Simulation-Based Optimization of Plastic Injection Molding Parameter for Automotive Car Wheel Fabrication Using Response Surface Methodology (RSM)

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Abstract. In the era of revolution industry 4.0, most companies can expect metal-to-plastic conversion to result in cost savings. The objectives of this study are to find the most appropriate material composition and the injection molding process parameter to produce a plastic car wheel as a substitute for metal and aluminum alloy. The Polyetherimide (PEI) with different compositions are simulated using MoldFlow software and optimized the quality of injection molding process parameter by using Central Composite Design (CCD) in Response Surface Methodology (RSM) as to get an optimal response and meets the car wheel requirement specification. The crucial factors are melting temperature, injection time and cooling time. The quadratic model fits the model response. As the results, the optimum values suggested by the software were melt temperature of 370.27°C, 1.8s of injection time and 2599.89s of cooling time for 0% of filler (pure PEI). With small differences error value between solution and simulation, 0.1% of shrinkage and 0.9% for warpage, the results were acceptable.

1. Introduction
In the automotive industry, there are many kinds of parts are available from the metal and plastic. Each of the parts has its own unique features and reason. The automotive industry keeps developing many technologies. It improves the performance, efficiency, and safety of the vehicles [1-5]. Most of the body parts use steel and aluminum alloy as their main or common material [6-10]. Apart from chassis to body part uses steel and metal because as for chassis; they can withstand a great impact if they got into a collision [11,12]. Aluminum alloy commonly used for the selected part in the vehicles to reduce its weight while maintaining its strength [13-15]. For the engine component, most of the manufacturers nowadays use the part from ceramics which is because they can withstand a higher temperature rather than steel [16]. The selection of plastic part will reduce the weight of the current part hence reducing the total weight of the car itself. While reducing the weight of the car, power efficiency will be higher because less power needed to move the car. Simulation based optimization is the most effective way to study the strength of plastic car wheel before the actual fabrication processes begin [17,18]. The injection molding parameters are to determine the most significant factor and accurate molding process parameter setting [19,20].

2. Methodology
2.1 Design
The design model of a car wheel is created in SolidWorks 2016 software. The diameter of the wheel is 14 inches or 35.56 cm and the width is 5 inches or 12.7 cm shown in Figure 1.
2.2 Numerical Factor
The processing parameters that are selected are melting temperature (A), molding temperature (B), and injection pressure (C). The factor selection is shown in Table 1. These parameters are selected because the value of three of them can be adjusted using Moldflow simulation. These factors will analyse the interaction with the response. Minimum and maximum level are based on the combination of the three materials. That means all factors of these three materials are in the range of level 1 to level 3.

| Column | Factor                  | Level 1 | Level 2 | Level 3 |
|--------|-------------------------|---------|---------|---------|
| A      | Melting temperature (°C)| 366 °C  | 385 °C  | 404 °C  |
| B      | Injection time (s)      | 1.8 s   | 2.85 s  | 3.9 s   |
| C      | Cooling time (s)        | 1450 s  | 2025 s  | 2600 s  |

2.3 Categorical Factor
The chosen material is Polyetherimide (PEI). PEI is selected because of its characteristics are capable of high strength and at high temperature. There are three composites of PEI are chosen. PEI without filler, PEI with 10% carbon fiber high strength and PEI with 20% carbon fiber high strength.

2.4 Response Selection
Two responses have been selected which is volumetric shrinkage and warpage. High volumetric shrinkage can cause part warpage, sink marks, critical dimensions that are too small, and internal voids [18,19]. Excessive wall thickness and inadequate packing can both contribute to high volumetric shrinkage in a part. Warpage can cause the surface of the final product do not follow the designated shape [21,22]. Warpage resulted from molded-in residual stresses, which is affected by the shrinkage in the molded part.

3. Results and Discussion
The experiments were conducted to run the simulation using Moldflow software simulation. The experiment was conducted under difference melt temperature, injection time and cooling time to control the response control which is volumetric shrinkage (Y1) and warpage (Y2). The numerical run that generated from Design Expert software totalled of 60 times with 15 of them have same value whilst 45 of them have different value order of processing parameters.

