Comprehensive evaluation of surface integrity and parameter optimization of 45 steel subjected to ultrasonic surface rolling process

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Abstract. In order to explore the influence of ultrasonic surface rolling process (USRP) parameters on 45 steel surface integrity, the significance of static pressure, amplitude, feed rate and rolling times on rolling effect was analyzed. The grey relational degree of the comprehensive index of surface integrity after USRP was obtained by orthogonal test and grey relational analysis, and the optimal combination of process parameters was obtained. The feasibility of process parameter optimization was verified by experiments. The results show that the significant influence of USRP parameters on 45 steel workpiece surface integrity was as follows: rolling times > feed speed > static pressure > amplitude. The optimal process parameters are rotational rolling times 9 times, feed speed 3200 mm·min⁻¹, static pressure 300 N and amplitude 6 μm. Under the optimum combination of process parameters, the surface roughness decreases by 70.8 %. The surface hardness and the surface residual compressive stress increase by 16.5 % and 134 % respectively compared with the surface performance parameters of the material before rolling.

1. Introduction

In the working process of metal structural parts, microcracks often sprout on the surface or sub surface due to external impact, forming fatigue sources [1-2]. With the further expansion of microcracks, structural parts are prone to wear failure and fatigue fracture, which will effect the overall working stability and service life of mechanical equipment. Therefore, it is necessary to adopt effective surface strengthening technology to improve the surface properties of metal materials, especially those working under alternating load [3-4].

Ultrasonic impact force acting on the material surface can realize the self nanocrystallization of surface grains, which plays a positive role in improving the fatigue strength of materials [5-6]. USRP is a new surface strengthening process that couples ultrasonic impact force and rolling pressure. Static pressure and ultrasonic impact force are coupled to the material surface, resulting in "peak cutting and valley filling" elastic-plastic deformation on the surface, and introducing residual compressive stress layer on the material surface and near surface. Therefore, the initiation and propagation of fatigue cracks are inhibited and reduced, which is essentially cold-plastic processing [7-8].
Under different combinations of ultrasonic rolling parameters, the surface integrity indexes such as surface roughness, hardness and residual stress are different significantly [9-11]. In this study, orthogonal test is used to explore the influence of static pressure, rolling times, amplitude and feed speed on material surface integrity in USRP parameters. Grey relational analysis is used to analyze and optimize the test results. And the test is used to verify the analysis results, which verifies the feasibility of process parameters optimization.

2. Materials and experiments

2.1. Principle
The working principle of the USRP device is that the ultrasonic generator first sends out a high-frequency oscillation electrical signal, and the transducer converts the received electrical signal into ultrasonic frequency vibration mechanical energy. The mechanical energy is transmitted to the rolling head after expanding the amplitude through the horn. The rolling head rolls and strengthens the material surface under the coupling action of high-pressure air and high-frequency vibration, forcing the surface grain to refine, so as to improve the surface mechanical properties of the material.

![Diagram of USRP process]  
Figure 1. The microprocess of USRP

2.2. Materials and dimensions
The test material is medium carbon quenched and tempered 45 steel. The size of the test piece is 40mm * 20mm * 10mm. The surface integrity parameters are shown in Table 1.

| Performance parameter | Roughness (µm) | Microhardness (HV0.3) | Residual compressive stress (MPa) |
|-----------------------|---------------|----------------------|-------------------------------|
| Content               | 0.106         | 195.48               | 151.67                        |

2.3. Experiment equipments
In this study, the surface roughness Ra, surface hardness HV0.3 and surface residual stress σ of 45 steel workpiece are taken as test indexes for experimental analysis. The ultrasonic rolling device is installed on the YCM-V116B vertical machining center. The rolling tool head is a cemented carbide ball with diameter of 10 mm. The feed speed and pressing amount are controlled by controlling the movement of the machine tool spindle. Coolant is added and lubricated during the whole machining process.

