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Research Article

Effect of bottle handle design on injection molding production parameters and usage performance

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ABSTRACT

The computer-aided engineering software that performs plastic flow analysis enables the optimization of injection molding processes in a faster, more accurate, and cost-effective way instead of the trial-and-error method used in injection molding machines. In the literature, there are many studies on the moldability of injection entry point variables. In this study, unlike the literature, the synergistic effect of three different injection entry point variables such as gate location, gate concept and gate diameter is aimed to optimize the moldability and required strength values for water bottle handles.
The injection moldability parameters of the bottle handles (filling time, filling pressure, temperature, frozen layer and joint line) were obtained using Moldflow Software for the optimum values of the variables of the selected High Density Polyethylene (HDPE) material. As a result of these analyses, the maximum strength values that the handles can carry at the best acceptance conditions in moldability were determined by considering the appropriate cap concept and cap diameter for the best cap filling zone.
As a result of the analysis for the same process parameters, the optimum production parameters were reduced to the final two by considering the optimum parameters in breaking force and molding. Although the first design has the highest breaking force, it is not suitable for mass production due to the weight increase of 12.1%. It was concluded that the second design should be approved as it provided a 44.4% increase in breaking force while the handle weight increased by 2.1%.

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INTRODUCTION

Injection molding is an efficient method that can produce products with complex shapes and geometries at the desired quality and in high production quantities. Factors affecting the quality of the product produced by plastic injection molding are material selection, product design, mold design, injection machine selection and processing parameters [1–4].

In injection molding machines, process parameters determined by trial-and-error settings, which is the traditional working method, cause losses in terms of time and

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cost and cannot guarantee that the optimum result is used. For this reason, computer-aided engineering software has gained importance in optimizing injection molding processes With computer-aided engineering (CAE) software, the quality of products to be produced by plastic injection molding, moldability parameters and injection machine settings can be optimized depending on design variables and material properties.

The effects of injection parameters such as melt temperature, injection speed, mold temperature, filling point size, filling pressure and time, cooling time on the strength, ovality and warpage of the product have been studied in different articles [5–7]. One of the most important factors affecting these parameters is the effect of gate system design in molding. Table 1 shows the literature information about gate type, gate radius and gate area in relation to the gate system.

Table 1. Purpose and Results of Reference Articles

Purpose	Results	Reference
Determination of part defects due to the choice of runner and gate type.	Design of gating system according to optimum molding parameters	[6] Rambhau et. al. (2016)
Investigation of runner design with plastic flow analysis	Shortening the design cycle of the injection mold.	[7] Hongyan et. al. (2022)
Optimization of gate location	Flow parameters were obtained for optimization of different gate position.	[9] Nuruzzaman et. al. (2012).
Filling Point Anaysis	Quality and cost optimization is determined by plastic flow analysis.	[10] Sedighi et. al. [2017]
Determine weld line and air trap defects due to temperature and pressure from injection parameters	Possible errors in mold design were identified and time and cost optimization was made in mold production.	[11] Wong et. al. [2004]
The manufacturability analysis of the plastic product used as a Bicycle Bottle Holder was made.	The parameters affecting the mold manufacturing costs were determined with Solidworks Plastic software.	[12] Mircheski et. al. [2019]
It is aimed to compare the analysis in molding and actual production parameters.	Experimental values and analysis results are approximately the same.	[13] Ravikiran et. al. [2021]
Comparison of Filling Time Analysis Methods.	The pressure gradient method was found to be more effective than the flow path algorithm.	[14] Zhai et. al. [2005]
A general methodology for gate location optimization is developed.	A proposed simulation is developed for any thermoplastic material and any complex mold geometry.	[15] Pandelis and Zou [1990], Part I
In this paper, a methodology for molding condition optimization is presented.	Theoretically, the optimum molding conditions are determined with the developed mathematical approach.	[16] Pandelis and Zou [1990], Part II
Adaptation of injection molding parameters to the actual production process.	A theoretical fundamental approach to improve the quality of molded products was achieved.	[17] Zhao et. al. [2010]
CAE analysis was performed to determine the manufacturability of the selected part.	An effective method for structural design of plastic injection mold using CAE technology is presented.	[18] Menga et. al. [2011]
To improve the design of the runner system of plastic parts, through the cooperative optimized design of structure and process, it is desirable to achieve good economic returns while ensuring product quality.	The Based on the optimization of the structure of the plastic parts and the forming process, material savings were achieved by improving the nozzle design.	[19] Yan and Han [2012]
Optimal injection molding conditions for minimum shrinkage had determined.	The importance of packing pressure and melt temperature was determined.	[20] Mirigul Altan [2010]
Determination of gate location depending on mold design.	It is concluded that the range of filling time is more important for gate location optimization and the flow path search scheme is more efficient.	[21] Zhai et. al. [2009]
The optimisation objective was to find gate location which led to minimum weld line length.	Optimization of the gate position for the possible situation of the welding line.	[22] Sedighi [2017]
The effect of gate type on molding was wanted to be determined.	The effect of different gate types was determined for air traps and various process parameters.	[23] Kapila [2015]
Design of bottle and handle with improved mechanical properties.	According to the bottle, the material saving in the handle is less, but the required strength for the handle was achieved.	[24]Thongkaew and Naemsai [2020]

According to the literature studies, there are very few studies on the synergistic effect of gate location, gate concept and gate diameter, which are critical parameters for gate system design, on injection molding and determination of the functional properties and defects of the product [8]. Unlike these studies [7,9] for standard specimens and plates, there are no studies on the effect of the gate system on injection molding and also on the usage performance of the gate system on thin section parts. For this purpose, it was aimed to investigate the effect of gate systems on the production and utilization performance of bottle handles.

