Effect of ultrasonic rolling on the surface integrity and corrosion properties of GCr15 steel before and after quenching

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Abstract

Two new surface strengthening processes, Ultrasonic rolling treatment before and after quenching were investigated on GCr15 steel. The surface integrity and corrosion were tested and ABAQUS simulation was conducted for the two processes. As a result, the proposed process is to carry out ultrasonic rolling on the GCr15 after quenching by the small static loads and rolling times. In comparison with the unquenched sample, the quenched sample is more prone to dislocation and slip, resulting in better grain refinement effect. When the static loads and rolling times are small, ultrasonic rolling has a good peak-cutting and valley-filling effect on the quenched sample surface, which leads to the roughness of the quenched samples less than that of the unquenched samples. The initial residual compressive stress in the quenched sample due to heat treatment is greater and deeper than that of the unquenched sample due to large plastic deformation under small static loads or rolling times. The hardness of the unquenched samples is much lower than that of the quenched samples, owing to better grain refinement effect in quenched samples. The corrosion resistance of quenched samples is better than that of unquenched samples.

1. Introduction

GCr15 bearing steel is widely applied in precision machine spindles, internal combustion engines, mining machinery and other fields [1, 2]. With the gradual development of industry, the increasingly harsh working environment requires GCr15 to have better surface properties, which determines the service performance of the parts. Traditional surface strengthening techniques like shot peening [3, 4], surface carburizing and nitriding have improved the surface properties of materials to some extent. But high roughness and severe deformation and stress concentration persist after shot peening [5, 6]. Surface carburizing and nitriding treatment have disadvantages of the shallow compressive stress layer and high surface brittleness [7], which cannot efficiently improve the fatigue life of the material. In contrast, ultrasonic rolling treatment, as an emerging surface strengthening technique, has the advantages of mechanical grinding and low plasticity polishing [8]. It can effectively enhances the surface integrity of metallic materials with deep residual compressive stress distribution, so as to improve the fatigue limit and reduce wear [9–11]. Thus, it is important to investigate the effect of ultrasonic rolling on the surface integrity of GCr15.

Ting Wang and Dongpo Wang [12, 13] applied ultrasonic rolling to 40Cr and found that the surface roughness of 40Cr decreases to Ra0.05, the surface microhardness increases by 63%, and a maximum residual compressive stress of ~ 846 MPa is introduced in the surface layer. Several literatures [14–17] show that ultrasonic rolling not only affects the processed surface, but also improves the corrosion resistance, wear resistance, and fatigue life of the material. Wagner [18] investigated the fatigue properties of titanium, aluminum and magnesium alloys after rolling and showed that high-cycle fatigue cracks are greatly reduced in parts after rolling. Linlin Li et al [19] found that ultrasonic rotary machining can significantly improve machining efficiency.
and machining effects. Zhao Jian [20] revealed the change pattern of microhardness of the rotary ultrasonic rolling surface of Ti6Al4V and the microstructure evolution of the processed surface layer material. As the research on the processing effect of ultrasonic rolling has been extended, the research on the ultrasonic processing parameters has begun. Zhu Lei et al [21] studied the effects of different ultrasonic rolling parameters on the surface roughness, microhardness and surface micromorphology of TC4 titanium alloy. Lei Jun and Su Yongxiang [22] pointed out that the static load exerts the greatest influence on the surface integrity of the workpiece by ultrasonic rolling, followed by the rotational speed, then the feed rate. A further study of machining parameters by Liqin Chen [23] showed that the axial residual stresses increased with the growth of static load and decreased with the rising feed rate. Gao Xinhuan et al [24] studied the effect of different ultrasonic rolling parameters on the ground state specimens of GCr15SiMn bearing steel. Most of the existing studies on ultrasonic rolling in the literature have focused on studying the effect of ultrasonic rolling or rolling parameters on the surface integrity of a particular material.

