

Optimization of ultrasonic rolling parameters act on thread root and its influence on the fatigue life of bolts

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Abstract. Due to the large stress concentration at the root of the external thread, fatigue failure is apt to occur when subjected to alternating loads. In present study, to improve the fatigue resistance of threaded components, an ultrasonic rolling method was used to strengthen the surface structure of the root of external threads. Parameters of the Ultrasonic Surface Rolling Process (USRP) were optimized based on Response Surface Model(RSM) method, and the optimization objectives are surface roughness, surface hardness, surface residual stress, and a combination of these three factors, respectively. The strengthened threaded components were then subjected to tensile-tensile fatigue tests. Results show that the fatigue life of threaded parts after ultrasonic rolling are significantly improved compared to the original samples, with an average improvement of more than 10 times.

1 Introduction

The threaded connection area is made extremely prone to fatigue failure and fracture when subjected to long-term alternating loads, primarily due to high stress concentration in the thread root. As a result of such failures, significant economic losses can be incurred and potential safety hazards are created for in-service equipment^[1]. This vulnerability can be mitigated by the application of surface strengthening technologies, through which surface quality is improved and the initiation of surface fatigue cracks is effectively delayed.

Surface strengthening of external thread roots has been studied extensively. Currently, commonly used methods include traditional rolling methods^[2], ultrasonic surface rolling process^[3], micro-particle shot peening methods^[4], laser surface strengthening methods^[5]. Compared with other methods, USRP has the advantages of low cost, good surface quality, and applicability to all metals. USRP combines high-frequency mechanical vibration with traditional rolling strengthening technology to significantly optimize the surface properties of metal materials, thereby greatly improving the fatigue resistance and service life of key components. Cheng et al.^[6] developed an ultrasonic thread root rolling (UTRR) technology

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and conducted a comparative study with the conventional process (CTRR). It was found that the fatigue life of the ultra-high-strength steel AerMet 100 thread treated with the UTRR process increased by approximately seven times. Amanov et al.^[7,8] performed USRP on the bottom of ball screw grooves, forming nanocrystals at the bottom of the grooves. Residual stress was transformed from tensile stress to compressive stress, effectively enhancing the material's fatigue resistance. Sun et al.^[9] studied the ultrasonic rolling of A100 steel threads, noting it is a discontinuous process of alternating tool-workpiece contact. This vibratory action reduces cutting and scraping, thereby significantly improving the specimen's surface properties and fatigue life. Guo et al.^[10] established a finite element simulation model for USRP that considers the initial surface roughness of the thread root and the thread lead angle, and validated it through experiments using M30 bolts.

In this paper, the single-objective and multi-objective optimization process parameters are obtained, and then fatigue testing on the processed bolts with optimized parameters are performed.

2 Test equipment and material

2.1 Test equipment

This test was conducted on a CAK4085 CNC lathe. Fig. 1 shows the ultrasonic rolling test equipment used for the thread ultrasonic rolling test, which mainly consists of an ultrasonic power supply, an ultrasonic vibration device, a dial indicator, and a roller tool head. The roller tool head was designed independently according to the test requirements.

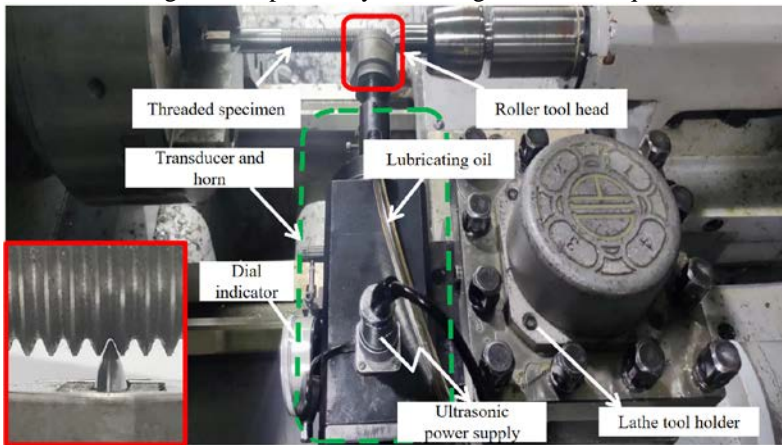


Fig. 1. Ultrasonic rolling test equipment for thread roots.

