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Research Paper

Prediction of Surface Roughness of End Milling for Cycloidal Gears Based on Orthogonal Tests

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End milling method is applied to machining of cycloidal gears to improve the cutting quality and efficiency. The influence of milling parameters on the surface roughness is investigated based upon orthogonal tests with the four factors and four levels, as well as analysis of range and variance. A model to predict the surface roughness is built up on basis of the probability statistics and multivariate nonlinear regression analysis. Significance tests are conducted on the prediction model, and the interactive effect of these parameters on the surface roughness is figured out so as to propose optimization schemes. The results show that the shaft inclination angle has the biggest impact on the surface roughness, followed by the feed per tooth, the radial feed and the spindle speed. The prediction model of surface roughness is proved to have high prediction accuracy. This study aims to provide references for the improvement of machining quality of cycloidal gears and optimization of milling parameters.

Key words: cycloidal gear; orthogonal test; milling parameters; surface roughness; prediction model.

1. Introduction

The machining part of end-plane milling cutters is the outer arc where all points on it have the same linear velocity which is the maximum in the cutter. Therefore, the milling cutter has the advantages of steady linear cutting velocities and forces, and application of maximum speed of main spindles.

On the other hand, the projection of the arc of end-plane cutters perpendicular to the cutting direction is ellipse which is closer to the surface of workpiece, compared to a circular shape for ball-end cutters. There are thus few residual materials on the workpiece machined by end-plane cutters than those by ball-end cutters. The quality of the workpiece surface can be obviously improved. The application of end-plane cutters can not only improve the dynamic characteristics of the process system, but also enhance machining efficiency and improve the surface quality. Because of this background, it is strongly recommended to use the end milling method (as shown in Fig. 1) to machine the cycloidal gears [1].

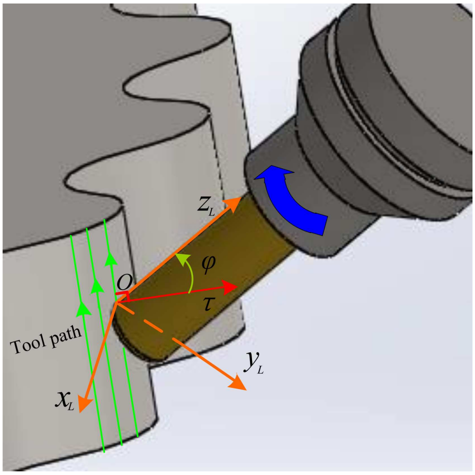

FIG. 1. End milling of cycloidal gears: φ is the shaft inclination angle, τ is the normal line of tooth profile, $x_L y_L z_L$ is the local coordinate of contact point.

The surface roughness is an important index to measure the machining quality, and the milling parameters have significant influence on the quality. Therefore, it is necessary to study the relation between the milling parameters and surface roughness. Currently, there is no analytical formula to describe their relation. The relationship is always determined by orthogonal tests, single-factor tests [2–5]. The prediction models of surface roughness are always established by multivariate regression analysis [6–8], artificial neural nets [9–13], least square support vector machine [14–15], RSM (Response Surface Methodology) [16–18] based on the experimental results. The multivariate regression analytical method is the most widely used one.

In this paper, an orthogonal test method and analysis of range and variance are used to study the influence of milling parameters, such as spindle speed, feed per tooth, radial feed and shaft inclination angle, on the surface roughness of end milling of cycloidal gears. The multivariate regression method is used to predict the surface roughness and significance tests are conducted. Finally, the effect of interaction of these parameters on the surface roughness is investigated in order to obtain a better scheme of milling parameters for the end milling of cycloidal gears.

2. Design of tests

2.1. Test equipment

The tests of end milling of cycloidal gears are carried out on five-axis machine tool using flat-end cutter, as shown in Fig. 2. The Taylor Hobson roughness profile meter is used to measure the surface roughness, as shown in Fig. 3. The devices and relevant parameters are presented as follows:

- Lathe: Five-axis CNC machining center (DMU 40 monoBLOCK) made by DMG Company in Germany. The maximum speed of main spindle is 24000 r/min.
- Cutter: end-plane cutters of tungsten steel with coating (S650-4E-D4.0-L50).
- Material of gears: GCr15 bearing steel. The cycloidal gears are processed by quenching heat treatment, the hardness of the cycloidal gears is 55HRC.
- Roughness: Taylor Hobson roughness profile meter (FORM TALYSURF) with a level measurement range of 200 mm and resolution ratio of 16 nm.

