cavity plate	200 × 250 × 40
Core plate	200 × 250 × 40
Side plate/support plate	37 × 250 × 70
Ejector-retainer plate	120 × 250 × 15
Ejector plate	120 × 250 × 20
Bottom clamping plate	250 × 250 × 25

the surface of the product. The product and the runner were released in a plane through the parting line during mould opening.

Standard or side gate was designed for this mould. The gate is located between the runner and the product. The bottom land of the gate was designed to have 20° slanting and has only 0.5 mm thickness for easy de-gating purpose. The gate was also designed to have 4 mm width and 0.5 mm thickness for the entrance of molten plastic.

In the mould design, the parabolic cross section type of runner was selected as it has the advantage of simpler machining in one mould half only, which is the core plate in this case. However, this type of runner has disadvantages such as more heat loss and scrap compared with circular cross section type. This might cause the molten plastic to solidify faster. This problem was reduced by designing in such a way that the runner is short and has larger diameter, which is 6 mm in diameter.

It is important that the runner designed distributes material or molten plastic into cavities at the same time under the same pressure and with the same temperature. Due to this, the cavity layout had been designed in symmetrical form.

Another design aspect that is taken into consideration was air vent design. The mating surface between the core plate and the cavity plate has very fine finishing in order to prevent flashing from taking place. However, this can cause air to trap in the cavity when the mould is closed and cause short shot or incomplete part. Sufficient air vent was designed to ensure that air trap can be released to avoid incomplete part from occurring.

The cooling system was drilled along the length of the cavities and was located horizontally to the mould to allow even cooling. These cooling channels were drilled on both cavity and core plates. The cooling channels provided sufficient cooling of the mould in the case of turbulent flow. Fig. 2 shows cavity layout with air vents and cooling channels on core plate.

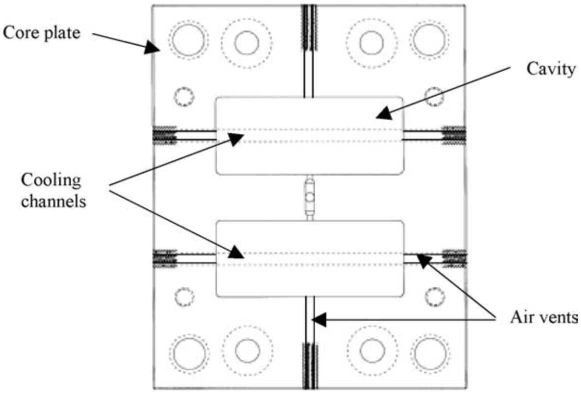


Fig. 2. Cavity layout with air vents and cooling channels.

In this mould design, the ejection system only consists of the ejector retainer plate, sprue puller and also the ejector plate. The sprue puller located at the center of core plate not only functions as the puller to hold the product in position when the mould is opened but it also acts as ejector to push the product out of the mould during ejection stage. No additional ejector is used or located at product cavities because the product produced is very thin, i.e. 1 mm. Additional ejector in the product cavity area might create hole and damage to the product during ejection.

Finally, enough tolerance of dimensions is given consideration to compensate for shrinkage of materials.

Fig. 3 shows 3D solid modeling as well as the wireframe modeling of the mould developed using Unigraphics.

3. Results and discussion

3.1. Results of product production and modification

From the mould designed and fabricated, the warpage testing specimens produced have some defects during trial run. The defects are short shot, flashing and warpage. The short shot is subsequently eliminated by milling of additional air vents at corners of the cavities to allow air trapped to

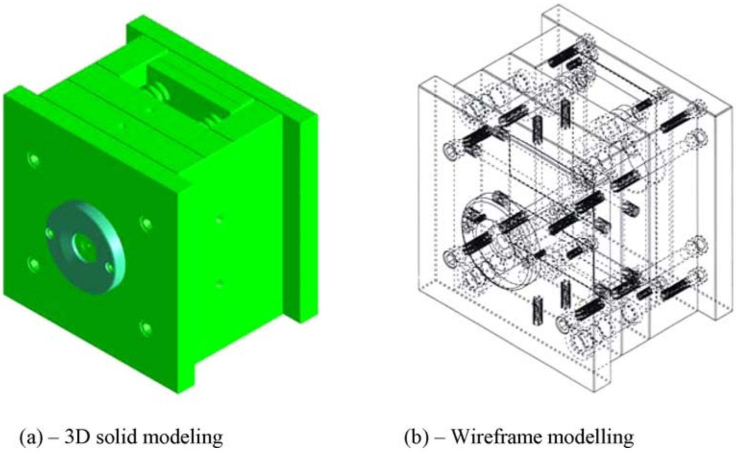

(a) – 3D solid modeling (b) – Wireframe modelling

Fig. 3. 3D solid modeling and wireframe modeling of the mould.

