Research Article

Experimental Analysis of Residual Stress and Bending Strength of Gear Tooth Surface after Shot Peening Treatment

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The fatigue strength of a gear tooth surface is affected by various factors, which subsequently impacts the transmission performance of gears. Usually, shot peening treatment is carried out during processing to improve the performance of gears. Most current studies focus on theoretical descriptions and simulation analyses of shot peening treatment. However, in this paper, the relationships among shot peening treatment, residual stress, and bending fatigue strength of a gear tooth surface are discussed, through experimental methods. Based on X-ray stress analysis, at select locations on the test samples, the residual stresses on gear tooth surfaces with and without shot peening treatment are determined and contrasted. The results show that shot peening treatment can effectively increase the residual stress on gear tooth surfaces. In addition, an electromagnetic resonance fatigue tester is used to analyze the bending fatigue strength of gear tooth surfaces. The test results indicate that the bending fatigue strength of the gear teeth with shot peening is higher than that of the gear teeth without shot peening. The obtained conclusions lay the foundation for further practical engineering applications of gears.

1. Introduction

Residual stresses in the parts are caused by various kinds of elastic and plastic deformation in the machining process [1]. The formation of residual stress is related to the material, shape, forming, and processing technology of a part, and residual stresses usually cannot be directly determined through formulas or empirical evidence. Residual stress greatly influences the fatigue strength, stress corrosion, and shape accuracy of the parts. In recent years, many scholars have used different principles and methods to conduct studies pertaining to residual stress, including the measurement and calculation of residual stress, analyses of residual stresses in key parts during service, and analyses of residual stresses in new materials and new technology [2–12].

Gear transmissions are an important part of the modern industry. Related research has gradually focused on

producing high-speed, heavy-duty, long-life, and low-cost gear transmissions. Shot peening treatment is usually used in gear processing to provide improved fatigue strength. At present, there are in-depth studies on shot peening strengthening that review the development of traditional shot peening machines and discuss new shot peening methods, such as laser impact technology and ultrasonic impact technology [13–17]. Scholars have found that shot peening treatment can improve material performance because of the residual compressive stress distributed on the part surface. However, the relationship between shot peening and residual stress and the relationship between residual stress and gear performance have gradually become the research focus in recent years.

Due to the limitations in experimental conditions, most studies on the relationship between shot peening and residual stress have been made based on finite element

simulation analysis or residual stress measurement with mechanical methods. For studies on gear strength, summarized conclusions have been obtained, but there is little specific experimental data to analyze.

In this paper, gears are subjected to shot peening treatments, wherein the shot peening variables are controlled during processing; other gears from the same batch are not subjected to shot peening and are used as a comparison. Furthermore, experimental studies based on an X-ray stress analyzer and an electromagnetic resonance fatigue tester is proposed. The results from these studies are utilized to determine the relationships among shot peening strengthening, residual stress, and bending strength of gears.

2. Residual Stress Comparison Test

2.1. Experimental Scheme. The gear material used in this experiment was 20CrMnMo, which has good comprehensive mechanical properties. The basic design parameters of the gears are shown in Table 1.

Fifty gears from the same batch were randomly selected and divided into groups A and B. For group A, shot peening treatment was performed on the tooth root after processing, whereas group B was not subjected to a shot peening treatment. Table 2 shows the parameters and the standard used in the shot peening process.

After performing the shot peening procedure, measurements were carried out using a Proto-iXRD type X-ray stress analyzer. Three gears were randomly selected from group A and group B. Locations T_1 , T_2 , and T_3 were also determined along the outer circle of the gear, wherein these locations are separated by 120° . Moreover, two test points were selected for each position. The stress analysis site is shown in Figure 1.

2.2. Residual Stress Test. The detected residual stresses on the gear surface for group A and group B are displayed in Table 3.