MATERIAL AND METHOD

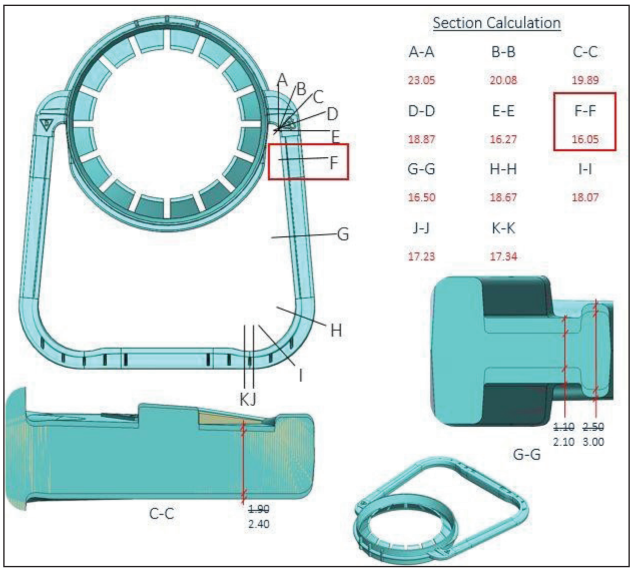
The effect of gate systems designed for bottle handles on molding was examined both experimentally and theoretically, and the designs were verified by tear test for the handles after production.

Material

Rigidex 6070UA brand High Density Polyethylene (HDPE) material obtained from INEOS POLYOLEFINS, which is suitable for injection molding production and can provide the required properties for the handle product, was chosen. Its high rigidity, ease of manufacturability, and advantages over other materials in terms of warpage were influential factors in its selection.

Handle Design

The handle designed in Figure 1 is a part produced for easy transportation of water and liquid foods. Especially the handles used on water bottles are subjected to torsion under constant tension during transportation. In order to have an ergonomic structure and to carry the liquid safely, they must have high resistance to torsional force and high strength against the risk of rupture/breakage.



Figue 1. Handle example.

In order to see the effect of injection molding parameters on the strength values required for safe handling of the handles, 48 mm diameter handle models with different filling points, different gate entry points and different gate diameters were designed with SolidWorks software (Figure 2).

Method

After design and material selection, plastic flow analysis with Moldflow software was used for moldability, static analysis of the handles theoretically with Abaqus software and tear test methodology was used experimentally to determine the usage performance.

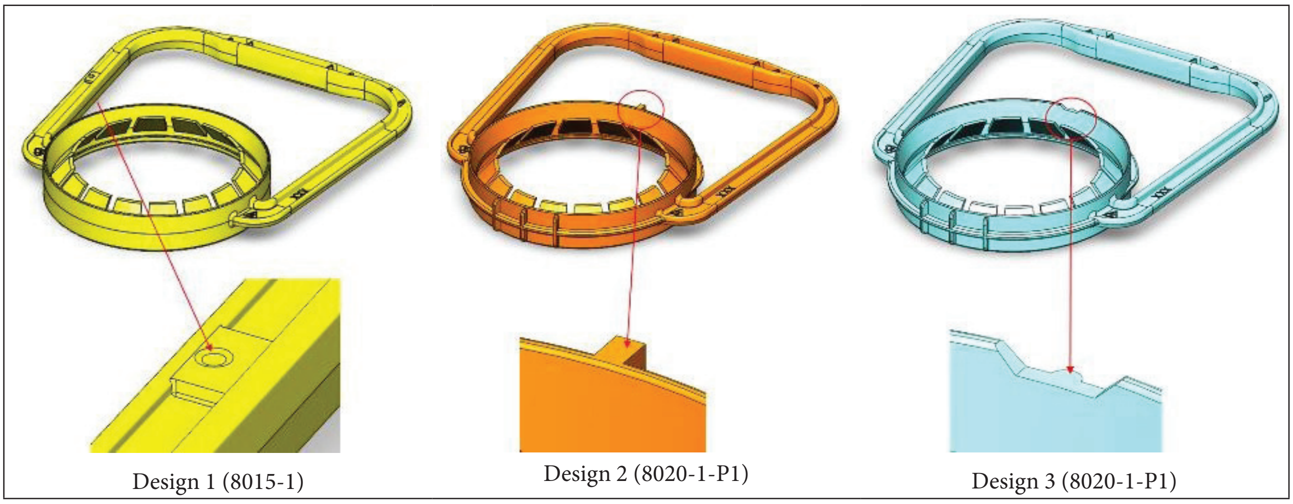


Figure 2. Identified injection filling points.

In terms of the performance of the handle material in terms of mechanical properties and ergonomic portability, two design scenarios were found suitable from the versions generated based on the stress analysis results. In order to ensure a quality approach in injection molding production parameters, designs were made for three different gate locations (8015, 8020-1, 8020-2), two different gate inlet concepts (8020-1-P1, 8020-2-P1) and two different gate diameters (8020-1-P1-1.0, 8020-1-P1-1.3) for the versions of these two designs shown in Table 2. For each design (Figure 2), Autodesk Simulation Moldflow Insight software was used to investigate the variation in injection molding parameters such as share rate, temperature, fill time, pressure, frozen layer and weld lines.

Static analysis of the designs in Abaqus program was performed by determining the boundary conditions to simulate the conditions of use and stress strain analysis was performed. Tedrahedral element type mesh was used. For Desing 2, the mesh was created with 1 021 475 elements and 188 589 nodes. The average aspect ratio of the elements is 5.86. An equal friction coefficient of 0.3 was defined for the contact areas of the handles. The bottle neck is not able to move in y-direction. A displacement in y-direction is set on the handle bar and the reaction force is evaluate.

The tear test methodology shown in Figure 3 was developed to determine the post-production use performance of the designed handles. The tear test apparatus was used to determine the maksimum force causing damage to the handles. The theoretical structural analysis and experimental tear test results were compared to confirm the accuracy of the final design obtained as a result of optimization of the injection molding parameters. The bottle handles were tested by tensile pulling at a speed of 317.5 mm/min after 30 N preload and the rupture force values were obtained for each design.

