Effects of ultrasonic surface rolling process on tribological behavior of 4Cr13 stainless steel

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Abstract

Ultrasonic surface rolling (USR) process is a novel surface strengthening technique based on the tool head's high-frequency impact on the workpiece. USR can cause severe plastic deformation on the superficial surface of metal material, and greatly improving the mechanical properties of the material. This paper elucidates the effects of USR passes on the surface roughness, sample height, microstructure, microhardness, residual stress, and tribological properties of 4Cr13 stainless steel. The results revealed that multiple USR treatments refined the near-surface layer grain of the sample. Compared with untreated sample, USR treatments significantly improved the surface roughness and microhardness of the samples. Obvious compressive residual stress and plastic deformed with a maximum value of about -723 MPa and a depth of about 229 μm were also introduced into the sample surface. Under a dry friction environment, the samples that underwent the USR treatments exhibited significantly enhanced wear resistance, and six rolling passes were found to be the most suitable treatment.

1. Introduction

Material failures, such as wear, fatigue, and corrosion, which usually occur on the surface of materials, lead to substantial economic repercussions and damage. Therefore, surface strengthening technologies for improving the surface quality of metallic materials are of great significance for extending their service life. Traditional surface modification technologies, such as thermal spraying, heat treatment technologies (carburizing and nitriding), and electroplating, can effectively improve the mechanical properties of metallic parts [1–2]. However, these surface treatment technologies often have problems such as poor bonding between the coating and substrate, large internal stress between the infiltration layer and substrate, environmental pollution, and high cost [3–4]. Galvanic corrosion can also occur owing to the introduction of other elements.

In recent years, surface mechanical deformation strengthening technologies, especially severe plastic deformation technologies, such as surface mechanical abrasion treatment [5], ultrasonic shot peening [6] and laser shock shot peening [7], have been widely used. Although these technologies improve the mechanical properties of metallic materials to a certain extent, they also increase their surface roughness, and cause surface cracking, resulting in decreased surface fatigue performances and corrosion resistance.

Ultrasonic surface rolling (USR) technology is a modern surface mechanical strengthening technology based on the aforementioned methods. In the USR process, static and ultrasonic dynamic loads act uniformly on the surface of a metal workpiece, thereby reducing the flow stress during deformation [8]. Therefore, a smaller static load can increase the plastic deformation of the metal material, and produce nanostructured layers [9–12]. Compared to other surface treatment technologies, USR process can more significantly reduce the surface roughness of metal materials [13–16], leading to changes in the surface structure and residual stress [17–19], and improve the wear resistance, fatigue strength, and corrosion

resistance of the workpiece [20–25]. Therefore, this technology has a wide application prospect in machinery manufacturing and maintenance.

Presently, carbon steel, cast iron, Cu-based alloys and aluminum alloy parts have been strengthened using the USR technique [26–29]. 4Cr13 stainless steel is commonly used for manufacturing hot oil pumps, valve bearings, and medical equipment and possesses good mechanical processing properties. However, the effects of USR surface strengthening on 4Cr13 stainless steel have seldom been studied. Since the USR process parameters of various metal materials differ greatly, the study of the USR process parameters of 4Cr13 stainless steel is of great significance for promoting its practical application.

In this study, the effects of different USR pass treatments on the surface roughness, sample height, microstructure, microhardness, and residual stress of 4Cr13 stainless steel were investigated. And the wear resistance properties of the USR-treated samples under a dry friction environment were studied. Finally a comparison of the actual surface modification effects of the USR samples was carried out, and the optimal surface strengthening parameters of 4Cr13 stainless steel were proposed.

2. Experimental

2.1 Experimental materials and USR device

The material used in this study was 4Cr13 stainless steel, and its nominal chemical compositions and properties are listed in Tables 1 and 2, respectively. The samples were processed into disks of 50 mm diameter and 15 mm thickness.

Table 1
Chemical compositions of 4Cr13 stainless steel (wt.%).

C	Si	Mn	P	S	Cr	Ni	Cu	V	Co	N	Zn	Fe
0.43	0.27	0.47	0.02	0.01	12.75	0.09	0.05	0.06	0.02	0.02	0.01	85.70

Table 2
Mechanical properties of 4Cr13 stainless steel.