The absolute value of the maximum stress difference between test point 1 and test point 2 was 41 MPa. Obviously, the residual stress was higher on the shot peened gear surface with shot peening treatment than on the gear surface without shot peening treatment. The increases in residual stress varied because of the randomness of the residual stress distribution. To evaluate the overall improvement level, we used the average residual stress as a comparison. The average stresses of group A and group B were -585.833 MPa and -513.278 MPa, respectively. Compared with group B, group A had 14% higher residual strength. Thus, shot peening treatment can effectively increase the residual stress in gear teeth.

3. Analysis of the Bending Strength of Shot Peened Gear Teeth

Usually, a gear tooth can be simplified as a cantilever beam under the working condition. Given the normal load on gear teeth, bending stresses will occur on the root of the teeth; as a result, cracks often appear due to the serious stress

TABLE 1: Design parameters of the gears.

Parameters	Values
Module m_n (mm)	5
Number of teeth Z	30
Tooth width B (mm)	50
Pressure angle α ($^\circ$)	30°
Modification coefficient x	0
Helix angle β	0°
Tooth root radius r_f (mm)	1.9

TABLE 2: Shot peening parameters and standard.

Shot peening standard	MIL-S-13165C
Projectile diameter	CW23
Shot peening intensity	0.35–0.4A
Coverage	200%

FIGURE 1: Stress analysis site.

concentrations. With continuous crack propagation, whole teeth or parts of teeth may fracture [18].

In this section, an analysis of shot peening treatment on the bending strength of gear teeth is discussed by means of experimental comparisons.

3.1. Experimental Scheme. This experiment adopted a high-frequency pulsation gear test, wherein the tested gear is always in a state of rest within the testing apparatus. Moreover, the pressure head applied a pulsating cyclic load on the tested gear teeth to allow the gear teeth to break off. The test equipment used for this test was a Zwick/Amsler 250 HFP 5100 electromagnetic resonance fatigue testing machine (Germany), as shown in Figure 2. The testing machine possessed a high loading precision: the static-dynamic loading was $\pm 0.5\%$, the static loading range was ± 150 kN, and the dynamic unidirectional pulsation was ± 125 kN. The loading frequency range was 35–300 Hz.

According to GB/T 14230-1993 [19], the following can be determined through calculations and simulations with the tested gear parameters while the gear was clamped. The test was performed on five teeth of the tested gears. The distance between the high point of action and the low point of action was 68.523788 mm, which was the same as the length of the common normal line spanning 5 teeth. The dimensional error during installation was controlled within ± 0.1 mm.

TABLE 3: Detected residual stresses.

Gear number	Gear location	Test point 1 (N)	Test point 2 (N)	Absolute value of difference $ \Delta $ (N)
B1	T ₁	-498	-518	20
B1	T ₂	-531	-521	10
B1	T ₃	-540	-535	5
A1	T ₁	-621	-612	9
A1	T ₂	-572	-551	21
A1	T ₃	-621	-611	10
B2	T ₁	-511	-491	20
B2	T ₂	-507	-488	19
B2	T ₃	-538	-562	24
A2	T ₁	-565	-553	12
A2	T ₂	-516	-529	13
A2	T ₃	-586	-577	9
B3	T ₁	-501	-486	15
B3	T ₂	-499	-504	5
B3	T ₃	-511	-498	13
A3	T ₁	-637	-596	41
A3	T ₂	-557	-565	8
A3	T ₃	-639	-637	2

FIGURE 2: Zwick/Amsler 250 HFP 5100.

This test adopted group and staircase methods. The test load can also be divided into four load levels. The group method was used to determine the diagonal part of the P-S-N curve, and the staircase method was used to determine the straight line in the curve.

The test load was set in accordance with GB/T14230-1993. The number of bending stress cycles of each test point at the highest stress level was $\geq 0.5 \times 10^5$. Random sampling in all products can reflect the general features. The test aimed to fully utilize each gear tooth and minimize the mutual effect of loading gear teeth. Two gear teeth separated every two tested gear teeth, and each loaded gear tooth was numbered accordingly. The tested gears can be divided into two categories under three kinds of numbering, which adhered to the following principles:

FIGURE 3: Gear teeth labeling.

TABLE 4: Calculation parameters of tooth root stress.

