Hindawi
Mathematical Problems in Engineering
Volume 2018, Article ID 4346015, 10 pages
https://doi.org/10.1155/2018/4346015

Research Article

Gray Relational Optimization of the Surface Performance of Splines Formed by Cold Roll-Beating

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Received 20 January 2018; Revised 17 May 2018; Accepted 22 July 2018; Published 31 July 2018

Academic Editor: Sergio Teggi

Surface roughness, residual stress, and work hardening are the key parameters characterizing the mechanical properties of a spline surface after undergoing cold roll-beating. A comprehensive optimization of the mechanical properties of such surfaces has not been previously reported. To improve the performance of the spline surface, gray theory is used to study the relationships between the surface roughness, residual stress, and work hardening in the pitch diameter of spline teeth. This method addresses the surface performance optimization of an involute spline as influenced by the cold roll-beating speed and feed rate as the main parameters during the cold roll-beating process. The results show that the surface roughness and hardening degree of the splines increase with an increasing feed rate but decrease with an increasing cold roll-beating speed; the residual stress of the spline decreases with an increasing feed rate and increases with an increasing cold roll-beating speed. The results also show that the feed rate has a strong influence on the surface performance of splines produced by cold roll-beating. The optimal process parameters in terms of the spline surface performance are a cold roll-beating speed of 1428 r/min and a feed rate of 42 mm/min. The results of the present work emphasize the significance of improving the surface performance of the cold roll-beating spline-forming process and determining the optimal process parameters.

1. Introduction

In machining, the cold roll-beating forming process is a nontraditional near-net forming processing method that is characterized by zero waste, high efficiency, low pollution, and near-net shape, among other advantages. The forming technology can be widely used in many types of equipment, including industrial machines, aircraft, ships, agricultural equipment, splines, and gears. The cold roll-beating and beating forming process is a gradual forming process of nonuniform thermal coupling. Due to the mechanical force on the surface of the workpiece, a certain degree of work hardening is inevitably generated. The surface roughness, residual stress, and work hardening are the main parameters used to evaluate the surface quality of a workpiece, which directly affects the physical and mechanical properties of the surface layer. However, in the actual production and processing process, developing a method of selecting the optimal cold roll-beating processing parameters to maximize the performance of a spline surface requires thorough scientific investigation. Therefore, the parameters of the surface and the surface properties of the spline are studied here; the results of the study are of high value in engineering applications to improve the performance of the spline surface as produced by cold roll-beating.

In recent years, much research has focused on the quality of workpiece processing. Grob E [1] discussed the impact of the workpiece processing quality of the cold wheel of the installation of the angle and proposed a method involving the combination of the roller and the rolling head of a thrust ring to form a tilt plane; the method allows the roller to be set in accordance with a preset installation angle fixed on the rolling head, thereby improving the workpiece machining accuracy and quality. Weck M [2] compared the surface properties of cold-rolled parts and conventional machined parts and demonstrated that the cold hardening of high-speed cold work causes a special hardening layer to form on the surface of the parts. Based on an analysis of the process of involute spline molding, Cui Fengkui [3] analyzed the relationship between the components of spline cold roll-beating and established a corresponding mathematical model. The dynamic responses of the process and the stress wave were analyzed, and the mechanism of metal flow and the forming mechanism were discussed at the macroscopic level. Regarding research on the spline cold roll-beating work-hardening process for 40Cr, Cui Fengkui [4] studied the process parameters related to the work-hardening mechanism. Xu Yongfu [5] conducted an experiment to study the high-speed cold roll-beating metal microstructure deformation, residual stress distribution, and tooth surface quality, among other parameters, and found that the high-speed cold roll-beating process can improve the surface of the spline surface metal structure as well as the surface hardness, thereby improving the spline strength and greatly improving the surface integrity. Wang Xiaoqiang et al. [6] established a 40Cr dynamic dislocation density model under cold roll-beating conditions. XRD experiments were used to obtain the diffraction patterns of 40Cr under various deformation conditions. The Dunn formula was used to obtain the dislocation density change of 40Cr under different deformation conditions and to further explain the changes occurring in 40Cr in the process of cold rolling from the microscopic perspective. Kong Xiangjian et al. [7] analyzed the forming principle of the high-speed cold roll-beating rack, studied the stress and strain in the forming process using ABAQUS, and conducted a cold roll-beating experiment to determine the hardness of the forming rack and the changes in the metal fiber. The analysis showed that the cold roll-beating process can effectively improve the microstructure of the workpiece surface.