The researches show that proper heat treatment can optimize the microstructure of GCr15 and improve the strengthening effect of surface treatment on the surface properties of GCr15 [25–29]. Hao Su et al [30] investigated the surface ultrasonic burnishing treatment of TC11 titanium alloy and found that the heating surface of TC11 titanium alloy has better ultrasonic burnishing treatment results, significantly higher corrosion resistance, lower surface roughness. Zhang [31] applied the combination of ultrasonic polishing and heating to laser melting of Fe-based coatings and found that the combination of a period of continuous heating reduces the roughness and porosity of Fe-based coatings, and increases the hardness and residual stresses. Such research has only been conducted for simple heating of ultrasonic burnishing workpieces, and no literature is available to cover studies of the effect of ultrasonic rolling on the surface integrity of materials under different heat treatment methods.

The processing effect of ultrasonic rolling is not only related to the material, but also depends on its order in the process route of parts to a large extent. On the one hand, there is little literature on ultrasonic rolling of GCr15. On the other hand, whether ultrasonic rolling is carried out before quenching or after quenching has a great influence on the surface properties of parts, which has not been studied in literatures. In this paper, two process plans which are ultrasonic rolling treatment with annealing before quenching (Unquenched-URT) and ultrasonic rolling treatment with annealing and quenching (Quenched-URT), respectively, are proposed and investigated. The two process plans are compared and discussed in order to present a new and reasonable process plan for surface strengthening of GCr15, as well as to reveal the influence mechanism of ultrasonic rolling parameters on the surface integrity and corrosion resistance of GCr15. This study also provides theoretical and data references for ultrasonic rolling of similar materials.

2. Materials, machining and test

2.1. Preparation of materials
GCr15 was selected as the test materials of ultrasonically rolling and divided into 20 samples in two groups, (1) Unquenched samples in isothermal spheroidizing annealing treatment: for the first 10 samples, they were heated to 770 °C ~ 790 °C isothermally and cooled until 550 °C in a furnace, then air-cooled. (2) Quenched samples: another 10 samples were heated to 855 ~ 875 °C, held for about 50~70 min, and then placed into an isothermal nitrate salt bath at 220 °C–240 °C for 3–4 h, using hot water (at 70 °C–80 °C) to rinse these 10 samples. The main chemical composition of GGr15 is summarized in table 1. In the last stage, these 20 samples were cut into pieces measuring 45 mm × 20 mm × 15 mm using a wire-cutting machine; the specimens were ground, then subjected to ultrasonic rolling.

2.2. Ultrasonic machining
An H1+ VM1260 CNC milling machine was equipped with HK30C ultrasonic generator as the ultrasonic machining equipment, as shown in figure 1. The principle of ultrasonic rolling is as follows: an ultrasonic generator generates an ultra-high-frequency ac electrical signal, which is then converted into mechanical vibration signal by a transducer. The vibration signal is amplified by an amplitude-change pole and then acts on the tool head to produce ultra-high-frequency squeezing and impact, so as to achieve the effect of surface strengthening (as shown in figure 2).
2.3. Surface integrity and corrosion test
In order to test the effect of ultrasonic rolling, the surface integrity and corrosion resistance of the samples were tested. Firstly, scanning electron microscopy (Phenom Prox) and three-dimensional superdepth of field observation microscopy (VHX-5000) were used to observe the surface morphology and metallographic structure of the samples. X-ray diffraction instrument (D8-Advance) was used to analyze the change of grain size and verify the residual stress simulation results. Residual stress detector (ZS21B) was used to measure the residual stress of the sample surface. The surface roughness of the samples was detected by a surface roughness detector (Mitutoyo SJ-210), and the surface topography changes were analyzed in combination with a three-dimensional optical microscope host (Contour Elite K). The hardness of the samples was tested by a microhardness tester (HXD-1000TMC) with the pressure of 3N and a pressure holding time of 15s. Finally, an electrochemical workstation (Interface1000) was used to detect the change of corrosion resistance of the samples. The electrolyte adopts 3.5wt% NaCl solution, the corrosion test temperature is (20 ± 1 °C), the reference electrode adopts saturated calomel electrode, and the auxiliary electrode adopts platinum electrode.

