Minimizing Warpage and Shrinkage of Plastic Car Rear Bumper Fabrication via Simulation Based Optimisation

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Abstract. Car bumpers are designed to absorb small impacts, such as accidentally bumping into another car while backing off a parking spot, not major road accidents. As to make it lighter, plastic is the best available material. To fabricate it by injection molding, thin-wall and complex parts such as car bumper might create a lot of defects such as shrinkage and warpage. So, the stronger plastic material and correct optimized parameters should be applied. Butadiene Styrene (ABS) is selected in this study. This project aims to optimize the injection moulding process parameters of plastic car bumper by using Central Composite Design (CCD) in Response Surface Methodology. Mould temperature, melt temperature, injection time are selected as factors to be studied. As the results, the optimum values suggested by the software were mould temperature of 25°C, 226.36°C melt temperature and 1.88s injection time. The best material suggested is ABS. With small differences in error value between solution and simulation, 0.895% of shrinkage and 10.3% for warpage, the results were acceptable.

1. Introduction
Today's automobile industry is a strongly competitive industry. Customers want high-performance cars that are more convenient, comfortable, fuel efficient, elegant and economical. [1]. A safety improvement automobile is essential to decrease the number of accidents and injuries. A car bumper aim is to minimize the impact of minor accidents, thus preventing significant damage to a car and to the car that was hit or bumped into [2]. Plated steel was used before plastic was used to make a car's entire body including the bumper. This material worked well since it was very strong in a crash. As the design of automobiles has improved, steel bumpers are no longer used except for classic cars [3,4].

Steel is heavy and adds weight to the vehicle which can affect the ride quality of the vehicles [5,6,7,8]. Since the function of the car bumper is for protection from low-speed impact collision, the metal could be change to plastic as the material. Modern technology has discovered that plastics can be reinforced with some materials to create new/novel materials known as polymeric composites that have mechanical properties like metals, which are needed for car structural components.

Continuous innovation is a key component of automotive plastics utilization. Plastics will continue to help engineers innovate and drive car performance further in the next decade [9]. In injection moulding technology, numerous elements can be created in shorter cycle times thus, improvement of moulding parameter result is very vital for the trade. Warpage, shrinking, venting, residual stress and runner size area unit are among the factors that need to be studied before production [10].
In a recent study of plastic car bumpers, Seong Sik Cheon et al. investigated engineering plastic car bumpers that square measure typically plastic or polycarbonate / PBT alloy are used by most passenger cars to reduce the burden of cars and increase energy absorption capacity [11]. Karthikeyan et al. analysed for crashworthiness. Different bumper materials, such as ABS, E-glass epoxy resin, and polyamide-30% glass fibres, are compared in terms of efficiency. The impact and collision of a car was simulated and investigated in this study using ANSYS explicit dynamics, [12].

During the fabrication of injection moulding, complex parts such as car bumper might create a lot of defects such as shrinkage, warpage, and others. Defects always encounter in plastic part shape and affect the product quality, functionality and production cost. These elements are highly influenced by the decision making process in determining the optimal processing parameter [13,14,15]. Injection moulding plastic parts with defects such as shrinkage and warpage should be avoided because it will waste the resource and consume time in the industry.

Optimization process by simulation is the most effective method way to elucidate the appropriate processing parameters before the actual fabrication processes begin. Without a proper pre-processing stage, inappropriate mould design or parameter setting for processing could have a bad impact on moulded part appearance [16]. Response Surface Methodology is among the optimization method used for the application of automotive body structure, such as a car bumper [17,18,19]. The correct optimized parameter should be applied to make sure the fabrication of the bumper can run smoothly without any major defects.

2. Methodology
The design model of a rear car bumper is created in SolidWorks software based on the actual dimension of the rear car bumper as shown in Figure 1. Moldflow software is used for injection moulding simulation. Figure 2 shows the gate location of the rear car bumper.