Presently, scholars are applying gray theory to research involving mechanical processing. In the process of turning, the roughness optimization process is limited by multiple parameters. The gray correlation method is used to analyze the turning process and identify the parameters with a strong influence on the roughness. Xia Xintao [8] used gray system theory to study a mechanical manufacturing process via two-data-sequence gray correlation analysis and calculated the size of the gray confidence level, in order to achieve stability in the manufacturing process assessment. Based on experimental research, Xia Xintao [9] also used gray system theory to compare and evaluate the impact of bearing vibration on the different natures of the processing quality indicators. Based on fuzzy mathematics theory, Yang Yufen [10] studied the geometrical features of the surface structure by the fuzzy mathematics theory. The geometrical features of the three-dimensional comprehensive parameters and the available practical information regarding the correlation among the three-dimensional comprehensive parameters and the single parameters were studied to realize the three synthetic parameters of the synthesis; in addition, this comprehensive measurement method was used on the processed surface to provide useful information and was applied to industrial production to improve the surface processing accuracy of mechanical parts.

Thus, numerous scholars have studied theoretical models, finite element simulations, and parametric models of the evaluation parameters (i.e., the surface roughness, residual stress, and work hardening) of the surface performance of the cold-rolling process. Both gray theory and fuzzy mathematics have been used to analyze the surface roughness of machined parts. However, there is no report on the optimization of the performance parameters of the spline surface after undergoing the cold roll-forming process. Here, we present an experimental study of the spline cold roll-beating forming process. Gray scale theory is used to analyze the surface performance evaluation parameters of the spline surface. The aim of this study is to achieve the control of the surface roughness, residual stress, and the degree of work hardening of the spline cold roll-beating forming process and the optimal choice of the process parameters to improve the surface properties of a spline formed by cold roll-beating.

2. Experimental Study of Splashing in the Cold Roll-Beating Process

2.1. Experimental Material. The cold roll-beating spline test blank material is 20 steel, which has a yield strength of 245 MPa, an elastic modulus of 206 GPa, and a tensile strength of 410 MPa; the chemical composition is shown in Table 1. The splines are involute splines, the spline modulus is 2.5, the pressure angle is 30°, and each has 14 teeth.

2.2. Experimental Equipment. The cold roll-beating involute spline was processed in the Swiss company Grob ZRme9 rolling machine. The surface roughness value was measured using a Leica DCM3D white-light copolymer interference microscope. The surface hardness was measured using a HVS-1000A microhardness tester, and the contour method was used to measure the surface roughness. Residual stress measurements were performed using a Serein-CMM FUNCTION 1000 coordinate-measuring instrument.

2.3. Experimental Procedures. The pull-out method was used in the rolling machine for cold roll-beating involute spline processing. Using a walking wire-cutting machine, a part of the spline teeth was taken from each spline to measure the surface roughness. A sample is shown in Figure 1. The samples were placed under the Leica microscope, a measurement area of 1.27×0.42 mm was selected for each sample, and the magnification was adjusted to 250 times to ensure the accuracy of the measurement results. For each sample index circle, the measured average value of each sample is used as the surface roughness value.

The cutting of the cut spline teeth was conducted by grinding and polishing the cut specimen using a thread-cutting machine. The microhardness tester was used to measure the surface. The Vickers hardness at the index-dividing circle was measured at 20 points for each part. The distance between each measuring point was 0.1 mm. The applied load was 1 N, and the loading time was 10 s.

Table 1: The chemical composition of 20 steel (mass fraction, %).

C	Si	Mn	P	S	Ni	Cr
0.20	0.17-0.37	0.35-0.65	≤0.035	≤0.035	≤0.30	≤0.25

Table 2: The test parameters and results.

Test serial number	Cold roll-beating speed (r/min)	Feed rate (mm/min)	Surface roughness (μm)	Residual stress (MPa)	Degree of hardening (%)
1	1428	21	0.469	-67.42	140.96
2	1428	28	0.479	-72.70	143.35
3	1428	35	0.530	-79.38	145.83
4	1428	42	0.625	-83.01	148.71
5	1581	21	0.440	-68.76	140.25
6	1581	28	0.449	-75.16	143.06
7	1581	35	0.467	-78.79	144.91
8	1581	42	0.508	-83.11	146.79
9	1806	21	0.383	-72.15	138.78
10	1806	28	0.397	-75.65	142.26
11	1806	35	0.442	-79.49	143.48
12	1806	42	0.495	-84.83	145.95
13	2032	21	0.345	-73.04	138.41
14	2032	28	0.361	-79.04	141.43
15	2032	35	0.433	-82.77	142.64
16	2032	42	0.500	-84.76	145.03
17	2258	21	0.357	-74.75	138.11
18	2258	28	0.368	-78.58	139.37
19	2258	35	0.411	-83.25	141.93
20	2258	42	0.472	-84.87	144.11