3. Calculation of residual stress by finite element method
An important function of ultrasonic rolling is to introduce residual compressive stress into the surface of the material. The high energy potential in the coarse grain of the surface of the material moves, interleaves, tangles and rearranges under high frequency impact, forming dislocation walls and producing residual stress in the strengthened layer [32, 33]. The common method for analyzing the residual stress distribution in the depth

Figure 1. Ultrasonic rolling equipment.

Figure 2. Principles of ultrasonic rolling.
direction is to use the x-ray diffraction method \cite{34} to test the surface residual stress, and then use an electrolytic polishing machine to corrode the surface layer to a certain thickness and then test it again. Repeat the operation for many times to obtain the residual stress distribution in the depth direction. However, the corrosion depth is difficult to control, and the surface state will be damaged after corrosion, which affects the measurement results of residual stress. In addition, the operation process of this method is very complicated and error-prone. The method adopted in this paper is: ABAQUS was used to simulate the ultrasonic rolling process to obtain the distribution of residual stress in the depth direction, and the accuracy of the simulation results was verified by the residual stress results tested on the top surface.

A cuboid block of 20 mm $\times$ 45 mm $\times$ 20 mm was established as a simulation geometric model. The rolling head was a D-shaped tool head, with a drum shape with a slightly smaller radius at both ends and a slightly larger radius in the middle (figure 3). Because the hardness of the tool head is much higher than the material being machined, it is set as rigid body in the simulation. The sample model adopts regional grid division, and the grid adopts eight-node linear reduced volume element (C3D8R). The rolling part is finely divided, while the rest part of model is roughly divided, which saves calculation time and guarantees the reliability of simulation results to the maximum extent. There are three main steps in rolling simulation: loading, rolling and unloading, all the steps were finished with a dynamic explicit analysis algorithm.

4. Results and analysis

4.1. Analysis of surface topography

4.1.1. Scanning electron microscopy analysis

Figure 4 shows the SEM images of the quenched and unquenched samples before and after the ultrasonic rolling treatment (URT) at a static load of 1000N and rolling time of 1. It can be observed from figures 4(a) and (b) that there are obvious scratches, wave peaks and troughs on the surface of quenched and unquenched samples before ultrasonic rolling treatment. After ultrasonic rolling, the peaks and troughs of the material surface are continuously flattened and filled, so that the surface of the sample is smooth and the roughness is significantly reduced. As shown in figures 4(c) and (d), the Quenched-URT surface was smoother and more homogenous than the Unquenched-URT surface, indicating a better surface finishing. Obvious pits appeared on the surface of the unquenched samples after rolling. This is because the hardness of the unquenched parts is much lower than the quenched parts, so that the surface of the unquenched parts is easy to spall and form pits under repeated high frequency impact rolling.

4.1.2. XRD analysis

The XRD results of the samples at different static loads and numbers of rolling cycles are shown in figures 5–7. Among them, the FWHM in figure 5(d) and 7 refers to the peak width at half of the peak height, which represents the range of the diffraction distribution of the material characteristic peaks and can indirectly reflect the change of the material grain size \cite{35, 36}. According to the Scherrer formula, the broadening of the diffraction peak and the increase of the FWHM imply a decrease in grain size.

As shown in figures 5–6: as the static load and number of rolling cycles increase, the XRD peaks become shorter and wider, and the FWHM become larger for both quenched and unquenched samples, indicating grain refinement and increasing residual compressive stresses. In ultrasonic rolling process, plastic strain occurs on the material surface, by which the surface crystal defects (twins, dislocation, etc) are annihilated and regenerated repeatedly. In this way, more subgrain boundaries are produced, and the surface grains develop into finer grains to achieve the effect of surface grain refinement. The increase in the static load and rolling cycles can repeatedly
stimulate the annihilation and regeneration of crystal defects on the surface of materials, resulting in continuous grain refinement.