Figure 1: 3D model of rear car bumper and gate location

2.1 Design of Experiment
Design Expert was used to analyse data. Mould temperature (A), melt temperature (B), injection time (C) are numerical factors and material is a categorical factor. The responses in this study are shrinkage (Y1) and Warpage (Y2). By using the Central Composite Design (CCD) of Response Surface Methodology method, a total of 40 runs were designed for the experiment based on Table 1.

| Factor         | Level 1 | Level 2 | Level 3 | Response       |
|----------------|---------|---------|---------|----------------|
| A Mould Temperature (°C) | 25      | 52.5    | 80      | Shrinkage (X)  |
| B Melt Temperature (°C)  | 200     | 240     | 280     | Warpage (Y)    |
| C Injection Time (s)      | 0.2     | 15.1    | 30      |

The analysis suggested quadratic as process order in this study. ANOVA provides a mathematical model for the predicted response of shrinkage and warpage. Based on the model, the predicted data will then produce will be compared with the experimental data to find the maximum and minimum
values of the responses. Then, the ANOVA analysis will determine the most recommended factor values to be simulated. Then, the result of the simulation will be compared with the predicted value to get the percentage difference. The result is accepted if the percentage difference is below 15%.

3. Results of Central Composite Design (CCD)
As shown in Table 2, the simulation was run with various melting temperatures, cooling times, and injection pressures to determine what factors affect shrinkage and warpage.

Table 2: Analytical comparison between simulation (X, Y) and model predicted (X1, Y1).

| No. | A    | B    | C    | Shrinkage, % (X) | Shrinkage, % (X1) | Percentage error (%) | Warpage (Y) | Warpage (Y1) | Percentage error (%) |
|-----|------|------|------|------------------|-------------------|---------------------|-------------|--------------|---------------------|
| 1   | 52.5 | 280  | 15.1 | 12.34           | 12.363            | 0.186               | 11.88       | 11.694       | 1.591               |
| 2   | 80   | 240  | 15.1 | 17.15           | 17.131            | 0.111               | 23.81       | 23.973       | 0.680               |
| 3   | 25   | 200  | 30   | 8.312           | 8.312             | 0.000               | 12.54       | 12.162       | 3.108               |
| 4   | 80   | 200  | 0.2  | 14.92           | 14.946            | 0.174               | 10.48       | 10.162       | 3.129               |
| 5   | 25   | 200  | 0.2  | 8.223           | 8.209             | 0.171               | 9.853       | 9.512        | 3.585               |
| 6   | 52.5 | 240  | 15.1 | 10.34           | 10.348            | 0.077               | 11.01       | 11.932       | 7.727               |
| 7   | 52.5 | 240  | 30   | 10.29           | 10.304            | 0.136               | 14.65       | 14.925       | 1.843               |
| 8   | 80   | 280  | 30   | 12.31           | 12.297            | 0.106               | 14.55       | 14.687       | 0.933               |
| 9   | 80   | 280  | 0.2  | 12.3            | 12.284            | 0.130               | 10.03       | 10.036       | 0.060               |
| 10  | 52.5 | 240  | 15.1 | 10.34           | 10.348            | 0.077               | 11.01       | 11.932       | 7.727               |
| 11  | 52.5 | 200  | 15.1 | 8.348           | 8.334             | 0.168               | 10.99       | 10.171       | 8.052               |
| 12  | 80   | 280  | 0.2  | 19.11           | 19.112            | 0.010               | 15.1        | 15.686       | 3.736               |
| 13  | 25   | 280  | 30   | 12.31           | 12.296            | 0.114               | 14.55       | 14.686       | 0.926               |
| 14  | 80   | 240  | 15.1 | 10.34           | 10.349            | 0.087               | 11.01       | 11.933       | 7.735               |
| 15  | 52.5 | 240  | 15.1 | 10.34           | 10.348            | 0.077               | 11.01       | 11.932       | 7.727               |
| 16  | 80   | 280  | 30   | 19.12           | 19.125            | 0.026               | 21.73       | 21.118       | 2.898               |
| 17  | 52.5 | 240  | 0.2  | 10.28           | 10.246            | 0.332               | 10.76       | 10.274       | 4.730               |
| 18  | 52.5 | 240  | 15.1 | 17.15           | 17.131            | 0.111               | 23.81       | 23.973       | 0.680               |
| 19  | 52.5 | 240  | 15.1 | 17.15           | 17.131            | 0.111               | 23.81       | 23.973       | 0.680               |
| 20  | 80   | 200  | 30   | 15.04           | 15.048            | 0.053               | 20.77       | 20.595       | 0.850               |
| Avg |      |      |      | 0.022           |                   |                     |             | Avg          | 0.625               |

3.1 Final equation in term of coded factor
Expert Design software generated shrinkage and warpage formulas as to calculate the predicted result as shown in Table 2. The equation given was in terms of coded factors then we can change in display option from actual value to a code value. In the formula, A stands for mould temperature, B for melt temperature and C for injection time.