2.2 Test bolts

The test bolts were made of 45 steel (GB/T 699). Its chemical composition is shown in Table 1^[11]. The threaded component specifications are M20×2.5-6g, with a thread root radius of 0.32 mm, as shown in Fig. 2. The material undergoes tempering treatment prior to thread turning to improve its overall mechanical properties.

Table 1. Chemical composition of the specimen material (wt.%).

| Element | C | Ni | Si | Mn | Cr | Cu | Fe |
|---------|------|------|------|------|------|------|------|
| Content | 0.46 | 0.30 | 0.27 | 0.65 | 0.25 | 0.25 | Bal. |

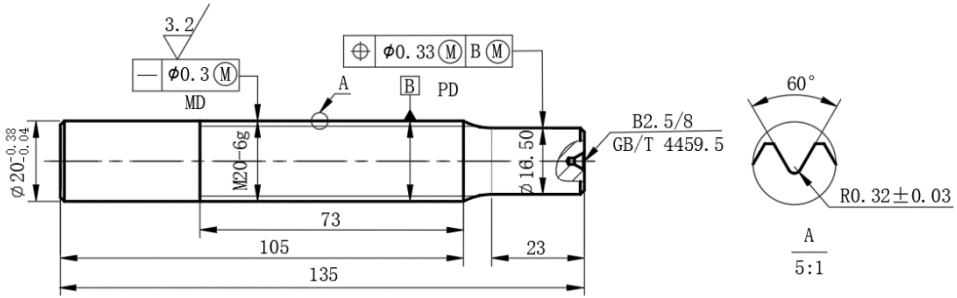


Fig. 2. Specimen dimensions.

3 Process parameter optimization for USRP of the thread root

In terms of optimization methods, the response surface method (RSM) was used to analyze the USRP parameters of static pressure, ultrasonic amplitude, rolling passes, and their interactions. The significant influencing factors of the response targets of surface roughness, surface residual stress, and surface microhardness were obtained, and the optimal solutions for single-objective and multi-objective parameters were obtained by combining the desired functions.

3.1 Multi-factor experimental design based on response surface methodology

A design experiment was created using the Box Behnken Design (BBD) response surface optimization method. In this response surface model, static pressure A, ultrasonic amplitude B, and rolling pass number C are used as independent variables, while surface roughness Sa, surface residual stress RS, and surface microhardness HV are used as the optimization objectives for this experiment. This experiment adopts a 3-factor, 3-level experimental design, and Table 2 lists the experimental factors and their level values.

Table 2. Test factors and level values.

| Factor | Level | | |
|-----------------------------|-------|-----|-----|
| | -1 | 0 | 1 |
| A: Static pressure (N) | 300 | 500 | 700 |
| B: Ultrasonic Amplitude(μm) | 6 | 8 | 10 |
| C: Number of rolling passes | 5 | 7 | 9 |

The experimental design, generated for three response objectives, is detailed in Table 3. A total of 17 experimental runs were specified, consisting of 12 factorial points for analyzing parameter effects and 5 center points for estimating experimental error. The experiments were then conducted according to these combinations, and the results were recorded for subsequent analysis.

3.2 Response surface model establishment and significance testing

The surface integrity of the thread root is the result of various process parameters and their interactions. By establishing a response surface model for the response targets of surface roughness, surface residual stress, and surface microhardness, and analyzing the F-statistic and corresponding P-values using an analysis of variance (ANOVA) table, the influence of

factors such as static pressure, ultrasonic amplitude, number of rolling passes, and their interactions on the response targets of surface roughness, surface hardness, and surface residual stress can be evaluated, thereby obtaining the optimal solutions for each response target.