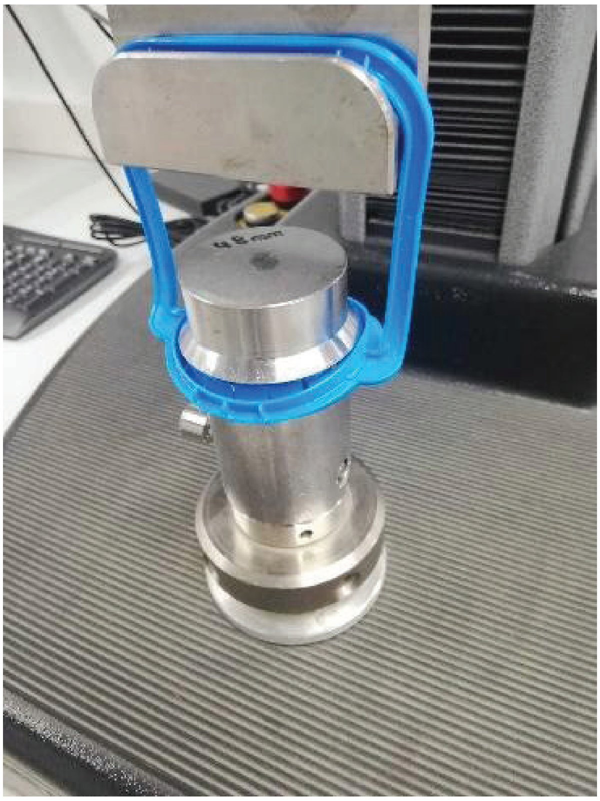


Figure 3. Tear test method.

RESULTS AND DISCUSSION

All variables of the gate system are of critical importance, affecting the flow profiles in the mold cavity and consequently the various characteristics of the part [25]. The results of the plastic flow analysis were optimized for the gate system variables (location, concept and diameters of the gate point). Design verification was performed by

Table 2. Parameters used in plastic flow analysis

Comparison Table	8015-P1	8020-1-P1	8020-2-P2-P1	
melt t	240	240	240	240
mold t	30	30	30	30
inj time	0,7	0,7	1,2	0,7
holding pressure	40	40	65	40
holding time	0,2	0,2	0,5	0,2
cooling time	6	6	6	6
Gate Diameter(mm)	1,0	1,0	1,0	1,0
	1,3	1,3		
	Design 1	Design 2	Design 3	

(yellow)	Gate Location Comparison
(red)	Gate Concept Comparison
(blue)	Gate Diameter Comparison
8015	Model
8020-1	Model
8020-2	Model
P1	Process Parameter 1
P2	Process Parameter 2

evaluating the weight and mechanical performance results of the final handle part determined as a result of optimizing the variables.

Gate Location Comparion

Fill Time Analysis, Filling Pressure Analysis, Temperature Analysis, Shear rate analysis, Frozen Layer Analysis, Joint Line Analysis results were obtained for two different gate filling points for Design 1 (8015-P1) and Design 2 (8020-P1). Although Design 1 was the most advantageous in the filling times of the designed handle, no significant difference was observed when the total filling times were compared (Figure 4).

As seen in Figure 5, Design 1 has the lowest filling pressure. The low filling pressure may be advantageous to reduce the energy consumed by the machine and therefore may be preferable. Another factor is that in the visual result of the analysis, it is seen that Design 1 is advantageous to avoid the point where the joints of the materials will be exposed to the breaking force during the use of the handle.

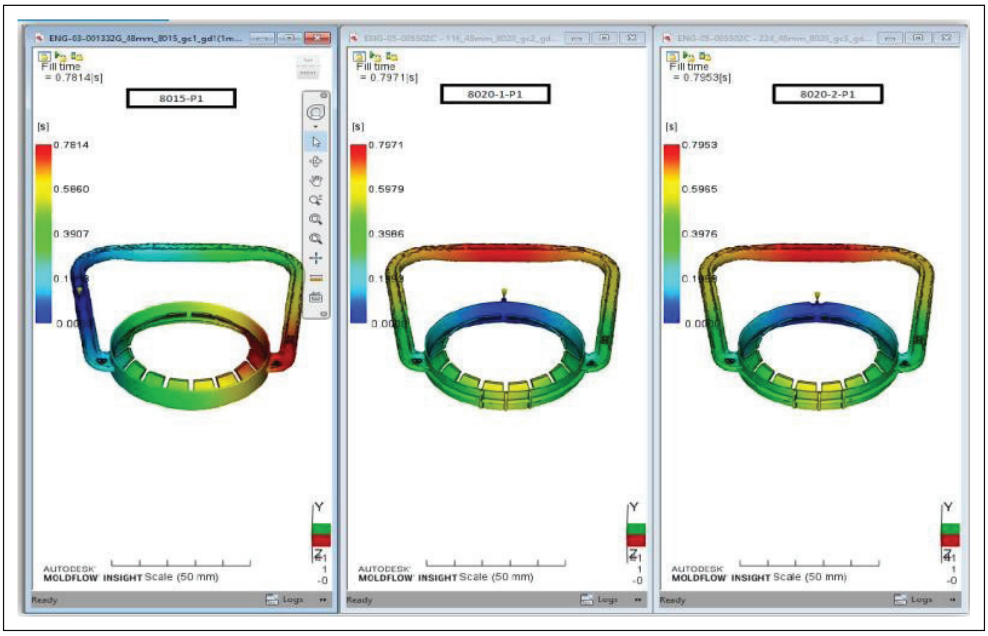


Figure 4. Fill time analysis.

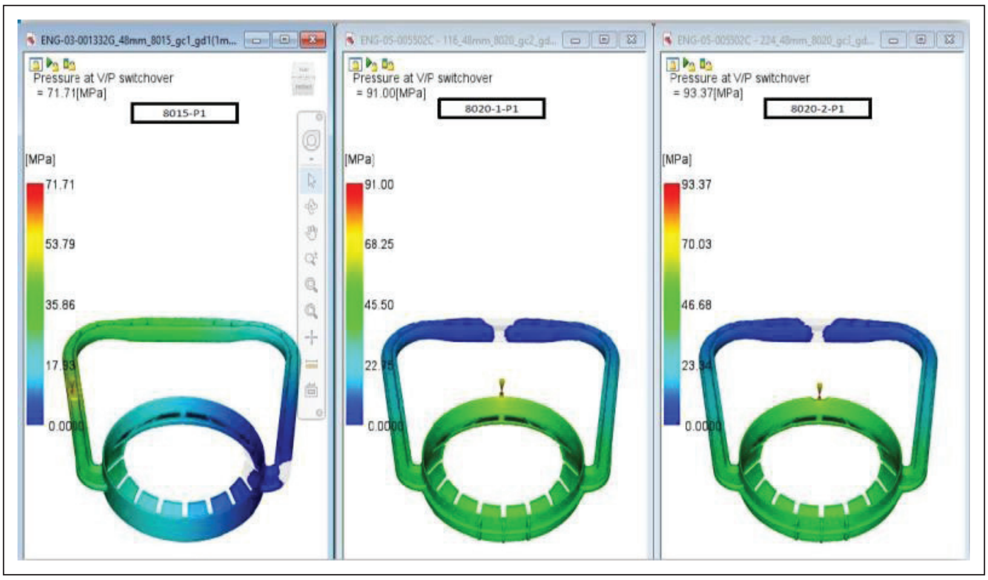


Figure 5. Filling pressure analysis.

