International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 8 Issue 1 Ser. I ‖ 2020 ‖ PP. 65-74

Effect of milling parameters on surface roughness in end milling of cycloidal gear based on response surface method

Jingyu MO [1,3], Shanming LUO [2,3](✉), Lingxia MAO [3], Jianmin XU [3]
1 School of Aerospace Engineering, Xiamen University, Xiamen, 361005, China
2 School of Mechanical and Energy Engineering, Jimei University, Xiamen, 361021, China
3 Key Laboratory of Precision Actuation and Transmission Fujian Province University, Xiamen, 361024, China

ABSTRACT *Milling parameters will influence the surface roughness of cycloidal gear in end milling, namely milling depth, spindle speed, feed speed, and cutter shaft inclination. And the relation between milling parameters and surface roughness of cycloidal gear is nonlinear. It is particularly important to investigate the effect of milling parameters on the surface roughness of cycloidal gear in muti axis end milling. Orthogonal tests is used for designing experiments and the analysis of variance analyses(ANOVA) is carried out to determine the significant factors affecting the quality of gear. The surface roughness prediction model of cycloidal gear is developed and analyzed by response surface methodology (RSM). And its optimization is also implemented with the use of the desirability function. The results indicated that cutter shaft inclination and feed speed are the dominant milling parameters for the surface roughness of cycloidal gear in end milling, accounting for 59.11% and 31.02% contributions, respectively. It has also been found that the predict results agree well with the test ones, the maximum relative error is only 2.56%. The methodology would be helpful for the prediction, simulation, and control of the surface roughness of cycloidal gear in end milling.*
Keywords *Surface roughness, Cycloidal gear, Response surface method, End milling*

Date of Submission: 28-02-2020 Date of acceptance: 08-03-2020

I. INTRODUCTION

Nowadays, the cycloid grinding machine is widely used to finish milling the tooth surface of cycloidal gear. Due to the cutter structure and complex geometric tooth, the tooth shape precision and surface quality of the cycloidal gear after machining are poor, which greatly reduces the transmission precision, transmission stability and service life of the cycloidal gear reducer. This problem is particularly prominent in the manufacture of small RV cycloidal gear reducers. Therefore, our researches group has put forward the technology of end milling for cycloidal gear instead of grinding [1]. By using the end milling cutter to realize end milling the non-over-cutting machining of precise cycloidal gear on the CNC machine. We have carried out in-depth research on the tool path planning, cutter interference and inspection, tooth profile deviation detection and other aspects [2-4] of cycloidal gear in end milling. However, surface roughness is a critical parameter to gear, and has a significant effect on wear, friction and transmission accuracy in driving [5-6]. Thus, understanding the effects of milling parameters on the surface roughness of cycloidal gear in end milling processes is vital to towards a longer gear contact fatigue life and also attain economic drives.

Among the various roughness parameters, the average of surface roughness(denote as R_a) is widely used parameter in industries[7-9]. It depends on the various process parameters, material and machining conditions. Due to the relation between milling parameters and surface roughness of cycloidal gear in end milling is nonlinearity, the analytical approach for its modelling is very difficult, and the milling parameters which is still depending on practical experience. Thus, it is necessary to study the relationship between gear surface roughness and milling parameters, predict the quality of gear and also select optimum machining parameters.

The relationship between milling parameters and workpiece surface roughness was instigated by different methods. These most frequently methods can be classified as follows: regression analysis[10], orthogonal test(OT)[11-12], response surface methodology(RSM)[13] and intelligent algorithm, including genetics algorithms (GA) and Particle Swarm Optimization(PSO) [14-15]. Some researchers preferred to use more than one method. Therein, the Orthogonal test(OT) can economically satisfy product quality through statistical analysis. Furthermore, OT when combined with other methods, like response surface methodology(RSM), genetic algorithms(GA) or analysis of variance(ANOVA), transforms into a powerful tool for study the relation between milling parameters and surface roughness.

E-mail:smluo@qq.com

Vu et al. [16] have integrated OT and RSM to investigate the effect of cutting speed, feed rate and axial depth of cut on surface roughness and cutting forces in end milling. It is observed that the cutting speed has a significant effect on surface roughness. Şener et al. [17] developed RSM model based on OT for estimating of the milling force and tool wear. Moreover, by combining between Taguchi method and RSM, many researchers have studied the effect of cutting speed, feed rate and depth of cut on the surface roughness in end milling process. However, end milling is complex process compared with turning since its more complicated cutting cutter shaft inclination motions and tool path strategy, the material removal rate of end milling process dependent on cutting cutter shaft inclination. Increasing cutting cutter shaft inclination caused a reduction the material removal rate and the surface morphology of the workpiece becomes worse[18-19]. Regarding this, cutter shaft inclination is also one of the factors to need be considered in the process of cycloidal gear end milling.

The main purpose of this paper is to develop and validate non-linear predictive models for surface roughness of cycloidal gear (R_a) in end milling by mean of the RSM. The model estimates surface roughness of cycloidal gear based on parameters such as milling depth (a_e) and spindle speed (n), feed speed (V_f) and cutter shaft inclination (φ) values. Analysis of variance (ANOVA) and F-test is applicated to find out the effect of milling parameters on the surface roughness of cycloidal gear. Furthermore, the interaction effects of milling parameters on the quality of cycloidal gear were investigated. The cycloidal gear end milling process is optimized by the desirability function approach (DFA). According to required surface roughness of gear, this milling parameters process adjust is optimized.

