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Comparison of Prediction Models of Spline Cold Roll-beating Surface Roughness

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Abstract: In order to improve the spline cold roll-beating surface roughness and surface quality, spline cold roll-beating test was taken according to cold roll-beating forming principle. The response surface method and gray prediction method were used to construct the prediction model of cold roll-beating surface roughness of spline and to verify the prediction model, compare and analyze two methods of constructing prediction model. The results shows: response surface method to build spline cold roll-beating surface roughness prediction model is simple and has a high prediction accuracy.

1. Introduction

Spline cold roll-beating forming technology [1-2] is a new type of plastic forming manufacturing method. The spline cold roll-beating surface roughness prediction model can be spline cold roll-beating forming parameters optimization provides an important theoretical basis. Therefore, studying the prediction model of spline cold roll-beating surface roughness has important scientific significance and engineering application value to improve the surface quality of cold roll-beating spline.

Domestic and foreign scholars mainly study the cold roll-beating forming technology from the aspects of metal flow[3], cold roll-beating screw[4-5], work hardening[6], residual stress[7] and so on. However, in comparison of the prediction models of cold roll-beating surface roughness , there were no relevant reports. Therefore, this paper carries out spline cold roll-beating test, respectively using response surface methodology and gray prediction method to build a spline cold roll-beating surface roughness prediction model. By comparing two prediction models, the prediction model constructed by response surface method is superior to the gray prediction method.

2. Spline Cold Roll-beating Test

2.1 Test Equipment and Materials

Grob company ZRme9 roll-beating machine, Leica DCM3D white light interference microscope, test material is 20 steel.

2.2 Experimental Process

In the ZRme9 roll-beating machine, the use of pull out of the way, spline gear blank diameter 35.15, modulus 2.5, the number of teeth 14, the pressure angle 30°, the top of the tooth coefficient of 0.5, the root coefficient of 0.75. Cold roll-beating forming process parameters: roll-beating wheel speed n is 1428, 1581, 1806, 2032, 2258r/min, feed rate f is 21, 28, 35, 42 mm/min.

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A wire cutting machine was used to take a portion of each spline sample and the spline sample was placed on a Leica DCM3D white light interference microscope stage, Select 1.27mm×0.42mm on the intercepted spline sample as the measurement area, adjust the magnification of the microscope to 250 times, measure the average value of the roughness values at three different positions on the indexing circle of the spline sample as the surface roughness value.

2.3 Test Results

Take the roll-beating wheel speed and workpiece feed as the spline cold roll-beating test processing parameters, spline cold roll-beating surface roughness test results shown in Table 1.

Table 1 Cold Roll-beating Spline Test Results

Test Order	Roll-beating Wheel Speed(r/min)	Feed Rate f (mm/min)	Surface Roughness/ μm
1	1428	21	0.469
2	1428	28	0.479
3	1428	35	0.530
4	1428	42	0.625
5	1581	21	0.44
6	1581	28	0.449
7	1581	35	0.467
8	1581	42	0.508
9	1806	21	0.383
10	1806	28	0.397
11	1806	35	0.442
12	1806	42	0.495
13	2032	21	0.345
14	2032	28	0.361
15	2032	35	0.433
16	2032	42	0.500
17	2258	21	0.357
18	2258	28	0.368
19	2258	35	0.411
20	2258	42	0.472

3. Spline Cold Roll-beating Surface Roughness Response Surface Prediction Model

3.1 Construction of Surface Roughness Response Surface Prediction Model

Set two-factor quadratic response surface equation as shown in equation (1)below.

$$y(x) = a + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2 \quad (1)$$

Where, a is a constant term, b_i is the linear effect of x_i, b_{ki} is the reciprocal effect of x_k and x_i, and b_{ii} are the quadratic effect of x_i (i=1,2; k=1,2).

By Table 1, select the first three sets of data at different speeds as the sample to build a predictive model. The latter set of data be as a test model to build a predictive model, selecting surface roughness as a dependent variable, roll-beating wheel speed n and workpiece feed rate f as independent variables, the least square method was used to fit the experimental data to construct a prediction model of spline cold roll-beating surface roughness response surface as shown in formula (2).

$$Ra = 1.5761 - 0.00093319\,n - 0.0183\,f + 0.0000017273\,nf + 0.00000020228\,n^2 + 0.0003449\,f^2 \quad (2)$$

Where, Ra is the surface roughness, n is the rotational speed of the roll-beating wheel, f is the workpiece feed rate.

3.2 Spline Cold Roll-beating Surface Roughness Response Surface Prediction Model Accuracy Test
Using F test to construct the spline surface roughness prediction model for significant test results shown in Table 2.