Symbol	Value
B	50 mm
m	5 mm
Y_{SA}	1.836
Y_{FA}	2.482
Y_{ST}	2
$Y_{\delta_{relT}}$	1
$Y_{R_{relT}}$	1.12
Y_x	1

- (1) In this test, a gear with shot peening treatment was an A series and a gear without shot peening treatment was defined as a B series.
- (2) According to the test order of the same gear series, the tested gear teeth were numbered as 1, 2, 3, etc.
- (3) The test load level was labeled.

TABLE 5: Bending fatigue test load of the gear.

Stress level	I	II	III	IV
Load value (kN)	78	75	73	72
Calculated tooth root stress (MPa)	579.15	556.88	542.03	534.60
Pulsating tooth root stress (MPa)	560.80	538.84	524.21	516.90
Mean test load (kN)	40.950	39.375	38.325	37.800
Test dynamic load (kN)	37.050	35.625	34.625	34.200
$F_{\min}$ (kN)	3.90	3.75	3.65	3.60
$F_{\max}$ (kN)	78	75	73	72

TABLE 6: Data processing of the bending fatigue test of the gear.

Ordinal number	Fatigue life at different stress levels							
	I		II		III		IV	
	Lifetime	No.	Lifetime	No.	Lifetime	No.	Lifetime	No.
1	52001	B2-4-78	80295	B16-2-75	189195	B19-1-73	803965	B1-3-72
2	54434	B13-4-78	150568	B6-2-75	532257	B18-2-73	925469	B5-2-72
3	66220	B13-1-78	164084	B18-1-75	879460	B15-4-73	1346204	B4-3-72
4	81369	B1-1-78	224971	B9-2-75	1057880	B2-2-73	2181065	B4-2-72
5	91155	B11-4-78	695260	B11-2-75	1515670	B15-1-73	2395745	B5-4-72
6	154634	B9-1-78	712435	B5-1-75	1721448	B17-2-73	2857876	B11-3-72
7	170261	B16-3-78	1020368	B8-4-75	1811442	B7-4-73	3000000	B19-2-72

TABLE 7: Distribution test results.

Lifetime distribution	Lifetime correlation coefficients (R) at different stress levels			
	560.80	538.84	524.21	516.90
Lognormal distribution	0.9615	0.9634	0.9296	0.9667
Three-parameter weibull distribution	0.9886	0.9758	0.9725	0.9765

TABLE 8: Fitting parameters.

Stress level	Three-parameter Weibull distribution parameters		
	Shape parameter (M)	Scale parameter (η)	Location parameter (r)
560.80	0.6154	43553	50889
538.84	0.7019	37900	66318
524.21	1.2976	1316760	0
516.90	0.7735	1149989	728240

TABLE 9: Bending fatigue test load of the gear.

Stress level	I	II	III	IV
Load value (kN)	74	72	70	68
Calculated tooth root stress (MPa)	549.45	534.60	519.75	504.90
Pulsating tooth root stress (MPa)	531.52	516.90	502.30	487.70
Mean test load (kN)	38.85	37.80	36.75	35.70
Test dynamic load (kN)	35.15	34.20	33.25	32.30
$F_{\min}$ (kN)	3.7	3.6	3.5	3.4
$F_{\max}$ (kN)	74	72	70	68

For example, B1-1-78 kN means testing the first tooth of the No. 1 gear without shot peening treatment with a load of 78 kN.

The tested gear teeth were in a certain order of test. The high working teeth were numbered 1, 2, 3, and 4, whereas the corresponding low working teeth were numbered 1', 2', 3', and 4'.

TABLE 10: Stability test data.