II. RESPONSE SURFACE METHOD

In the end milling processes, owing to the nonlinear relationship between the milling parameters and the surface roughness of the cycloidal gear, and the influence of the interaction between the milling parameters on the surface roughness of the cycloidal gear, the establishment of the surface roughness prediction model is extremely complicated. Thus, a study of the influence of different milling parameters on surface roughness of the cycloidal gear is essential. These problems can be effectively avoided by using RSM based on experimental data to establish the surface roughness prediction model of cycloidal gear. RSM is a method of combining mathematics and statistics principles. Based on the experimental data, By using higher-order polynomial fitting to build an accurate function model, so as to obtain satisfactory prediction results. In this research paper, according to the OT experimental data, the surface roughness prediction model between milling parameters and surface roughness of cycloidal gear is established by using the polynomial fitting method in RSM [20]. In addition, aim to explore the internal relation between milling parameters and the surface roughness of cycloidal gear, the interaction effect between milling parameters on the surface roughness of cycloidal gear is evaluated, and the optimal combination of milling parameters is found by combining the prediction model. Hence, the prediction model of surface roughness of cycloidal gear was established by mean of RSM and parameter optimization can be described as follows:

Step 1. Postulation of the surface roughness prediction model of cycloidal gear. In order to construct the surface roughness response of cycloidal gear y(x) and the milling parameters input variables x_1, x_2, ……, x_n. The second-order response model is used to fit the experimental data to obtain a reliable surface roughness prediction model of cycloidal gear, and then regression analysis was conducted with MINITAB. For N input variables, the quadratic polynomial response model is

$$y(x) = \beta_0 + \sum_{i=1}^{N}\beta_i x_i + \sum_{i=1}^{N}\sum_{j=1,i<j}^{N}\beta_{ij}x_i x_j + \sum_{i=1}^{N}\beta_{ii}x_i^2 + \varepsilon \quad (1)$$

Where, y(x) is the response value, β_0 is the intercept, β_i is the main effect term coefficient, β_{ij} is the parameter coefficient of the interaction term, β_{ii} is the parameter coefficient of the quadratic term, N is the number of variables, x is the response factor parameters, and ε is the random error.

Step 2. Optimization of milling parameters. It is difficult to select a set of optimal milling parameters based on workers' experience in end milling for cycloidal gear. But on the basis of the prediction model, the response surface can be constructed by the control variables method, and the interaction effects of the milling parameters on the surface roughness of cycloidal gear can be obtained. Meanwhile, the optimization of milling parameters which contribute to the minimization of surface roughness of cycloidal gear can be realized by combining the satisfaction function optimization method.

III. ORTHOGONAL TEST OF CYCLOIDAL GEAR IN END MILLING

3.1 Experimental details

The tool path of end milling for cycloidal gear in this experiment is shown in Fig.1(a). Germany DMG40 five-axis linkage machining center is selected to carry out end milling processing on cycloidal gear, as shown in Fig.1(b). The cutter is a German tungsten carbide end mill with a diameter of 4mm, the number of cutting edges is 4, and the maximum hardness of the workpiece is HRC 65. Tooth blank material: 20CrMnTi; The cooling mode is emulsion cooling. Compared with traditional involute gear, cycloidal gear is more complex in tooth shape and tooth profile curvature changes greatly, so it is difficult to detect the machining quality of tooth profile by traditional mechanical contact method. Thus, the ZYGO optical surface roughness meter of TRIMOS company in Switzerland was used to measure the tooth surface roughness of cycloidal gear, as shown in Fig.1(c).

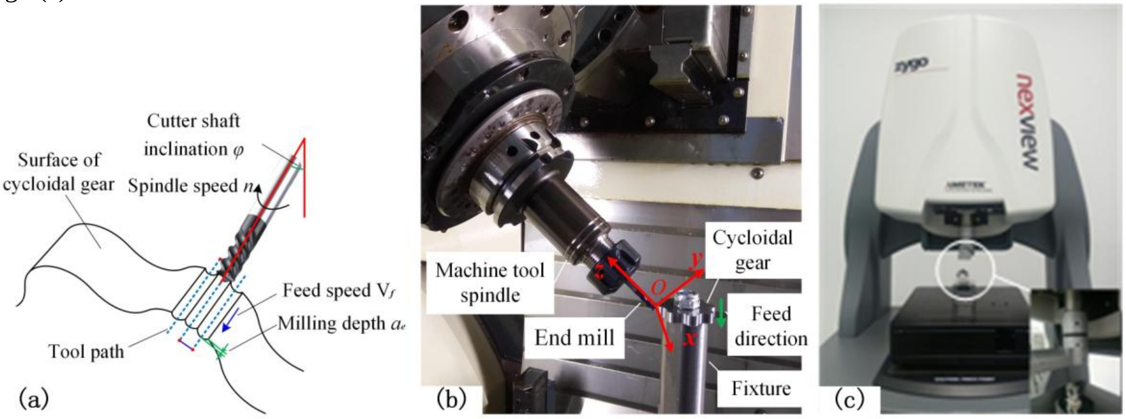


Fig.1 Orthogonal test of end milling for cycloidal gear. a) Sketch of tool path, b) End milling of cycloidal gear, c) Detection of the surface roughness of cycloidal gear.

3.2 Experimental details

In this study, design of experiments (DOE) has been used to study the effect of the key milling parameters of cycloidal gear such as milling depth (a_e), spindle speed (n), feed speed (V_f) and cutter shaft inclination (φ) on arithmetic average roughness when end milling of cycloidal gear. However, if the value in the range of each milling parameters is matched with other values for a comprehensive experiment, there is a series of problems such as long experimental period and high cost. OT is an experimental design method based on statistics and the principle of orthogonality to select representative points for experiments and obtain reliable experimental results with a small number of experiments [21]. Furthermore, in order to ensure that surface roughness of cycloidal gear have a certain level of quality, it is fundamental to select the values of the milling parameters properly. Therefore, in order to decrease the processing cost and to ensure the quantity of experimental data, OT was carried out to design experiments. Milling depth a_e, spindle speed n, feed speed V_f and cutter shaft inclination φ were considered as influencing factors, and the average surface roughness of cycloidal gear (R_a) was considered as the evaluation index. Factors and their levels as shown in Table 1.