Compared with the quenched sample, the diffraction peak of the unquenched sample moves to a higher angle $\theta$. According to Bragg equation, the increase in diffraction angle means the decrease in crystal plane spacing, that is, the increase in compressive stress. This is because the structure of the unquenched parts is mainly pearlite, with low hardness and strength. Under the impact of ultrasonic rolling, the unquenched samples will produce greater plastic deformation, resulting in greater residual compressive stress. The diffraction characteristic peaks of the quenched samples are lower and wider than those of the unquenched samples, indicating that the grains of the quenched samples are finer than those of the unquenched samples. In unquenched samples, the pearlite and cementite are regularly distributed. The original crystal structure is destroyed resulting in original crystal defects, dislocation and slip under the action of ultrasonic rolling. The grain boundaries are repeatedly destroyed and regenerated to form new grain boundaries, making the grains refine. In the quenching samples, the outer layer of the material cools rapidly, while the inner part cools slowly, which results in the large internal stress of the quenched sample. And the internal pearlite gradually transforms into unbalanced structures such as martensite, bainite and residual austenite resulting in the increase of grain boundaries as well as the weaker of the obstruction of dislocation and slip along grain boundaries. The interlacing distribution of martensite, the existence of microcracks in martensite, the irregular distribution of bainite and polygonal austenite grains make the quenched sample more prone to dislocation and slip, resulting in better grain refinement effect than unquenched sample under ultrasonic rolling.

4.1.3. Metallographic analysis

The metallographic results are shown in figures 8–9. From figure 8(left), there are larger cementite and pearlite in the core of the unquenched sample, and the surface layer are composed of smaller grains in a uniform distribution. In figure 8(right) there are obvious martensite and bainite in the core and fine grains in the surface layer of the quenched sample, indicating a refinement layer is formed in the surface layer. It can be found from the comparison that the unquenched sample has a thicker refining layer, but the grain refinement degree of
quenched sample is more significant. With the increase in static pressure, the grain becomes more refined and the refinement layer becomes thicker. (consistent with the XRD test results).

As can be seen from figure 9: with the increase in rolling cycles, the surface grain is refined better, but the thickness of refinement layer does not change significantly. In addition, the surface layer of the unquenched samples has obvious rheological structure, and the thickness of the rheological structure increases obviously with the increase of rolling times, up to about 235 μm, while the quenched samples have no obvious rheological structure. The apparent rheological structure in unquenched samples is caused by the large surface plastic deformation resulting from the energy generated by ultrasonic rolling. Due to the high hardness of quenched samples, plastic deformation is not easy to occur. Part of the energy generated by ultrasonic rolling is used to overcome grain boundary resistance to refine the grain, and the other part is transferred to the non-grain refining part of the material through vibration. Therefore, no obvious rheological structure is formed inside the quenched samples. This is consistent with the FWHM result as evinced by XRD.

4.2. Surface roughness analysis

Figures 10–14 shows the surface roughness and three-dimensional surface topography of samples under different static loads and rolling cycles. It can be seen from figure 10 that the surface roughness of both quenched samples and unquenched samples decreases by ultrasonic rolling, and they change little first and then increase with the increasing static loads and rolling times. This is because the material will undergo plastic deformation under ultrasonic rolling, resulting in peak-cutting and valley-filling effect, which significantly reduces the surface roughness (as low as 0.06Ra). However, when the static loads or rolling times are too large, excessive plastic deformation will result in surface accumulation of materials to generate the increase of roughness. It indicates that there exists an optimal static load and rolling time to minimize the surface roughness of the sample under ultrasonic rolling. According to the test results, the optimal static load and the rolling time of both quenched and unquenched samples are smaller than 1100N and 3times, respectively.

From figure 10(left), 11, and 12: when the static load is less than 1000 N, the roughness of the quenched samples is less than that of the unquenched samples. This is because, when the static load is small, ultrasonic
rolling has a good peak-cutting and valley-filling effect on the quenched sample surface. However, the hardness of unquenched samples is low, resulting in excess plastic deformation and the formation of local bumps and depressions. When the static load is greater than 1000N, the roughness of quenched samples is much larger than that of unquenched samples. Due to the high hardness and poor plasticity of the quenched samples, the plastic
deformation caused by the subsequent impact cannot fill the vacancies generated by the previous impact shown in figure 15 to result in the formation of bulge and gully, which increase the surface roughness.