No.	Sample no.	Load value (kN)	Lifetime ($N \times 10^5$)	$F_N = (1/n) \sum_{i=1}^n F_i$	$\sigma_n = (F_n - F_{n-1})/F_n $
1	B6-3-72	72	4.3	72.00000	—
2	B6-4-70	70	30.0	71.00000	0.014080
3	B15-2-72	72	2.3	71.33333	0.004673
4	B16-1-70	70	1.1	71.00000	0.00469
5	B16-4-68	68	30.0	70.40000	0.00852
6	B14-1-70	70	7.0	70.33333	0.00095
7	B14-3-68	68	30.0	70.00000	0.00476
8	B20-2-70	70	2.7	70.00000	0
9	B20-4-68	68	30.0	69.77778	0.003180
10	B10-4-70	70	30.0	69.80000	0.000318
11	B10-3-72	72	4.2	70.00000	0.002857
12	B20-5-74	74	8.0	70.33333	0.004739
13	B5-3-72	72	2.6	70.46154	0.001820
14	B1-4-70	70	30.0	70.42857	0.000470
15	B18-3-72	72	1.4	70.53333	0.001485
16	B9-4-70	70	30.0	70.50000	0.00047
17	B9-3-72	72	30.0	70.58824	0.00125
18	B5-5-74	74	7.7	70.77778	0.002678

The gear teeth labeling is shown in Figure 3.

The criteria for stopping the bending fatigue test are as follows.

During the test, if one of the following conditions occurs, then the bending is terminated:

- (1) Fatigue cracks observed in the tooth root.
- (2) The load or frequency dropped by 5%–10%.
- (3) The tooth broke along the root. If the gear does not fail within the 3×10^6 stress cycle, then the test will also be stopped.

3.2. *Tooth Root Stress Calculation.* According to the load capacity calculation method for an involute cylindrical gear [20], the equation for tooth root stress calculation is shown as follows:

$$\sigma'_F = \frac{F_t \cdot Y_{FA} \cdot Y_{SA}}{b \cdot m \cdot Y_{ST} \cdot Y_{\delta_{relT}} \cdot Y_{R_{relT}} \cdot Y_x}, \quad (1)$$

where F_t is the nominal tangential force of the pitch circle in the end face (N), b is the tooth width, m is the tooth modulus, Y_{FA} is the tooth profile coefficient of the action point of the gear teeth under load, Y_{SA} is the stress correction coefficient of the action point of the gear teeth under load, Y_{ST} is the stress correction coefficient of the tested gear, $Y_{\delta_{relT}}$ is the relative sensitivity coefficient of the root fillet, $Y_{R_{relT}}$ is the relative condition coefficient of the root surface, and Y_x is the bending strength calculation dimension coefficient.

Table 4 shows the parameters settings for the calculation of the root stress in this test.

Substituting the parameter values into the equation above indicated that the relationship of root stress and load is as follows:

$$\sigma'_F = \frac{F_t \cdot Y_{FA} \cdot Y_{SA}}{b \cdot m \cdot Y_{ST} \cdot Y_{\delta_{relT}} \cdot Y_{R_{relT}} \cdot Y_x} = 0.007425 F_t. \quad (2)$$

FIGURE 4: Up-and-down test results with the staircase method.

Due to the limitations in the test equipment, the loading pressure head created instability in the clamp and the test piece. Therefore, to avoid this instability effect, a certain minimum load, which is the cyclic performance coefficient $R = F_{\min}/F_{\max}$, is maintained in the test. The actual root stress should be converted to the pulsating cycle root stress σ_F when $R = 0$. The conversion equation is as follows:

$$\sigma_F = \frac{(1 - R)\sigma'_F}{1 - R(\sigma'_F/(\sigma_b + 350))}, \quad (3)$$

where σ_b is the tensile strength (N/mm^2).

3.3. Bending Fatigue Strength Test of the Gear without Shot Peening Treatment

3.3.1. *Test with Group Method and Data Processing.* Through the gear root stress calculations and the preliminary experiments, the experimental load with the group method was determined, as shown in Table 5.

The results of the test with the group method are shown in Table 6.

Lognormal distribution and three-parameter Weibull distribution tests were performed on the fatigue life at the load levels above.

FIGURE 5: P-S-N curve of the bending fatigue strength of the gear without shot peening treatment.

TABLE 11: Ultimate bending strength of the tested gear without shot peening treatment under different degrees of reliability.

