Numerically design the injection process parameters of parts fabricated with ramie fiber reinforced green composites

L P Chen¹, L P He¹,², D C Chen¹, G Lu¹, W J Li¹ and J M Yuan¹,³

¹ State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan 410082, P.R. China.
² College of Civil Engineering, Hunan University, Changsha, Hunan 410082, P.R. China
³ College of Materials Science and Engineering, Hunan University, Changsha, Hunan 410082, P.R. China
E-mail: lphe@hnu.edu.cn

Abstract. The warpage deformation plays an important role on the performance of automobile interior components fabricated with natural fiber reinforced composites. The present work investigated the influence of process parameters on the warpage behavior of A pillar trim made of ramie fiber (RF) reinforced polypropylene (PP) composites (RF/PP) via numerical simulation with orthogonal experiment method and range analysis. The results indicated that fiber addition and packing pressure were the most important factors affecting warpage. The A pillar trim can achieved the minimum warpage value as of 2.124 mm under the optimum parameters. The optimal process parameters are: 70% percent of the default value of injection pressure for the packing pressure, 20 wt% for the fiber addition, 185 °C for the melt temperature, 65 °C for the mold temperature, 7 s for the filling time and 17 s for the packing time.

1. Introduction
Along with the increasingly environmental pollution, natural fiber-reinforced polymer composites have received widely concern, especially in automotive industry. By comparison with synthetic fibers, natural fiber exhibits significant advantages, such as lower cost, high specific modulus and environmental friendliness [1-3]. Recently many researchers focus on using the natural fibers such as lignocellulosic fillers to replace glass fiber filler. Ramie fiber (RF) is a kind of natural fiber and its production is quite big in China [4]. Thus, more and more researches were carried out for the ramie fiber reinforced composites. So far, lots of work [5-8] aimed to obtain the good interfacial adhesion property of the composites through the pretreatment of ramie fiber. Limited work [9-10] tried to investigate the influence of process parameters on the performance of industry products.

Injection molding possess has been widely used to manufacture automotive parts, particularly for automotive interiors, which are made of polymer and polymer-matrix composites. The qualities of injection-molding parts were ordinarily influenced by the materials, the geometry of the parts, mold design and the process parameters. Warping deformation is one of the significant criteria for evaluating the quality of injection-molding parts [11-13]. Recently, many researchers were interested in investigating the warpage of parts made of natural fiber-reinforced composites. This is because...
fiber-reinforced composites are more and more widely used in various fields. Rahman et al. [14] investigated the window frame fabricated with the natural fibers by using the Moldflow Software. They reckoned that the natural fiber composite material was suitable to manufacture window frame. Azaman et al. [15, 16] evaluated the warpage of a molded thin-walled part composed of wood-filled polypropylene (PP) composites during the injection-molded process under different process conditions and fiber addition percentages. The optimum process parameters and minimum warpage were investigated, and the results showed that cooling time and packing time had less effect on warpage. Anyway, so far no simulation work addresses the parts made of ramie fiber-filled PP composites. Therefore, this work numerically eco-design the injection process parameters in order to obtain a minimum warpage deformation of A pillar trim made of ramie fiber (RF) reinforced polypropylene (PP) composites (RF/PP) with fiber aspect ratio of 20.

2. Materials and methodology

2.1. Materials
In this work, the short ramie fiber (RF) with fiber aspect ratio of 20 was used as the filler, and the polypropylene (PP) used as the matrix. The RF/PP green composites were applied to fabricate automobile A pillar trim using injection-molding process. The properties of PP were obtained from the materials database of Autodesk Moldflow as shown in Table 1. The tested properties of degummed ramie fiber were also listed, which are consistent with that reported in literature [17].

| Properties                          | PP     | Ramie fiber |
|-------------------------------------|--------|-------------|
| (Melt) Density (g/cm³)              | 0.862  | 1.50        |
| Elastic modulus (MPa)               | 1,340  | 90,000      |
| Poisson’s ratio                     | 0.4    | 0.3         |
| Tensile Strength (MPa)              | —      | 900         |
| Recommended melt temperature (℃)    | 190    | —           |
| Recommended mold temperature (℃)    | 50     | —           |
| Fiber addition (wt%)                | —      | 10-40       |

2.2. Simulation model details
An automotive A pillar trim model was established using Unigraphics NX, with dimensions of $680 \times 81 \times 17$ mm, and a thickness of 3 mm. The 3D model is shown in Figure 1.
The warpage of A pillar trim made of RF/PP were simulated and investigated using the software Autodesk Moldflow. The simulation model was established with Moldflow software based on standard design guidelines, including a sprue, a runner and a cooling system [14], which is shown in Figure 2. The analysis model applied fusion mesh type and consisted of 8122 triangular elements.