2.4. Process parameters
For the strengthening test of ultrasonic rolling 45 steel, the principle of selecting process parameters is refered to the process parameters in actual production. In this experiment, static pressure, rolling times,
amplitude and feed rate are selected as four process parameters of the strengthening test of ultrasonic rolling 45 steel. For the milling machine type ultrasonic rolling strengthening equipment, the excessive amplitude will have an adverse impact on the accuracy of the working head and the machine tool, resulting in uneven plastic deformation and excessive error of the test results. Therefore, the values of static pressure are 300N, 500N, 750N and 1000N, the values of rolling times are 1, 3, 6 and 9, and the values of amplitude are 4 μm, 5 μm, 6 μm and 7 μm. The values of feed speed are 800 mm·min⁻¹, 1600 mm·min⁻¹, 2400 mm·min⁻¹ and 3200 mm·min⁻¹.

3. Analysis and discussion of experimental results

3.1. Results
SJ-410 surface roughness tester is used to measure the surface roughness of each group of machined workpieces. 402MVD Vickers hardness tester is used to measure the surface hardness of each group of machined workpieces, and PROTO iXRD-Combo residual stress tester is used to measure the surface residual stress of each group of machined workpieces. The test results are shown in table 2.

| No. | Static force (N) | Rolling times (cycle) | Amplitude (μm) | Feed rate (mm·min⁻¹) | Ra (μm) | HV₀.₃ (MPa) | σ (MPa) |
|-----|-----------------|-----------------------|----------------|----------------------|---------|-------------|---------|
| 1   | 300             | 1                     | 4              | 800                  | 0.092   | 203.23      | -284.93 |
| 2   | 300             | 3                     | 7              | 1600                 | 0.038   | 213.12      | -270.60 |
| 3   | 300             | 6                     | 6              | 2400                 | 0.040   | 205.94      | -343.40 |
| 4   | 300             | 9                     | 5              | 3200                 | 0.034   | 216.65      | -244.88 |
| 5   | 500             | 1                     | 1              | 2400                 | 0.086   | 207.78      | -323.96 |
| 6   | 500             | 3                     | 4              | 3200                 | 0.041   | 219.62      | -270.41 |
| 7   | 500             | 6                     | 5              | 800                  | 0.044   | 206.83      | -309.13 |
| 8   | 500             | 9                     | 6              | 1600                 | 0.041   | 210.58      | -266.05 |
| 9   | 750             | 1                     | 6              | 3200                 | 0.048   | 218.78      | -268.01 |
| 10  | 750             | 3                     | 5              | 2400                 | 0.052   | 217.81      | -287.85 |
| 11  | 750             | 6                     | 4              | 1600                 | 0.048   | 207.79      | -357.50 |
| 12  | 750             | 9                     | 7              | 800                  | 0.057   | 221.98      | -198.22 |
| 13  | 1000            | 1                     | 5              | 1600                 | 0.053   | 202.69      | -276.47 |
| 14  | 1000            | 3                     | 6              | 800                  | 0.118   | 221.99      | -295.42 |
| 15  | 1000            | 6                     | 7              | 3200                 | 0.068   | 235.72      | -274.67 |
| 16  | 1000            | 9                     | 4              | 2400                 | 0.066   | 229.55      | -274.11 |

3.2. Signal-to-Noise Ratios analysis
The test results are obtained in the form of taking the mean value of 5 measurements. In order to avoid the adverse effects of multiple measurement test results and random errors on surface integrity measurement, signal-to-noise ratios (SNR) analysis is used to process the test results of each group firstly, to obtain more accurate surface integrity indicators. Among them, SNR can be divided into large-scale characteristics, small-scale characteristics according to different application occasions. In this test, the surface roughness is expected as small as possible. Therefore, the Smaller-the-Better characteristic is selected for calculation, as shown in formula (1). The expected surface hardness and surface residual compressive stress are as large as possible, so the Larger-the-Better characteristics are selected for calculation, as shown in formula (2).

\[
S_N = -10 \log \frac{1}{k} \sum_{t=1}^{k} a_t^2
\]

\[
S_N = -10 \log \frac{1}{k} \sum_{t=1}^{k} \frac{1}{b_t^2}
\]
Where, $S/N$ represents the SNR values of ultrasonic rolling surface integrity, $a_t$ represents the result of the t-th surface roughness test, $b_t$ represents the result of the t-th surface hardness and surface residual stress test, and $k$ represents the number of repeated tests.

The SNR of surface roughness, surface hardness and surface residual stress are obtained by bringing all the results of each group of tests into formula (1) and formula (2) as required. The results are shown in Table 3.