Degree of reliability (%)	99	95	90	50	10	5
Ultimate bending strength (MPa)	444.64	466.89	477.07	504.77	523.25	527.40

TABLE 12: Bending fatigue test load of the gear.

Stress level	I	II	III	IV
Load value (kN)	81	78	76	75
Calculated tooth root stress (MPa)	601.43	579.15	564.30	556.88
Corrected tooth root stress (MPa)	582.81	560.80	546.16	538.84
Mean test load (kN)	42.525	40.950	39.900	39.375
Test dynamic load (kN)	38.475	37.050	36.100	35.625
$F_{\min}$ (kN)	4.05	3.90	3.80	3.75
$F_{\max}$ (kN)	81	78	76	75

Weibull distribution is derived from the weakest link model. It can be simply described that a chain is formed by many chain links in series. When both ends are under tension, any one of the links breaks and the chain fails. Obviously, the chain fracture occurs in the weakest link. The life of components, parts, devices, and equipment stopping whole running due to a certain local failure can be regarded as following the Weibull distribution, while the fatigue strength, fatigue life, and wear life in machinery mostly

follow the Weibull distribution. The probability density function and distribution function of three-parameter Weibull distribution are defined as

$$f(x) = \frac{\beta}{\eta} \left(\frac{x - \gamma}{\eta} \right)^{(\beta-1)} \exp \left[- \left(\frac{x - \gamma}{\eta} \right)^\beta \right], \quad (x \geq \gamma),$$

$$F(x) = 1 - \exp \left[- \left(\frac{x - \gamma}{\eta} \right)^\beta \right], \quad (x \geq \gamma), \quad (4)$$

TABLE 13: Data processing of the gear bending fatigue life.

Ordinal number	Fatigue life at different stress levels							
	I		II		III		IV	
	Lifetime	No.	Lifetime	No.	Lifetime	No.	Lifetime	No.
1	50892	A8-4-81	141594	A10-3-78	190347	A1-2-76	543860	A17-3-75
2	79582	A7-2-81	156529	A6-1-78	194017	A2-2-76	726517	A19-2-75
3	111899	A7-3-81	251908	A2-1-78	241713	A8-1-76	1227752	A6-2-75
4	112428	A3-4-81	269224	A17-2-78	278029	A1-1-76	1324990	A10-3-75
5	124084	A10-2-81	342719	A7-4-78	811387	A4-1-76	1748937	A4-2-75
6	156865	A11-1-81	376832	A11-2-78	1125686	A1-3-76	1939033	A15-2-75
7	—	—	—	—	1401843	A2-4-76	2057398	A17-4-75
	—	—	—	—	—	—	4251335	A13-4-75

TABLE 14: Distribution test results.

Lifetime distribution	Lifetime correlation coefficients (R) at different stress levels			
	582.81	560.80	546.16	538.84
Lognormal distribution	0.9524	0.9644	0.9323	0.9734
Three-parameter Weibull distribution	0.9767	0.9676	0.9816	0.9707

TABLE 15: Fitting parameters.

Stress level	Three-parameter Weibull distribution parameters		
	Shape parameter (M)	Scale parameter (η)	Location parameter (r)
582.81	2.5720	123053	0
560.80	2.5528	292756	0
546.16	0.3518	279014	189939
538.84	2.0620	1585335	0

TABLE 16: Bending fatigue test load of the gear.

Stress level	I	II	III	IV
Load value (kN)	75	74	73	72
Calculated tooth root stress (MPa)	556.88	549.45	542.03	534.60
Pulsating tooth root stress (MPa)	538.84	531.52	524.21	516.90
Mean test load (kN)	38.85	37.80	36.75	35.70
Test dynamic load (kN)	35.15	34.20	33.25	32.30
$F_{\min}$ (kN)	3.7	3.6	3.5	3.4
$F_{\max}$ (kN)	75	74	73	72

where β , γ , and η are three parameters for describing Weibull distribution, β is a shape parameter, which determines the shape of the distribution curve, γ is a position parameter and it determines the starting position of the distribution curve, and η is a scale parameter, which reflects the dispersion of the life data.