Fig. 2. Process of five-axis end milling of cycloidal gears.

Fig. 3. Measurement of surface roughness of gears.

2.2. Test process

An orthogonal test is used to study the influence of factors on the test index through some tests and the orthogonal table is always used to arrange the test. The test objective (i.e. test index) should be first determined. Secondly, the influencing factors and level of factors are determined based on the test index. Finally, the test is conducted according to the orthogonal table.

The surface roughness R_a is taken as the test index in this study, denoted as y_i. The factors include spindle speed n, feed per tooth f_z, radial feed a_e, shaft inclination angle φ. Four levels are selected for each factor. One blank column is left to consider the influence of other uncertainties on the quality. Therefore, an orthogonal form $L_{16}(4^5)$ [19] is used as listed in Table 1. The measured results are also listed in Table 1.

Table 1. Orthogonal form and test results.

Test No. i	A		B		C		D		E	y_i
	n [r/min]		f_z [mm]		a_e [mm]		φ [°]			R_a [μm]
	Level	Value	Level	Value	Level	Value	Level	Value	Level	Value
1	1	7000	1	0.15	1	0.10	1	25	1	0.405
2	1	7000	2	0.25	2	0.20	2	35	2	0.629
3	1	7000	3	0.20	3	0.15	3	45	3	0.625
4	1	7000	4	0.10	4	0.05	4	55	4	0.542
5	2	11000	1	0.15	2	0.20	3	45	4	0.541
6	2	11000	2	0.25	1	0.10	4	55	3	0.739
7	2	11000	3	0.20	4	0.05	1	25	2	0.356
8	2	11000	4	0.10	3	0.15	2	35	1	0.329
9	3	9000	1	0.15	3	0.15	4	55	2	0.684
10	3	9000	2	0.25	4	0.05	3	45	1	0.550
11	3	9000	3	0.20	1	0.10	2	35	4	0.500
12	3	9000	4	0.10	2	0.20	1	25	3	0.329
13	4	13000	1	0.15	4	0.05	2	35	3	0.381
14	4	13000	2	0.25	3	0.15	1	25	4	0.507
15	4	13000	3	0.20	2	0.20	4	55	1	0.743
16	4	13000	4	0.10	1	0.10	3	45	2	0.312

3. Analysis of test results

3.1. Analysis of range

The analysis of range is one of the simplest methods to deal with orthogonal test data. It can efficiently obtain the degree of impact of factors on the test index and the optimal combination of factors. The results of surface roughness from the analysis of range are shown in Table 2.

In Table 2, K_{pj} is the sum of surface roughness of the factor j ($j = 1, 2, 3, 4, 5$) in the level of p ($p = 1, 2, 3, 4$). The range R is the difference between the

Table 2. Results of range analysis of surface roughness.

Factors	A	B	C	D	E
K_{1j}	2.201	2.011	1.956	1.597	2.027
K_{2j}	1.965	2.425	2.242	1.839	1.981
K_{3j}	2.063	2.224	2.145	2.028	2.074
K_{4j}	1.943	1.512	1.829	2.708	2.090
R	0.258	0.913	0.413	1.111	0.109

maximum and minimum of K_{pj}. The bigger the value of R is, the bigger the influence of the factor on surface roughness.

From Table 2, it can be found that $R_{\mathrm{D}} > R_{\mathrm{B}} > R_{\mathrm{C}} > R_{\mathrm{A}}$, which shows that the shaft inclination angle (φ) is the major factor affecting the surface roughness, followed by the feed per tooth (f_z), the radial feed (a_e) and the spindle speed (n). The smaller the K_{pj} is, the smaller the surface roughness for a given level of the factor [19]. Therefore, it is confirmed that the optimal level of the milling parameters is $\mathrm{A_4B_4C_4D_1}$: $n = 13\,000$ r/min, $f_z = 0.1$ mm, $a_e = 0.05$ mm, $\varphi = 25°$. A test is conducted by using $\mathrm{A_4B_4C_4D_1}$, and the results are shown in Fig. 4. The mean of the surface roughness R_a is measured as 0.237 μm which is the smallest of all the tests.