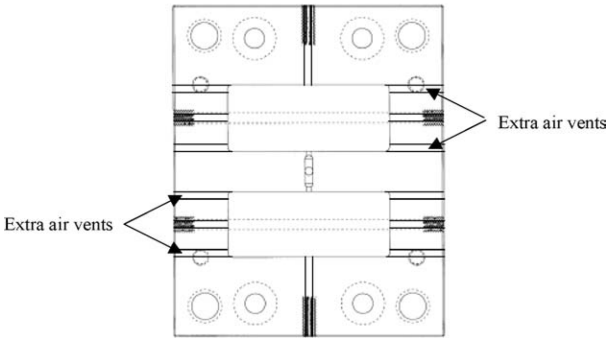


Fig. 4. Extra air vents to avoid short shot.

escape. Meanwhile, flashing was reduced by reducing the packing pressure of the machine. Warpage can be controlled by controlling various parameters such as the injection time, injection temperature and melting temperature.

After these modifications, the mould produced high quality warpage testing specimen with low cost and required little finishing by de-gating. Fig. 4 shows modifications of the mould, which is machining of extra air vents that can eliminate short shot.

3.2. Detail analysis of mould and product

After the mould and products were developed, the analysis of mould and the product was carried out. In the plastic injection moulding process, molten ABS at 210 °C is injected into the mould through the sprue bushing on the cavity plate and directed into the product cavity. After cooling takes place, the product is formed. One cycle of the product takes about 35 s including 20 s of cooling time.

The material used for producing warpage testing specimen was ABS and the injection temperature, time and pressure were 210 °C, 3 s and 60 MPa respectively. The material selected for the mould was AISI 1050 carbon steel.

Properties of these materials were important in determining temperature distribution in the mould carried out using finite element analysis. Table 2 shows the properties for ABS and AISI 1050 carbon steel.

The critical part of analysis for mould is on the cavity and core plate because these are the place where the product is formed. Therefore, thermal analysis to study the temperature distribution and temperature at through different times are performed using commercial finite element analysis software called LUSAS Analyst, Version 13.5. A two-dimensional (2D) thermal analysis is carried out for to study the effect of thermal residual stress on the mould at different regions.

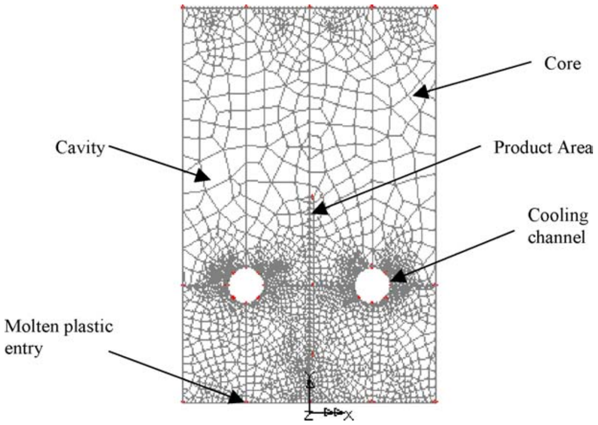


Fig. 5. Model for thermal analysis.

Due to symmetry, the thermal analysis was performed by modeling only the top half of the vertical cross section or side view of both the cavity and core plate that were clamped together during injection. Fig. 5 shows the model of thermal analysis analyzed with irregular meshing.

Modeling for the model also involves assigning properties and process or cycle time to the model. This allowed the finite element solver to analyze the mould modeled and plot time response graphs to show temperature variation over a certain duration and at different regions.

For the product analysis, a two dimensional tensile stress analysis was carried using LUSAS Analyst, Version 13.5. Basically the product was loaded in tension on one end while the other end is clamped. Load increments were applied until the model reaches plasticity. Fig. 6 shows loaded model of the analysis.