The correlation coefficients (R) were calculated, and the results are shown in Table 7.

The three-parameter Weibull distribution exhibited the best fitting effect on the bending fatigue life of the gear. Thus, the three-parameter Weibull distribution calculation in each stress level is shown in Table 8.

The position parameter r showed that the lifetime of the gear without shot peening treatment followed the three-

parameter Weibull distribution at stress levels I, II, and IV. This gear also followed the two-parameter Weibull distribution at stress level III.

3.3.2. *Test with Staircase Method and Data Processing.* The test loads with the staircase method are shown in Table 9.

The test data with the staircase method are shown in Table 10.

Table 10 shows that the test from the 6th testing point through the 18th testing point satisfies the following stability error condition:

$$\sigma_n \leq 0.5\%. \quad (5)$$

TABLE 17: Stability test data.

No.	Sample no.	Load value F_N (kN)	Lifetime ($N \times 10^5$)	$F_N = (1/n) \sum_{i=1}^n F_i$	$\sigma_n = (F_n - F_{n-1})/F_n $
1	A13-2-75	75	3.83	75.00000	—
2	A13-1-74	74	30.00	74.50000	0.006710
3	A12-1-75	75	3.49	74.66667	0.002232
4	A13-3-74	74	30.00	74.50000	0.002240
5	A12-2-75	75	3.54	74.60000	0.001340
6	A16-1-74	74	6.09	74.50000	0.001340
7	A6-3-73	73	30.00	74.28571	0.002880
8	A14-2-74	74	3.57	74.25000	0.000480
9	A20-1-73	73	30.00	74.11111	0.001870
10	A20-2-74	74	30.00	74.10000	0.000150
11	A20-3-75	75	1.65	74.18182	0.001103
12	A14-1-74	74	6.25	74.16667	0.000200
13	A6-4-73	73	7.89	74.07692	0.001210
14	A4-4-72	72	30.00	73.92857	0.002010
15	A12-4-73	73	30.00	73.86667	0.000840
16	A20-2-74	74	30.00	73.87500	0.000113

The up-and-down test results obtained with the staircase method are shown in Figure 4. The total number of samples was 18, of which 9 broke.

The median load of this gear can be obtained as $F = 70.5$ kN through calculation with the staircase method. The median fatigue strength of the gear is shown as follows:

$$\sigma_{A50} = 505.95 \text{ MPa.} \quad (6)$$

The P-S-N curve of the bending fatigue strength of the gear without shot peening treatment is displayed in Figure 5.

According to the results in the figure above, the ultimate bending strength of the gear without shot peening treatment under different degrees of reliability is shown in Table 11.

3.4. Bending Fatigue Strength Test for the Shot Peened Gear

3.4.1. Test with Group Method and Data Processing. The test loads were determined, as shown in Table 12. The results of the test with group method are displayed in Table 13.

Lognormal distribution and three-parameter Weibull distribution tests were also performed on the fatigue life at the load levels above. The R values are shown in Table 14.

The three-parameter Weibull distribution exhibited the best fitting effect on the bending fatigue life of the gear. Thus, the three-parameter Weibull distribution calculation at each stress level is depicted in Table 15.

The location parameter showed that the bending fatigue life of the shot peened gear followed the two-parameter Weibull distribution at stress levels I, II, and IV and followed the three-parameter Weibull distribution at stress level III.

3.4.2. Test with Staircase Method and Data Processing. Through preliminary tests with the test data collected from the group method, the test loads with the staircase method were obtained, as shown in Table 16. The results of the test with the staircase method are also shown in Table 17.

Table 17 shows that the staircase test from the 3rd testing point through the 16th testing point satisfies the stability error $\sigma_n \leq 0.5\%$.

FIGURE 6: Test results with the staircase method.

The up-and-down test results with the staircase method are shown in Figure 6. The total number of samples was 16, of which 8 broke.