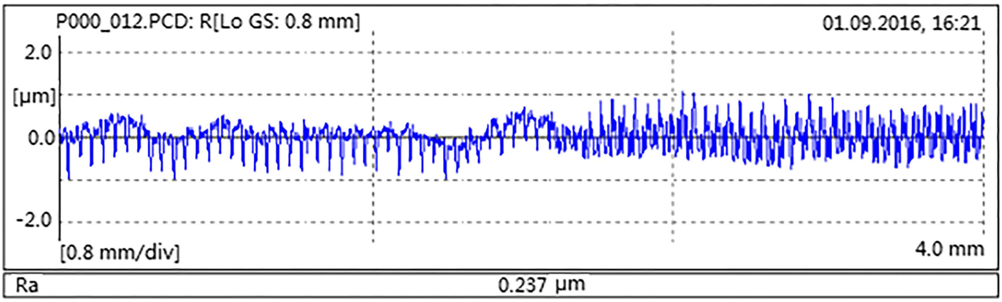

Fig. 4. Test result of surface roughness under $\mathrm{A_4B_4C_4D_1}$, where 0.8 mm/div represents the cutoff, 4 mm represents the traversing length.

3.2. Influence of milling parameters on the surface roughness

The influence of factors on the surface roughness can be seen from the relation between the test level and the test index, as shown in Fig. 5. The abscissa represents the milling parameters and the ordinate represents the average surface roughness ($K_{pj}/4$).

Figure 5a shows that the surface roughness decreases as the spindle speed increases. It is worth noting that the surface roughness increases in the range

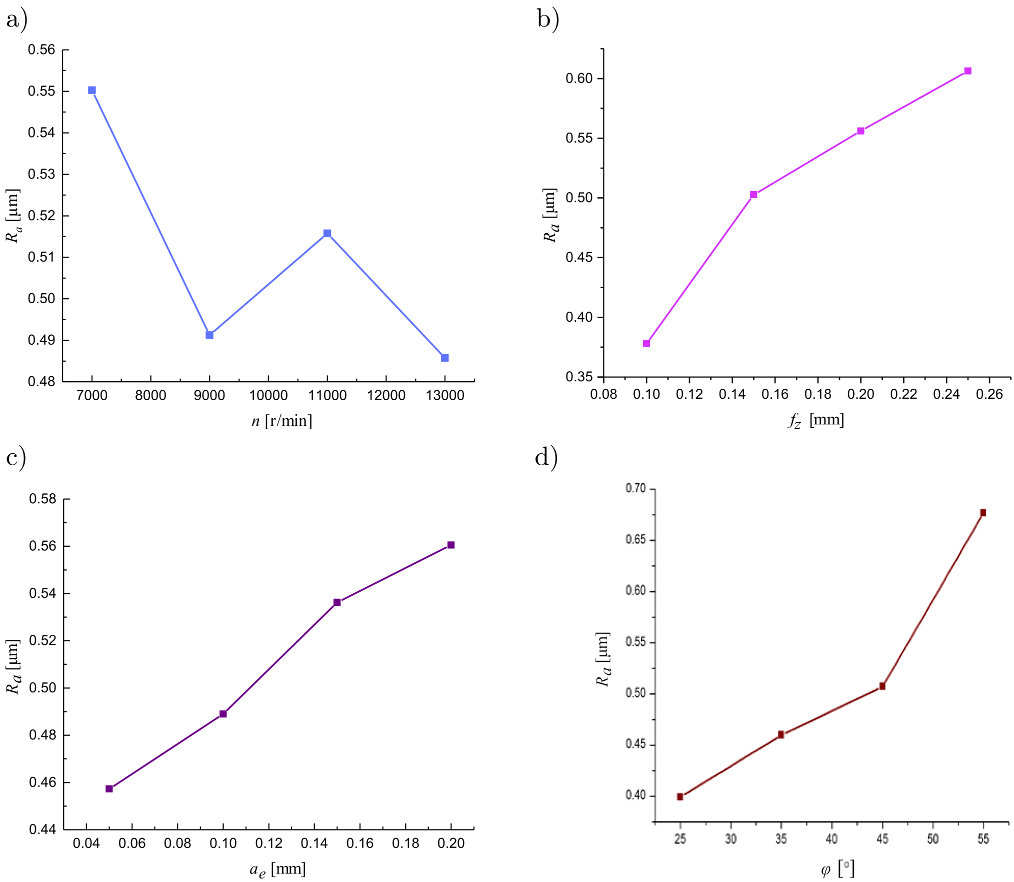

FIG. 5. Influence of milling parameters on the surface roughness.

of 9000 r/min to 11 000 r/min. This changing trend is consistent with the Carl J. Salomon theory [20]. The reason is that a large amount of heat is taken away, which reduces the plastic deformation of gear surfaces and prevents the occurrence of built-up edges.