Table 1 Factors and their levels in the orthogonal test for cycloidal gear surface roughness.

Factors	Notation	Unit	Levels			
			1	2	3	4
A- spindle speed	n	r/min	5000	10000	7500	13000
B- feed speed	V_f	mm/min	300	600	450	150
C- milling depth	a_e	mm	0.06	0.1	0.08	0.04
D- cutter shaft inclination	φ	°	35	40	45	50

Furthermore, considering the influence of the other random factors than milling parameters on the milling process of cycloidal gear, a column of blank (E) is added as error . And the experimental design for five influencing factors with four levels are organized by the L_{16} (4^5) orthogonal array as shown in Table 2. In this study, the order of the 16 experiments is randomized first. Then, these cycloidal gear samples can be obtained and the average surface roughness (R_a) detection results of cycloidal gear are also recorded in Table 2.

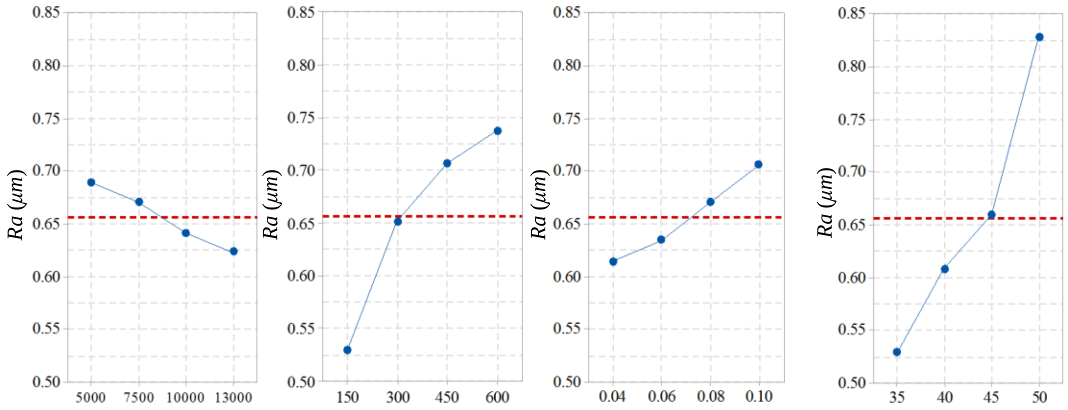
Table 2 Orthogonal test scheme and results of end milling for cycloidal gear

No.	Levels					Experiment parameters					Experimental results		
	A	B	C	D	E	n (r/min)	V_f (mm/min)	a_e (mm)	φ (°)	E	Exp. value R_a(μm)	Pre.value $\hat{R}_a$ (μm)	Error
1	1	1	1	1	1	5000	300	0.06	35	1	0.531	0.53	0.19%
2	1	2	2	2	2	5000	600	0.1	40	2	0.757	0.752	0.66%
3	1	3	3	3	3	5000	450	0.08	45	3	0.773	0.787	1.81%
4	1	4	4	4	4	5000	150	0.04	50	4	0.694	0.698	0.58%
5	2	1	2	3	4	10000	300	0.1	45	4	0.691	0.707	2.32%

6	2	2	1	4	3	10000	600	0.06	50	3	0.887	0.900	1.47%
7	2	3	4	1	2	10000	450	0.04	35	2	0.507	0.520	2.56%
8	2	4	3	2	1	10000	150	0.08	40	1	0.476	0.467	1.89%
9	3	1	3	4	2	7500	300	0.08	50	2	0.837	0.818	2.27%
10	3	2	4	3	1	7500	600	0.04	45	1	0.71	0.699	1.55%
11	3	3	1	2	4	7500	450	0.06	40	4	0.653	0.647	0.92%
12	3	4	2	1	3	7500	150	0.1	35	3	0.482	0.481	0.21%
13	4	1	4	2	3	13000	300	0.04	40	3	0.543	0.532	2.03%
14	4	2	3	1	4	13000	600	0.08	35	4	0.593	0.591	0.34%
15	4	3	2	4	1	13000	450	0.1	50	1	0.892	0.885	0.78%
16	4	4	1	3	2	13000	150	0.06	45	2	0.463	0.473	2.16%

3.3 Analysis of variance of milling parameters

According to Table 2, the order of every factor on target index is determined by analysis of range. As the analysis of range is greater, the influence of milling parameters on the surface roughness of the gear is greater, and vice versa [21]. The analysis of range results as shown in Fig. 2. The abscissa of the figure represents the four horizontal values of influencing factors, and the ordinate represents the average surface roughness of cycloidal gear. Results indicated that Cutter shaft inclination has a greatly significant influence on the surface roughness of gear and spindle speed was found to be the least influencing factor for the surface roughness of gear. As a consequence, the surface roughness of gear reduced as well when the values of milling parameters were at their greatest levels. Furthermore, cutter shaft inclination was an important factor on the surface roughness of cycloidal gear. The main reason for this is that increase of cutter shaft inclination leads to the increase of residual allowance between adjacent cutter paths, and therefore surface roughness is increased. Therefore, the reduction of the value of cutter shaft inclination is an option to lower that surface roughness.



