Simulation-based optimization for preform's dimensions of an automotive bevel gear

Tối ưu hóa kích thước phôi dập sơ bộ của bánh răng côn sử dụng mô phỏng số

Nguyễn Trung Thành*, Nguyễn Trường An
Faculty of Mechanical Engineering, Military Technical Academy
**Email: trungthankk21@mta.edu.vn*
Tel: +84-69515368; Mobile: 0982649266

Keywords:

Preform design, Bevel Gear, Forging process, Simulation, RSM, GA.

Abstract

The objective of this paper is to optimize preform's dimensions of the bevel gear in the forging process. The considered design parameters include whole height (*H*), large diameter (*D*), and chamfer length (*B*). Firstly, numerical simulations were applied in conjunction with the Box-Behnken design (BBD) method and response surface methodology (RSM) on the DEFORM 3D software to render the relationships of the preform parameters with the forging load (*F*) and filling ratio (F_R). A non-dominated sorting genetic algorithm-II (NSGA-II) was used to solve multi-objective optimization problems and search for Pareto optimal solutions. Finally, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was adopted to determine the best solution compromised from the Pareto set. The results indicated that the optimized preform with multi-criterion has shown better performance in improving the material flow and ensuring filling cavity. Therefore, this research is intended to contribute toward making forging processes of bevel gears more efficient.

Từ khóa:

Phôi dập sơ bộ, Bánh răng côn, Quá trình dập, Mô phỏng, Bề mặt đáp ứng, Thuật toán di truyền.

Tóm tắt

Mục tiêu của bài báo này là tối ưu hóa kích thước phôi dập sơ bộ của quá trình dập bánh răng côn. Các tham số cân nhắc là chiều cao phôi, đường kính phôi, và cạnh vát. Quá trình mô phỏng dập bánh răng thực hiện trên phần mềm DEFORM 3D kết hợp với ma trận Box-Behnken để xây dựng phương trình hồi quy của lực dập và tỉ lệ điền đầy trong mối liên hệ với các tham số. Thuật toán di truyền đa mục tiêu được sử dụng để giải quyết mối tương quan giữa các hàm mục tiêu và xây dựng đồ thị Pareto. Kỹ thuật xác định giải pháp tối ưu được dùng để xác định giải pháp tốt nhất. Kết quả nghiên cứu chỉ ra rằng phôi dập sơ bộ được thiết kế đảm bảo khả năng điền đầy của bánh răng. Nghiên cứu này được kì vọng như một đóng ghóp có ý nghĩa để quá trình dập bánh răng côn trở nên hiệu quả hơn.

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1. INTRODUCTION

Bevel gears are widely used as an important component of drive mechanisms in the automotive industry due to high contact ratio and smooth transmission. The bevel gears were manufactured by means of metal cutting, in which large quantities of metal chips were produced as waste and metal streamlines were cut off, thus lowering properties. Fortunately, the net-shape forging technology has become an effective approach in the production of gears. The forging process possesses several benefits, such as excellent mechanical properties, less raw material, good tolerance, high productivity, and cost savings, compared to metal cutting.

The realization of optimal performs shapes has attracted the attention of many researchers. A new approach considering various different performs was proposed to decrease waste materials and forging loads for complex components [1]. Shao et al. developed a topology-based approach in order to optimize perform geometries of the blade forging [2]. Similarly, the artificial neural network was applied to obtain the optimal perform shape for the bevel gear [3]. However, the aforementioned publications indicated that the complex interplay of objective functions, (e.g. forming force, product quality, and production rate) with respect to perform parameters is not clearly understood yet, which makes the optimization process rather inefficient and insufficient. Furthermore, simulations and perform parameter optimization of the bevel gear precision forging has not been conducted.