Material	σ_b /MPa	$\sigma_{0.2}$ /MPa	Elongation/%	HV
4Cr13	730	540	12	240

Figure 1 shows the configuration of the USR device. The 4Cr13 stainless steel sample was processed using a USR system. The W-Co cemented carbide cylindrical roller under a certain static load produced a high-frequency impact on the surface of the sample. The main parameters of the USR process were selected as follows: output ultrasonic vibration frequency: 27.5 kHz, static load: 1200 N, amplitude: 6 μ m, constant linear velocity: 0.17 m/s, and tool feed-speed: 0.1 mm/r. The samples numbered as U2, U4, U6, U8, and U10 were processed using 2, 4, 6, 8, and 10 passes, respectively, during the USR treatment. U0 is the original sample that did not undergo the USR treatment.

2.2 Sliding test

Dry wear and friction tests were conducted using a reciprocating ball-on-flat contact tribometer (Rtec Instrument, USA) under a working environment temperature of 25°C. The samples were repeatedly moved back and forth under a stationary GCr15 ball (hardness: 62 HRC, diameter: 6.4 mm). All sample surfaces were ultrasonically cleaned in an ethyl alcohol bath before and after sliding. Tests were performed with a normal load of 20 N and a frequency of 2 Hz with an 8 mm stroke for a sliding time of 1800 s. At least two replicates were conducted out for each sample. An analog-to-digital converter was used to measure the friction coefficients, which were then stored and recorded on a personal computer.

2.3 Characterization methods

Microhardness measurements were conducted using a V20091833 WHV-1MDT Vickers hardness tester with a load of 100 g and dwell time of 10 s at 25°C. The residual stress of the samples treated using different USR passes was measured with a portable X-ray residual stress analyzer (μ -x360s, PULSTEC). Three individual measurements were conducted to calculate the average microhardness and residual stress.

The microstructures and chemical composition were characterized by optical microscopy (Leica DMI8-C), electron backscatter diffraction (EBSD) and scanning electron microscopy (SEM, JSM-5610LV). EBSD was conducted on an FEI Quanta450 FEGFE-SEM equipped with an EDAX-TSL system. A white light confocal microscope (CM, Micromesure2 STLE, France) was used to study the surface morphology and wear morphology in the measuring ranges of 2×2 mm and 4×2 mm, respectively.

3. Results And Discussion

3.1 Surface morphology and roughness

Figure 2 depicts the surface morphology and three-dimensional (3D) CM images of samples treated with different numbers of USR passes. Numerous evenly spaced machining traces are observed on the untreated sample, as shown in Figure 2(a) and 2(a'). In general, these machining marks are the preferred sites for crack initiation and stress concentration, which significantly affect the wear, fatigue, and corrosion properties of the metal parts. After the samples were processed by two and four passes of USR, the machined peaks and valleys were flattened (Fig. 2b and 2c). During USR, static force and ultrasonic vibration are applied to the surface of the metal sample, producing large elastic and plastic deformations owing to impact extrusion. The mechanism of the sample surface becoming smooth after USR treatment is that the metal plastic flow flattens the wave crest and fills the wave hollow in the process of tool rolling. As the number of rolling passes increased, the surface of the sample U6 flattened and formed slight adhesion, as shown in Figure 2(d'). However, when the number of USR treatments exceeded six passes, adhesion spall and adhesion accumulation occurred on the surface of the samples, as shown in Figure 2(e', f').

From the surface profile presented in Fig. 3(a), it is evident that the untreated sample had a rough surface and a large peak-and-valley height of approximately 10 μ m. However, the peak-and-valley height

decreased to approximately 3 μm after multiple rolling passes by USR. Fig. 3(b) illustrates the roughness of the samples treated using the USR treatment with various rolling passes. The average Ra of U0 was approximately 1395 nm, while after 2, 4, 6, 8, and 10 passes of the USR treatment, the average values of Ra of the samples decreased to 128, 104, 86, 119, and 154 nm, respectively. Compared to the Ra of U0, the Ra of the USR-treated sample decreased significantly as the number of rolling passes increased, but when the number of rolling passes exceeded six, the roughness increased slightly. Excessive repeated rolling causes surface adhesion spall and adhesion accumulation, producing in a slight increase in surface roughness. Hence, a larger number of rolling passes does not yield better results. Since rough surfaces wear faster and cause higher friction than smooth surfaces, the surface roughness must be optimized to lower friction.

The effects of USR on the size of the samples was studied by processing half of the samples with the same USR process parameters, and then testing the surface topography with a white light CM (Fig. 4). Fig. 4(a) displays a photographic image of the sample processed by the USR for six passes, while Fig. 4(b) and (c) depict the 3D CM images and surface profiles of the samples. Fig. 4(a) and (b) illustrate that the surface of the USR-treated side of the samples is bright and smooth, while the untreated side has a darker and rougher surface. As observed from the surface profile curve in Fig. 4(c), the maximum height of the sample is reduced by approximately 28 μm after multiple USR treatments. This was mainly due to the plastic flow of metal material in the USR-treated side, resulting in material accumulation in the untreated side, as shown in Fig. 4(b).