3.3. Result and discussion for mould and product analysis

For mould analysis, the thermal distribution at different time intervals was observed. Fig. 7 shows the 2D analysis

Table 2
Material properties for mould and product

Carbon Steel (AISI 1050), mould		ABS Polymer, product	
Density, ρ	7860 kg/m^3	Density, ρ	1050 kg/m^3
Young's modulus, E	208 GPa	Young's modulus, E	2.519 GPa
Poisson's ratio, ν	0.297	Poisson's ratio, ν	0.4
Yield strength, S_{Y}	365.4 MPa	Yield strength, S_{Y}	65 MPa
Tensile strength, S_{UTS}	636 MPa	Thermal expansion, α	65×10^{-6} K^{-1}
Thermal expansion, α	11.65×10^{-6} K^{-1}	Conductivity, k	0.135 W/(m K)
Conductivity, k	49.4 W/(m K)	Specific heat, c	1250 J/(kg K)
Specific heat, c	477 J/(kg K)		

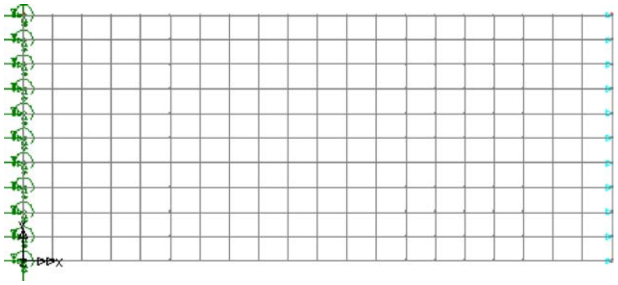


Fig. 6. Loaded model for analysis of product.

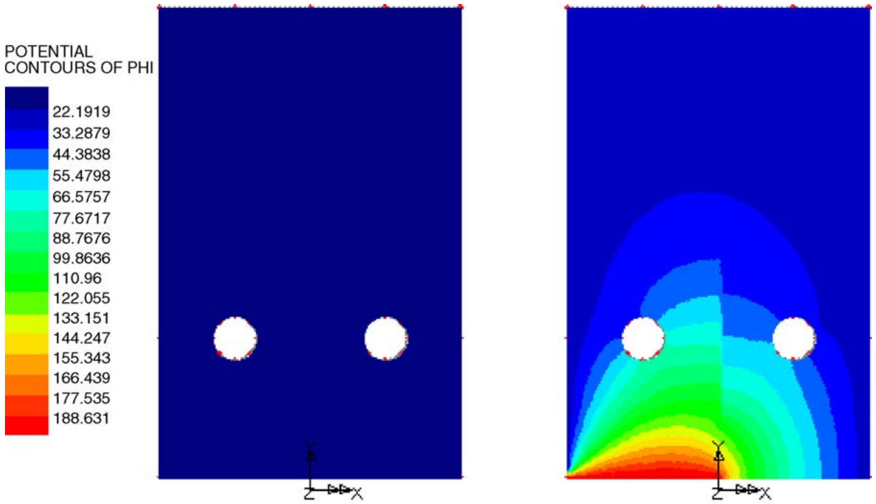
contour plots of thermal or heat distribution at different time intervals in one complete cycle of plastic injection molding.

For the 2D analysis of the mould, time response graphs are plotted to analyze the effect of thermal residual stress on the products. Fig. 8 shows nodes selected for plotting time response graphs.

Figs. 9–17 show temperature distribution curves for different nodes as indicated in Fig. 8.

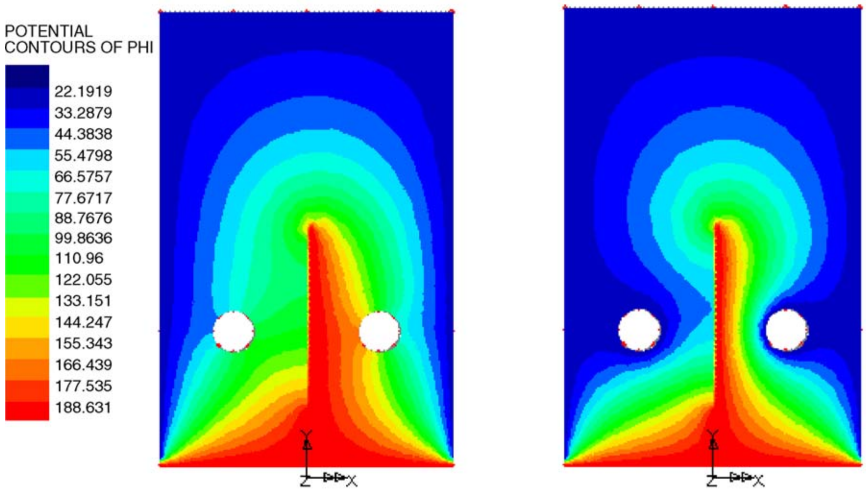
From the temperature distribution graphs plotted in Figs. 9–17, it is clear that every node selected for the graph plotted experiencing increased in temperature, i.e. from the ambient temperature to a certain temperature higher than the ambient temperature and then remained constant at this temperature for a certain period of time. This increase in temperature was caused by the injection of molten plastic into the cavity of the product.