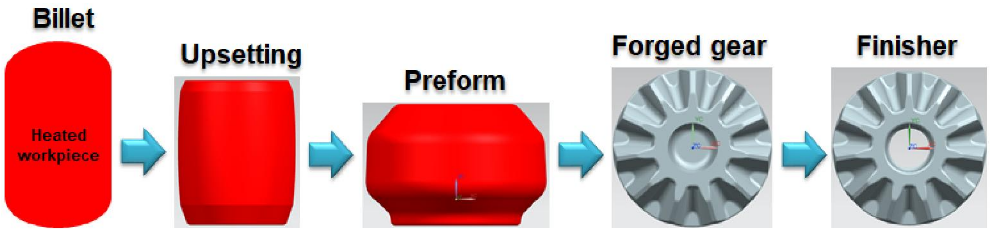


Fig. 1. Bevel gear forging process

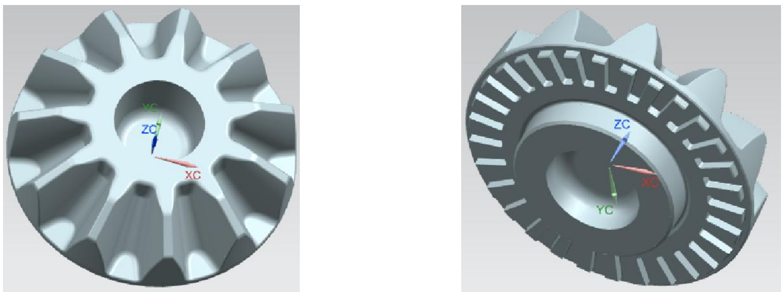


Fig. 2. Forged bevel gear

To overcome the challenge of bevel gear forging accuracy, we introduce a multi-objective optimization of the preform shape of an automotive bevel gear (Fig. 1 & 2). This is a common component within the automotive industry, which is manufactured in large quantities. It is essential to have the reliable model for conducting parametric studies in order to improve the forging quality and accuracy. Additionally, we found out that altering workpiece parameters such as the height, diameter, and chamfer length would affect the variation in forming load, die filling potential, and product uniformity. This is a complicated problem and an effective approach remains important issues for improved reliability, durability, and performances, as well as reduced cost and weight. Therefore, an effective approach describing forging process behavior and the optimization of performing shape parameters is an important area of research.

In the remainder of this paper, a scientific framework to solve multi-objective optimization problems is first introduced. Next, a reliable simulation model is developed, and numerical experiments as well as optimization results are discussed. Finally, conclusions are drawn and future research is suggested.

2. METHODS

2.1. Optimization problem

As previously discussed in Section 1, two response variables, including the forging load (F) and filling ratio (F_R) are optimized simultaneously by means of numerical experiments and a multi-objective optimization process. The filling ratio, an indicator of quantifying die filling, can be described as follows [4]:

$$F_R = \frac{V_{Gear}}{V_{Workpiece}} \tag{1}$$

where $V_{Workpiece}$ and V_{Gear} are the volume of the workpiece and gear before and after the forging process, respectively.

For simulation approach, the forging load (F) and filling ratio (F_R) can be calculated by extracting the result of the forming force components and deformed volumes after each numerical experiment.

Based on an analysis of the perform parameters and the reference from previous studies, three key factors, namely, whole height (H), large diameter (D), and chamfer length (B) were considered as design variables (Fig. 3). The parameter ranges have been selected according to common technical values used in current bevel gear forging, the capacities of the devices used (i.e., the forging machine and die), as well as the properties of SCr420R material (Table 1).

According to the discussed analysis, the multi-objective optimization is stated as follows:

Find $X = [H, D, B]$
Minimize forging load (F)
Maximize filling ratio (F_R)
Constraints:
$52.7 \le H \le 58.7$ (mm),
$82.9 \le D \le 86.9$ (mm),
$10 \le B \le 17.2$ (mm)

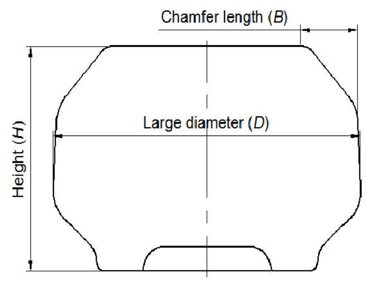


Fig. 3. Design parameters for 2nd preform

Table 1. Preform parameters and their levels

Levels	Preform parameters		
	Height *H* (mm)	**Diameter *D* (mm)**	**Chamfer *B* (mm)**
-1	52.7	82.9	10
0	55.7	84.9	13.6
1	58.7	86.9	17.2