Shrinkage = -1.97918 + 1.45455E-005A + 0.050927B (0.020880) (C) - 3.75419E-005BC - 3.28814E-004(C²)

Warpage = 3.60234 + 2.18182E-005A + 0.019040C + 0.50788C - 0.012761(C²)
In any form of simulation analysis, the accuracy of the simulation modelling and process is critical for reliable and accurate predictions. From the result shown in Table 1, the average percentage of error are within 0.02% to 0.6% and we can conclude the experimented value and predicted result was close and acceptable.

3.2 3D Surface Graph
The 3D Surface plot is a projection of the contour plot giving shape in addition to the colour and contour. Figure 2 shows the 3D surface model graph for shrinkage and warpage of rear car bumper. The lowest value of shrinkage is 8.2% and the lowest value of warpage is 7.5% when the melt temperature is 200°C and injection time at 0.2s.

![3D Surface Graph](image)

Figure 2: 3D surface model graphs of shrinkage and warpage

3.3 Optimisation of process parameter
Table 3 shows the optimum process parameter setting from Design Expert software. The factors such as mould temperature, melt temperature, injection time are in range. The responses of shrinkage and warpage are set as minimized. Design Expert has suggested minimum shrinkage value and minimum warpage value to achieve the best parameter setting. The mould temperature suggested is 25°C, the melt temperature is 226.36°C and injection time is 1.88s.

| Parameter       | Unit | Optimal Value |
|-----------------|------|---------------|
| Mould temperature | °C   | 25            |
| Melt temperature   | °C   | 226.36        |
| Injection time     | s    | 1.88          |

Table 3: Optimized value suggested by Design Expert

3.4 Validation
Table 4 shows the comparisons of responses between expected and simulation values. For volumetric shrinkage and warpage, the percentage difference between expected and simulation is just 0.89% and 10.37%, respectively. Since the difference in percentage between the two responses is less than 15%, the result can be approved.

| Response | Simulation | Predicted | Percentage difference % |
|----------|------------|-----------|-------------------------|
| Shrinkage| 9.657      | 9.571     | 0.895                   |
| Warpage  | 9.121      | 8.222     | 10.37                   |

Table 4: Result of error between predicted and simulation

Figure 3 shows the optimized simulation of shrinkage and warpage in car bumper. In shrinkage result, the green and the blue area is shown on the model are shows that the effect of volumetric shrinkage is low at 4.994% until 19.09%. In warpage result, the red colour area represents the highest probability of warpage at 22.91%. The yellow area shown on the model means the effect of
the warpage is significant at 12.98%. The green and the blue area on the model represent the lowest effects of warpage which are at -16.80% until 3.054%.

![Image of model with warpage percentage]

Figure 3: Optimized shrinkage and warpage result.

4. Conclusion
In this study, the optimization of rear car bumper fabrication process was simulated by utilising Response Surface Methodology as DOE. Mould temperature, melt temperature and injection time are factors that considered to minimize the shrinkage and warpage defects. By utilising Design Expert software, the optimum values for mould temperature is 25°C, melt temperature of 226.36°C and injection time is 1.88 s. Based on the suggested value, the optimum value of shrinkage and warpage were determined 9.657% and 9.121% in simulation Moldflow Software. With the discrepancy between model responses and simulation results was in the range of 0.02% to 0.6%, implies that reliable prediction can be achieved through the suggested model response. In final simulation run, small differences in error value between solution and simulation, 0.895% of shrinkage and 10.3% for warpage, which is below 15%, the results were satisfactory.