Using the wire-cutting machine, from a 0.1 mm bronze wire, a tooth was cut from the spline at a feed rate of 2 mm/min. The sample was cut at a feed rate of 0.5 mm/min along the symmetry plane shown in the shaded area of Figure 2(a). The specimen had the following dimensions: l = 10 mm, w = 4.35 mm, and h_0 = 2.68 mm. The point coordinates on the cross section shown in Figure 2(a) were measured using the Serein-CMM coordinate-measuring instrument (measured on both sides after cutting). The measured point interval was 0.2 mm × 0.2 mm, and the measurement trajectory was top-down, reciprocating. According to the coordinates of the measured points, the processing of the model was completed along the direction indicated in Figure 2(b), with the spline indexing the location of the residual stress at the extraction point interval of 0.25 mm [11–14]. The dimensions were h_a = 2.20 mm, h_d = 1.39 mm, and h_f = 0.5 mm.

2.4. Experimental Parameter Design and Experimental Results. The experiment parameters selected for the cold-rolling speed and feed rate were as follows: the speed was set to one of 5 levels, and the feed rate was set to one of 4 levels. The test parameters and results are shown in Table 2.

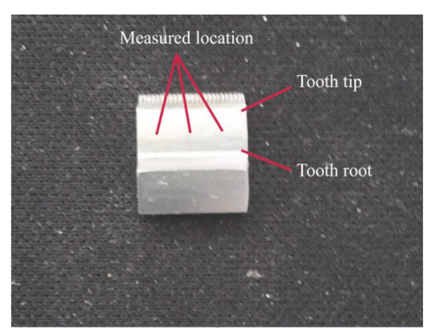
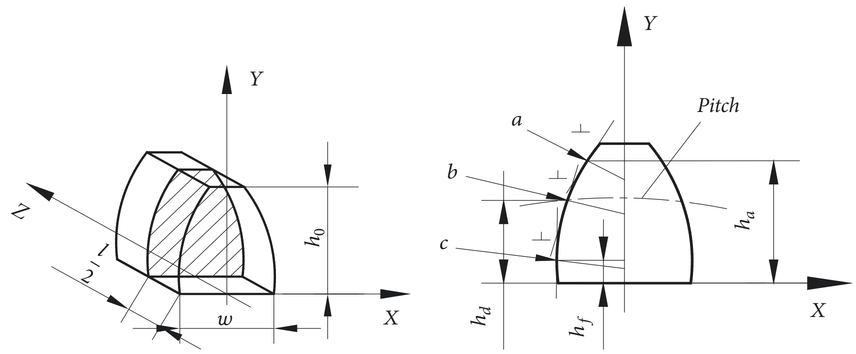


Figure 1: The spline specimen.

2.5. Analysis of the Experimental Results

2.5.1. Influence of the Cold-Rolling Speed and Feed Rate on the Spline Surface Roughness. The relationships between the cold roll-beating speed, feed rate, and spline surface roughness are shown in Figure 3.

When the cold-rolling speed is constant, the spline surface roughness gradually increases with increasing feed rate. In terms of the physical factors, the increase in the feed rate results in an increase in the rolling force and a further increase



(a) The shape of the specimen and the position of the cross section to be measured

(b) The residual stress extraction location and direction

FIGURE 2: The measurement scheme of the residual stress using the contour method.

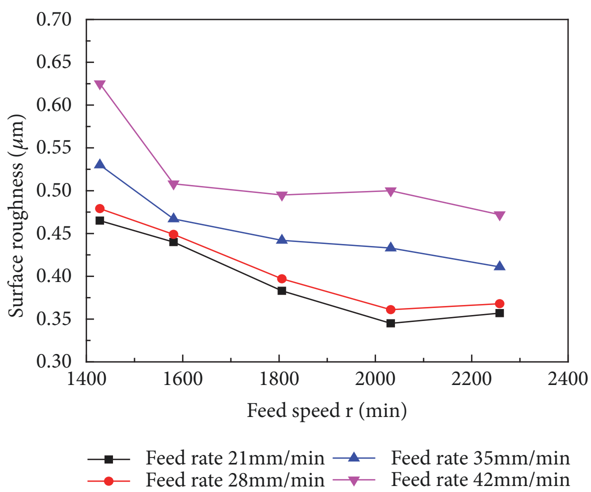


FIGURE 3: Influence of the speed and feed rate on the surface roughness.