It is seen in Figure 6 and Figure 7 that the injection filling entry point for the handle part has no effect on the temperature and maximum shear rate.

When the injection filling is complete, it is preferable that the cut of the frozen layer does not exceed 0.25. In the second and third designs, possible problems are predicted to occur on the center ring after filling (Figure 8). When the colors and values are evaluated, the filling point to be determined in the second and third designs will have points that will freeze early in the regions shown in red. Therefore, in case of production without thickening in the red regions of these designs, surface problems caused by the frozen layer will be observed.

In the comparison of the analyses of the joint lines, it is seen that Design 1 (8015-P1) is more risky than the other designs at this point (Figure 9).

Gate Location Concept Comprarion

Incorrect Gate design will create overheating and flow eruption problems. These problems will cause cosmetic defects and loss of strength in the part. The effect of different gate entry point design on molding parameters (Fill Time Analysis, Filling Pressure Analysis, Temperature Analysis, Shear Rate Analysis, Frozen Layer Analysis, Joint Line Analysis) for Design 2 and Design 3 specified in Table 2 was investigated. In both designs, the gate entry diameter

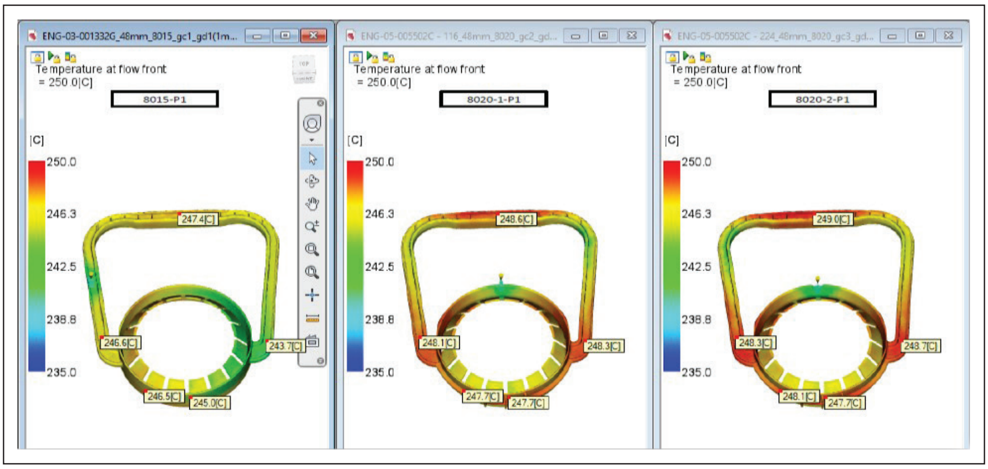


Figure 6. Temperature analysis.

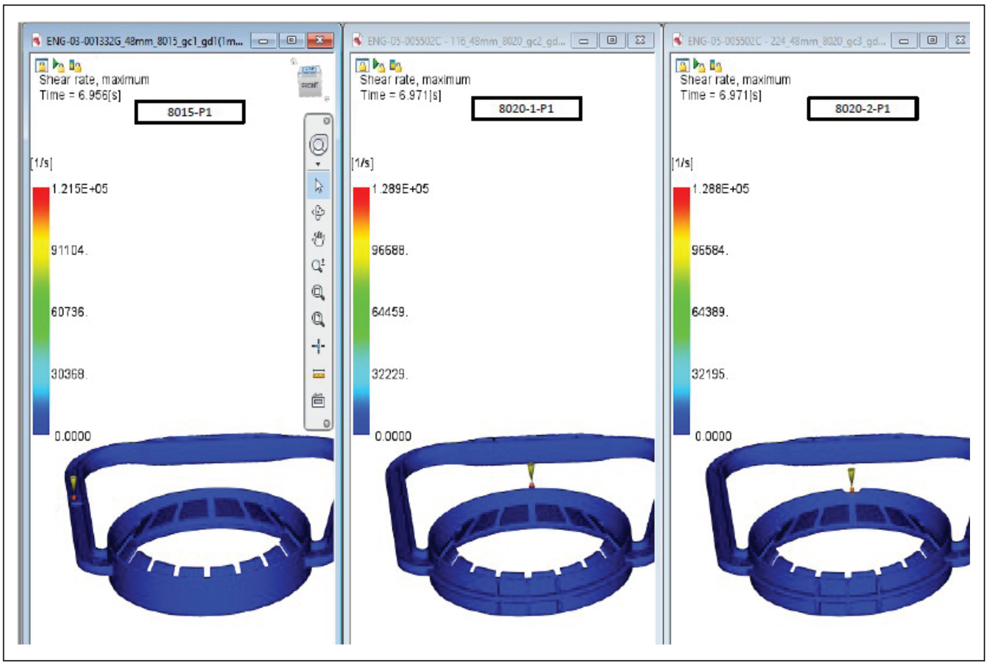


Figure 7. Shear rate analysis.