After the establishment of the injection-molding system model, it was necessary to verify its reliability. So, a simulation was conducted through using the material parameters given in Table 1, and the mold temperature and melt temperature were set with recommended value in Table 1. The simulation results were obtained, such as the filling time, the temperature at flow front, weld line distribution and so on, which manifested that the established injection-molding system model was reasonable.

![Figure 2. Simulation model of the injection-molding system.](image)

### 2.3. Simulation and orthogonal experiment design

The orthogonal experiment method was applied in order to achieved the minimal warpage of the A pillar trim. The parameters used for evaluating the warpage behaviors were the packing pressure (A), melt temperature (B), mold temperature (C), filling time (D), packing time (E) and fiber addition (F). The values of these parameters were listed in Table 2, in which packing pressure was given by the percent of the default value of injection pressure. The four levels for the six process parameters were designed as an $L_{32} (4^3)$ orthogonal array, with 32 trials.

| Levels | A-Packing pressure (%) | B-Melt Temperature (°C) | C-Mold temperature (°C) | D-Filling time (s) | C-Packing time (s) | F-Fiber content (%) |
|--------|------------------------|-------------------------|-------------------------|-------------------|-------------------|--------------------|
| 1      | 70                     | 180                     | 50                      | 5                 | 17                | 10                 |
| 2      | 80                     | 185                     | 55                      | 6                 | 19                | 20                 |
| 3      | 90                     | 190                     | 60                      | 7                 | 21                | 30                 |
| 4      | 100                    | 195                     | 65                      | 8                 | 23                | 40                 |

### 3. Orthogonal experiment results and discussion

#### 3.1. Warpage results of each group

The warpage results of the 32 trials are presented in Table 3. It can be found that the warpage of the A pillar trim varied in the range of 2.2-6.1 mm when various parameters are used. Therefore, it is necessary to optimize the parameters in order to obtain the minimal warping deformation.
Table 3. Warpage results of 32 trials.

| Trials number | A   | B   | C   | D   | E   | F   | Warpage |
|---------------|-----|-----|-----|-----|-----|-----|---------|
| 1             | 1   | 1   | 1   | 1   | 1   | 1   | 3.945   |
| 2             | 1   | 2   | 2   | 2   | 2   | 2   | 2.221   |
| 3             | 1   | 3   | 3   | 3   | 3   | 3   | 2.461   |
| 4             | 1   | 4   | 4   | 4   | 4   | 4   | 2.962   |
| 5             | 2   | 1   | 1   | 2   | 2   | 3   | 3.276   |
| 6             | 2   | 2   | 2   | 1   | 1   | 4   | 3.234   |
| 7             | 2   | 3   | 3   | 4   | 4   | 1   | 4.701   |
| 8             | 2   | 4   | 4   | 3   | 3   | 2   | 2.633   |
| 9             | 3   | 1   | 2   | 3   | 4   | 2   | 3.124   |
| 10            | 3   | 2   | 1   | 4   | 3   | 1   | 5.226   |
| 11            | 3   | 3   | 4   | 1   | 2   | 4   | 4.312   |
| 12            | 3   | 4   | 3   | 2   | 1   | 3   | 3.588   |
| 13            | 4   | 1   | 2   | 4   | 3   | 4   | 3.796   |
| 14            | 4   | 2   | 1   | 3   | 4   | 3   | 3.398   |
| 15            | 4   | 3   | 4   | 2   | 1   | 2   | 3.365   |
| 16            | 4   | 4   | 3   | 1   | 2   | 1   | 6.082   |
| 17            | 1   | 1   | 4   | 1   | 4   | 3   | 2.421   |
| 18            | 1   | 2   | 3   | 2   | 3   | 4   | 2.996   |
| 19            | 1   | 3   | 2   | 3   | 2   | 1   | 3.847   |
| 20            | 1   | 4   | 1   | 4   | 1   | 2   | 2.337   |
| 21            | 2   | 1   | 4   | 2   | 3   | 1   | 4.861   |
| 22            | 2   | 2   | 3   | 1   | 4   | 2   | 2.610   |
| 23            | 2   | 3   | 2   | 4   | 1   | 3   | 2.852   |
| 24            | 2   | 4   | 1   | 3   | 2   | 4   | 3.267   |
| 25            | 3   | 1   | 3   | 3   | 1   | 4   | 4.026   |
| 26            | 3   | 2   | 4   | 4   | 2   | 3   | 3.122   |
| 27            | 3   | 3   | 1   | 1   | 3   | 2   | 3.514   |
| 28            | 3   | 4   | 2   | 2   | 4   | 1   | 5.474   |
| 29            | 4   | 1   | 3   | 4   | 2   | 2   | 2.804   |
| 30            | 4   | 2   | 4   | 3   | 1   | 1   | 5.037   |
| 31            | 4   | 3   | 1   | 2   | 4   | 4   | 4.269   |
| 32            | 4   | 4   | 2   | 1   | 3   | 3   | 4.648   |