Table 3. Box-Behnken design test results.

| Sample Number | Static Force (N) | Ultrasonic Amplitude (µm) | Number of rolling passes | Surface Roughness Sa (µm) | Surface Residual Stress (MPa) | Surface Microhardness (HV) |
|---------------|------------------|---------------------------|--------------------------|---------------------------|-------------------------------|----------------------------|
| 1 | 500 | 10 | 5 | 0.624 | -583.61 | 274.84 |
| 2 | 500 | 8 | 7 | 0.521 | -581.17 | 276.62 |
| 3 | 500 | 6 | 9 | 0.565 | -571.59 | 272.54 |
| 4 | 500 | 8 | 7 | 0.521 | -581.17 | 275.72 |
| 5 | 500 | 6 | 5 | 0.645 | -563.49 | 267.28 |
| 6 | 500 | 8 | 7 | 0.519 | -581.17 | 276.98 |
| 7 | 300 | 8 | 9 | 0.701 | -530.80 | 263.58 |
| 8 | 300 | 10 | 7 | 0.758 | -546.04 | 264.83 |
| 9 | 700 | 8 | 5 | 0.663 | -595.49 | 273.43 |
| 10 | 500 | 8 | 7 | 0.518 | -581.17 | 276.71 |
| 11 | 700 | 6 | 7 | 0.664 | -585.54 | 277.16 |
| 12 | 300 | 8 | 5 | 0.774 | -525.82 | 260.12 |
| 13 | 300 | 6 | 7 | 0.701 | -516.08 | 261.45 |
| 14 | 500 | 10 | 9 | 0.678 | -569.41 | 278.91 |
| 15 | 500 | 8 | 7 | 0.518 | -581.17 | 275.92 |
| 16 | 700 | 10 | 7 | 0.678 | -599.53 | 298.54 |
| 17 | 700 | 8 | 9 | 0.714 | -578.96 | 293.85 |

A second-order regression analysis was performed on the surface roughness under various combinations of process parameters, yielding the surface roughness response surface regression equation, as shown in Eq. (1):

$$Sa = 0.520 - 0.027A + 0.020B - 0.006C - 0.011AB + 0.031AC + 0.034BC + 0.133A^2 + 0.048B^2 + 0.061C^2 \tag{1}$$

Where S_a represents the predicted value of surface roughness; A, B, C are the coded values of the static force, ultrasonic amplitude, and number of rolling passes, respectively. The terms AB, AC, BC are the interaction terms, while A^2, B^2, C^2 are the quadratic terms.

By performing an analysis of variance (ANOVA) on the surface roughness data, a highly significant predictive model was obtained ($P < 0.0001$), with the predicted results closely matching the experimental validation results. The analysis results indicate that the order of influence of individual factors is as follows: static pressure > ultrasonic amplitude > rolling passes. The interactions among all process parameters are also highly significant, with the BC interaction being the strongest, followed by the AC interaction.

Using the above methods, the regression equations for the surface residual stress response surface shown in Eq. (2) and the surface microhardness response surface shown in Eq. (3) can be obtained, respectively:

$$RS = 581.17 - 31.35A - 7.74B + 0.96C + 3.99AB + 2.88AC + 5.58BC + 15.57A^2 + 3.81B^2 + 5.34C^2 \tag{2}$$

$$\begin{aligned}
 HV = & 278.62 + 11.63A + 4.21B + 3.53C + 4.50AB \\
 & + 4.24AC - 1.55BC - 0.2613A^2 - 0.8638B^2 - 3.61C^2
 \end{aligned}
 \tag{3}$$

3.3 Process parameter optimization based on the desirability function method

Single-objective optimization is a direct and focused method that aims to determine the global optimal solution for a specific aspect by minimizing or maximizing a single predefined objective function $f(x)$. In contrast, multi-objective optimization addresses the inherent complexity of processes that require consideration of multiple, often conflicting performance characteristics. This method does not seek a single optimal solution, but rather a solution that represents the best trade-off. The results are shown in the Table 4.

Table 4. Comparison of process parameters after single- and multi-objective optimization.

| Sample Number | Static Force (N) | Ultrasonic Amplitude (μm) | Number of rolling passes |
|------------------------------------------|------------------|----------------------------------------|--------------------------|
| 0: Untreated Control Group | - | - | - |
| 1: Optimized for Surface Roughness | 520 | 8 | 7 |
| 2: Optimized for Surface Microhardness | 700 | 10 | 9 |
| 3: Optimized for Surface Residual Stress | 670 | 10 | 7 |
| 4: Multi-Objective Optimized Group | 570 | 8 | 7 |

4 Effect of USRP on the fatigue life of threaded parts

In this section, the effect of USRP on the fatigue life of threaded components is evaluated. The components were made of 45 tempered steel, with a tensile strength of 935 MPa, a yield strength of 690 MPa, and an elastic modulus of 214 GPa. To facilitate a direct comparison, both unstrengthened samples and samples strengthened using previously optimized process parameters were subjected to tensile-tensile fatigue tests.