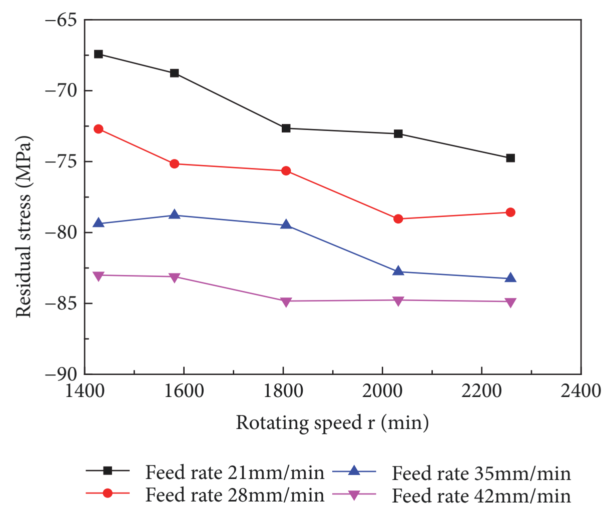


FIGURE 4: Influence of the speed and feed rate on the residual stress.

in temperature, thereby increasing the plastic deformation of the metal and the surface roughness. In addition, as the feed rate increases, the amplitude of the roll wheel vibrates and increases the roughness. When the feed rate is constant, the spline surface roughness decreases gradually with increasing workpiece speed. When the workpiece speed increases, the feed rate of the workpiece decreases; in addition, the vibration amplitude of the roller is reduced, and the influence of the feed rate on the surface roughness shows that the surface roughness of the spline will decrease.

2.5.2. Influence of the Rolling Speed and the Feed Rate on the Spline Residual Stress. The relationships between the rolling speed, feed rate, and spline residual stress are shown in Figure 4.

When the feed rate is constant, the spline surface residual stress decreases with increasing cold-rolling speed. When the rotational speed is between 1400 r/min and 2000 r/min, the residual stress is affected primarily by the nonuniform plastic deformation, and the plastic deformation increases with increasing rotational speed; thus, the residual stress also increases with the speed. When the speed rises from 2000 r/min to 2400 r/min, the material is thermally deformed due to the increase of the surface layer temperature during the striking process, which leads to a decrease of the residual stress. At the same speed, the spline residual stress increases with increasing feed rate, but this influence is less prominent than that of the rotational speed.

2.5.3. Influence of the Cold-Rolling Speed and Feed Rate on the Degree of Spline Work Hardening. The relationships between the rolling speed, feeding rate, and spline work-hardening degree are shown in Figure 5.

When the feed rate is 21 mm/min, the degree of hardening is the smallest at the spline graded circle, and when the feed rate is 42 mm/min, the degree of hardening is the highest. The degree of hardening of the spline surface increases with increasing feed rate at the same speed because the deformation and stress increase, resulting in a more prominent degree of hardening. When the feed rate is constant, the degree of hardening at the spline graded circle is slightly reduced with increasing speed because as the speed increases, the number

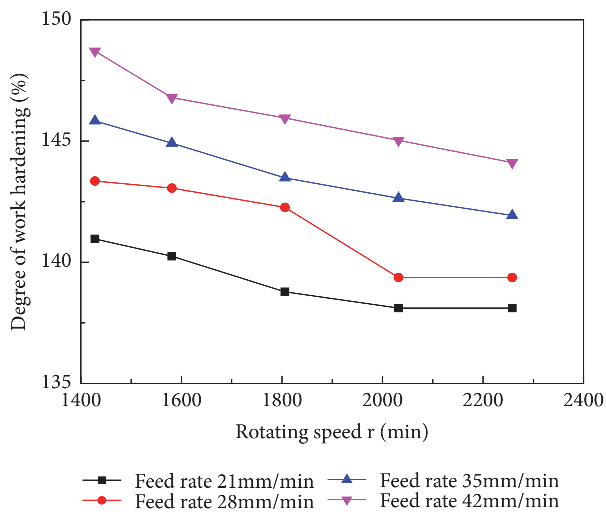


FIGURE 5: Influence of the speed and the feed rate on the degree of work hardening.

of roll-beating strikes per unit time increases, the workpiece temperature increases, and, thus, the temperature-softening effect is strong, resulting in a reduction in the degree of hardening.