2.2. Optimization approach

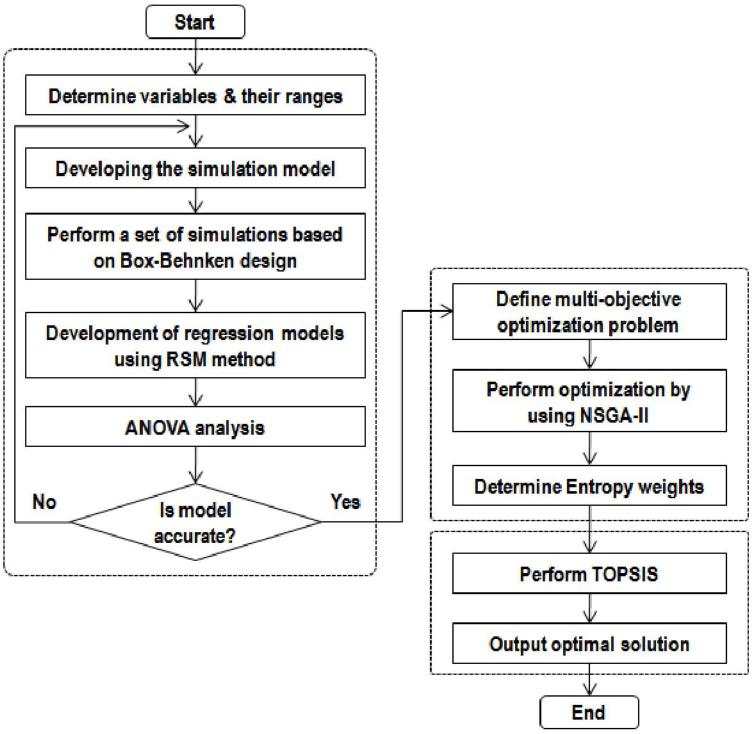


Fig. 4. Systematic procedure for the simulation-based design of experiments and optimization

To obtain the optimal parameters, a simulation-based experimental design and multi-objective optimization framework are proposed in Fig. 4. The proposed method consists of five main steps: design of experiments with the Box-Behnken design (BBD) method, performing numerical experiments, development of regression models using response surface methodology (RSM)[5], generating the Pareto font by the non-dominated sorting genetic algorithm-II (NSGA-II)[6], and using the application of techniques for order preference by similarity to the ideal solution (TOPSIS) to obtain the best optimization point [7].

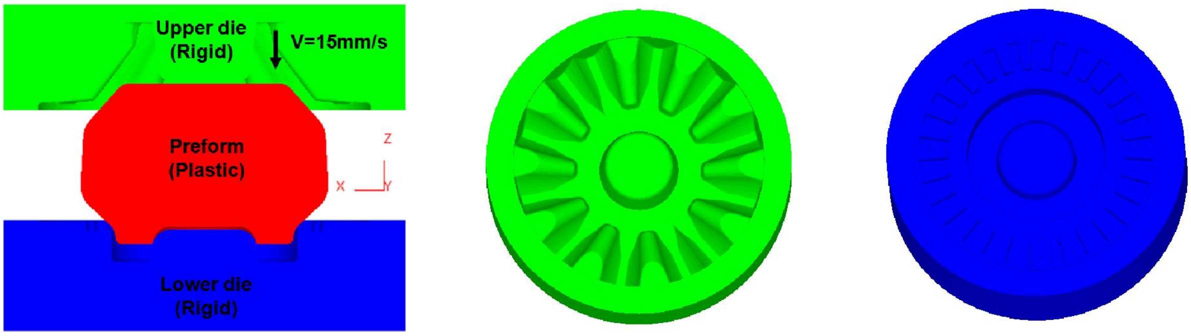
Table 2. Material properties of SCr420R and SKD61 [8]

Parameters	SCr420R	SKD61
Density (g/mm^3)	7.85×10^{-3}	7.85×10^{-3}
Young’s modulus (MPa)	210×10^3	210×10^3
Poison ratio	0.3	0.3
Thermal conductivity (W/(m°C))	35.5	35.5
Specific heat (J/(g°C))	0.46	0.49

2.3. FE-based forging simulation

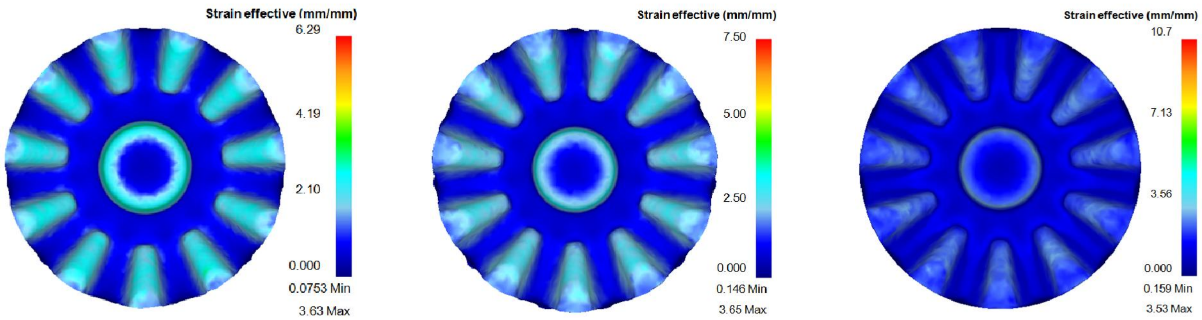
The thermal-physical properties of the preform and forging die were assumed to be constant and are presented in Table 2.