J Adv Manuf Eng, Vol. 4, No. 1, pp. 12–24, June, 2023

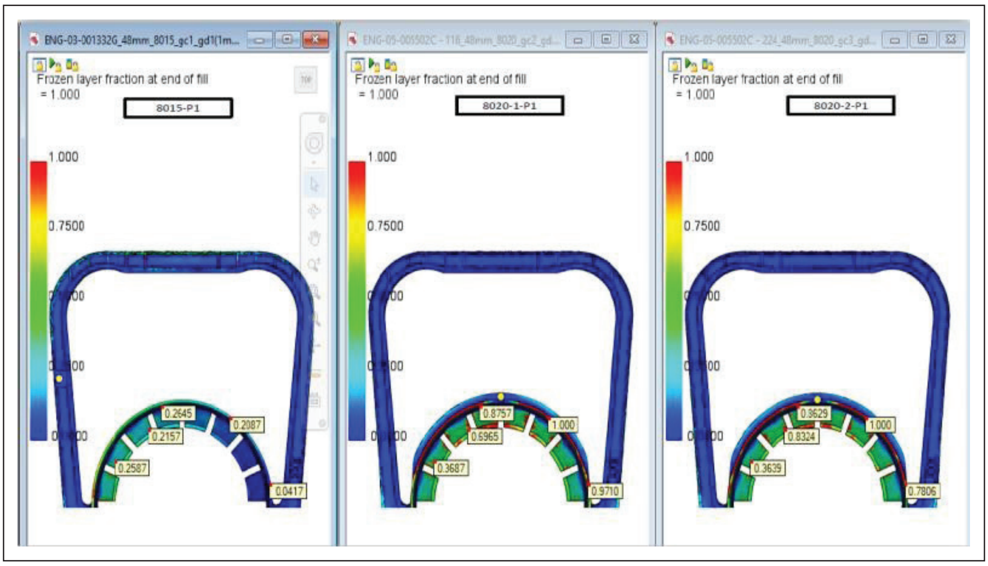


Figure 8. Frozen layer analysis.

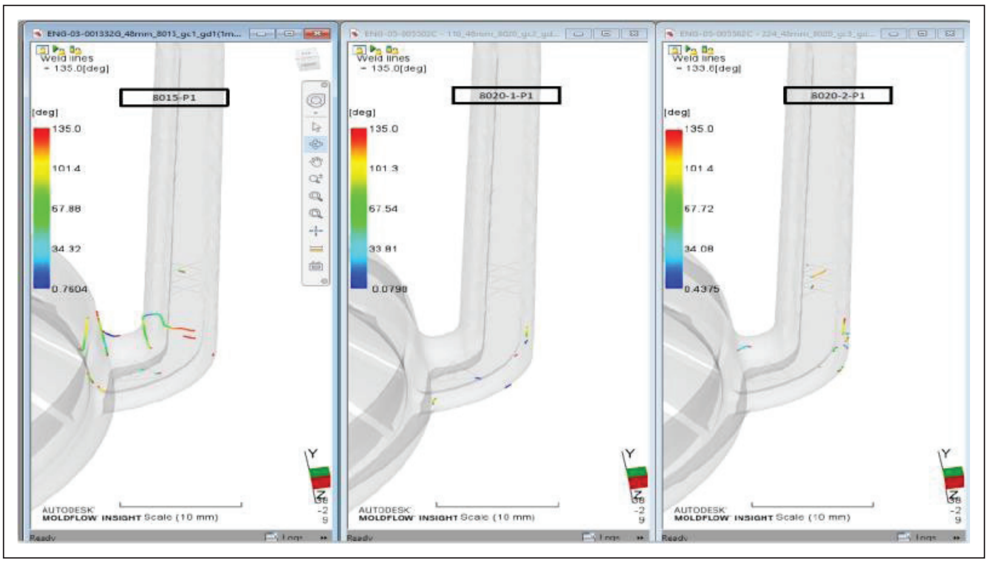


Figure 9. Joint line analysis.

on the part is 1 mm and an open end hot type gate is used (Figure 10).

As seen in Figure 4, there is no effect of the gate concept on the filling time. In Moayyedian (2017) study, the modified cross-section geometry did not affect the filling time [25]. Although there is a slight decrease in pressure in Design 2, the same pressure is valid for both designs (Figure 5). The temperature at the flow front (Figure 6), the shear rate value (Figure 7), and the frozen layer fraction at the end of the fill (Figure 8) are the same for both designs.

Joining lines are less visible in design 3 compared to Design 2 (Figure 9). In addition, according to the stress analysis, less weld line in the area where the damage will occur will ensure that the damage will occur later and at higher forces.

Gate Diameter Comparion

Filling time, Filling Pressure Analysis, Temperature Analysis, Shear Rate Analysis, Frozen Layer Analysis, Joint Line Analysis were performed for two versions of gate diameter selection, 1 mm and 1.3 mm. As can be seen in Figure 11, there is no difference for the diameter values selected for filling time. G1.3 version required filling pressure is 15%

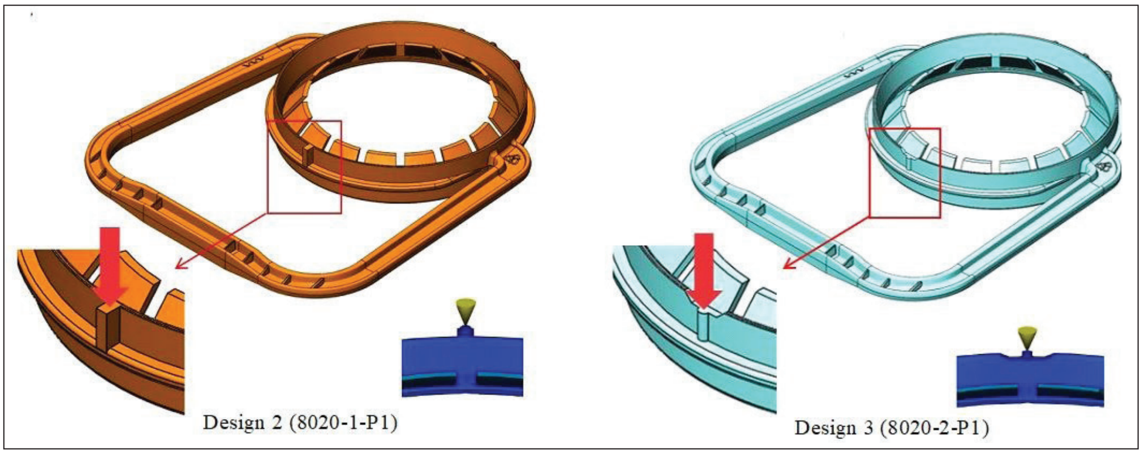


Figure 10. Gate concept design.