(a) Spindle speed n (r/min) (b) Feed speed V_f (mm/min) (c) Milling depth a_e (mm) (d) Cutter shaft inclination φ (°)

Fig. 2 Milling parameters effects on the surface roughness of cycloidal gear

ANOVA is a statistical tool used for comparing two or more means and the results obtained using this approach is tested to forecast whether any symbolic relationship exists among the variables. ANOVA provides detailed clues about interaction of the process variables with the quality characteristics. ANOVA is also proficient for analysing multivariable optimization problems hence. Therefore, in order to estimate the influence of experimental error on the surface roughness of cycloidal gear, ANOVA was carried to identify the interaction of a_e, n, V_f and φ on surface roughness of cycloidal gear. The results of ANOVA analysis as shown in Table 3. In this study, ANOVA analysis was performed considering 95% confidence level and 5% significant level.

Table 3 Analysis of variance of milling parameters for the surface roughness of cycloidal gear

Source	Sum of squares (SS)	Degree of freedom (DF)	Mean of squares (MS)	F ratio	P value	Contribution (%)
A Spindle speed	0.0105	3	0.0035	5.8333	0.0947	3.22
B Feed speed	0.1012	3	0.0337	56.1667	0.0041	31.02
C Milling depth	0.0198	3	0.0066	11	0.0419	6.07
D Cutter shaft inclination	0.1928	3	0.0643	107.1667	0.0016	59.11
Error	0.0019	3	0.0006			0.58
Total	0.3262	15				100

From Table 3 it can be noticed that the cutter shaft inclination has the greatest influence on the surface roughness of cycloidal gear, and its significance ratio was 59.11%. The influence of spindle speed, feed speed and milling depth on the surface roughness of cycloidal gear significance ratio was 3.22%, 31.02% and 6.07%, respectively. The F ratio of all milling parameters was $F_D > F_B > F_{0.01}(3, 3) > F_C > F_{0.05}(3, 3) > F_A$. The results discussed above are consistent with analysis of range. The significance value of error column E was 0.58%. Therefore, due to the high percentages obtained, this experimental data can be generate the responses model (R_a) of surface roughness of cycloidal gear for random datasets for the second phase.

IV. MATHEMATICAL MODELING FOR SURFACE ROUGHNESS OF CYCLOIDAL GEAR

4.1 Mathematical model development and significance analysis

According to Table 2 experimental data, the surface roughness prediction model of cycloidal gear was established by RSM so as to optimize the milling parameters and evaluate the machining quality. There are two methods to establish the prediction model: orthogonal term regression model and response surface regression model. However, the fitting error of the orthogonal polynomial regression model is much larger than that of the response surface model. Therefore, this paper uses the response surface regression to fit the polynomial regression equation between milling parameters and surface roughness of cycloidal gear R_a. Assuming that $x_1=n$, $x_2=V_f$, $x_3=a_e$, $x_4=\varphi$, $y(x)=R_a$. By substituting the above parameters into Eq. (1), the second-order response surface model of surface roughness of end milling for cycloidal gear can then be rewritten into the following non-linear mathematical model:

$$R_a = \beta_0 + \beta_1(n) + \beta_2(V_f) + \beta_3(a_e) + \beta_4(\varphi) + \beta_5(n^2) + \beta_6(V_f^2) + \beta_7(a_e^2) + \beta_8(\varphi^2) + \beta_9(nV_f) + \beta_{10}(na_e) + \beta_{11}(n\varphi) + \beta_{12}(V_f a_e) + \beta_{13}(V_f\varphi) + \beta_{14}(a_e\varphi) \quad (2)$$

The data analysis function in MINITAB 18 software was used for regression analysis of the experimental data, and the surface roughness prediction model of cycloidal gear can be calculated as:

$$R_a = 0.6805 + 0.00004n - 0.00012V_f + 2.25791a_e - 0.03422\varphi - 0.1618\times10^{-7}n^2 - 0.000002V_f^2 + 10.08076a_e^2 + 0.00065\varphi^2 + 0.2\times10^{-6}nV_f - 0.00002na_e - 0.000001n\varphi + 0.0075V_f a_e + 0.000026V_f\varphi - 0.112a_e\varphi \quad (3)$$

To check whether the predicted value of the model is close enough to the value of the experimental data, the adequacy of the prediction model must be verified by significance. In this paper, the residual diagram analysis method and goodness of fit R^2 mathematical calculation method were used to check the model.