3.2. Effects of process parameters on warpage
In this study, the effects of parameters on the warpage were investigated using range analysis method. The range analysis method was applied to analyze the optimal parameters [18]. In the range analysis method, $\bar{u}_{pk}$ is used to determine the optimum level of each parameter, and it can be calculated using equation (1). The minimal value among $\bar{u}_{p1}$, $\bar{u}_{p2}$, $\bar{u}_{p3}$ and $\bar{u}_{p4}$ is corresponding to the optimum level of the process parameter p.

$$\bar{u}_{pk} = \frac{1}{8}(\sum u_{pk})$$  \hspace{1cm} (1)
where p stands for parameters (A, B, C, D, E and F), k stands for levels (1, 2, 3 and 4), \( \bar{u}_{pk} \) means the warpage when process parameter is p and level is k. Range is defined as the difference between the maximal (\( \bar{u}_{pmax} \)) and minimal (\( \bar{u}_{pmin} \)) values of \( \bar{u}_{pk} \) as shown in equation (2), and it can be applied for evaluating the effects of parameters on the warpage. The larger the range is, the more prominent the effect of the parameter on the warpage will be.

\[
\text{Range} = \bar{u}_{pmax} - \bar{u}_{pmin}
\]  

Taking parameter F (Fiber content) as an example, the range analysis is shown as follows:

\[
\bar{u}_{F1} = \frac{1}{8}(3.945 + 4.701 + 5.226 + 6.082 + 3.847 + 4.861 + 5.474 + 5.037) = 4.897,
\]

\[
\bar{u}_{F2} = \frac{1}{8}(2.221 + 2.633 + 3.124 + 3.365 + 2.337 + 2.610 + 3.514 + 2.804) = 2.826,
\]

\[
\bar{u}_{F3} = \frac{1}{8}(2.461 + 3.276 + 3.588 + 3.398 + 2.421 + 2.852 + 3.122 + 4.648) = 3.221,
\]

\[
\bar{u}_{F4} = \frac{1}{8}(2.962 + 3.234 + 4.312 + 3.796 + 2.996 + 3.267 + 4.026 + 4.269) = 3.608,
\]

\[
\text{Range} = \bar{u}_{pmax} - \bar{u}_{pmin} = \bar{u}_{F1} - \bar{u}_{F2} = 4.897 - 2.826 = 2.071.
\]

Based on the above method, the results of range analysis for all parameters are included in Table 4. Therefore, the optimal levels of each parameter can be obtained as shown in Table 5.

### Table 4. Results of range analysis.

| A (Packing pressure) | B (Melt temperature) | C (Mold temperature) | D (Filling time) | E (Packing time) | F (Fiber content) |
|----------------------|----------------------|----------------------|------------------|------------------|-------------------|
| \( \bar{u}_{p1} \)  | 2.899                | 3.532                | 3.654            | 3.846            | 3.548             | 4.897             |
| \( \bar{u}_{p2} \)  | 3.429                | 3.481                | 3.650            | 3.756            | 3.616             | 2.826             |
| \( \bar{u}_{p3} \)  | 4.048                | 3.665                | 3.659            | 3.474            | 3.767             | 3.221             |
| \( \bar{u}_{p4} \)  | 4.175                | 3.874                | 3.589            | 3.475            | 3.620             | 3.608             |
| \( \bar{u}_{pmax} \)| 4.175                | 3.874                | 3.659            | 3.846            | 3.767             | 4.897             |
| \( \bar{u}_{pmin} \)| 2.899                | 3.481                | 3.589            | 3.474            | 3.548             | 2.826             |
| Range               | 1.276                | 0.393                | 0.069            | 0.372            | 0.219             | 2.071             |

### Table 5. Optimal level of each parameter.

| A (Packing pressure) | B (Melt temperature) | C (Mold temperature) | D (Filling time) | E (Packing time) | F (Fiber content) |
|----------------------|----------------------|----------------------|------------------|------------------|-------------------|
| A1 (70%)             | B2 (185 °C)          | C4 (65 °C)           | D3 (7 s)         | E1 (17 s)        | F2 (20%)          |