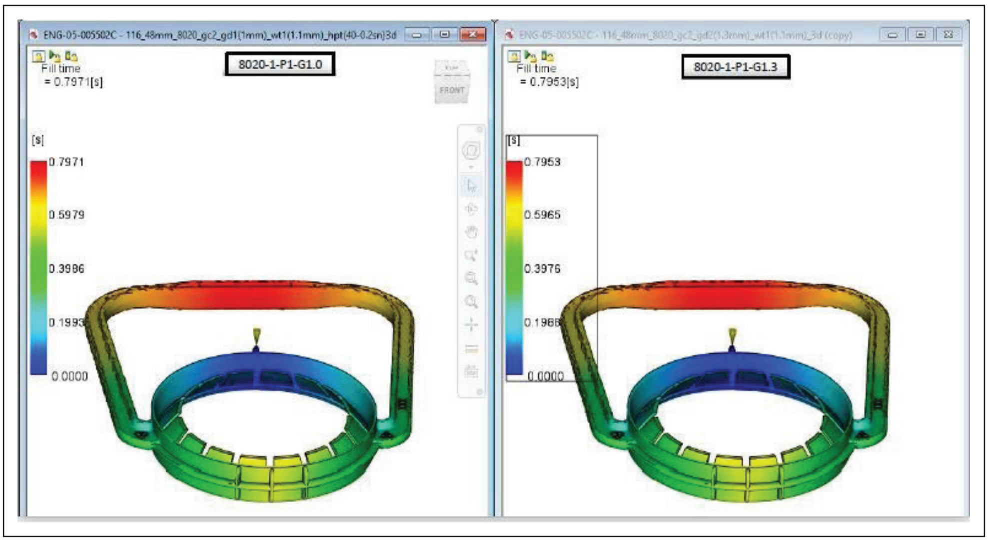


Figure 11. Effect of gate design on fill time analysis.

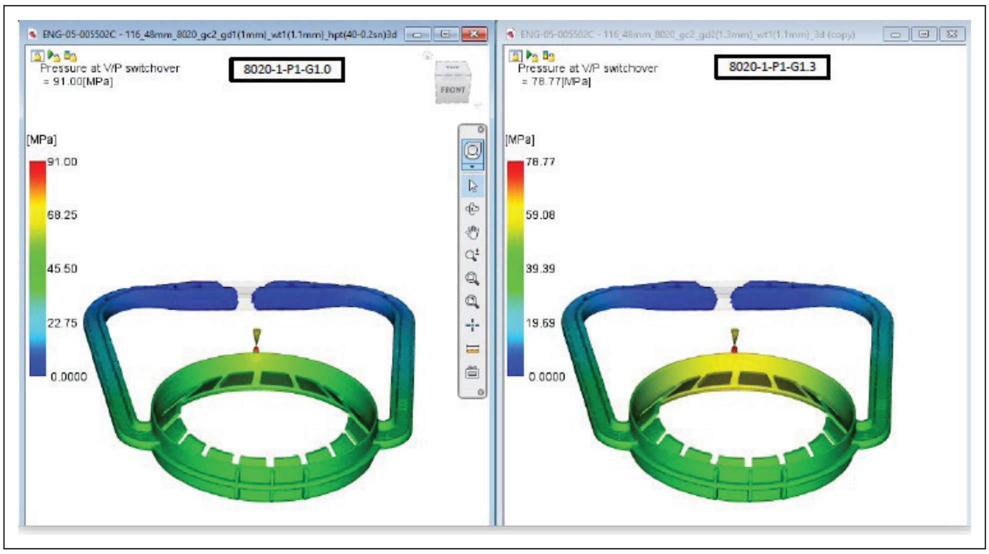


Figure 12. Effect of gate design on pressure.

less than G1.0 version (Figure 12). Temperature at Flow Front increased by 5 °C in G1.3 version while it increased by 10 °C for smaller gate diameter (Figure 13).

The G1.3 version has a more suitable maximum shear rate value compared to G1.0. There is not a major difference in the maximum shear rate at the resulton. However, for a 1mm gate, the shear rate is slightly lower than the other gate (Figure 14).

As seen in Figure 15, the frozen layer results at the end of fill are the same for both inlet diameters. Both version frozen layer fraction at end of fill result is not better on bottom ring portion.

Validation of the Designs

The change in breaking force for Design 1, Design 2 and Design 3 was determined by the tear test method designed according to the conditions of use. The experimentally obtained breaking force results are presented in Figure 16 in comparison with the weight values of the designed handles.

After determining the contact zones and fixed nodes for the handle in Figure 17, simulations were performed. Only the analysis results for Design 2 are given in Figure 18 and Figure 19. The experimentally obtained results and the theoretically obtained stress results are consistent with each

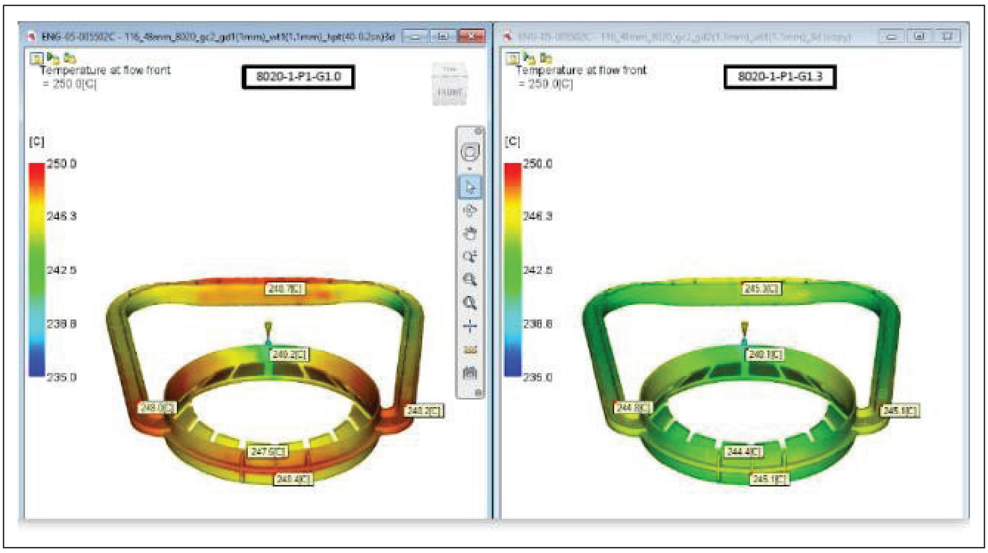


Figure 13. Effect of gate design on temperature.