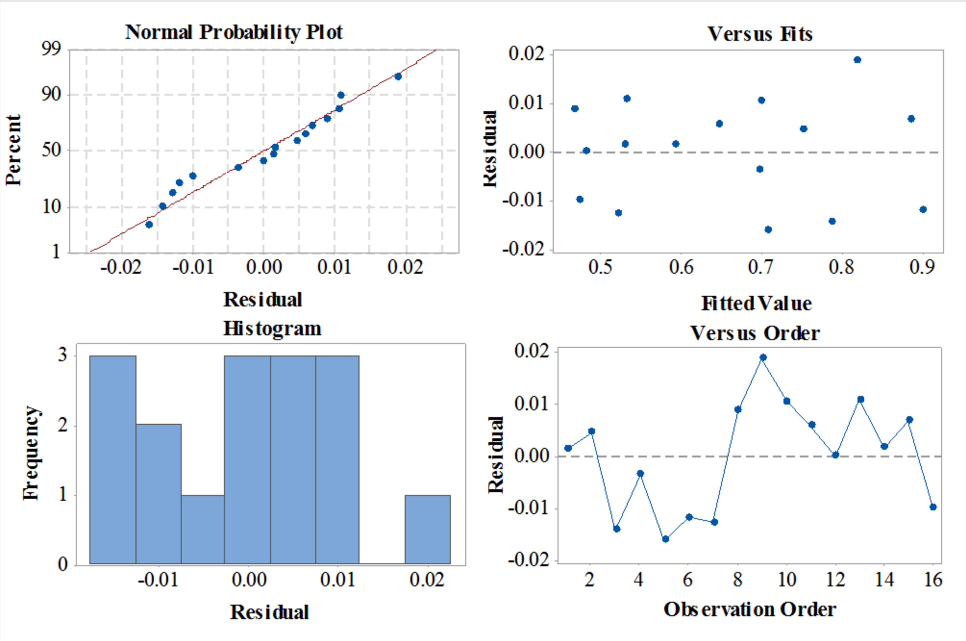


Fig. 3 Residual diagram of surface roughness prediction model for cycloidal gear

According to Table 2 and Eq. (3), MINITAB 18 software was used to process the experimental data to obtain the residual diagram of surface roughness of cycloidal gear, as shown in Fig. 3. It can be found that the residual difference of the surface roughness prediction model of cycloidal gear was distributed on both sides of the middle position of the straight line, which basically presents a normal distribution. It is indicated that the prediction model has high reliability. The residual scatter plot maintains homogeneity of variance and has no missing terms, and it does not show special "funnel shape" or "bell shape". It is shown that the proposed s surface roughness prediction model of cycloidal gear follows normal distribution and the influencing factors of the surface roughness prediction model of cycloidal gear were reasonable. Hence, it is can be concluded that the predicted value of the model is adequate to express the end milling for cycloidal gear.

Furthermore, the R^2 was used to judge the degree of fit of the prediction model between milling parameters and surface roughness of cycloidal gear. When R^2 is close to 1, it is indicates a good correlation between the milling parameter variables and the surface roughness prediction model variables. The mathematical expression of the R^2 is defined as follows:

$$R^2 = 1 - \frac{SS_{\text{residual}}}{SS_{\text{model}} + SS_{\text{residual}}} \quad (4)$$

Where, SS_{model} is the sum of squares of total deviations of the prediction model, and $SS_{resdual}$ is the sum of squares of residual deviations of the prediction model. MINITAB 18 software was used for goodness of fit analysis of the prediction model established by Eq. (3). The value of R^2 was 99.5%, which indicated that the model can better explain the influence of milling parameters on the surface roughness of cycloidal gear, and the regression fitting degree was good.

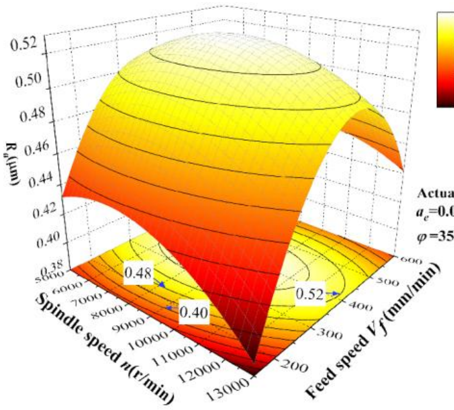
In addition, to further check the reliability of the surface roughness prediction model of cycloidal gear, the model was used to predict the surface roughness of cycloidal gear with the machining results of the 16 groups of milling parameters in Table 2, and the predicted value $\hat{R}_a$ were also shown in Table 2. It can be observed that the maximum error between the experimental value and the predicted value of surface roughness of cycloidal gear was only 2.56%. Hence, it can be conceived that the surface roughness prediction model of cycloidal gear fitted by RSM was applicable to the nonlinear relationship between milling parameters and surface roughness of cycloidal gear. The model can predict and analyze the variation of surface roughness of cycloidal gear with milling parameters.

4.2 Milling parameters interaction effects analysis

In the end milling processes of cycloidal gear, by analyzing the 3D surface plots, the optimum milling parameters which lead to minimum surface roughness can be obtained, and the uncertainty of surface roughness of cycloidal gear caused by the selection of milling parameters relying on manual experience can be reduced. In the 3D surface plot, two milling parameters are varied while the other two are held at its best value. Fig. 4 to Fig. 9 shows the effect of milling depth, spindle speed, feed speed and cutter shaft inclination on the surface roughness of cycloidal gear.

The response surface plot and contour lines for the surface roughness of cycloidal gear with respect to spindle speed n and feed speed V_f is shown in Fig. 4. It is observed that as the value of spindle speed is fixed, the surface roughness of cycloidal gear has the tendency to increase first and then decrease with the increase of feed speed. Thus, as the value of feed speed is fixed, the surface roughness of gear has the tendency to increase first and then decrease with the increase of spindle speed. The main reason is for spindle speed increases, the milling temperature also increases and the material becomes softer which improved milling performance that leads to reduction of the gear's surface roughness. It is noticed that maximum the surface roughness can be achieved when spindle speed is 8500 r /min and feed speed is 380r/min. It is also found that the effect of feed speed on the surface roughness for cycloid gear is greater than the spindle speed.

The response surface plot and contour lines for the surface roughness of cycloidal gear with respect to milling depth a_e and spindle speed n is shown in Fig. 5. It is observed that the interaction between the two factors has different effects on the surface roughness of cycloidal gear under different conditions. It is also perceived that the surface roughness of cycloidal gear will be lowest when spindle speed increase and milling depth decrease. When spindle speed increases, milling performance also will be improved. Besides, milling forces and machining deformation associated to milling depth, as milling depth decreases, the milling forces and machining deformation also decreases [22]. As a consequence, the minimum surface roughness of cycloidal gear can be achieved. Furthermore, milling depth has a significant effect on the gear surface roughness.