Figure 5b shows that the surface roughness significantly increases as the feed per tooth increases. As the feed per tooth increases, the cutting thickness increases, thus the bearing force of cutters increases. This accelerates the wear and vibration, and reduces quality of workpiece. The reduction of quality becomes obvious for a change of feed per tooth from 0.1 mm to 0.15 mm.

As shown in Fig. 5c, the surface roughness steadily increases as the radial feed increases. The reason is that the residual thickness of the surface increases as the radial feed increases, leading to intense vibration and reduction in quality.

Figure 5d shows that the surface roughness significantly increases as the shaft inclination angle increases. The increasing angle may increase the bearing force of cutters and accelerate the wear of cutters and deformation of shafts. Moreover, when the shaft angle exceeds 45°, the bearing force of cutters sharply increases, leading to severe wear of cutters and degradation of surface roughness.

Therefore, the quality of gear surface can be improved by increasing the spindle speed, reducing feed per tooth, radial feed and shaft inclination angle.

3.3. Analysis of variance

The analysis of variance is the more accurate method to deal with the test data. It can efficiently obtain the degree of impact of factors on the test index, and further determine their level of significance. The significance and characteristics of the influence of factors on the test index can be represented by the ratio F_j of the mean sum of squares of deviations, V_j, to the mean sum of squares of error, V_e [19]

$$F_j = \frac{V_j}{V_e} = \frac{S_j/f_j}{S_e/f_e}, \tag{3.1}$$

where S_j and f_j are the sum of squares of deviations of factor and its degree of freedom, respectively; S_e and f_e are the sum of squares of error and its degree of freedom, respectively. According to [19], they can be expressed as follows:

$$\begin{cases} S_j = r\sum\limits_{p=1}^{m}(k_{pj}-\overline{y})^2 = \dfrac{1}{r}\sum\limits_{p=1}^{m}K_{pj}^2 - \dfrac{1}{T}\left(\sum\limits_{i=1}^{T}y_i\right)^2, \\ f_j = m-1, \\ S_e = \sum\limits_{i=1}^{T}y_i^2 - \dfrac{1}{r}\sum\limits_{p=1}^{m}K_{pj}^2, \\ f_e = f_T - \sum\limits_{j}^{m} f_j, \end{cases} \tag{3.2}$$

where $j = 1, 2, 3, 4$, corresponding, respectively, to spindle speed, feed per tooth, radial feed, shaft inclination angle; T is the total number of tests, $T = 16$; r is the number of replication of levels, $r = T/m$; m is the level of every factor, $m = 4$; y_i is the measurement value of surface roughness; f_T is the total freedom, $f_T = T - 1$. Submitting Eq. (3.2) into Eq. (3.1) yields

$$F_j = \frac{\left[\dfrac{1}{r}\sum\limits_{p=1}^{m}K_{pj}^2 - \dfrac{1}{T}\left(\sum\limits_{i=1}^{T}y_i\right)^2\right](T-m)}{\left(\sum\limits_{i=1}^{T}y_i^2 - \dfrac{1}{r}\sum\limits_{p=1}^{m}K_{pj}^2\right)(m-1)}. \tag{3.3}$$

Based on the test results in Table 1 and Table 2, the results of variance analysis, which are shown in the Table 3, can be obtained from Eq. (3.3).

Table 3. Results of variance analysis of surface roughness.

Sources of variation	Sum of squares of deviations	Freedom	Mean sum of squares of deviations	F_j	Critical value F_α	Significance
A ($j = 1$)	0.01040	3	0.003470	5.717	$F_{0.1}(3,3) = 5.390$ $F_{0.05}(3,3) = 9.280$ $F_{0.01}(3,3) = 29.457$	*
B ($j = 2$)	0.11500	3	0.038300	63.097		***
C ($j = 3$)	0.02580	3	0.008600	14.168		**
D ($j = 4$)	0.17100	3	0.057000	93.904		***
Error	0.00182	3	0.000607			
T	0.32400	15				

According to the mean sum of squares of deviations as shown in Table 3, the same conclusion of the impact sequence of milling parameters on the surface roughness can be obtained as that from the range analysis, i.e. shaft inclination angle (φ), feed per tooth (f_z), radial feed (a_e), spindle speed (n).