### Table 3. SNR, dimensional normalization value and grey relational coefficient of each test index and system grey relational degree.

| No. | Ra | HV 0.3 | $\sigma$ | $l_{mn}$ | Ra | HV 0.3 | $\sigma$ | $\phi_{mn}$ | $\gamma_{mn}$ |
|-----|----|--------|---------|--------|----|--------|---------|-----------|-------------|
| 1   | 51.06 | 53.87 | 15.23 | 0.07  | 0.62 | 0.25 | 0.35 | 0.57 | 0.40 | 0.44 |
| 2   | 50.98 | 53.42 | 19.21 | 0.02  | 0.53 | 1.00 | 0.34 | 0.52 | 1.00 | 0.62 |
| 3   | 50.95 | 55.49 | 18.75 | 0.01  | 0.93 | 0.91 | 0.34 | 0.88 | 0.85 | 0.69 |
| 4   | 51.68 | 52.55 | 19.09 | 0.46  | 0.36 | 0.98 | 0.48 | 0.44 | 0.96 | 0.63 |
| 5   | 50.94 | 54.98 | 15.43 | 0     | 0.83 | 0.29 | 0.33 | 0.75 | 0.41 | 0.50 |
| 6   | 51.64 | 53.41 | 18.75 | 0.43  | 0.53 | 0.91 | 0.47 | 0.52 | 0.85 | 0.61 |
| 7   | 51.21 | 54.11 | 18.14 | 0.17  | 0.66 | 0.80 | 0.38 | 0.60 | 0.71 | 0.56 |
| 8   | 51.16 | 53.58 | 18.54 | 0.14  | 0.56 | 0.87 | 0.37 | 0.53 | 0.79 | 0.56 |
| 9   | 51.95 | 53.33 | 17.53 | 0.62  | 0.51 | 0.68 | 0.57 | 0.51 | 0.61 | 0.56 |
| 10  | 51.82 | 53.95 | 17.53 | 0.54  | 0.63 | 0.68 | 0.52 | 0.57 | 0.61 | 0.57 |
| 11  | 50.94 | 55.84 | 18.05 | 0     | 1.00 | 0.78 | 0.33 | 1.00 | 0.69 | 0.67 |
| 12  | 51.68 | 50.71 | 17.21 | 0.46  | 0     | 0.62 | 0.48 | 0.33 | 0.57 | 0.46 |
| 13  | 51.10 | 53.60 | 17.53 | 0.10  | 0.56 | 0.68 | 0.36 | 0.53 | 0.61 | 0.50 |
| 14  | 51.61 | 54.18 | 13.91 | 0.41  | 0.68 | 0     | 0.46 | 0.61 | 0.33 | 0.47 |
| 15  | 52.56 | 53.55 | 16.38 | 1.00  | 0.55 | 0.47 | 1.00 | 0.53 | 0.49 | 0.67 |
| 16  | 51.72 | 53.53 | 16.38 | 0.48  | 0.55 | 0.47 | 0.49 | 0.53 | 0.49 | 0.50 |

3.3. Normalization method

Because the dimensions of test indexes such as surface roughness, surface hardness and surface residual stress are not unified, it is necessary to normalize the SNR according to formula (3) in order to eliminate the influence of different dimensions between indexes and the interference of singular test data on the analysis results.

$$l_{mn} = \frac{x_{mn} - \min_n x_{mn}}{\max_n x_{mn} - \min_n x_{mn}}$$

(3)

Where, $l_{mn}$ represents the standardized dimensioned data. $x_{mn}$ represents the SNR of the m-th test under the n-th index of 45 steel subjected to USRP.

3.4. Grey relational analysis

The grey relational coefficient is the relationship between the idealized data results and the normalized data which characterize the surface roughness, hardness and residual stress of 45 steel subjected to USRP. The values of grey relational coefficient are calculated by formula (4).

$$\phi_{mn} = \frac{\min_m \min_n |l_{mn}^0 - l_{mn}| + \rho \max_m \max_n |l_{mn}^0 - l_{mn}|}{|l_{mn}^0 - l_{mn}| + \rho \max_m \max_n |l_{mn}^0 - l_{mn}|}$$

(4)

Where, $\phi_{mn}$ represents the grey relational coefficient of the n-th test index of group m. $l_{mn}^0$ represents the ideal state value of the m-th test index of surface integrity of ultrasonic rolled 45 steel. In this test, the ideal values of surface roughness, surface hardness and surface residual stress are all 1. $\rho$ is the resolution coefficient, 0.5 is taken here.
The grey relational degree of surface integrity of each group of ultrasonic rolling 45 steel test is calculated according to formula (5).

\[
\gamma_m = \frac{1}{q} \sum_{n=1}^{q} \varphi_{mn}
\]  

(5)

Where, \( \gamma_m \) is the grey relational degree of surface integrity of 45 steel tested in group \( m \).