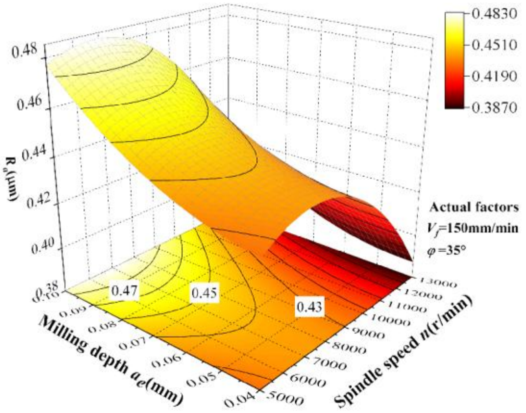
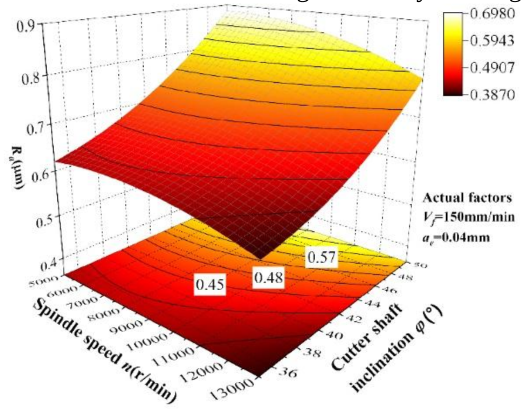


Fig. 4 Response surface and contour lines of R_a=f (n, V_f) **Fig. 5** Response surface and contour lines of R_a=f (a_e, n)

The response surface plot and contour lines for the surface roughness of cycloidal gear with respect to spindle speed n and cutter shaft inclination φ is shown in Fig. 6. The difference of contour distribution density indicated that the interaction effect of two factors has a different influence on the surface roughness of cycloidal gear under different conditions. It is found that the surface roughness of cycloidal gear increases with the decrease of spindle speed while an increases in cutter shaft inclination increases the surface roughness of cycloidal gear. This is due to the fact that cutter shaft inclination increases, the thickness of unmilling material increases and tool is badly wear. Therefore, the reduction of cutter shaft inclination and increase of spindle speed is an option to lower that the surface roughness of cycloidal gear.

The response surface plot and contour lines for the surface roughness of cycloidal gear with respect to feed speed V_f and milling depth a_e is shown in Fig. 7. It is shown that lower feed speed and milling depth result in smaller the surface roughness value of cycloidal gear. This also could contribute to the machining quality of the gear surface is better. It is noticed that the effect of milling depth has a on the gear surface roughness is significant. As the milling depth increases, the contact length, the thickness of unmilling material, and milling force also increase which lead to the frictional forces change significantly. Hence, milling depth has a significant effect on the surface roughness of cycloidal gear.



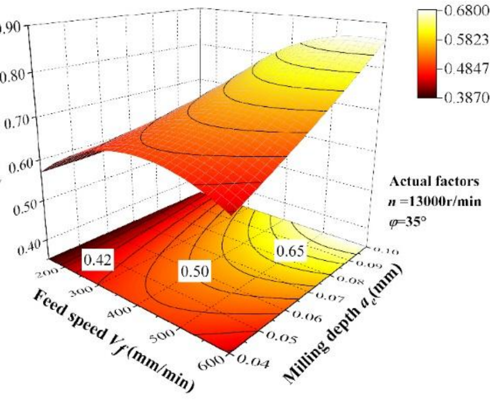
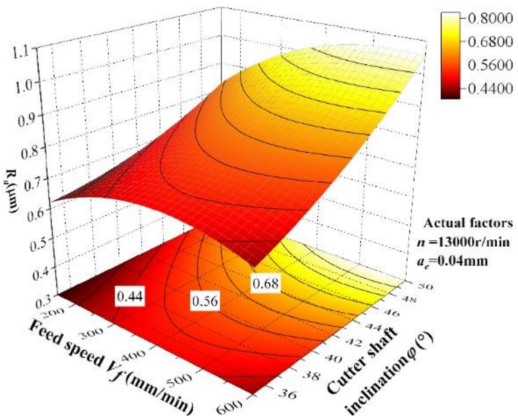


Fig. 6 Response surface and contour lines of R_a=f (n, φ) **Fig. 7** Response surface and contour lines of R_a=f (V_f, a_e)

By analyzing Fig. 8, It can be concluded that the cutter shaft inclination has a significant effect on the surface roughness of cycloidal gear compared to feed speed. As the milling depth increases, the effective cutting length of the tool decreases and the cutting vibration of the tool increased that leads to the gear's surface roughness varies greatly. It is also found that minimum the surface roughness of cycloidal gear can be achieved when feed speed and cutter shaft inclination at low values.

The response surface plot and contour lines for the surface roughness of cycloidal gear with respect to milling depth a_e and cutter shaft inclination φ is shown in Fig. 9. It can be concluded that the surface roughness value of cycloidal gear is lower than 0.4 μm when the cutter shaft inclination and milling depth are small. The surface roughness value of cycloidal gear increase when the cutter shaft inclination and the milling depth increase simultaneously. The synergistic effect of milling depth and cutter shaft inclination has a significant influence on the end milling of the quality of cycloidal gear.