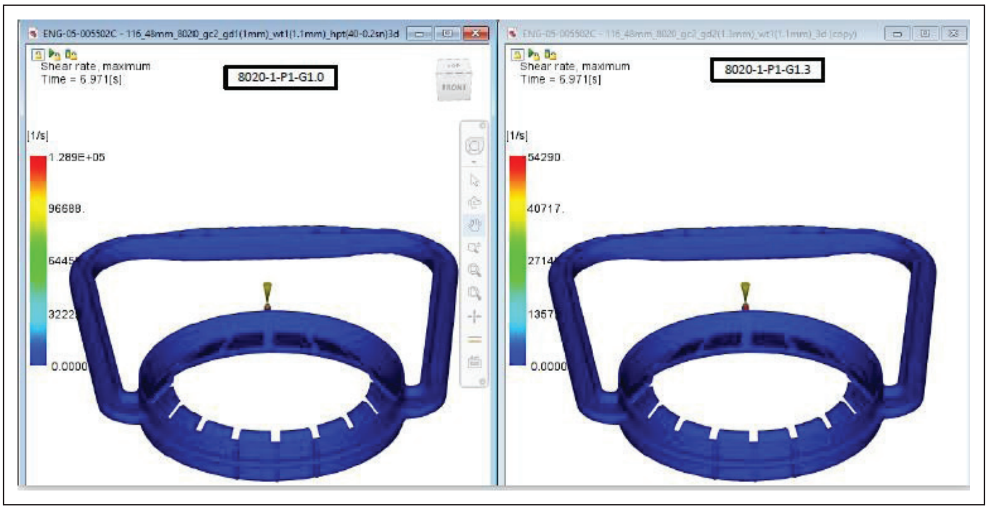


Figure 14. Effect of gate design on share rate.

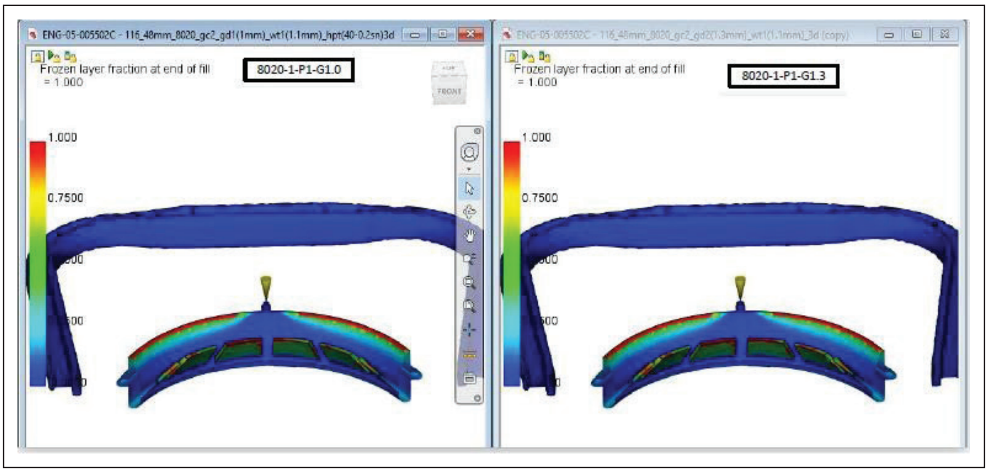


Figure 15. Effect of gate design on frozen layer at end of fill.

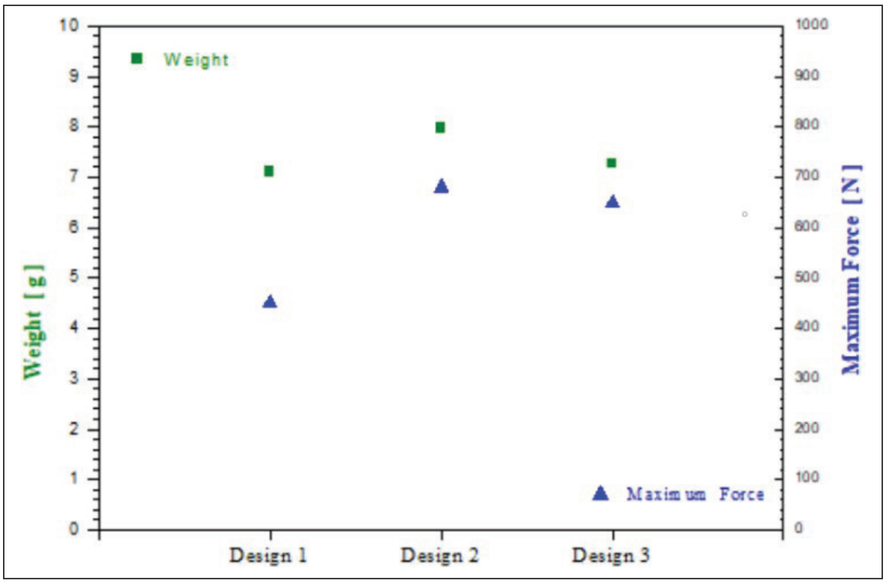


Figure 16. Effect of design changes on weight and breaking force.