For the forming simulations, a FE-based forging process model was designed using a commercial explicit finite element software DEFORM-3D (Fig. 5). To minimize the simulation time, the forging tool was modeled as perfectly rigid, while the workpiece was considered to have plastic properties. The workpiece was fixed in the X, Y, and Z-directions. The velocity and displacement of the die are 15 mm/s and 0.1 mm, respectively. The forging tool and various perform shapes were generated using CATIA V5R20 and then transferred to DEFORM 3D by means of an STL-format file. The representative outputs of the forging simulation were shown in Fig. 6.



(a) Forging conditions (b) Upper die © Lower die

Fig. 5. Simulation model of the forming stage



(a) Height of 52.7mm, large diameter of 82.9mm, chamfer length of 13.6mm

(b) Height of 52.7mm, large diameter of 86.9mm, chamfer length of 13.6mm

(c) Height of 55.7mm, large diameter of 84,9 mm, chamfer length of 13.6mm

Fig. 6. An representative output of simulation

3. RESULTS AND DISCUSSION

3.1. Development of predictive models

The simulation results of the bevel gear forging were shown in Table 3. In the current paper, a Box-Behnken experimental design with 17 trials for three factors and three levels was chosen. Among the 17 experiments, 12 trials were performed on the edge of the experimental space cube, and 5 replicate runs were conducted at its central point. In each simulation, the inputs were H, D, and B; and the outputs considered were the forging force (F) and filling ratio (F_R). The response surface models showing the objective functions are expressed as follows:

$$F = -1004.9822 - 142.8970H + 91.8844D + 50.9284B + 0.9029HD$$
$$+0.2840HB - 0.7766DB + 0.6952H^2 - 0.7009D^2 - 0.2789B^2 \quad (2)$$

$$F_R = 7.5097 - 0.0956H - 0.1000D + 0.0484B + 0.00047HD$$
$$-0.00025HB - 0.00049DB + 0.00053H^2 + 0.00048D^2 + 0.00025B^2 \quad (3)$$

Table 3. Simulation results

Whole height *H*	**Diameter *D***	**Chamfer length *B***	**Forging force F**	**Filling rate F_R**
mm	mm	mm	Ton	
55.7	86.9	10.0	218.261	1.000218
58.7	84.9	10.0	240.170	1.000419
58.7	84.9	17.2	197.701	0.989181
55.7	84.9	13.6	170.628	0.986406
52.7	82.9	13.6	108.342	0.991851
55.7	82.9	10.0	159.108	0.988235
55.7	84.9	13.6	170.628	0.986406
55.7	84.9	13.6	170.628	0.986406
55.7	84.9	13.6	170.628	0.986406
52.7	84.9	10.0	154.974	0.994317
55.7	84.9	13.6	170.628	0.986406
58.7	82.9	13.6	186.977	0.989210
58.7	86.9	13.6	250.656	1.000054
55.7	82.9	17.2	121.342	0.990089
55.7	86.9	17.2	158.128	0.987823
52.7	86.9	13.6	150.351	0.991403
52.7	84.9	17.2	100.235	0.993923

The analysis of variance (ANOVA) is used to evaluate the adequacy of developed models. F-value, a ratio of the regression mean square to the mean square error, is used to prove the significance of each factor. The large model *f*-values reach to 164.74 and 147.07 for forging force and filling ratio, respectively, indicating the regression models are significant. The other important coefficient is R-sq, which is defined as the ratio of the explained variation to the total variation, indicates the accuracy of the model. The coefficients of determination R-sq for forging force and filling ratio were 99.53% and 99.47%, respectively. Consequently, F-values and R-sq coefficients indicated that the RSM models could be successfully applied as prediction models.

3.2. Factor affects analysis

Fig. 7 is a perturbation plot which illustrates the effects of perform parameters on the forging forge (*F*). It is evident from the results that all the input parameters have a significant effect on the output (*F*). For the forming load, the condition at a height = 52.7 mm, large diameter = 82.9 mm, and chamfer length = 17.2 mm can be considered as the lowest force level. The cause of the characteristic feature is the higher workpiece volume as the perform parameters increases. Therefore, the minimum value of this objective is achieved when the whole height as well as the large diameter is at the lowest level and the chamfer length is at the highest level.