After a certain period of time, the temperature is then further increased to achieve the highest temperature and remained constant at that temperature. Increase in temperature was due to packing stages that involved high pressure,



Time = 1 second
(initial condition)

Time = 5 second
(during injection)



Time = 14 second
(before cooling)

Time = 35 second
(after cooling)

Fig. 7. Contour plots of heat distribution at different time intervals.

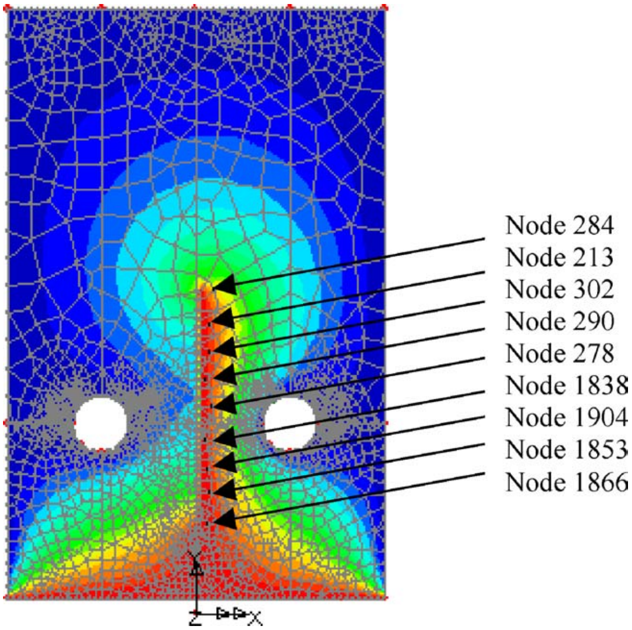


Fig. 8. Selected nodals near product region for time response graph plots.

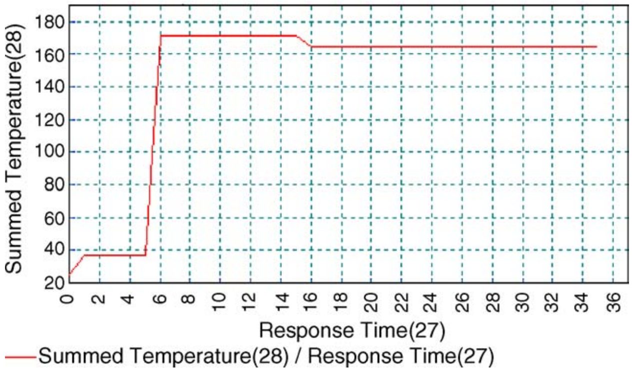


Fig. 9. Temperature distribution graph for Node 284.

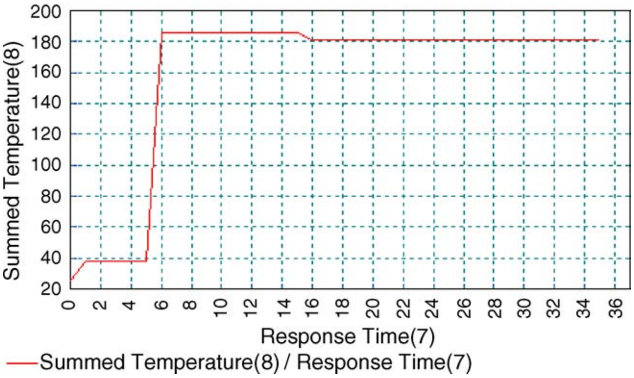


Fig. 10. Temperature distribution graph for Node 213.