The median load of this type of gear can be obtained as $F = 73.875$ kN through calculation with the staircase method. The median fatigue strength of the gear is shown as follows:

$$\sigma_{A50} = 530.61 \text{ MPa.} \quad (7)$$

The P-S-N curve of the gear with shot peening treatment is displayed in Figure 7.

Table 18 shows the ultimate bending strength of the gear with shot peening treatment under different degrees of reliability, according to Figure 7.

3.5. Results and Discussion. In accordance with reliability theory, the P-S-N curves of the gears with and without shot peening treatment and the bending fatigue strength of these gears under different reliability degrees can be obtained. The results are summarized in Table 19.

The shot peening treatment increased the bending fatigue strength by 14.35% at a reliability degree of 99%. The residual stress test indicated that the residual compressive stress in the shot peened gear roots (group A) was 14% higher than that of gear roots without shot peening (group B). The mean values of the gear residual compressive stress with and without shot peening were -585.5 MPa and

FIGURE 7: P-S-N curve of the bending fatigue strength of the gear with shot peening treatment.

TABLE 18: Ultimate bending strength of the gear with shot peening treatment under different degrees of reliability.

Degree of reliability (%)	99	95	90	50	10	5
Ultimate bending strength (MPa)	508.46	517.06	520.90	531.09	537.69	539.15

TABLE 19: Ultimate bending strength under different degrees of reliability.

Degree of reliability (%)	99	95	90	50	10	5
Bending fatigue strength test with shot peening treatment (MPa)	508.46	517.06	520.9	531.09	537.69	539.15
Bending fatigue strength test without shot peening treatment (MPa)	444.64	466.89	477.07	504.77	523.25	527.40
Bending fatigue strength increase (%)	14.35	10.75	9.12	5.21	2.76	2.23

–513.3 MPa, respectively. The data showed that the residual compressive stress layer distributed at the root of the gear teeth after shot peening treatment can effectively increase the gear tooth bending fatigue strength.

Further study on analysis of the microstructure and surface roughness of gear tooth surface after shot peening treatment will be carried out. And, the influences of different shot peening conditions on microstructure and surface roughness will also be analyzed.

4. Conclusions

The relationships among shot peening treatment, residual stress, and bending fatigue strength of the gear tooth surface were discussed based on the experimental study in this paper. Based on X-ray stress analysis, the residual stresses on

gear tooth surfaces with and without shot peening treatment were determined and contrasted. The average residual stress in group A (shot peening treatment) and group B (without shot peening treatment) were –585.833 MPa and –513.278 MPa, respectively, illustrating that shot peening produced a 14% increase in residual stress. Thus, shot peening treatment can effectively improve the residual stress of gear teeth. The bending fatigue strength of the gear tooth surfaces was also analyzed with an electromagnetic resonance fatigue tester. The test results indicated that the bending fatigue strength of the gear teeth with shot peening was higher than that of gear teeth without shot peening; the shot peening treatment increased the bending fatigue strength of the gears by 14.35% at a reliability degree of 99%. Therefore, the data showed that the residual compressive stress layer distributed at the root of the gear teeth after shot

peening treatment can effectively increase the gear tooth bending fatigue strength.

Data Availability

All data generated or analyzed during this study are included within this article.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