3. Gray Relational Analysis of the Spline Surface Performance from Cold Roll-Beating

According to the gray theory, first, dimensionless processing of test data, the reference sequence, and the comparison sequence are determined, and then the gray correlation coefficient of each evaluation parameter is calculated. Because the gray correlation coefficient is the correlation degree between the comparison sequence and the reference sequence in each experimental sequence, its value is more than one, and the information is too scattered to facilitate the overall comparison. Therefore, it is necessary to average the correlation coefficient of the experimental sequence as the quantity of the correlation degree between the comparison sequence and the reference sequence. That is, the gray correlation degree r_i, the closer the r_i value is to 1, the better the correlation is. The degree of association between the evaluation parameters is mainly described by the order of the degree of association. By arranging the correlations of each sequence in order of magnitude, they form an association order, which mainly reflects the “pros and cons” relationship between subsequences.

We now apply the dimensionless method to each evaluation parameter. A certain correlation exists among the surface roughness, the residual stress, and the hardening degree of the spline; as a result, the gray correlation coefficient can be calculated by solving the gray correlation coefficient of each evaluation parameter. Next, the average gray correlation degree of each processing parameter is obtained to judge the influence degree of each processing parameter on the performance of the spline surface and determine the processing parameters corresponding to the optimal surface performance of a spline formed by cold roll-beating.

3.1. Dimensional Processing of the Surface Performance Test Data. In the cold roll-beating spline-forming test data, the numerical range and the units of the three parameters for evaluating the surface performance are different, and the purpose and direction of each evaluation factor are also different. Therefore, the experimental data are nondimensionalized to transform the original data sequence into a comparative data sequence [15–17].

In the process of cold roll-beating spline forming, the surface roughness affects the wear and fatigue strength of the spline: a larger surface roughness is correlated with a smaller effective contact area between the mating surfaces and an increase in wear. A large trough exists in the rough spline surface that is sensitive to stress concentrations, thus affecting the fatigue strength of the spline. Therefore, to meet the requirements of processing and use, a smaller surface roughness value is selected, and (1) is used for dimensionless processing. The results of the spline test show that when the residual stress of the spline tooth profile is compressive, the expansion of the microcrack on the spline surface can be reduced and the fatigue strength of the spline improved by appropriately increasing the residual compressive stress. Therefore, to select a larger residual compressive stress, (1) is again adopted for the dimensionless treatment. Work hardening can increase the strength, hardness, and wear resistance of the spline. When the local stress of the spline exceeds the yield limit of the material, plastic deformation occurs, and the associated work hardening limits further development of the plastic deformation to improve the safety of the spline and mating parts. Under these conditions, we adopt (2) for the dimensionless treatment.

$$x_i^* (k) = \frac{\max x_i^o (k) - x_i^o (k)}{\max x_i^o (k) - \min x_i^o (k)} \tag{1}$$

$$x_i^* (k) = \frac{x_i^o (k) - \min x_i^o (k)}{\max x_i^o (k) - \min x_i^o (k)} \tag{2}$$

$$i = 1, 2, 3 \ldots m; \;\; k = 1, 2, 3, \ldots n$$

In these formulas, i is the number of experiments; k is the number of data sequence parameters; $x_i{}^o(k)$ is the original data sequence; $x_i{}^*(k)$ is the sequence obtained after dimensionless processing; $\max x_i{}^o(k)$ is the largest value in the original data sequence; and $\min x_i{}^o(k)$ is the smallest value in the original data sequence.

Table 3 presents the sequence of each evaluation parameter of the surface performance of the cold roll-beating spline-forming process obtained by substituting the test results in Table 2 into (1) and (2).

3.2. Establishment of the Spline Cold Roll-Beating Forming Surface Performance Evaluation Parameter Correlation Degree. Once the test data are in dimensionless form, the parameters of the spline surface can be evaluated using (3). The results are shown in Table 4.

$$\Delta_{oi} = \left| X^o (k) - x_i^* (k) \right| \tag{3}$$

$\triangle_{\text{oi}}(1)$ is the surface roughness reference sequence and the contrast sequence deviation, $\triangle_{\text{oi}}(2)$ is the deviation of the

Table 3: Dimensionless processing of the cold roll-beating spline-forming test data.

		Surface roughness (mm)	Residual stress (MPa)	Work hardening (%)
Reference sequence $x^o(k)$		1.000	1.000	1.000
Contrast sequence	1	0.557	0.000	0.269
	2	0.521	0.303	0.495
	3	0.339	0.685	0.728
	4	0.000	0.893	1.000
	5	0.661	0.077	0.202
	6	0.629	0.444	0.467
	7	0.564	0.652	0.641
	8	0.418	0.899	0.819
	9	0.864	0.271	0.064
	10	0.814	0.472	0.392
	11	0.654	0.692	0.507
	12	0.464	0.998	0.740
	13	1.000	0.322	0.028
	14	0.943	0.666	0.313
	15	0.686	0.880	0.428
	16	0.446	0.994	0.653
	17	0.957	0.420	0.000
	18	0.918	0.640	0.119
	19	0.764	0.907	0.360
	20	0.546	1.000	0.566

Table 4: The evaluation parameter deviation sequence of the cold roll-beating spline-forming test.