In the previous research about the influence of process parameters on warpage, Ozcelik et al. [19] found that packing pressure was the most important process parameter affecting warpage, while Tang et al. [20] showed that melting temperature had the greatest influence. Besides, Hakimian et al. [21] reported that glass fiber gave the highest influence on the warpage and shrinkage. However, there is rare research about the influence of process parameters on the warpage behavior of component made of RF/PP. In this study, the effects of parameters on the warpage of A pillar trim fabricated with RF/PP were investigated using range analysis method. It is found from Figure 3 that fiber addition (F) and packing pressure (A) are the most important factors affecting warpage, while other process parameters have less influence.
Figure 3. Range results of process parameters

The injection process was then simulated using the optimal processing parameters in Table 5 in order to achieve the minimal warpage of the A pillar trim. The minimal warpage value is 2.124 mm, which is within the acceptable warpage as prescribed by DIN 16901 standard [22] for plastic moldings. According to the DIN 16901 standard, the maximum permissible tolerance value of the investigated A pillar trim part should be less than 7.2 mm. Thus the optimized warpage of the part meets the requirement of tolerance standard.

4. Conclusion
In conclusion, this study aimed to investigate the warpage of an injection-molded automotive interior component made of RF/PP composite and numerically design the process parameters of minimal warpage deformation using orthogonal experiment method and range analysis method. The analysis showed that the fiber percentage and packing pressure gave the most significant influence on warpage compare to melt temperature, mold temperature, filling time and packing time. The optimal packing pressure was of 70% injection pressure and 20 wt% for fiber addition. The A pillar trim part can achieved the minimum warpage value as of 2.124 mm under the optimal parameters.

Acknowledgements
The authors thank the financial support of National High Technology Research and Development Program of China (863 Program), No. 2008AA030905 from MOST, and the Natural Science Foundation of China, No. 51073051. This work is also financially supported by the State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body (Hunan University), No. 71475003, and the Green Car Collaboration Innovation Center of Hunan Province.

References
[1] Guo R C, Wu N and Zhang G R 2012 Adv. Mat. Res. 341 226-230
[2] Faruk O, Bledzki A K, Fink H P and Sain M 2014 Macromol. Mater. Eng. 299 9-26
[3] La Mantia F P and Morreale M 2011 Compos. Part. A-Appl. S. 42 579-588
[4] Yuan J, Yu Y, Wang Q, Fan X, Chen S and Wang P 2013 Fiber. Polym. 14 1254-60
[5] Li X, He L, Zhou H, Li W and Zha W 2012 Carbohyd. Polym. 87(3) 2000-04
[6] Li Y, Sun J, Cheng P, Jiang Y, Zhou Z, Zhang Q and Qiu Y 2013 J. Adhes. Sci. Technol. 27(22) 2387-97
[7] Wang X, Zhao Y, Li W and Wang H 2015 Appl. Surf. Sci. 342 101-105
[8] Yan H, Wang H and Fang Z 2014 Ind. Eng. Chem. Res. 53(1) 19961-69
[9] Gu Y, Tan X, Yang Z and Zhang Z 2014 Mater. Design. 56 852-861
[10] Feng Y, Hu Y, Zhao G, Yin J and Jiang W 2011 J. Appl. Polym. Sci. 122(3) 1564-71
[11] Ho M P, Wang H, Lee J H, Ho C K, Lau K T, Leng J and Hui D 2012 Compos. Part. B-Eng.
43(8) 3549-62

[12] Friedrich K and Almajid A A 2013 Appl. Compos. Mater. 20(2) 107-128
[13] Panthapulakkal S and Sain M 2007 J. Appl. Polym. Sci. 103 2432-41
[14] Rahman W AW A, Sin L T and Rahmat A R 2008 J. Mater. Process. Tech. 197 22-30
[15] Azaman M D, Sapuan S M, Sulaiman S, Zainudin E S and Khalina A 2013 Mater. Design. 52 1018-26
[16] Azaman M D, Sapuan S M, Sulaiman S, Zainudin E S and Khalina A 2015 Polym. Eng. Sci. 55(5) 1082-95
[17] Akil H, Omar M F, Mazuki A A M, Safiee S Z A M, Ishak Z M and Bakar A A 2011 Mater. Design. 32 4107-4121
[18] Shi L N, Zhang X and Chen Z L 2011 Water. Res. 45(2) 886-892
[19] Ozcelik B, Erzurumlu T. Ozcelik, B and Erzurumlu T 2006 J. Mater. Process. Tech. 171(3) 437-445
[20] Tang S H, Tan Y J, Sapuan S M, Sulaiman S, Ismail N and Samin R 2007 J. Mater. Process. Tech. 182(1) 418-426
[21] Hakimian E and Sulong A B 2012 Mater. Design. 42 62-71
[22] DIN 16901:1982. Plastics mouldings-tolerances and acceptance conditions for linear dimensions.