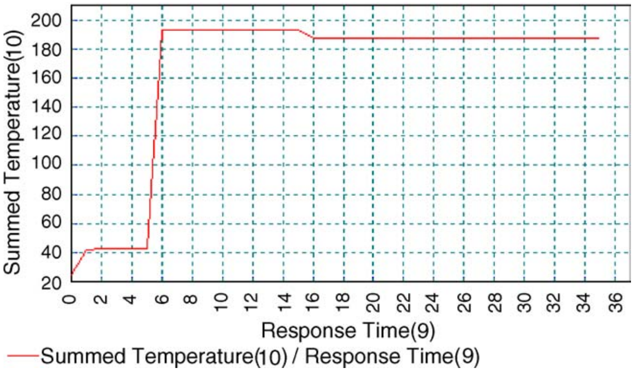


Fig. 11. Temperature distribution graph for Node 302.

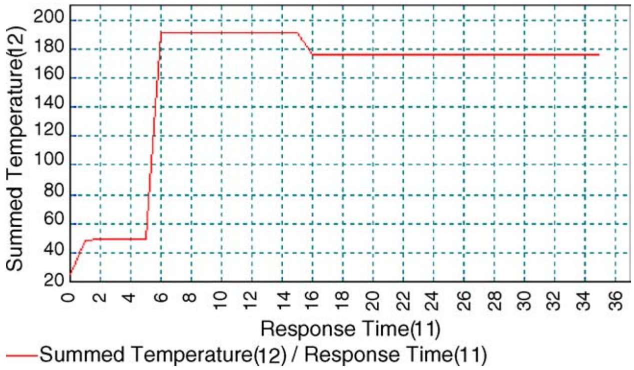


Fig. 12. Temperature distribution graph for Node 290.

which caused the temperature to increase. This temperature remains constant until the cooling stage starts, which causes reduction in mould temperature to a lower value and remains at this value. The graphs plotted were not smooth due to the absence of function of inputting filling rate of the molten plastic as well as the cooling rate of the coolant. The graphs plotted only show maximum value of temperature that can be achieved in the cycle.

The most critical stage in the thermal residual stress analysis is during the cooling stage. This is because the cooling

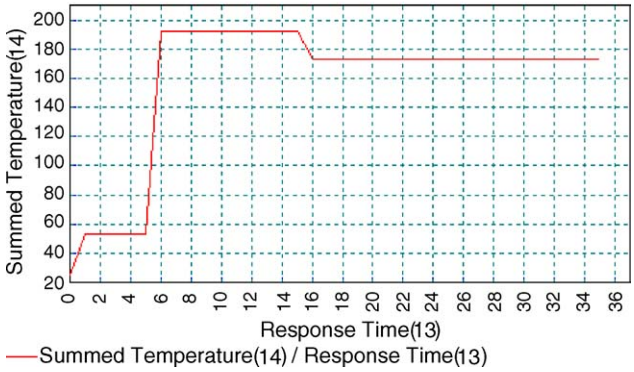


Fig. 13. Temperature distribution graph for Node 278.

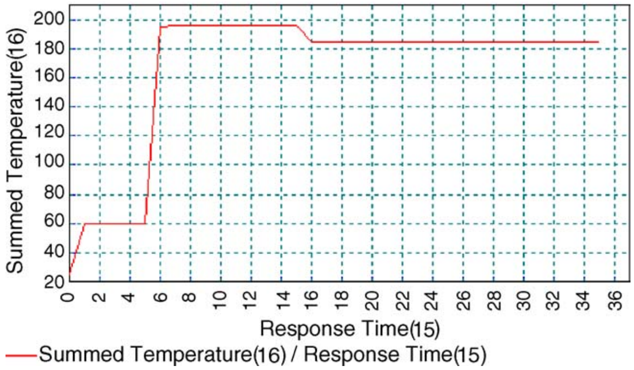


Fig. 14. Temperature distribution graph for Node 1838.