- [1] Y. Sun, H. T. Liu, and Z. S. Lu, "Finite element simulation and experimental research of residual stresses in the cutting based on the coupled thermo-mechanical model," *Journal of Mechanical Engineering*, vol. 47, no. 1, pp. 187–193, 2011.
- [2] V. Savaria, F. Bridier, and P. Bocher, "Predicting the effects of material properties gradient and residual stresses on the bending fatigue strength of induction hardened aeronautical gears," *International Journal of Fatigue*, vol. 85, pp. 70–84, 2016.
- [3] K. Salonitis and A. Kolios, "Experimental and numerical study of grind-hardening-induced residual stresses on AISI 1045 steel," *The International Journal of Advanced Manufacturing Technology*, vol. 79, no. 9–12, pp. 1443–1452, 2015.
- [4] B. A. Szost, S. Terzi, F. Martina et al., "A comparative study of additive manufacturing techniques: residual stress and microstructural analysis of CLAD and WAAM printed Ti-6Al-4V components," *Materials and Design*, vol. 89, pp. 559–567, 2016.
- [5] P. Ferro, F. Berto, and N. M. James, "Asymptotic residual stress distribution induced by multipass welding processes," *International Journal of Fatigue*, vol. 101, pp. 421–429, 2017.
- [6] W. Y. Zhang, W. C. Jiang, X. Zhao, and S.-T. Tu, "Fatigue life of a dissimilar welded joint considering the weld residual stress: experimental and finite element simulation," *International Journal of Fatigue*, vol. 109, pp. 182–190, 2018.
- [7] Y.-K. Son, K.-H. Lee, K.-S. Yang, D.-C. Ko, and B.-M. Kim, "Prediction of residual stress and deformation of enameled steel," *International Journal of Precision Engineering and Manufacturing*, vol. 16, no. 7, pp. 1647–1653, 2015.
- [8] K. Jin, T. Jeong, T. Kim, N. Kim, and B. Kim, "Analysis and design for reducing residual stress and distortion after ejection of injection molded part with metal-insert," *International Journal of Precision Engineering and Manufacturing*, vol. 15, no. 12, pp. 2533–2542, 2014.
- [9] J. Xia and H. Jin, "Numerical analysis for controlling residual stresses in welding design of dissimilar materials girthjoints," *International Journal of Precision Engineering and Manufacturing*, vol. 19, no. 1, pp. 57–66, 2018.
- [10] D.-W. Lee and S.-S. Cho, "Comparison of X-ray residual stress measurements for rolled steels," *International Journal of Precision Engineering and Manufacturing*, vol. 12, no. 6, pp. 1001–1008, 2011.
- [11] C. Du, X. Chen, Y. Yang, Y. Chen, and S. Jiang, "Experimental study on the complete tensile stress-deformation curve of fully graded concrete," *Experimental Techniques*, vol. 42, no. 5, pp. 491–497, 2018.
- [12] R. D. Lambert, C. J. Aylott, and B. A. Shaw, "Evaluation of bending fatigue strength in automotive gear steel subjected to shot peening techniques," *Procedia Structural Integrity*, vol. 13, pp. 1855–1860, 2018.
- [13] P. Fu, R. Q. Chu, Z. J. Xu, G. J. Ding, and C. H. Jiang, "Relation of hardness with FWHM and residual stress of GCr15 steel after shot peening," *Applied Surface Science*, vol. 431, pp. 165–169, 2018.
- [14] K. Zhan, Y. H. Wu, J. L. Li et al., "Investigation on surface layer characteristics of shot peened graphene reinforced Al composite by X-ray diffraction method," *Applied Surface Science*, vol. 435, pp. 1257–1264, 2018.
- [15] M. A. S. Torres and H. J. C. Voorwald, "An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel," *International Journal of Fatigue*, vol. 24, no. 8, pp. 877–886, 2002.
- [16] S.-J. Yoon, J.-H. Park, and N.-S. Choi, "Fatigue life analysis of shot-peened bearing steel," *Journal of Mechanical Science and Technology*, vol. 26, no. 6, pp. 1747–1752, 2012.
- [17] K. Shiozawa and L. Lu, "Very high-cycle fatigue behaviour of shot-peened high-carbon-chromium bearing steel," *Fatigue Fracture of Engineering Materials and Structures*, vol. 25, no. 8–9, pp. 813–822, 2010.
- [18] A. Kubo, "Cause of failure beyond conjugate theory of gear meshing," *Theory and Practice of Gearing and Transmissions*, vol. 34, pp. 67–96, 2016.
- [19] State Standard of the People's Republic of China, Standard of test method for bending load capacity of gears, GB/T 14230-1993, in Chinese.
- [20] J. I. Pedrero, M. Pleguezuelos, and M. Muñoz, "Critical stress and load conditions for pitting calculations of involute spur and helical gear teeth," *Mechanism and Machine Theory*, vol. 46, no. 4, pp. 425–437, 2011.