According to the theory of grey relational analysis, the greater the mean value of grey relational degree, the greater the impact of this level on surface integrity, indicating that this level is one of the best parameter combinations in this test. Therefore, the best parameter combination of ultrasonic rolling 45 steel surface integrity is \( A_1B_3C_3D_4 \), that is, when the value of static pressure is 300 N and the value of amplitude is 6 μm. The value of feed speed is 3200 mm·min\(^{-1}\) and value of the rolling times is 9 times.

The greater the range of the mean value of the grey relational degree of the factor, the more significant the influence of the factor on the test index. Therefore, the order of significance of the influence of process parameters on surface integrity is: rolling times > feed speed > static pressure > amplitude.

### Table 4. Grey relational degree of USRP parameters.

| Factor          | Average value of grey relational degree | Range |
|-----------------|----------------------------------------|-------|
|                 | 1           | 2         | 3           | 4           |
| Static force    | 0.595       | 0.5       | 0.5575      | 0.4825      | 0.06        |
| Rolling times   | 0.5575      | 0.5675    | 0.5625      | 0.59        | 0.15        |
| Amplitude       | 0.5675      | 0.65      | 0.57        | 0.565       | 0.0125      |
| Feed rate       | 0.535       | 0.5375    | 0.565       | 0.6175      | 0.135       |

### 4. Experimental verifications

Ultrasonic strengthening verification test is carried out according to the process parameter combination optimized by grey relational analysis. The surface integrity test results are shown in Table 5.

### Table 5. Test results of surface properties under optimum process parameters

| No. | Roughness (μm) | Microhardness (HV\(_{0.3}\)) | Residual compressive stress (MPa) |
|-----|----------------|------------------------------|----------------------------------|
| 1   | 0.029          | 227.28                       | -354.25                          |
| 2   | 0.032          | 229.91                       | -353.87                          |
| 3   | 0.032          | 226.31                       | -358.28                          |
| Average | 0.031          | 227.83                       | -355.47                          |

According to the results in Table 5, the SNR values of surface roughness, surface hardness and surface residual compressive stress are 20.15, 51.87 and 55.76 respectively. The values of grey relational coefficient are 1, 0.54 and 0.96 respectively. The value of grey relational degree is 0.83, which is greater than the grey relational degree 0.69 obtained in group 3 in the orthogonal test. And the surface roughness is reduced from 0.04 to 0.031, with a reduction range of 22.5 %, 70.8 % lower than that before rolling. The surface hardness increased from 205.94 HV\(_{0.3}\) to 227.83 HV\(_{0.3}\), with an increase of 10.6 %, which was 16.5 % higher than that before rolling. The residual compressive stress increased from 343.4 MPa to 355.47 MPa by 3.5 %, 134 % higher than that before USRP.

### 5. Conclusions

Under the optimum combination of USRP parameters, the surface roughness of 45 steel is reduced by 70.8 %, the surface hardness is increased by 16.5 %, and the surface residual compressive stress is increased by 134 %. The results show that ultrasonic rolling can reduce the surface roughness of the workpiece effectively, improve the surface hardness and increase the surface residual compressive stress greatly, so as to improve the fatigue strength and working life of the material.
Through the analysis of SNR and grey relational degree, it is concluded that the significant degree of influence on the surface integrity of 45 steel material: rolling times > feed speed > static pressure > amplitude. The best combination of process parameters is the value of rolling times is 9 times, the value of feed speed is 3200 mm·min⁻¹, the value of static pressure is 300 N and the value of amplitude is 6 μm. The optimized process parameters not only ensure that the material surface has certain surface roughness, surface hardness and surface residual compressive stress, but also improve the machining efficiency, which provides a reliable reference for high surface integrity and high efficiency manufacturing.

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