Test serial number	$\triangle_{oi}(1)$	$\triangle_{oi}(2)$	$\triangle_{oi}(3)$
1	0.443	1	0.731
2	0.479	0.697	0.505
3	0.661	0.315	0.272
4	1	0.107	0
5	0.339	0.923	0.798
6	0.371	0.556	0.533
7	0.436	0.348	0.359
8	0.582	0.101	0.181
9	0.136	0.729	0.936
10	0.186	0.528	0.608
11	0.346	0.308	0.493
12	0.536	0.002	0.26
13	0	0.678	0.972
14	0.057	0.334	0.687
15	0.314	0.12	0.572
16	0.554	0.006	0.347
17	0.043	0.58	1
18	0.082	0.36	0.881
19	0.236	0.093	0.64
20	0.454	0	0.434

residual stress reference sequence and the contrast sequence of the cold roll-beating, and $\triangle_{oi}(3)$ is the hardening degree of the reference sequence and contrast sequence deviation.

Equations (4) to (6) were used to calculate the gray correlation coefficient of each evaluation parameter according to the deviation sequence of the evaluation parameters of the forming test, and (7) and (8) were used to solve the gray correlation among the surface roughness, the residual stress, and the hardening degree of the spline, as shown in Table 5. Because splines produced by cold roll-beating

TABLE 5: Cold roll-beating spline-forming evaluation parameter comparison of the sequence gray correlation coefficient and the gray correlation degree.

Test time	Gray correlation coefficient			Gray correlation degree	Sorting
	Surface roughness	Residual stress	Degree of hardening		
1	0.5302	0.3333	0.4062	0.141	20
2	0.5107	0.4177	0.4975	0.159	18
3	0.4307	0.6135	0.6477	0.191	10
4	0.3333	0.8237	1.0000	0.249	1
5	0.5959	0.3514	0.3852	0.146	19
6	0.5741	0.4735	0.4840	0.169	16
7	0.5342	0.5896	0.5821	0.190	11
8	0.4621	0.8319	0.7342	0.227	3
9	0.7862	0.4068	0.3482	0.166	17
10	0.7289	0.4864	0.4513	0.182	15
11	0.5910	0.6188	0.5035	0.188	12
12	0.4826	0.9960	0.6579	0.236	2
13	1.0000	0.4244	0.3397	0.188	13
14	0.8977	0.5995	0.4212	0.206	7
15	0.6143	0.8065	0.4664	0.204	8
16	0.4744	0.9881	0.5903	0.225	4
17	0.9208	0.4630	0.3333	0.183	14
18	0.8591	0.5814	0.3621	0.192	9
19	0.6793	0.8432	0.4386	0.211	6
20	0.5241	1.0000	0.5353	0.224	5

are used in various applications, the surface performance evaluation parameters depend on the specific requirements of each application. Here, we focus on the use of splines in agricultural equipment. As the spline in the device must have sufficient strength to bear the main load and because work hardening can improve the strength of the spline, the spline response after hardening is of interest; thus, $w_1 = 0.3$, $w_2 = 0.3$, and $w_3 = 0.4$.

$$\xi_i(k) = \frac{\Delta_{\min} + \psi\Delta_{\max}}{\Delta_{oi}(\mathrm{k}) + \psi\Delta_{\max}} \tag{4}$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left| X^o(k) - x_j^*(k) \right| \tag{5}$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left| X^o(k) - x_j^*(k) \right| \tag{6}$$

$$r_i = \frac{1}{n} \sum_{k=1}^{n} w_k \xi_i(k) \tag{7}$$

$$\sum_{k=1}^{n} w_k = 1 \tag{8}$$

where $\triangle_{oi}(k)$ is the reference sequence, $X^o(k)$ is the comparison sequence, $x_i * (k)$ is the deviation, and ψ is the deviation coefficient, whose value is between 0 and 1. Typically, $\psi = 0.5$, and w_k is the normalized measure of factor k.