It can be seen from figure 10(right), 13 and 14 that when rolling times are less than 3 times, ultrasonic rolling produces good peak-cutting and valley-filling effect, and the surface roughness of unquenched and quenched parts is stable. When the rolling times are more than 3 times, the surface roughness of the unquenched sample is obviously lower than that of the quenched sample, the reason is the poor plasticity of the quenched samples which results in the subsequent impact cannot fill the vacancies generated by the previous impact to cause the increase in the surface roughness, as shown in figure 15.
Figure 10. Surface roughness of samples (Left: static loads, Right: rolling cycles).

Figure 11. Quenched samples under different static loads (a): Unprocessed sample, (b): 900 N, (c): 1100 N, (d): 1300 N.

Figure 12. Unquenched samples under different static loads (a): Unprocessed sample, (b): 900 N, (c): 1100 N, (d): 1300 N.
Figure 13. Quenched samples under different rolling cycles (a): Unprocessed sample, (b): 3, (c): 8, (d): 12 (static loads: 1000 N).

Figure 14. Unquenched samples under different processing cycles (a): Unprocessed sample, (b): 3, (c): 8, (d): 12 (static loads: 1000 N).

Figure 15. Material surface during rolling (left: Quenched, right: Unquenched).
4.3. Residual stress

The test and simulation results of residual stress are shown in figure 16. It can be seen that the residual compressive stress increases with the increase of static loads and rolling times. The increase of static load leads to the increase of kinetic energy of single impact, which leads to the increase of plastic deformation and compressive stress inside the material. The more rolling times, the greater the residual compressive stress. In addition, repeated rolling will produce cold-working hardening effect, which makes it difficult for the compressive stress to release itself through aging, so that the residual compressive stress can be maintained for a longer time.

The initial residual compressive stress in the quenched sample due to heat treatment is greater than that of the unquenched sample due to large plastic deformation under small static loads or rolling times, as shown in figure 16. With the increasing of static load and rolling times, the residual compressive stress in the unquenched sample due to large plastic deformation exceeds that in the quenched sample due to heat treatment and plastic deformation, as shown in figure 17.

As can be seen from figure 16, the variation trend of simulation curve and test curve is the same. In figure 16(left), the error between simulation results and test results is less than 9%. In figure 16(right), the error between simulation results and test results increases gradually with the increase in rolling cycles, up to 14%. The reasons for the error are as follows: The rolling head is set as rigid body and the rolling speed is constant in the simulation, but in the machining process, the rolling head is not ideal rigid body and the rolling speed is vary. In addition, in order to save the calculation time, the mesh division is limited such that the errors between simulation results and the real machining results are inevitable. The longer the rolling cycles, the greater the error of simulation results. The comparison between the test results and the simulation results shows that the error is within a reasonable range, so the simulation results are reliable. Thus, the simulation results can be used to predict distribution of the residual stress along the depth direction of the samples. Simulation results of stress distribution in depth direction are shown in figure 18.

It can be seen from figure 18 that the compressive stress increases with the increase in depth. After reaching the maximum value, the compressive stress gradually decreases with the increase in depth and finally becomes the pulling stress. The greater the static load and rolling times, the farther the position of maximum residual compressive stress is from the surface, and the greater the absolute value of residual compressive stress. When
static load is less or equal to 1000N or rolling times is less or equal to 3 the residual compressive stress in the quenched specimen is larger and deeper. In other cases the residual compressive stress in the unquenched specimen is larger and deeper than that of the quenched specimen. Figure 19 shows the stress distribution cloud in depth direction of the samples by ultrasonic rolling (static load: 1000N rolling cycle: 3). It can be seen that the residual compressive stress layer in the quenched sample is thicker, the residual compressive stresses in the quenched sample are larger (matching the XRD analysis results).

4.4. Hardness analysis
As can be seen from figure 20, with the increase of static load, the surface hardness of the sample increases. When the static pressure is higher, the hardness increase is not obvious. According to the XRD analysis in section 4.1, the increase in static load will continually lead to refinement of grain, and the finer the grain, the higher the surface hardness according to the Hall-Petch expression.

For quenched samples, the surface hardness shows an obvious increasing trend when the number of rolling cycles are less than 3, but no significant change occurs when the rolling times are more than 3 times. For the unquenched samples, when the number of rolling cycles is less than 8, the surface hardness shows a slight increasing trend, when the number of rolling cycles is more than 8, the surface hardness remains stable.