The perturbation plot of interactions between the preform parameters and filling ratio (F_R) can be seen in Fig. 8. As shown in Fig. 8, the condition at a whole height =58.7 mm, large diameter = 86.9 mm, and chamfer length = 10 mm can be considered as the highest filling level. It indicates that higher input values are beneficial for ensuring die filling and improving forged quality.

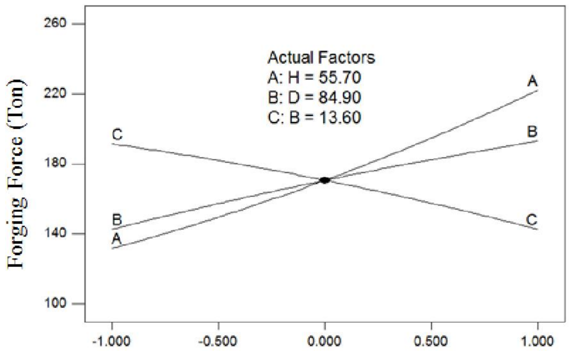


Fig. 7. Perturbation plot for *F*

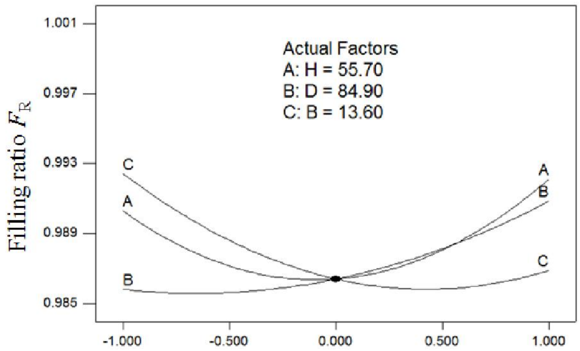


Fig. 8. Perturbation plots for F_R

3.3. Optimization results

NSGA-II can converge to the feasible optimal solutions of both objectives, as shown in Fig. 9, which means that the formation of the Pareto front results in the final set of solutions. 46 Pareto solutions are obtained at the end of NSGA-II operation. Based on the entropy method, the weight factors calculated of the forging force (*F*) and filling ratio (F_R), are 0.4, and 0.6, respectively. Coupled with the TOPSIS approach, the no. 32 solution was selected as the best solution among all alternatives, which is depicted as an intersection point between two pink lines. The perform shape and forged bevel gear at the end of the operation for experimental procedures are shown in Fig. 10 and 11, respectively.

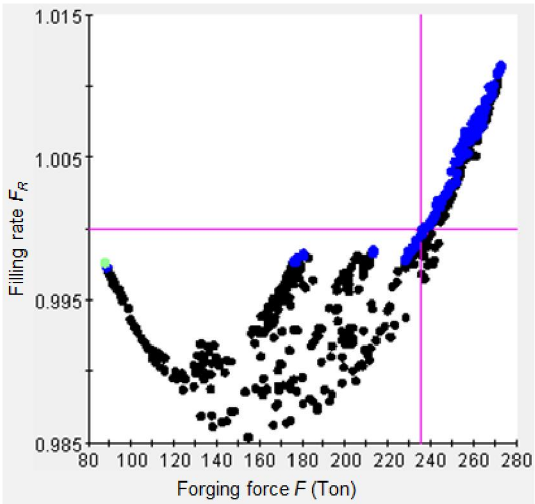


Fig. 9. Pareto optimal solutions

The values of optimal parameters and objectives can be seen in Table 4.

Fig. 10. Optimal preform

Fig. 11. Forged bevel gear

Table 4. Optimization results

Parameters	Explanatory variables			Responses	
	B **(mm)**	***H*** **(mm)**	***D*** **(mm)**	***F*** **(Tonne)**	F_R
Optimal design	55.2	86.2	14.6	173.04	1

4. CONCLUSIONS

In summary, a particular approach toward preform optimization of the bevel gear was presented through an FE model, DOE, ANOVA, genetic algorithm, and multi-criteria decision-making methods. A 3D FEM model was used to perform a set of forging simulations based on Box-Behnken experimental designs. Quadratic mathematical models of the forging load, filling ratio and strain effective deviation were created with a mixed regression model and response surface methods. The best optimal point of the multi-objective optimization problem was determined by adopting TOPSIS techniques with entropy weights based on the Pareto-optimal solutions generated by the NSGA-II algorithm. The results showed that optimized preform facilitates complete filling of the die cavity and more uniform deformation. Moreover, optimization results show that FEM coupled with RSM can be used as a powerful tool for optimization of the complicated forming processes such as the forging process of the bevel gears.

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