3.3. Performance Correlation Analysis of the Forming Surface

3.3.1. Influence of the Processing Parameters on the Surface Performance of the Spline. The gray correlation degree of the evaluation parameter is grouped according to the parameter level, and the average gray correlation value is calculated for each level of each process parameter; next, the maximum average correlation degree of the parameter level and the minimum average correlation degree difference are obtained. The results are shown in Table 6.

The maximum η value corresponds to the cold roll-beating process parameter with the greatest impact on the spline performance. From Table 6, the maximum η value is 0.0676, indicating that the feed rate has the strongest influence on the surface properties of the spline. According to this test study and analysis, when the cold roll-beating speed is constant, based on the value of w_k in (8), the degree of standardization of work hardening is greater than the residual stress and surface roughness. The influence of the cold roll-beating speed and feed rate on the degree of spline work hardening is shown in Figure 5; the influence of the feed rate on the degree of spline work hardening is much greater than that of the cold roll-beating speed. Comprehensive experimental study and gray correlation analysis verify that the cold roll-beating feed rate has the greatest impact on the performance of the spline surface layer.

Table 6: Horizontal average gray correlative degree of the cold roll-beating spline-forming process parameters.

Processing parameter	Average gray correlation degree					η (max. - min.)
	Level 1	Level 2	Level 3	Level 4	Level 5	
Cold roll speed	0.1849	0.1832	0.1928	0.2057	0.2024	0.0225
Feed speed	0.1646	0.1817	0.1968	0.2321	---	0.0676

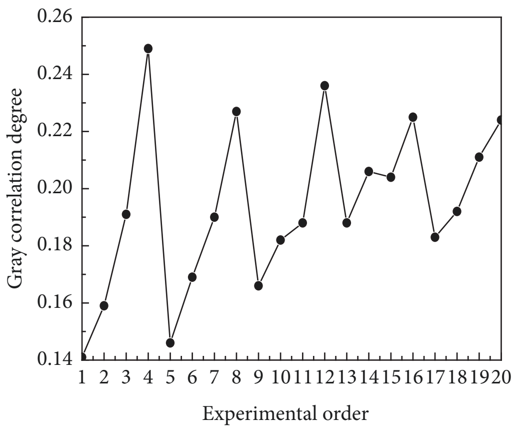


Figure 6: Gray correlation degree corresponding to the test sequence of spline forming.

3.3.2. Design of the Optimal Processing Parameters for the Surface Performance of Spline Cold Roll-Beating. The order of the corresponding gray correlation degrees shown in Figure 6 is studied by sorting Table 6.

Figure 6 shows that the fourth test has the largest gray correlation. Thus, the fourth test of the process parameters (a cold roll-beating speed of 1428 r/min and a feed rate of 42 mm/min) is determined through 20 iterations to correspond to the optimal spline cold roll-forming process parameters; the corresponding surface roughness value is 0.625 μm, the residual stress is -83.01 MPa, and the work-hardening degree is 148.71.

3.3.3. Cold Roll-Beating Spline Optimization Results Test Verification. According to the gray relational theory, the relative merits of each sequence are mainly described by the order of correlation. Therefore, it can be seen from the above correlation analysis that the 12th group test is relatively good; therefore, the cold roll-beating forming test was newly conducted for the 4th and 12th groups of tests; firstly, the surface quality image of the processing spline was measured as shown in Figure 7; secondly, scanning electron microscopy test to observe the microstructure of the spline tooth cross-section morphology is shown in Figure 8; finally, the surface TEM of the spline tooth is shown in Figure 9.

Because the cold roll-beating processing is a nonblade processing, there is no feature that the blade is scratched on the surface of the workpiece. During the cold rolling process, the interaction between the workpiece and the roller is changed due to the different rotational speed and feed rate, which affects the metal flow, plastic deformation, and elastic recovery of the workpiece surface. They are the main cause of the surface roughness of the cold rolling spline. As can be seen from Figure 7, the surface quality of Figures 7(a) and 7(b) diagrams is not much different, and overall the surface roughness of Figure 7(b) diagram is slightly better. The essence of residual stress is the nonuniform plastic deformation of the workpiece material. From Figure 8, it can be seen that the microstructure of the spline microstructure shows that, compared with Figures 8(a) and 8(b), the degree of the crystal grains being stretched and the degree of compaction are large, and the degree of metal plastic flow is not uniformly higher. The residual stress in Figure 8(a) is greater. Figure 9 shows the surface of the spline tooth TEM image. It can be seen from Figure 9(a) that the surface of the spline tooth produces a large number of cotton-like dislocations in the ferrite near the grain boundary, distributed in the pearlite and ferrite. Near the grain boundary, a certain amount of dislocations are generated at the surface of the spline tooth in Figure 9(b), but the surface deformation is relatively small compared with Figure 9(a). Due to the formation of dislocations near the grain boundary, the density of dislocations increases, eventually increasing the flow stress, making the material more resistant to deformation, and thereby increasing work hardening on the workpiece surface. Therefore, the work-hardening ratio in Figure 9(a) is higher than Figure 9(b) and bigger. To sum up, when the processing parameters cold roll-beating speed is 1428r/min, the feed speed is 42mm/min, and the surface performance of the cold-rolled spline is better.