Table 3 also shows that distribution critical value F_α of every factor is found at the points of $\alpha = 0.01$, $\alpha = 0.015$ and $\alpha = 0.1$ in F function table [19]. From the magnitude of F i.e. $F_{\mathrm{D}} > F_{\mathrm{B}} > F_{0.01}(3,3) > F_{\mathrm{C}} > F_{0.05}(3,3) > F_{\mathrm{A}} > F_{0.1}(3,3)$, it can be seen that the shaft inclination angle and feed per tooth have significant effect on the surface roughness, labeled as "***", the radial feed had secondary effect, marked as "**", and the spindle speed had limited effect, denoted as "*".

4. Prediction model of surface roughness

The analysis of range and variance can only be used to study the macro impact of factors on the test index. The function of their relation should be determined based on principle of probability and statistic.

4.1. Establishment of prediction model

For given lathes and milling parameters, there is an exponential relationship between the surface roughness and milling parameters as below [21]

$$R_a = Qn^{b_1} f_z^{b_2} a_e^{b_3} \varphi^{b_4}, \tag{4.1}$$

where Q is the correction factor related to the material and cutting conditions, b_1, b_2, b_3, b_4 are the corresponding exponents.

Equation (4.1) is a typical nonlinear equation. Taking logarithm of both sides of the equation yields:

$$\lg R_a = \lg Q + b_1 \lg n + b_2 \lg f_z + b_3 \lg a_e + b_4 \lg \varphi. \tag{4.2}$$

Let $y = \lg R_a$, $x_1 = \lg n$, $x_2 = \lg f_z$, $x_3 = \lg a_e$, $x_4 = \lg \varphi$, $b_0 = \lg Q$, the linear regression equation can be obtained:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4. \tag{4.3}$$

Based on the test data in Table 1 and the principle of least square, the prediction model of surface roughness can be expressed as:

$$R_a = 10^{0.3463} n^{-0.2776} f_z^{0.523} a_e^{0.1352} \varphi^{0.6245}. \tag{4.4}$$

4.2. Significance test

In order to check the performance of the proposed prediction model, significance tests are conducted on the regression equation. The F-test is selected to determine the significance of accuracy of regression equations [19].

$$F = \frac{V_R}{V_{ye}} = \frac{S_R/f_R}{S_{ye}/f_{ye}}, \tag{4.5}$$

where V_R is the mean sum of squares of regression; V_{ye} is the mean sum of squares of residual variance; S_R and f_R are the sum of squares of regression and its degree of freedom, respectively; S_{ye} and f_{ye} are the residual sum of squares and its degree of freedom, respectively. According to [19], they can be expressed as follows:

$$\begin{cases} S_R = \sum\limits_{i=1}^{T} (\widehat{y}_i - \overline{y})^2, \\ f_R = m, \\ S_{ye} = \sum\limits_{i=1}^{T} (y_i - \widehat{y}_i)^2, \\ f_{ye} = T - m - 1, \end{cases} \tag{4.6}$$

where $\widehat{y}$ is the predicted value of surface roughness, $\overline{y}$ is the mean of test results of surface roughness. Substituting Eq. (4.6) into Eq. (4.5) yields

$$F = \frac{(T - m - 1) \sum\limits_{i=1}^{T} (\widehat{y}_i - \overline{y})^2}{m \sum\limits_{i=1}^{T} (y_i - \widehat{y}_i)^2}. \tag{4.7}$$

Based on Eq. (4.7) and the test data in Table 1, the results of variance analysis of the prediction model of surface roughness are shown in Table 4.

Table 4. Results of variance analysis of the prediction model of the surface roughness.

Sources of variation	Sum of square	Freedom	Mean of squares	F	Critical value F_α	Significant
Regression	$S_R = 0.226$	$f_R = 4$	$V_R = 0.0565$	$F = 24.145$	$F_{0.05}(4,11) = 3.36$ $F_{0.01}(4,11) = 5.67$	***
Residual	$S_{ye} = 0.026$	$f_{ye} = 11$	$V_{ye} = 0.00234$			
Total	$S_{yy} = 0.252$	$f_{yy} = 15$				

Table 4 shows that $F = 24.145$ is far larger than the critical value $F_{0.01}(4,11) = 5.67$. This means that the prediction model has a high level of significance and the confidence value reaches $(1 - 0.01) \cdot 100\% = 99\%$ [19]. Also, a comparison of measured and predicted results is carried out as illustrated in Fig. 6. The average error is 7.662% which shows a high accuracy for the prediction model.