3.2 Microhardness and residual stress

The compressive residual stress of the surface layer and microhardness distributions along the depth of the samples are illustrated in Fig. 5. The surface microhardness of the USR-treated samples is improved compared to that of the untreated sample, which may be attributed to the change of surface structure and work hardening. The microhardness of the USR-treated samples decreased from the surface to the matrix, and the influence depth, which was mainly determined by the thickness of the plastic deformation layer, increased with the increase in the number of rolling passes.

Figure 5(b) illustrates the residual stress on the surface of the samples under different numbers of USR passes. Under the influence of machining, The untreated sample exhibits residual tensile stress (+135 MPa), while the USR-treated samples demonstrate residual compressive stress. With the increase of USR passes, the residual compressive stress increases. The surface residual compressive stress values of the USR-treated samples after 2, 4, 6, 8, and 10 passes are approximately -487, -591, -673, -696, and -723 MPa, respectively, indicating that the residual compressive stress increases with the rolling passes. This is attributed to the severe deformation occurring under the combined action of static pressure and high-frequency repeated shocks. The increase in residual compressive stress can effectively improve the fatigue performance and wear resistance of mechanical parts [30].

3.3 Microstructures

Figure 6 illustrates the cross-sectional microstructures of the untreated and multiple USR-treated 4Cr13 stainless steel samples. Comparing Fig. 5(a) and (b-f), the surface structure of the samples treated with USR exhibits plastic deformation, and the thickness of the plastic deformation surface layer increases with the number of rolling passes. The thickness of the plastic deformation surface layer increased to 58, 114, 181, 203, and 229 μm with 2, 4, 6, 8, and 10 rolling passes, respectively. Many studies have demonstrated that severe plastic deformation is closely related to the microstructure and mechanical properties of the metallic materials [31].

To investigate the effects of USR treatment on the microstructure of the superficial layer more clearly, the cross-sections of samples U0 and U6 were characterized by EBSD. Figure 7(a) and (e) illustrate the results of the EBSD analysis for sample U0. As depicted in Figure 7(a) and (e), the grain size of the untreated sample was evenly distributed, with an average grain diameter of 7.53 μm . However, after six passes of USR processing, the severe plastic deformation introduced during the USR processing causes the formation of an obvious structural gradient on the surface of the sample, as illustrated in Figure 7(b).

Figure 7(c) and (d) demonstrate enlarged images of the C and D regions in Figure 7(b), respectively. Grain size in Figure 7(c) is significantly smaller than that in Figure 7(d). The grain distribution in Figure 7(f) and (g) shows that the grain diameters of Figure 7(c) are mainly distributed below 1 μm , with an average grain diameter of 0.75 μm . In Figure 7(d), the grain diameters are mainly distributed between 1 and 3 μm with an average grain diameter of 2.19 μm . After six passes of USR treatment, the surface grains of the sample are greatly refined, and the grain size gradually increases along the depth. According to the Hall-Petch relationship, grain refinement can improve microhardness [32], which is consistent with the test results in Fig. 5(a).

Figure 8(a) and (b) are the dislocation distribution diagrams of samples U0 and U6 obtained by EBSD, where the different colors represent the magnitude of the dislocation density. A higher proportion of red and green colors indicates a greater dislocation density, while a higher proportion of blue indicates a smaller dislocation density. Figure 8(c) and (d) divide the grain boundary misorientation into two types: high-angle grain boundaries (black) and small-angle grain boundaries (green). As shown in Figure 8(a~d), the dislocation density and the number of small-angle grain boundaries of sample U6 significantly exceeds those of sample U0. The corresponding frequency disorientation angle curves (Fig. 8e) of sample U6 also show that the refined area contains a high fraction of low-angle grain boundaries.

From Fig. 8(b) and (d), it is observed that the dislocation density and the number of small-angle grain boundaries in the outermost layer of the sample U6 are smaller than those in the sub-surface layer. Because the USR introduces a large number of dislocations in the matrix, its potential energy increases significantly. To reduce the overall energy, the dislocation entanglement closes to form dislocation cells. This unit structure minimizes the free energy of dislocations per unit length. The continuous accumulation of strain rearranges and annihilates the dislocations in the cell wall, turning the cell wall into a small-angle grain boundary. To increase the misorientation, the small-angle grain boundary continuously absorbs dislocations and transforms into a large-angle grain boundary. The formation of

large-angle grain boundaries consumes many dislocations and increases the misorientation. Thus, the dislocation density and number of small-angle grain boundaries in the fine-grained region of the processed surface are relatively low.