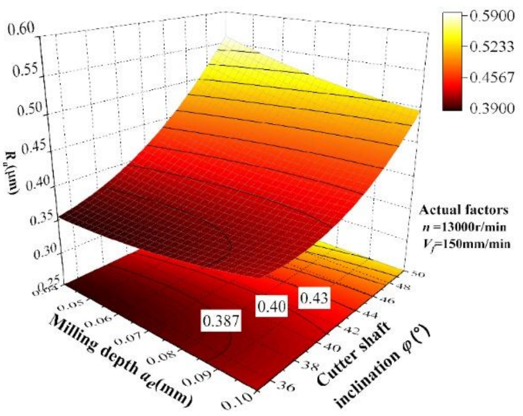


Fig. 8 Response surface and contour lines of R_a=f (V_f, φ) **Fig. 9** Response surface and contour lines of R_a=f (a_e, φ)

4.3 Optimization of milling parameters

(1) Optimization method. The aim of the optimization process in this study is to determine the optimal values of milling parameters that provided a reduction of surface roughness of cycloidal gear. A desirability analysis is used to further identify the optimal milling parameter combination set. Desirability Function Approach (DFA) [23] is utilized to optimize the parameters of the surface roughness prediction model of cycloidal gear. For the response variable R_{ai} of surface roughness of cycloidal gear with small characteristics, based on the expected value T_i of surface roughness of cycloidal gear, R_{ai} of each estimated response variable is converted into a specific satisfaction function d, 0≤d≤1. When response variable R_{ai} reaches expected value T_i, desirability d is 1. If the response variable R_{ai} exceeds the maximum setting value of gear surface roughness, the desirability d is 0. As d is close to 1, the surface roughness of cycloidal gear is satisfaction under the optimized combination of milling parameters. Therefore, set T_i as the target value of gear surface roughness optimization, L_i as the lower limit of gear surface roughness value, U_i as the upper limit of gear surface roughness value, and t as the weight. Then, the satisfaction function model of cycloidal gear is expressed as follows:

$$d=\begin{cases}0 & y_i>U_i\\ \left((U_i-y_i)/(U_i-T_i)\right)^t & T_i\le y_i\le U_i,\ t\ge 0\\ 1 & y_i>T_i\end{cases}\qquad(5)$$

In this study, the desired characteristic for the surface roughness of cycloidal gear is 'smaller-the-better'. Therefore, the surface roughness of cycloidal gear only needs to set an upper limit U_i. The weight t=1, the target value of gear surface roughness optimization U_i=0.8μm.

(2) Optimized objective function. The optimization objective function of the minimum surface roughness value of cycloidal gear can be written as follows:

$$\min(R_a)=f(n,V_f,a_e,\varphi)=f(x)\qquad(6)$$

The Euclidean space of the optimized variable is x= (n, V_f , a_e , φ) ϵE^4, The ranges of milling parameters in this analysis are as follows:

$$R_1=\left\{x\in E^4 \mid 5000\le n\le 13000,\ 150\le V_f\le 600,\ 0.04\le a_e\le 1,\ 35\le\varphi\le 50\right\}\qquad(7)$$

To find out the optimal milling parameters which contribute to the minimization of surface roughness of cycloidal gear, the objective optimization mathematical model is established. The model is given as follows:

$$\begin{cases}\min(R_a)=f(n,V_f,a_e,\varphi)=f(x)\\ f(x)\in(0,0.38)\\ x\in E^4,t=1\end{cases}\qquad(8)$$

(3) Solution of the optimization model. Combined with Eqs. (5)and (8), the surface roughness prediction model of cycloidal gear was calculated and analyzed with the optimizer function of MINITAB 18 software, and the milling parameters was obtained when the surface roughness of cycloidal gear was minimized.

x= (n, V_f, a_e, φ) = (13000,150,0.0418,35)

Under the optimized combination of milling parameters, the predicted value of surface roughness of cycloidal gear $R_{a\,min}$ was 0.3872μm, and the desirability d was 0.9828. The desirability d was close to 1, which indicated that the optimization effect was good, as shown in Table 4. It can be found that in the end milling process of cycloidal gear, the orthogonal experiment was used to obtain experimental data, and the response surface method was combined to construct the surface roughness prediction model of cycloidal gear, which can effectively obtain the influence law of the interaction between milling parameters on the surface roughness of cycloidal gear. By optimizing the surface roughness prediction model of cycloidal gear, the optimization of milling parameters can be realized so as to predict and control the surface roughness of cycloidal gear before machining.

Table 4 Optimization results of milling parameters for cycloidal gear in end milling

Response	Goal	Optimum combinations				Target	Predicted	Desirability
		n(r/min)	V_f(mm/min)	a_e(mm)	φ(°)	(μm)	(μm)	d
R_a	Min.	13000	150	0.0418	35	0.38	0.3872	0.9828

V. CONCLUSIONS

(1) ANOVA of individual milling parameters revealed that cutter shaft inclination was the most significant factor influence to the surface roughness of cycloidal gear accounting for 59.11% contribution. Additionally, spindle speed, feed speed and milling depth have also a significant effect on the surface roughness of cycloidal gear accounting for 3.22%, 31.02% and 6.07% contributions, respectively.

(2) It was verified that the prediction model between milling parameters and surface roughness of cycloidal gear established by RSM has high confidence and practicability under the experimental conditions. The value of R^2=99.5%, which was indicated that the prediction model can be used to select milling parameters before end milling and to predict or control the surface roughness of cycloidal gear.

(3) The interaction effects of milling parameters on the surface roughness of cycloidal gear was obtained: The interaction between the feed speed and the cutter shaft inclination has an most significant effect on the surface roughness of cycloidal gear. The interaction between spindle speed and cutter shaft inclination, feed speed and milling depth, milling depth and cutter shaft inclination, spindle speed and feed speed have a significant effect on the surface roughness of cycloidal gear. The interaction between spindle speed and milling speed has a general effect on the surface roughness of cycloidal gear.

(4) The optimal parameters combination set of the prediction model was obtained by using the desirability function approach method: n =13000r/min, V_f =150 mm/min, a_e =0.0418mm, φ =35°. Meanwhile, the surface roughness predicted value of cycloidal gear $R_{a\ min}$ was 0.3872μm. The value of desirability d was 0.9828, which was very close to 1. It was indicated that the optimization effect was good.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China under No. 51975499, the Educational Research Fund for Young and Middle-aged Teachers in Fujian Province under No. JT180445, the Program for Innovative Research Team in Science and Technology in Fujian Province University. The financial and technique supports are gratefully acknowledged.