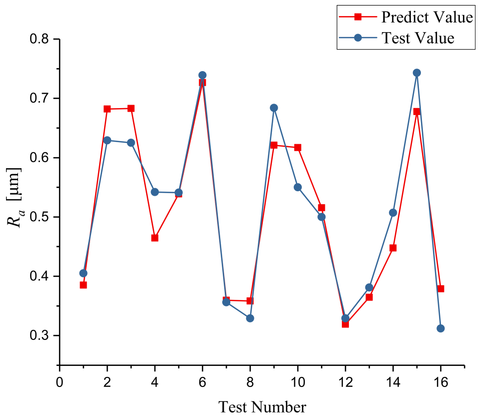

Fig. 6. Comparison of measured and predicted results of surface roughness.

4.3. Interaction of parameters

In order to better understand the effect of factors on the surface roughness, there is need to consider not only the impact of single factor on the test index, but also their interaction on the test index. According to the prediction model Eq. (4.4), numerical simulations for the influence of interaction of milling parameters on the test index are carried out, which are shown in Fig. 7.

Figure 7a shows the influence of shaft inclination angle and radial feed on the surface roughness for the given feed per tooth $f_z = 0.1$ mm and spindle speed $n = 13\,000$ r/min. The maximum roughness is 0.6 μm which satisfies the