3.4 Wear performance

The effectiveness of the USR technique on friction and wear behavior was investigated using a ball-on-flat contact tribometer under dry reciprocating sliding conditions. As illustrated in Fig. 9(a), the friction coefficient of the untreated sample is very large and fluctuates greatly in the first 150 s, which is the running-in stage. In the following stage (150-900 s), the friction coefficient tends to stabilize gradually, which corresponds to the steady wear stage. After 900 s, the friction coefficient drops to 0.61 and stabilizes. In the friction stability stage, the friction coefficients of USR-treated samples are smaller than that of the untreated sample, and demonstrates small fluctuations. The average friction coefficients under various USR passes are illustrated using a bar chart, as shown in Fig. 9(b). The average friction coefficients of the USR-treated samples were lower than that of the untreated sample. The lowest average friction coefficient (0.54) was exhibited by U6 owing to the higher surface hardness and better surface quality of the sample.

Figure 10 demonstrates the worn surfaces of untreated and USR-treated samples after sliding for 1800 s under dry sliding environment. The width and depth of the wear marks of the USR-treated samples are significantly smaller than those of the untreated sample. For the USR-treated samples, the width and depth of the wear marks first decrease and then increase with the increase in the USR treatment passes. Fig. 11 displays the wear rates under different numbers of USR passes. The wear rate of the USR-treated samples are observed to be significantly lower than that of the untreated sample, probably owing to the high hardness and low surface roughness. The wear rate of the untreated sample is $126 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$. With the increase of rolling passes, the wear rate first decreased and then increased slightly. The wear rate of the USR-treated sample U6 has the lowest value of $48 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$, indicating that the wear rate of the USR-treated sample is reduced by 62% compared with that of U0.

Figure 12, which shows the worn surface morphology of samples after sliding for 1800 s under different USR-treated passes, indicates the surface features of the last stage of dry sliding wear. Fig. 12(a, a') illustrates the worn surface morphology of the untreated sample, which exhibits numerous parallel grooves along the sliding direction. These grooves are mainly attributed to the plowing of micro-asperities during friction testing. In addition to the grooves, adhesive layers and delamination behaviors are also observed on the worn surface. With a further increase in the number of USR passes (Fig. 12b, c, d), the worn surface was covered by a large amount of adhesion. The formation of the adhesion layers increased the actual contact area of the friction pairs and improves the wear resistance of the friction pairs. This can also be proved in this study via the wear rate evolution depicted in Fig. 11, where the formation of adhesion layers led to a substantial reduction in the wear rate until the wear track was almost covered by the adhesion layers. The wear mechanism of sample U6 was mainly adhesion wear,

and its wear rate was the lowest. When the USR treatment exceeded six passes, the wear rate increased slightly because the adhesion layers were reduced.

Figure 13 shows the normalized statistical results of surface roughness, hardness, residual stress, plastic deformation thickness and wear rate with rolling passes. With the increase of rolling passes, the hardness, residual stress, and plastic deformation thickness all increased, while the surface roughness and wear rate show a trend of first decreasing and then slightly increasing, indicating that the surface roughness of the sample has an effect on the wear rate. The rougher the surface is, the more likely abrasive wear occurs in the early wear stage, resulting in high wear rate. However, the smooth surface reduces the incidence of abrasive wear in the early wear stage. This may be the reason for the different wear rate and wear mechanism of samples with different rolling passes. In a nutshell, USR-treated samples are more wear-resistant owing to their brighter surface, higher surface hardness, and residual compressive stress [15, 21, 33]. However, excessive rolling will lead to surface adhesion and roughness increase, which will reduce wear-resistance.

3.5 The relationship between strengthening mechanisms and tribological properties of USR treatment

The effect of surface roughness improvement and microstructure evolution on the mechanical properties of 4Cr13 stainless steel is shown in Fig. 14. The USR tool head performs high-frequency impact on the surface of the 4Cr13 stainless steel under a certain static pressure, causing serious plastic deformation on the surface of the sample, and the dislocation density increases sharply under the action of stress. Dislocations form dislocation tangles through slip, accumulation, interaction, annihilation and rearrangement, which divide the original grains into smaller dislocation cells.