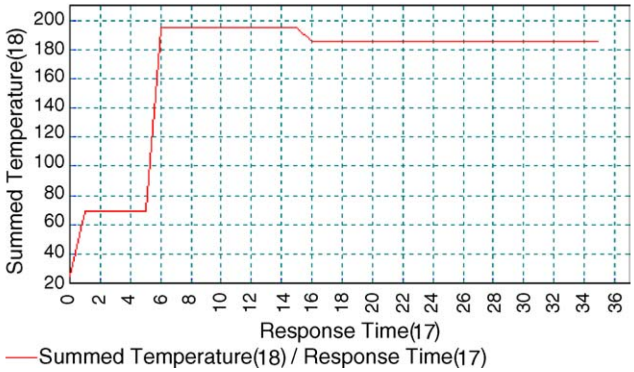


Fig. 15. Temperature distribution graph for Node 1904.

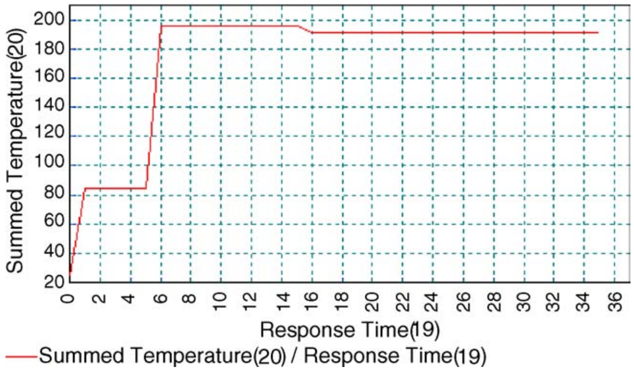


Fig. 16. Temperature distribution graph for Node 1853.

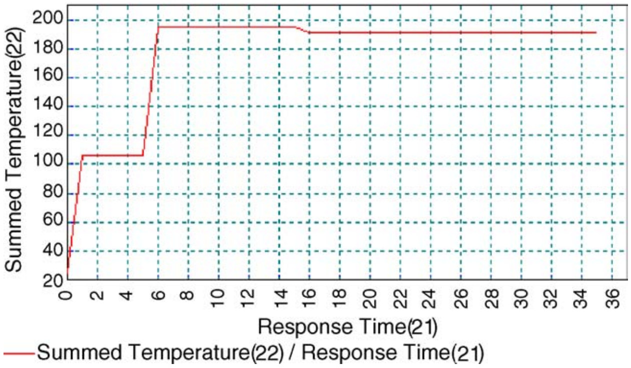


Fig. 17. Temperature distribution graph for Node 1866.

stage causes the material to cool from above to below the glass transition temperature. The material experiences differential shrinkage that causes thermal stress that might result in warpage.

From the temperature after the cooling stage as shown in Figs. 9–17, it is clear that the area (node) located near the cooling channel experienced more cooling effect due to further decreasing in temperature and the region away from the cooling channel experienced less cooling effect. More cooling effect with quite fast cooling rate means more shrinkage is occurring at the region. However, the farthest region, Node 284 experience more cooling although far away from cooling channel due to heat loss to environment.

As a result, the cooling channel located at the center of the product cavity caused the temperature difference around the middle of the part higher than other locations. Compressive stress was developed at the middle area of the part due to more shrinkage and caused warpage due to uneven shrinkage that happened. However, the temperature differences after cooling for different nodes are small and the warpage effect is not very significant. It is important for a designer to design a mould that has less thermal residual stress effect with efficient cooling system.

For the product analysis, from the steps being carried out to analyze the plastic injection product, the stress distribution on product at different load factor is observed in the two dimensional analysis. Figs. 18–21 show the contour plots of equivalent stress at different load increments.

A critical point, Node 127, where the product experiences maximum tensile stress was selected for analysis. The stress versus strain curve and the load case versus stress curves at this point were plotted in Figs. 22 and 23.

From the load case versus stress curves at this point plotted in Fig. 23, it is clear that the product experiencing increased in tensile load until it reached the load factor of 23, which is 1150 N. This means that the product can withstand tensile load until 1150 N. Load higher than this value causes failure to the product. Based on Fig. 23, the failure is likely to occur at the region near to the fixed end of the product with maximum stress of 3.27×10^7 Pa.

The product stress analysis reveals very limited information since the product produced was for warpage testing purposes and had no relation with tensile loading analysis. In future, however, it is suggested that the product service condition should be determined so that further analysis may be carried out for other behaviors under various other loading.