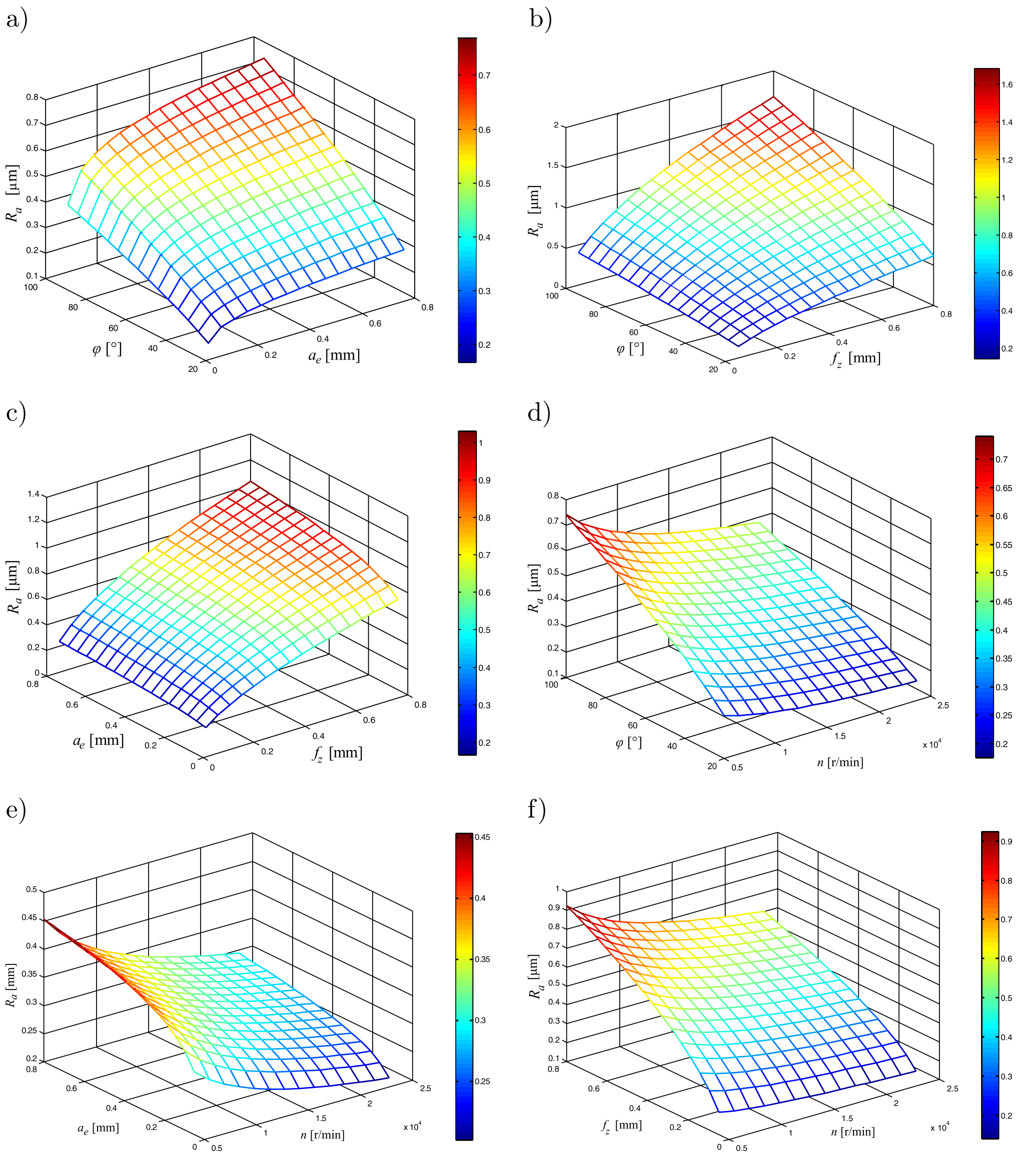

Fig. 7. Influence of interaction of milling parameters on the surface roughness.

requirement of $R_a < 0.8$ μm. Therefore, the interaction of shaft inclination angle and radial feed has little effect on the machining quality.

Figure 7b shows the influence of shaft inclination angle and feed per tooth on the surface roughness for the given spindle speed $n = 13\,000$ r/min and radial feed $a_e = 0.05$ mm. The maximum roughness is 1.3 μm which does not satisfy the requirement. The shaft inclination angle and feed per tooth should be smaller than 50° and 0.35 mm, respectively, for $R_a < 0.8$ μm. The interaction of shaft inclination angle and feed per tooth has significant effect on the machining quality.

Figure 7c shows the influence of radial feed and feed per tooth on the surface roughness for the given spindle speed $n = 13\,000$ r/min and shaft inclination angle $\varphi = 25°$. The radial feed and feed per tooth should be smaller than 0.4 mm and 0.45 mm, respectively, for $R_a < 0.8$ μm. The interaction of radial feed and feed per tooth has limited effect on the machining quality.

Figure 7d shows the influence of shaft inclination angle and spindle speed for the given radial feed $a_e = 0.05$ mm and feed per tooth $f_z = 0.1$ mm. The maximum roughness is 0.65 μm which satisfies the requirement. The interaction of shaft inclination angle and spindle speed has little effect on the machining quality.

Figure 7e shows the influence of radial feed and spindle speed for the given shaft inclination angle $\varphi = 25°$ and feed per tooth $f_z = 0.1$ mm. The maximum roughness is 0.45 μm which satisfies the requirement. The interaction of radial feed and spindle speed has negligible effect on the machining quality.

Figure 7f shows the influence of spindle speed and feed per tooth on the surface roughness for the given radial feed $a_e = 0.05$ mm and shaft inclination angle $\varphi = 25°$. The feed per tooth should be smaller than 0.6 mm and the spindle speed should be larger than 5000 r/min for $R_a < 0.8$ μm. The interaction of spindle speed and feed per tooth has obvious effect on the machining quality.

In summary, the interaction of shaft inclination angle and feed per tooth has significant effect on the milling accuracy of cycloidal gears. The interaction of radial feed and spindle speed has little effect. To improve the machining quality, the better scheme of milling parameters is recommended that the spindle speed greater than 5000 r/min, the feed per tooth less than 0.35 mm, the radial feed less than 0.4 mm, the shaft inclination angle less than 50°.

5. Conclusions

1. The orthogonal tests and multivariate nonlinear regression analysis method are used to create an analytical model to predict surface roughness of gears. The results from probabilistic analyses show high level of significance and high accuracy.
2. The shaft inclination angle has the biggest impact on the surface roughness, followed by the feed per tooth, the radial feed and the spindle speed.
3. The interaction of shaft inclination angle and feed per tooth have significant effect on the surface roughness, while the interaction of radial feed and spindle speed have little effect.

4. By applying the end milling method and seeking the optimal cutting parameters, the surface roughness of cycloidal gears can reach 0.4 μm and satisfies the requirement.

Acknowledgments

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