4. Conclusion

Through gray correlation analysis of the experimental results of the cold roll-beating forming test, the following conclusions are obtained:

(1) The surface roughness of the spline and the work hardening of the spline splines increase as the feed rate increases and decrease as the cold roll-beating speed increases. The residual stress of the spline decreases as the feed rate increases and increases as the cold roll-beating speed increases.

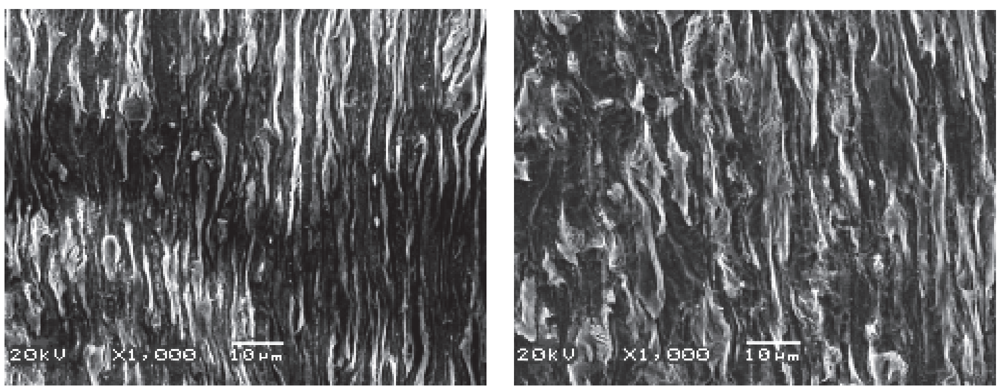
(2) The influence of the feed rate on the work hardening of the spline is greater than that of the cold roll-beating speed. The influence of the cold roll-beating speed on the spline residual stress is greater than that of the feed rate.

(3) A comparison of the size difference among each processing technology parameter of the average gray correlation between the maximum and the minimum values was used to determine that the feed rate has the maximum degree of influence on the performance of the spline surface, followed by the cold roll-beating speed.

(4) The gray processing degree was sorted to select the optimal processing parameters (namely, a cold roll-beating

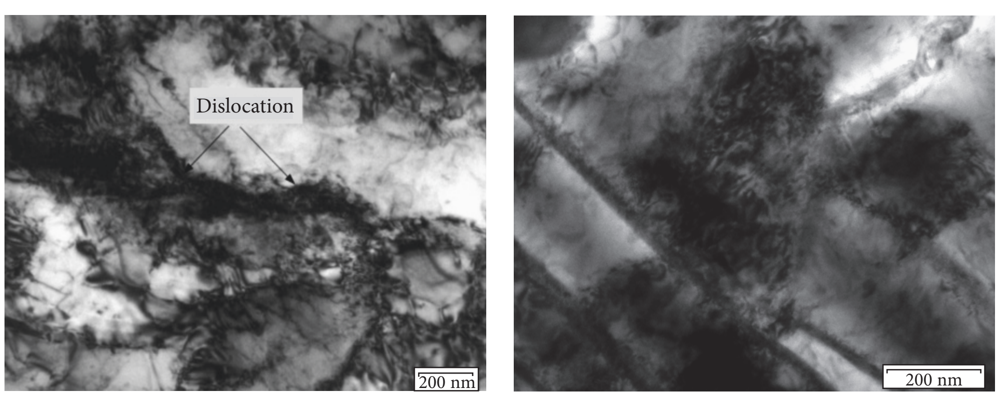
(a) The fourth group test (b) The twelfth group test

Figure 7: Image of the cold roll-beating spline's surface quality.



(a) The fourth group test (b) The twelfth group test

Figure 8: Image of cold roll-beating spline microstructure topography.



(a) The fourth group test (b) The twelfth group test

Figure 9: Image of cold roll-beating spline TEM.

speed of 1428 r/min and a feed rate of 42 mm/min) to maximize the performance of the spline surface.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This project was supported by the National Natural Science Foundation of China (Grant no. 51475146/51475366).

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