With the continuous increase of strain, the dislocation density continues to increase. In order to reduce the total energy of the system, high-density dislocations will annihilate and rearrange near the dislocation entanglement, causing the dislocation entanglement to develop into small-angle grain boundaries. The formation of small-angle grain boundaries reduces the density of dislocations, thereby also reducing the lattice microscopic strain. As the strain continues to increase, more dislocations are generated and annihilated at the small-angle grain boundaries, causing the orientation difference on both sides of the grain boundaries to increase continuously, and the small-angle grain boundaries are transformed into large-angle grain boundaries, and the grains are refined.

As the strain continues to increase, dislocation entanglement will also occur inside the refined grains to divide them into dislocation cells. In the same mechanism, the refined grains are further refined to make the grain size further reduce. When the rate of dislocation generation and annihilation reaches equilibrium, the increase of strain will not lead to the continuous decrease of grain size, and the grain size reaches a stable value correspondingly. Simultaneously, the surface roughness of the processed sample was low, and the hardness and residual compressive stress were improved. These factors have the combined effect of increasing the wear resistance of the USR-treated sample.

4. Conclusions

In this study, the effects of USR-treated passes on the surface roughness, sample height, microstructure, microhardness, residual stresses, and wear behavior of 4Cr13 stainless steel were evaluated. The main conclusions are listed below:

- (1) Multiple USR treatments could introduce lower roughness, high microhardness, and compressive residual stress in 4Cr13 stainless steel. Compared to the untreated sample, the surface roughness decreased from 1395 to 86 μm , the surface microhardness increased from 251 to 329 HV, and the compressive residual stress of the surface increased from +135 to -723 MPa. The height of the sample after USR-treatment was reduced by approximately 28 μm at most.
- (2) After multiple USR treatments of 4Cr13 stainless steel, a gradient structure was formed on the surface, and the surface grains were refined. With the increase in processing passes, the depth of the plastic deformed layer increased from 58 to 229 μm . The average grain diameters of the matrix and surface layer after six passes of USR treatment were 7.53 and 0.75 μm , respectively.
- (3) Under a dry friction environment, the average friction coefficients and wear rates of the USR-treated samples were lower than those of the untreated samples. Six rolling passes were the most suitable for 4Cr13 stainless steel. The average friction coefficient was reduced from 0.65 to 0.54, the wear rate was reduced by 62%, and the wear mechanisms were mainly adhesion wear.

Declarations

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

Schematic diagram of the configuration of the USR device.

Figure 2

3D CM images and SEM micrographs of (a, a') U0, (b, b') U2, (c, c') U4, (d, d') U6, (e, e') U8, and (f, f') U10 after different rolling passes.

Figure 3

(a) surface profile and (b) roughness of samples treated at different USR passes

Figure 4

4Cr13 stainless steel sample (a), 3D CM images (b), and surface profiles (c).

Figure 5

(a) cross-sectional microhardness distribution and (b) residual stress of the samples at different numbers of USR passes.

Figure 6

Metallographic images of cross-sectional microstructures for the samples: (a) U0, (b) U2, (c) U4, (d) U6, (e) U8, and (f) U10 under various rolling passes. Therefore, after many times of ultrasonic rolling, the mesh carbide in the surface matrix of the stainless steel can be eliminated, the toughness of the surface layer can be improved, and the fatigue performance can be improved.

Figure 7

EBSD figures of grain orientation maps for samples: (a) U0 and (b) U6. (c) and (d): Magnified images of regions C and D. The statistical results of the grain distribution of (a), (c), and (d) are (e), (f), and (g) respectively.

Figure 8

EBSD figures of the dislocation cell distribution maps of samples: (a) U0 and (b) U6; grain boundary misorientation maps of samples: (c) U0 and (d) U6; corresponding frequency-disorientation angle curves of (c) and (d).

Figure 9

(a) Evolution histories of the friction coefficient and (b) variation of the average friction coefficient under various USR passes.

Figure 10

3D CM morphologies showing the worn surfaces of samples: (a) U0, (b) U2, (c) U4, (d) U6, (e) U8, and (f) U10. Ultrasonic machining rolled sample and the sample is not trace grinding marks is not smooth, due to debris accumulation on the surface of the wear and the elimination of lead.

Figure 11

Wear rate of samples under various USR passes.

Figure 12

SEM images showing worn surfaces of samples: (a, a') U0, (b, b') U2, (c, c') U4, (d, d') U6, (e, e') U8, and (f, f') U10.

Figure 13

The normalized statistical results of surface roughness, microhardness, residual stress, deformation layer thickness, and wear rate

Figure 14

Effect of surface roughness improvement and microstructure evolution on the mechanical properties of 4Cr13 stainless steel after USR treatment