Table 2 Spline Cold Roll-beating Surface Roughness Prediction Model Test

Sources of Sariance	Sum of Square	Degree of Freedom	Mean Square Error	F Value	$F_{0.05}$
Return	0.095763	5	0.0191526	27.79	3.48
Residual	0.006202	9	0.0006891		
Total	0.101965	14			

As can be seen from Table 2, F is greater than $F_{0.05}$, this shows that the construction of the prediction model is 95% confidence level, the complex correlation coefficient R^2 was 93.9%, indicating a high correlation between the experimental value and the regression value. The use of formula (2) combined with Table 1 to get the spline cold roll-beating surface roughness test value and the regression relationship between the changes shown in Figure 1.

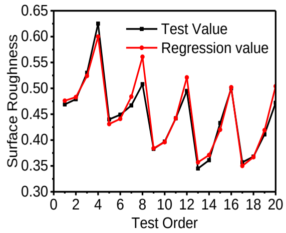

Figure 1 Spline Cold Roll-beating Surface Roughness Test Value and Regression Analysis

The test sample was used to test the pre-response spline surface roughness prediction model, and the relative errors between test values and regression values were 4%, 10.4%, 5.3%, 0.4%, 6.8%, from Figure 1, the maximum relative error between the experimental value and the regression value of the spline cold roll-beating surface roughness is 10.4%, which shows the correctness and feasibility of the constructed spline cold roll-beating surface roughness response surface prediction model.

4. Spline Cold Roll-beating Surface Roughness Gray Prediction Model

4.1 Data Processing
As can be seen from Table 1, the test data of the surface roughness as the main behavioral sequence, the play wheel speed and the workpiece feed rate test data as a factor sequence. Due to the order of magnitude of the main behavioral and factorial sequences, different orders of magnitude affect the data analysis, so to the surface roughness, roll-beating wheel speed and workpiece feed rate, the equal treatment. Equal treatment formula as shown in formula (3).

$$x_j = \frac{X_j}{\sum_{j=1}^{n} X_j} \qquad (j = 1, 2, \cdots, n) \tag{3}$$

Where, x_j is the data processed by the jth equalization, X_j is the jth experimental data, the ratio of the jth data of jth column to the sum of all data of jth column is the data after the jth equalization processing.

Since the data of the main behavioral sequence and the factor sequence after the equal treatment are disorganized and irregular, we have to do sequence 1 -AGO gray processing. Through the 1-AGO ash treatment, it can be found that the development trend during the accumulation of the ash content fully embodies the characteristics and laws contained in the original random sequence data. Using the formula (4), we can get the immediate average value of the main behavioral sequence after 1-AGO gray treatment. Based on the formula (4), the gray differential model of gray prediction is obtained as shown in formula (5).

$$Z_1^{(1)} = 0.5x_1^{(1)}(k) + 0.5x_1^{(1)}(k-1) \quad (4)$$

Where, $Z_1^{(1)}$ is an immediate sequence of the main behavioral sequence after 1-AGO gray processing, $x_1^{(1)}(k)$ is a factor sequence after 1-AGO gray processing, (k=2,3, …,20).

$$x_1^{(0)}(k) + aZ_1^{(1)}(k) = \sum_{i=2}^{n} b_i x_i^{(1)}(k) \quad (5)$$

Where, $x_1^{(0)}(k)$ is the main behavior sequence after equal weight treatment, a is the system development coefficient, $Z_1^{(1)}(k)$ is the immediately adjacent mean sequence of the main behavioral sequence after 1-AGO gray processing, , b is the driving coefficient, $b_i x_i^{(1)}(k)$ is the driving term, (i = 2, 3,..., n; k=1,2,3, …,20), said formula (5) for the gray differential model, a and b_i constitute the parameter column (6).

$$\hat{a} = [a, b_2, \cdots, b_{20}]^T = (B^T B)^{-1} B^T Y \quad (6)$$

$$B = \begin{bmatrix} -Z_1^{(1)}(2) & x_2^{(1)}(2) & x_3^{(1)}(2) \\ -Z_1^{(1)}(3) & x_2^{(1)}(3) & x_3^{(1)}(3) \\ \vdots & \vdots & \vdots \\ -Z_1^{(1)}(20) & x_2^{(1)}(20) & x_3^{(1)}(20) \end{bmatrix} \qquad Y = \begin{bmatrix} x_1^{(0)}(2) \\ x_1^{(0)}(3) \\ \vdots \\ x_1^{(0)}(20) \end{bmatrix}$$

Where, B is a gray prediction data matrix, Y is a gray prediction data vector matrix, and the least squares estimation of the parameter column yields a of 0.0172, b_1 of -0.6128 and b_1 of 0.6718.