Fatigue testing was conducted at 118 Hz on the QBG-300 high-frequency testing machine shown in Fig. 3(b). A constant stress level was maintained with a static load of 44 kN and a dynamic load of 36 kN. A custom fixture, designed according to the GB/T 13682-1992 standard^[12], ensured an 8-10 thread engagement with the specimen.

The primary objective of this fatigue test was to investigate and compare the effects of different optimized parameter combinations on the fatigue life of threaded components. All tests were conducted under a uniform stress level, with three samples evaluated for each parameter set. The results are summarized in Fig. 3(a).

The results show that USRP can significantly improve the fatigue life of threaded components, with an average increase of more than ten times. The comprehensively optimized group demonstrated the most substantial improvement, with fatigue life increasing from 81.2k to 1010.1k cycles—a 12.44-fold enhancement. This performance gain is attributed to several key strengthening mechanisms: reduced surface roughness eliminates stress concentrations from machining marks; introduced residual compressive stress offsets tensile stress to inhibit crack initiation^[13]; and increased surface hardness results from a refined and densified surface grain structure. In summary, these

improvements to surface integrity can effectively delay the initiation and propagation of fatigue cracks.

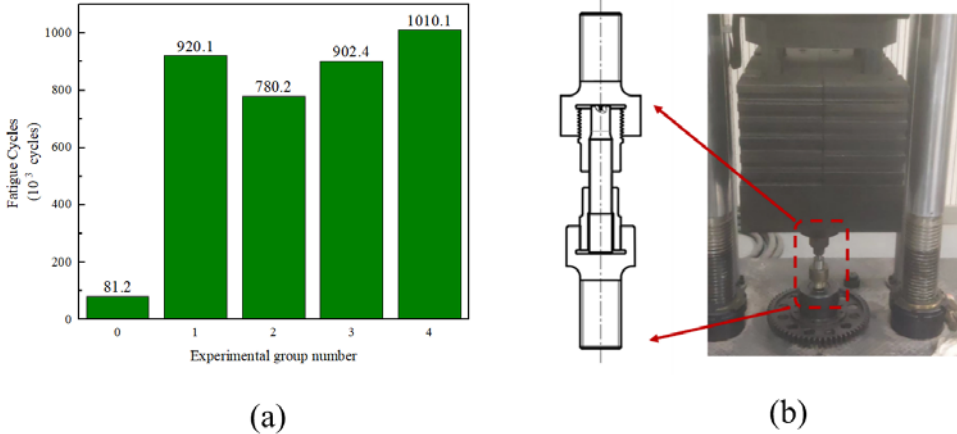


Fig. 3. (a) Fatigue Life Results for Different Process Parameter Combinations (b) Fatigue fixtures and fatigue testing site.

5 Conclusion

This study utilized the Box-Behnken Design (BBD) to guide experiments and employed the desirability function for multi-objective optimization of process parameters. Based on fatigue tests performed on bolts strengthened using the optimized parameters, the main conclusions are as follows:

(1) Significant predictive models for surface roughness, residual stress, and microhardness were established using RSM and validated by ANOVA. These models revealed that the order of process parameter influence on surface integrity is: static pressure > ultrasonic amplitude > number of rolling passes. Furthermore, single-objective optimization based on these models yielded the optimal parameter combinations for minimizing surface roughness, maximizing residual stress, and maximizing microhardness.

(2) Multi-objective optimization using the desirability function identified the globally optimal process parameters as a static pressure of 570 N, an ultrasonic amplitude of 8 μm , and 7 rolling passes.

(3) Fatigue tests on the threaded components confirmed that USRP significantly improved their fatigue performance. Specifically, the fatigue life of the treated thread roots increased, on average, by more than tenfold compared to the untreated components.

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