Appendixes

List of symbols

n	Spindle speed	a_e	Milling depth
V_f	Feed speed	φ	Cutter shaft inclination
y(x)	Response value	R_a	Experimental value of average surface roughness
β_i	Main effect term coefficient	$\hat{R}_a$	Predicted value of average surface roughness
N	Number of variables	β_{ij}	Parameter coefficient of the interaction term
x	Response factor parameters	β_{ii}	Parameter coefficient of the quadratic term
β_0	Intercept	ε	Random error
d	Desirability	R^2	Goodness of fit
		T_i	Expected value of gear surface roughness

REFERENCES

[1]. Luo S M, Liao L X, Wang Y, et al. A method of end milling for cycloidal gear. 2016; CN105665838A.
[2]. Mo J Y. Research on the tool path planning for five-axis NC machining of universal cycloidal gear. 2017.
[3]. Luo S M, Liao L X, Wang J, et al. Study on inspection and avoidance of interferences in five-axis end milling of cycloidal gears. The International Journal of Advanced Manufacturing Technology 2017; 91 (9):3307-3314.
[4]. Mo J Y, Luo S M, Mao L X, et al. Detection and analysis of tooth profile deviation of cycloidal gear based on projection method. Journal of Mechanical Transmission 2018; 42(1):88-93.
[5]. Zorko D, Kulovec S, Duhovnik J, et al. Durability and design parameters of a Steel/PEEK gear pair. Mechanism and Machine Theory 2019; 140: 825-846.
[6]. Britton R D, Elcoate C D, Alanou M P, et al. Effect of surface finish on gear tooth friction. Journal of Tribology 2000; 122(1):354-360.
[7]. Vallejo A, Ruben M M, Hugo E S. Surface roughness modeling in peripheral milling processes. Transactions of the North American Manufacturing Research Institution of SME 2009; 37:25-32.
[8]. Zhang B Y, Liu H J, Bai H Y, et al. Ratchetting–multiaxial fatigue damage analysis in gear rolling contact considering tooth surface roughness. Wear 2019;428-429:137-146.
[9]. Al Hazza M , Adesta E Y T . New approach in cost structuring of high speed hard turning. Advanced Materials Research 2011; 264-

265:1003-1008.
[10]. Adesta E Y T, Al Hazza M H F, Suprianto M Y, et al. Predicting surface roughness with respect to process parameters using regression analysis models in end milling. Advanced Materials Research, 2012. 576:99–102.
[11]. Huang X M, Sun J. Research on surface roughness of 7050-T7451 aluminum alloy by high speed milling. Chinese Journal of Construction Machinery 2014; 12(3):248-251.
[12]. Tlhabadira I, Daniyan I A, Machaka R, et al. Modelling and optimization of surface roughness during AISI P20 milling process using taguchi method. International Journal of Advanced Manufacturing Technology 2019; 102(9-12):3707-3718.
[13]. Bhardwaj B, Kumar R, Singh P K. An improved surface roughness prediction model using Box-Cox transformation with RSM in end milling of EN 353. Journal of Mechanical Science and Technology 2014; 28(12) :5149-5157.
[14]. Zhou J H, Ren J X, Yao C F. Multi-objective optimization of multi-axis ball-end milling Inconel 718 via grey relational analysis coupled with RBF neural network and PSO algorithm. Measurement: Journal of the International Measurement Confederation 2017; 102:271-285.
[15]. Leo Kumar S P. Experimental investigations and empirical modeling for optimization of surface roughness and machining time parameters in micro end milling using Genetic Algorithm. Measurement: Journal of the International Measurement Confederation 2018; 124:386-394.
[16]. Vu N C, Huang S C, Nguyen H T. Multi-objective optimization of surface roughness and cutting forces in hard milling using taguchi and response surface methodology. Key Engineering Materials 2018; 773: 220–224.
[17]. Şener K, Henifi C, Halil K. Experimental investigation and optimization of cutting force and tool wear in milling Al7075 and open-cell SiC foam composite. Arabian Journal for Science&Engineering 2016. 41:1797-1812.
[18]. T. Childs, K. Maekawa, T. Obikawa, et al. Metal machining theory and applications, John Wiley & Sons Inc. New York-Toronto 2000.
[19]. Duan X Y, Yu S, Peng F Y, et al. Study of the effect of tool orientation on surface roughness in five-axis milling of 300M steel. IOP Conference Series: Materials Science and Engineering 2018. 382(2):1-5.
[20]. He Z, Zhu P F, Park S H. A robust desirability function method for multi-response surface optimization considering model uncertainty. European Journal of Operational Research 2012; 221 (1):241-247.
[21]. Li Y Y, Hu C R. Test design and data processing. Beijing: Chemical Industry Press, 2008.
[22]. Dikshit M K , Puri A B , Maity A . Modelling and application of response surface optimization to optimize cutting parameters for minimizing cutting forces and surface roughness in high-speed, ball-end milling of Al2014-T6. Journal of the Brazilian Society of Mechanical Sciences and Engineering 2017. 39(12):5117-5133.
[23]. Jeong I J, Kim K J. Interactive desirability function approach to multi-response surface optimization. International Journal of Reliability Quality & Safety Engineering 2003; 10 (02):205-217.

Jingyu MO, et.al " Effect of milling parameters on surface roughness in end milling of cycloidal gear based on response surface method" *International Journal of Research in Engineering and Science (IJRES)*, vol. 08(1), 2020, pp. 65-74.