4.2 Gray Prediction Model Construction of Spline Cold Roll-beating Surface Roughness

From the approximation time response formula (7), the approximate time response of spline cold roll-beating surface roughness (8) is obtained based on the values of a, b_1 and b_2 obtained from parameter column (6).

$$\hat{x}_1^{(1)}(k+1) = [x_1^{(0)}(1) - \frac{1}{a}\sum_{i=2}^{3} b_i x_i^{(1)}(k+1)]e^{-ak} + \frac{1}{a}\sum_{i=2}^{3} b_i x_i^{(1)}(k+1) \quad (7)$$

$$\hat{x}_1^{(1)}(k+1) = [x_1^{(0)}(1) - \frac{1}{0.0172}(-0.6128x_2^{(1)}(k+1) + 0.6718x_3^{(1)}(k+1))]e^{-0.0172k} + \frac{1}{0.0172}[-0.6128x_2^{(1)}(k+1) + 0.6718x_3^{(1)}(k+1)] \quad (8)$$

Where, before the equal sign for the 1-AGO gray forecast after the main behavioral sequence of predictions, $x_1^{(0)}(1)$ for the right to deal with the main behavior of the first sequence, a is the system development coefficient, b is the driving coefficient, $b_i x_i^{(1)}$ is the driving term, (i = 2,3; k = 0,1,2,..., 20).

Use formula (9) to restore the predicted value of the main behavior sequence after the equal weight treatment, and the formula for reducing the predicted value is as shown in (9).

$$\hat{x}_1^{(0)}(k) = \hat{x}_1^{(1)}(k) - \hat{x}_1^{(1)}(k-1) \qquad (k = 2,3,\cdots,20) \quad (9)$$

Where, the predicted value of the main behavioral sequence after equal treatment before the equal sign is the predicted value of the factor sequence after the 1-AGO ashes after the equal sign.

The predictive value of the factor sequence after 1-AGO gray treatment is obtained from the formula (8), and the predicted value of the main behavior sequence after the equal weight treatment is restored by using the formula (9), through the equal treatment of the reverse operation to obtain the predicted value of the surface roughness, spline cold roll-beating surface roughness test value and the predicted changes in the relationship shown in Figure 2.

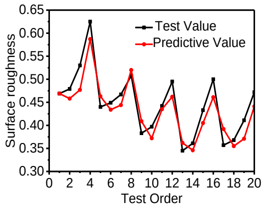

Figure 2 Spline Cold roll-beating Surface Roughness Test Values and Predicted Values

4.3 Spline Sold Roll-beating Surface Roughness Gray Prediction Model Accuracy Test

From Figure 2, the average value of the spline cold roll-beating surface roughness test value is 0.44655, the variance of the test value is 0.06717, spline cold roll-beating surface roughness of the test value and the predicted residual value of the mean 0.014105, the variance of the residuals between the experimental and predicted values is 0.02466, the posterior difference ratio is 0.367, the probability of small errors is greater than 0.95. Therefore, it is reasonable and valid to construct the gray prediction model of the spline cold roll-beating surface roughness.

5. Comparison and Analysis of Two Predictive Models

(1) Response surface method to build a predictive model is simple and convenient comparing to gray prediction method which has to go through many data processing and more formulas. The gray prediction method increases the difficulty of constructing the prediction model and reduces the overall accuracy of the prediction model. It can be seen from the fitting difficulty that the response surface method is superior to the gray prediction method

(2) From Figure 1, the test values and regression values have very similar trends. The trend of the test values and the predicted values are roughly the same as shown in Figure 2, and some changes in the trend shows that there is larger deviation at that time. It can be seen from the curve fitting trend that the response surface prediction accuracy is better than the gray prediction.

6. Conclusion

The F-test and complex correlation coefficient are used to verify the predictive model constructed by response surface methodology. The prediction model constructed by gray prediction is verified by using posterior difference ratio and small error probability. The verification results shows that the two kinds of prediction models are reasonable and feasible. Comparing the prediction models constructed by the two methods, the response surface method is simple and feasible. Additionally, the prediction accuracy of response surface method is better than the gray prediction method.

References

[1] Yang J X, Cui F K, Wang X Q, et al. Design theory and experimental amends of involute spline roller[J]. China Mechanical Engineering, 2008, 19(4): 419-422.
[2] Cui F K, Li Y, Zhou Y W, et al. CAD system of roller for involute spline and simulation of grinding process[J]. Journal of Mechanical Engineering, 2005, 41(12): 210-215.
[3] Cui F K, Xie Y F, Dong X D, et al. Simulation analysis of metal flow in high-speed cold roll-beating[J]. Applied Mechanics & Materials, 2014, 556-562: 113-116.
[4] Yang M S, Yuan Q L, Li Y, et al. Deformation force simulation of lead screw cold roll-beating based on ABAQUS[J]. Foundry Technology, 2011, 15(1): 5164-5169.
[5] Li Y, Zhang Y, Yang M S, et al. Analysis of lead screw high-speed roll-beating forming[J]. Key Engineering Materials, 2011, 455: 151-155.
[6] Cui F K, Ling Y F, Xue J X, et al. Research on work-hardening behavior of surface layer of spline during cold roll-beating[J]. Acta Armamentarii, 2017, 38(2): 358-366.
[7] Ding Z H, Cui F K, Liu Y B, et al. A model of surface residual stress distribution of cold roll spline[J]. Mathematical Problem in Engineering, 2017, 2017(4): 1-21