3.1 Results of central composite design (CCD)
There are three minimum values of volumetric shrinkage from all 60 simulations, which is run number 2, 29 and 58. While the value of maximum volumetric shrinkage is at run number 22. For the minimum and maximum values of warpage, the minimum is at run number 19. While the values of maximum volumetric shrinkage are at run number 49 and 58.
The significant factor for shrinkage for all is needed. In this study, the minimum value of the response volumetric shrinkage and warpage are the important goals that need to achieve. The 3D surface plot can display the maximum or minimum value need to get the most optimal results for shrinkage and warpage. The 3D surface response and contour plots of the warpage and shrinkage were plotted using Design Expert software to study the interactive relationship between each factor and responses. In the 3D surface response, the selection of two variables and a constant variable was determined according to the level of sensitivity towards the responses that depended on the perturbation plots. The significant factor for shrinkage for all the three materials is melting temperature and injection time. To find the most optimize results which are the lowest value of shrinkage, lower melt temperature and higher injection time were needed. In Figure 2 shows the most optimal results for shrinkage is at 366°C and 3.9s.

### Table 2. Result of CCD.

| #  | Parameters |   |   |   | Parameters |
|----|------------|---|---|---|------------|
|    | A          | B | C | D (%) | Y1 | Y2      |
|----|------------|---|---|-------|----|--------|
| 1  | 385        | 2.85 | 2025 | 20 | 12.91 | 2.68 | 31 | 385 | 1.8 | 2025 | 0   | 13.01 | 2.64 |
| 2  | 366        | 3.9  | 2600 | 10 | 11.96 | 3.27 | 32 | 385 | 2.85 | 2025 | 0   | 12.92 | 2.69 |
| 3  | 404        | 2.85 | 2025 | 20 | 13.74 | 2.16 | 33 | 385 | 2.85 | 2025 | 0   | 12.91 | 2.69 |
| 4  | 385        | 2.85 | 2025 | 10 | 12.92 | 2.69 | 34 | 366 | 1.8  | 1450 | 0   | 12.07 | 2.90 |
| 5  | 385        | 2.85 | 2025 | 20 | 12.91 | 2.68 | 35 | 404 | 2.85 | 2025 | 10  | 13.75 | 2.16 |
| 6  | 366        | 1.8  | 2600 | 20 | 12.06 | 2.89 | 36 | 404 | 1.8  | 1450 | 0   | 13.87 | 2.40 |
| 7  | 385        | 2.85 | 2025 | 20 | 12.91 | 2.68 | 37 | 366 | 3.9  | 1450 | 20  | 11.97 | 2.37 |
| 8  | 404        | 3.9  | 2600 |  0 | 13.68 | 2.33 | 38 | 366 | 1.8  | 1450 | 20  | 12.07 | 2.89 |
| 9  | 385        | 2.85 | 2600 | 10 | 12.91 | 2.68 | 39 | 385 | 2.85 | 2025 | 10  | 12.92 | 2.69 |
| 10 | 366        | 1.8  | 2600 | 10 | 12.06 | 2.89 | 40 | 366 | 1.8  | 2600 | 0   | 12.06 | 2.89 |
| 11 | 385        | 2.85 | 2025 | 10 | 12.92 | 2.69 | 41 | 385 | 2.85 | 2025 | 0   | 12.91 | 2.69 |
| 12 | 385        | 2.85 | 1450| 10 | 12.92 | 2.69 | 42 | 385 | 2.85 | 2025 | 0   | 12.91 | 2.69 |
| 13 | 404        | 3.9  | 2600 | 20 | 13.68 | 2.32 | 43 | 404 | 3.9  | 1450 | 0   | 13.68 | 2.33 |
| 14 | 385        | 2.85 | 2600 |  0 | 12.91 | 2.68 | 44 | 366 | 2.85 | 2025 | 0   | 12   | 3.15 |
| 15 | 385        | 3.9  | 2025 | 20 | 12.85 | 2.65 | 45 | 404 | 3.9  | 1450 | 10  | 13.68 | 2.34 |
| 16 | 385        | 2.85 | 2025 |  0 | 12.91 | 2.69 | 46 | 385 | 3.9  | 2025 | 10  | 12.85 | 2.66 |
| 17 | 366        | 1.8  | 1450| 10 | 12.07 | 2.89 | 47 | 385 | 2.85 | 2025 | 20  | 12.91 | 2.68 |
| 18 | 385        | 2.85 | 2025 | 10 | 12.92 | 2.69 | 48 | 385 | 2.85 | 2025 | 10  | 12.92 | 2.69 |
| 19 | 404        | 2.85 | 2025 |  0 | 13.74 | 2.15 | 49 | 366 | 3.9  | 1450 | 0   | 11.97 | 3.28 |
| 20 | 366        | 2.85 | 2025 | 10 | 12.01 | 3.15 | 50 | 385 | 2.85 | 1450 | 0   | 12.92 | 2.69 |
| 21 | 385        | 2.85 | 2025 |  0 | 12.91 | 2.69 | 51 | 404 | 3.9  | 1450 | 20  | 13.68 | 2.32 |
| 22 | 404        | 1.8  | 1450| 10 | 13.88 | 2.41 | 52 | 385 | 3.9  | 2025 | 0   | 12.85 | 2.65 |
| 23 | 404        | 1.8  | 1450| 20 | 13.87 | 2.40 | 53 | 385 | 1.8  | 2025 | 20  | 13.01 | 2.63 |
| 24 | 385        | 2.85 | 2025 | 20 | 12.91 | 2.68 | 54 | 385 | 2.85 | 2025 | 0   | 13.01 | 2.64 |
| 25 | 385        | 2.85 | 2025 | 20 | 12.91 | 2.68 | 55 | 366 | 3.9  | 2600 | 0   | 11.97 | 3.17 |
| 26 | 404        | 1.8  | 2600| 10 | 13.85 | 2.40 | 56 | 385 | 2.85 | 2025 | 0   | 12.91 | 2.69 |
| 27 | 404        | 1.8  | 2600|  0 | 13.85 | 2.38 | 57 | 404 | 1.8  | 2600 | 20  | 13.85 | 2.40 |
| 28 | 385        | 2.85 | 2600| 20 | 12.91 | 2.69 | 58 | 366 | 3.9  | 1450 | 10  | 11.96 | 3.28 |
| 29 | 366        | 3.9  | 2600| 20 | 11.96 | 3.27 | 59 | 366 | 2.85 | 2025 | 20  | 12   | 3.15 |
| 30 | 404        | 3.9  | 2600| 10 | 13.68 | 2.33 | 60 | 385 | 2.85 | 1450 | 20  | 12.92 | 2.69 |
As for warpage, the significant factor for all the three materials is also melting temperature and injection time. To find the lowest value of warpage, melting temperature needs to be high and the injection time likewise needs to be set to high setting. In Figure 3, it shows the lowest value of the warpage is when melting temperature at 404°C and injection time at 3.9s.