References

[1] Rosli, M., Ariffin, M., Sapuan, S., & Sulaiman, S. (2014). Survey of Malaysian Car owner needs of a Car Interior. International Journal of Mechanical & Mechatronics Engineering, 14(1), 62-69.
[2] Marzbanrad, J., Aljani, M., & Kiasat, M. S. (2009). Design and analysis of an automotive bumper beam in low-speed frontal crashes. Thin-walled structures, 47(8-9), 902-911.
[3] Vishwanatha, R. H., Ajith, A., Anand, N., B, P. R. K., & Kumar, V. (2018). Design and Strength Validation of Front Car Bumper Using Composite Material. International Research Journal of Engineering and Technology, 5(5), 3427-3434.
[4] Liu, Z., Lu, J., & Zhu, P. (2016). Lightweight design of automotive composite bumper system using modified particle swarm optimizer. Composite Structures, 140, 630–643.
[5] Rosli, M. U., Ariffin, M. K. A., Sapuan, S. M., & Sulaiman, S. (2013). Integrated AHP-TRIZ innovation method for automotive door panel design. Int. J. Eng. Technol, 5(3), 3158-3167.
[6] Beyene, A. T., Koricho, E. G., Belingardi, G., & Martorana, B. (2014). Design and manufacturing issues in the development of lightweight solution for a vehicle frontal bumper. Procedia Engineering, 88, 77–84.
[7] Rosli, M. U., Ariffin, M. K. A., Sapuan, S. M., & Sulaiman, S. (2013). Integrating TRIZ and AHP: A MPV” s Utility Compartiment Improvement Design Concepts. International Journal of Materials, Mechanics and Manufacturing, 1(1), 32-35.
[8] Cheon, S. S., Choi, J. H., & Lee, D. G. (1995). Development of the composite bumper for passenger cars. Composite Structures, 32(1-4), 491–499.
[9] Rosli, M. U., Jamalludin, M. R., Khor, C. Y., Ishak, M. I., Jahidi, H., Wasir, N. Y., ... & Ismail, R. I. (2017). Analytical hierarchy process for natural fiber composites automotive armrest thermoset matrix selection. In MATEC Web of Conferences (Vol. 97, p. 01039). EDP Sciences.
[10] Rosli, M. U., Ishak, M. I., Jamalludin, M. R., Khor, C. Y., Nawi, M. A. M., & Syafiq, A. M. (2019, August). Simulation-Based Optimization of Plastic Injection Molding Parameter for Aircraft Part Fabrication Using Response Surface Methodology (RSM). In IOP Conference Series: Materials Science and Engineering (Vol. 551, No. 1, p. 012108). IOP Publishing.

[11] Cheon, S. S., Choi, J. H., & Lee, D. G. (1995). Development of the composite bumper for passenger cars. Composite Structures, 32(1–4), 491–499.

[12] Karthikeyan, M., Jenarthanan, M. P., Giridharan, R., & Shunmugesh, K. (2019). Investigation on crash analysis of a frontal car bumper. Transactions of the Indian Institute of Metals, 72(10), 2699-2709.

[13] Rosli M U, Ariffin M K A, Sapuan S M and Sulaiman S (2014) Integrated TRIZ-AHP support system for conceptual design Applied Mechanics and Materials vol 548–549 (Trans Tech Publications) pp 1998–2002

[14] Che Hassan M F, Mohd Rosli M U and Mohd Redzuan M A (2018) Material selection in a sustainable manufacturing practice of a badminton racket frame using Elimination and Choice Expressing Reality (ELECTRE) Method J. Phys. Conf. Ser. 1020

[15] Khan B, Rosli M U, Jahidi H, Ishak M I, Jamalludin M R, Khor C Y, Faizal W M, Rahim W M and Nawi M A M 2017 Effect of zinc addition on the performance of aluminium alloy sacrificial anode for marine application AIP Conference Proceedings vol 1885 (American Institute of Physics Inc.)

[16] Khor, C. Y., Ishak, M. I., Rosli, M. U., Jamalludin, M. R., Zakaria, M. S., Yamin, A. F. M., ... & Abdullah, M. Z. (2017). Influence of material properties on the fluid-structure interaction aspects during molded underfill process. In MATEC Web of Conferences (Vol. 97, p. 01059). EDP Sciences.

[17] Chen, W. C., Nguyen, M. H., Chiu, W. H., Chen, T. N., & Tai, P. H. (2016). Optimization of the plastic injection molding process using the Taguchi method, RSM, and hybrid GA-PSO. International Journal of Advanced Manufacturing Technology, 83(9–12), 1873–1886.

[18] Rosli, M. U., Termizi, S. A., Khor, C. Y., Nawi, M. A. M., Omar, A. A., & Ishak, M. I. (2020, June). Simulation Based Optimization of Thin Wall Injection Molding Parameter Using Response Surface Methodology. In IOP Conference Series: Materials Science and Engineering (Vol. 864, No. 1, p. 012193). IOP Publishing.

[19] Arunkumar, N., Venkatesh, P., Srinivas, K. S., & Kaushik, S. (2012). Response surface modeling and optimization of single axis automatic application of automotive polyurethane coatings on plastic components. International Journal of Advanced Manufacturing Technology, 63(9–12), 1065–1072.