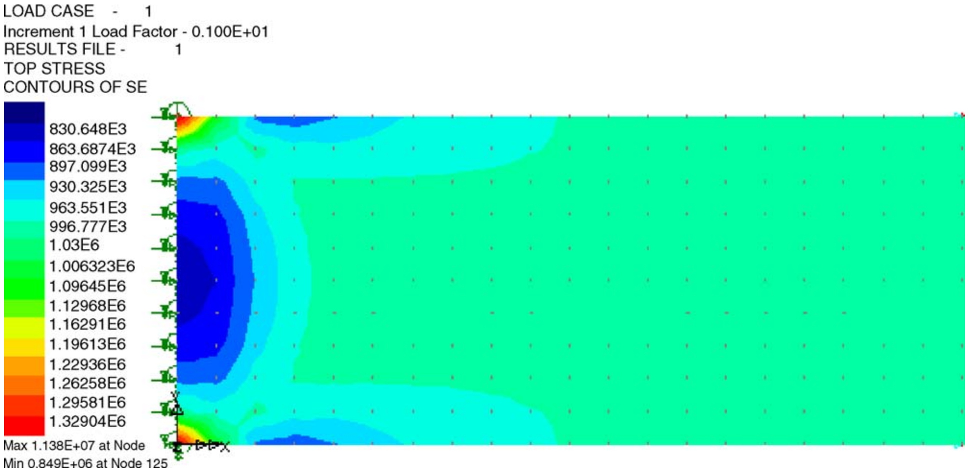


Fig. 18. Equivalent stress plot at load increment 1.

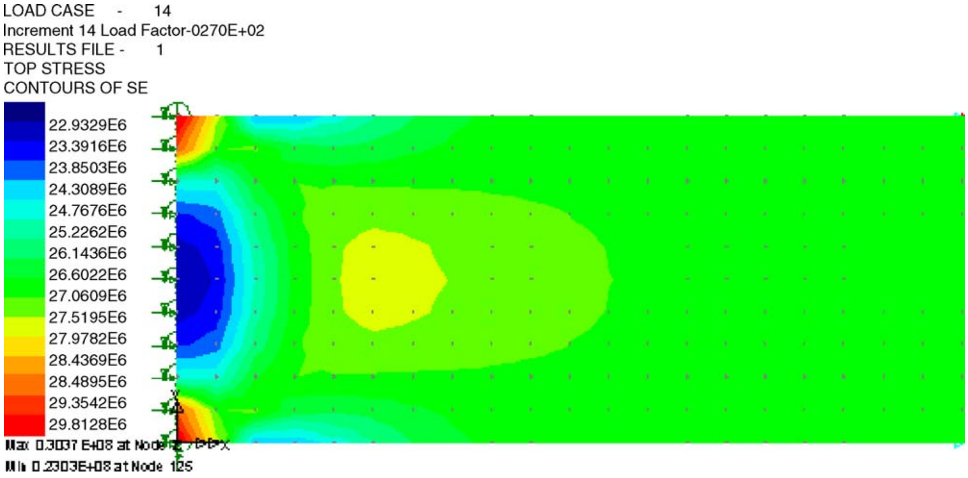


Fig. 19. Equivalent stress plot at load increment 14.

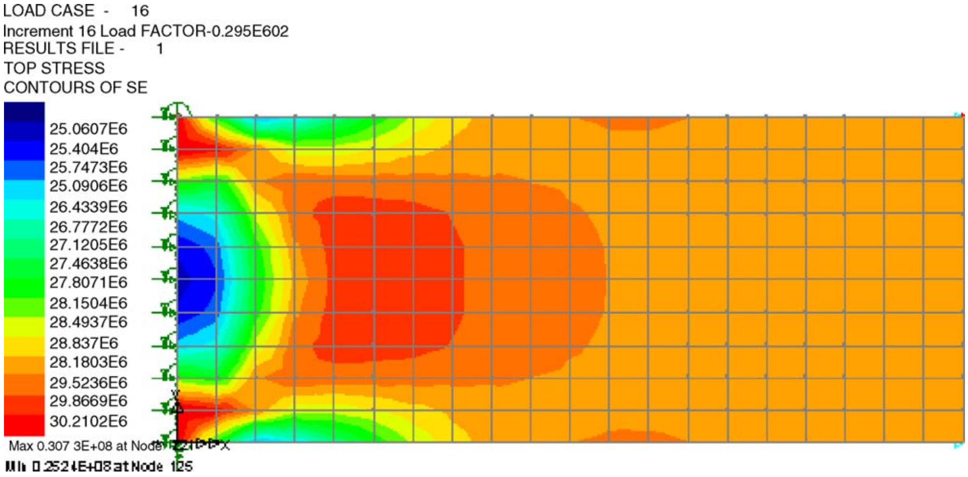


Fig. 20. Equivalent stress plot at load increment 16.