3.3 Optimization of design parameters
Table 3 shows the suggested optimized value suggest by Design Expert. The factors are put in range according to the design ranges. The shrinkage and warpage values of selected solutions are 12.27768% and 2.829566mm respectively. To minimize the responses, a simulation by Moldflow software need to be done by using the suggested parameters which are melting temperature = 370.27 c, injection time = 1.8 s mm and cooling time = 2599.89 s with 0% percentage of filler (pure PEI).

| A     | B     | C        | D                        | Shrinkage   | Warpage   |
|-------|-------|----------|--------------------------|-------------|-----------|
| 370.27| 1.8   | 2599.98  | No filler                | 12.27768%   | 2.829566  |

3.4 Validation of simulation result
The comparisons of responses between the predicted and simulation values are shown in Table 4.

| Response     | Predicted | Simulation | % Difference |
|--------------|-----------|------------|--------------|
| Volumetric   | 12.27768% | 12.29%     | 0.1          |
| Shrinkage    |           |            |              |
| Warpage      | 2.829566mm| 2.803mm    | 0.94         |
The values of the percentage difference between predicted and simulation for volumetric shrinkage and warpage are only 0.1% and 0.9% respectively. The percentage difference between the two responses are small, therefore the result can be accepted. The result of volumetric shrinkage and warpage may not be lowest by individuals, but by combining two of the responses together, the result is the lowest compared to all 60 runs. In summary, we can conclude that the optimum values for each factor were determined by RSM.

4. Conclusions

In conclusion, the most significant factors and interaction relationship of plastic wheel parameter towards the strength of the plastic wheel have been evaluated. The optimum values suggested by DesignExpert software were melting temperature = 370.27°C, injection time = 1.8 s mm and cooling time = 2599.89 s with 0% percentage of filler (pure PEI). The values of the percentage difference between predicted and simulation for volumetric shrinkage and warpage are only 0.1% and 0.9% respectively. With the percentage of error value is small, thus the result is acceptable. In this case, cooling time does not affect the value of volumetric shrinkage and warpage.

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