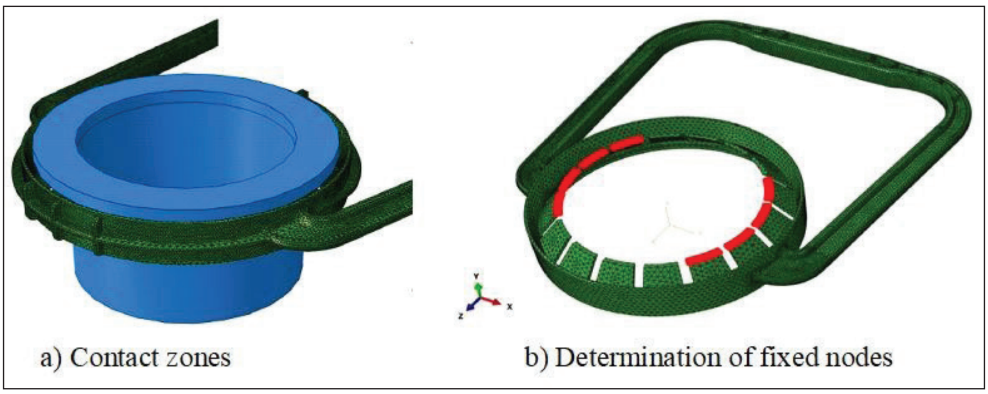


Figure 17. Modeling of the bottle handle based on cad data.

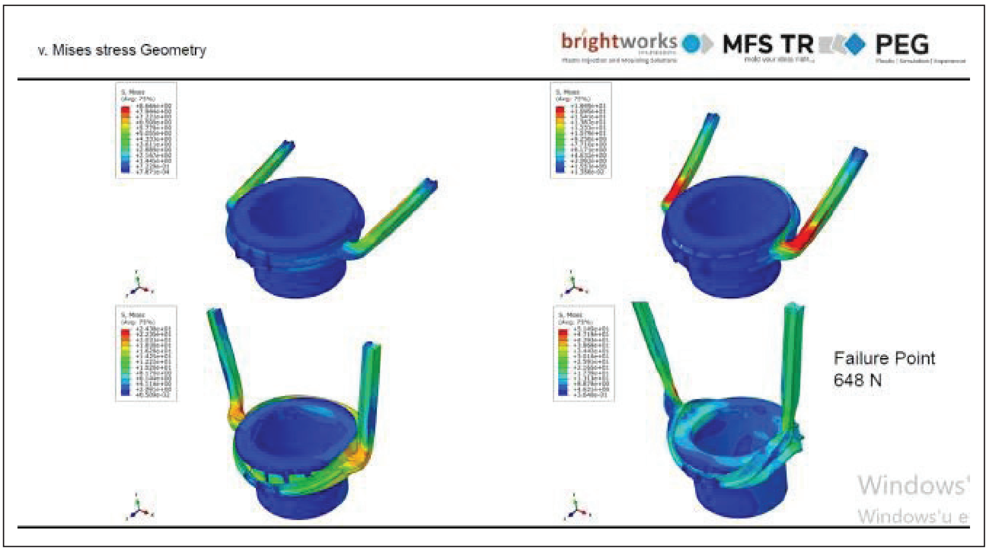


Figure 18. Stress analysis for design 2.

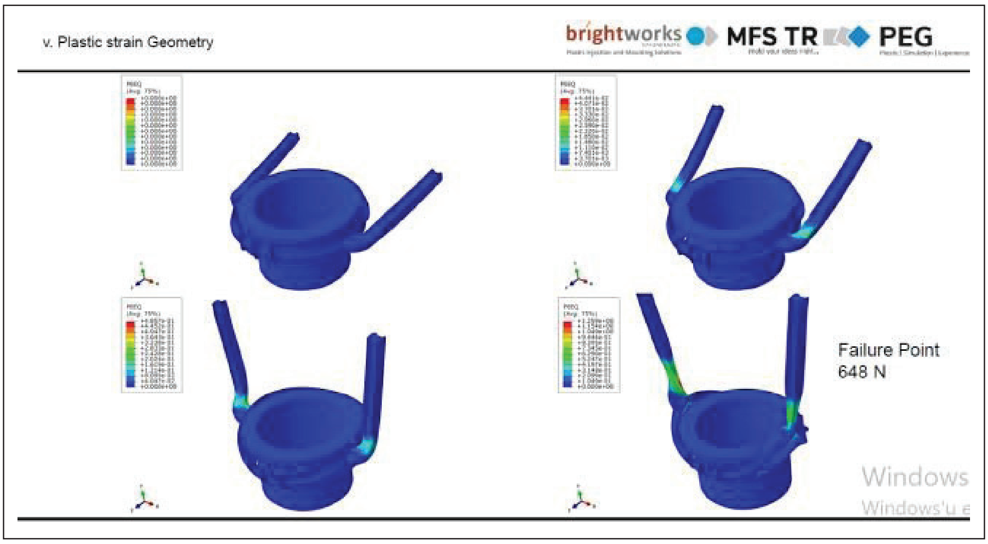


Figure 19. Strain analysis for design 2.

other. Figure 19 shows the permanent damage strain and damage zone at maximum force.

RESULTS

Plastic injection mold gate design plays a big role in ensuring mold quality and productivity. A correct gate design is an important factor in achieving perfect molds as opposed to imperfect ones. At the same time, the right injection mold gate design helps to reduce production costs and optimize cycle times.

In the filling pressure analysis, it was determined that Design 1 was advantageous as it was concluded that it could be filled at low pressure. In the temperature analysis, it was determined that all designs showed similar temperature values. In the frozen layer analysis, it was concluded that frozen layers could form on the ring for Design 2 and Design 3.

Despite all these advantages of Design 1, the joint line analysis showed that the joint line was formed at the point where the product would be forced to torsion, revealing that the risk of premature breakage of the handle in accordance with the load-bearing purpose was high. In addition, it was determined that the product did not fulfill its function in the experimental application of the design. Therefore, Design 2 and Design 3 are more advantageous than design 1. Design 2 was preferred because it provides a weight advantage compared to Design 3. Design 2 is more advantageous with a 44% increase in strength despite a 2.1% increase in weight. Similar to our study, Moayyedian (2017), who compared sprue and edge gates [24], found a reduction in the amount of material by changing the gate cross-section.

By using computer-aided engineering software to identify improvements in product and mold design, defects were predicted and designs were improved. In this way, designs could be optimized before mold costs were incurred.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author Contribution

Author 1 contributed to the literature review, realization of the design, writing the article, preparation of the test setups. Author 2 contributed to the formation of the idea, evaluation of the results obtained, writing supervision of the article. Author 3 contributed to the planning of the theoretical and experimental study and obtaining the results. Author 4 contributed to the literature review, writing the article, interpretation of the experimental results.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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