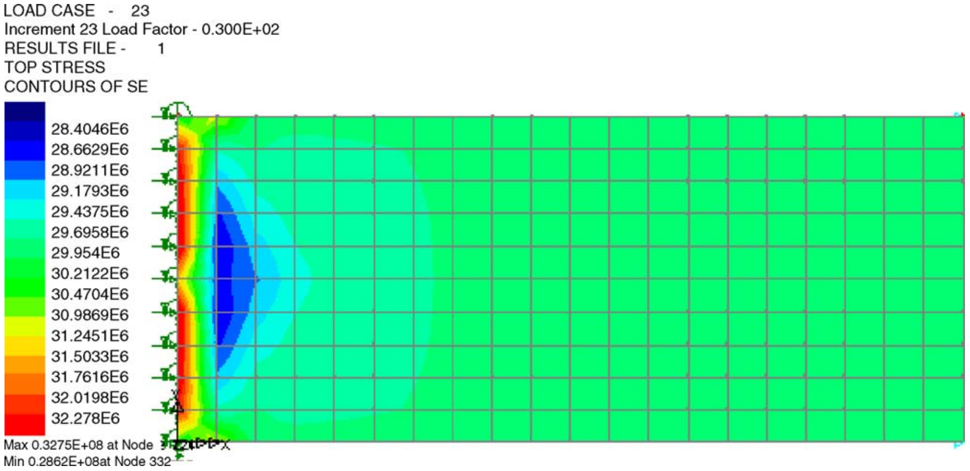


Fig. 21. Equivalent stress plot at load increment 23.

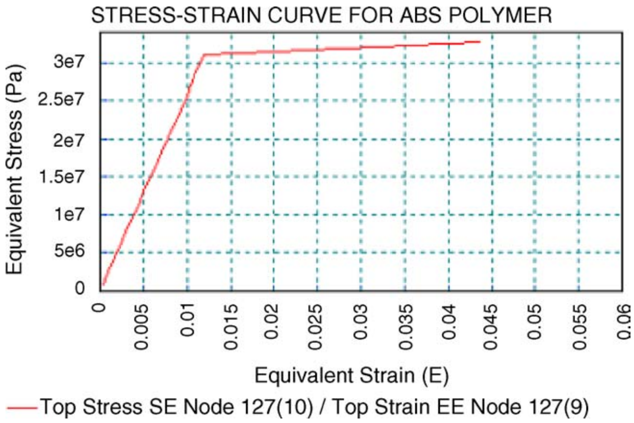


Fig. 22. Stress versus strain curve for ABS.

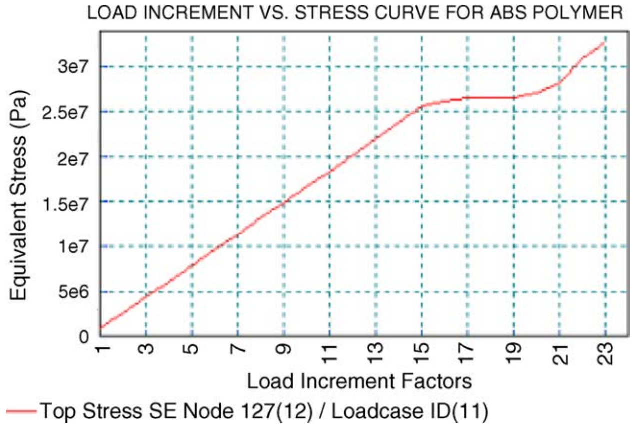


Fig. 23. Stress versus load increment curve for ABS.

4. Conclusions

The mould designed has made it possible to produce high quality warpage testing specimen to determine parameters that affect warpage. The testing specimen was produced at low cost and involves only little finishing that is de-gating.

The thermal analysis of plastic injection mould has provided an understanding of the effect of thermal residual stress on deformed shape of the specimen and the tensile stress analysis of product managed to predict the tensile load that the warpage testing specimen can withstand before experiencing failure.

Acknowledgement

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