Repeated rolling refines the grain continuously, increasing the density of dislocations and grain boundaries, which leads to increase the resistance to further grain refinement. Therefore, grain refinement and hardness increase are very limited when the number of rolling cycles exceed a certain value. This indicates that there is an optimal number of rolling cycles, which is related to the process parameters such as heat treatment of the material.

4.5. Corrosion resistance analysis
Figure 21 (left) is the Nyquist curves of samples. The radius of the capacitive reactance arc can reflect the corrosion performance of the sample. The larger the radius, the better the corrosion resistance of the sample [37]. It can be seen from the figure that the radius of the capacitive reactance arc of the quenched sample is larger.
Figure 19. Stress distributions (a: Quenched sample, b: Unquenched sample).

Figure 20. Hardness under different static loads and numbers of rolling cycles.

Figure 21. Left: Nyquist impedance spectroscopy, Right: Potential polarization curves.
than that of the unquenched sample before ultrasonic rolling, indicating that the corrosion resistance of the quenched sample is better than that of the unquenched sample. The radius of the capacitive reactance arc of the sample ultrasonic rolled is larger than that of the untreated samples, indicating that the corrosion resistance of the samples can be improved by ultrasonic rolling. In addition, after ultrasonic rolling, the radius of the capacitive reactance arc of the quenched sample is also larger than that of the unquenched sample, indicating that the corrosion resistance of the quenched sample is still better than that of the unquenched sample after ultrasonic rolling. The phenomenon of capacitance real part shrinkage occurred in the middle and low frequency regions of the rolled samples, indicating that local corrosion occurred on the surface of the sample in the middle and low frequency regions. It can be seen from figure 22 that after the corrosion test, the surface of the sample after ultrasonic rolling has obvious local corrosion marks.

Figure 21(right) is the potential polarization curve of samples. The corrosion potential ($E_{\text{corr}}$) and corrosion current density ($I_{\text{corr}}$) of the sample can be obtained by the Tafel curve extrapolation method. $E_{\text{corr}}$ can reflect the degree of corrosion tendency of the material, the larger the value, the smaller the corrosion tendency; $I_{\text{corr}}$ can reflect the rate of corrosion of the material, the larger the value, the faster the corrosion. The calculation results are shown in table 2. It can be seen from table that after ultrasonic rolling, $E_{\text{corr}}$ of all samples is improved, and $I_{\text{corr}}$ of all samples is reduced, indicating that the corrosion resistance of all ultrasonic rolled samples is improved. There are two main reasons: on the one hand, the surface roughness affects the corrosion resistance of the sample, the lower the surface roughness of sample, the less likely it is to be corroded. On the other hand, the refinement of the grains also helps to improve the corrosion resistance of the material. After ultrasonic rolling, $E_{\text{corr}}$ of quenched samples is greater than that of the unquenched samples, indicating that the quenched samples are less likely to be corroded. $I_{\text{corr}}$ of the unquenched samples is greater than that of the quenched samples, that is, the rate of corrosion of the unquenched samples is greater. This is because the surface of the unquenched sample contains many tiny pits. These tiny pits not only make the surface of the unquenched sample easier to release electrons and more prone to electrochemical corrosion, but also increase the contact area of the unquenched sample during the corrosion reaction and accelerate the corrosion rate.

In summary, it can be seen that the surface integrity and corrosion resistance of GCr15 are improved whether ultrasonic rolling is performed before or after quenching. Regardless of static pressure and rolling

| Sample           | $E_{\text{corr}}$ (mV) | $I_{\text{corr}}$ ($\mu$A cm$^{-2}$) |
|------------------|------------------------|-------------------------------------|
| Unquenched       | −890.5                 | 21.933                              |
| Quenched         | −804.9                 | 6.315                               |
| Unquenched-URT   | −780.9                 | 10.418                              |
| Quenched-URT     | −759.7                 | 2.016                               |

Figure 22. Corroded surface of a sample.
times, ultrasonic rolling after quenching (quenched-URT) is much better than ultrasonic rolling before quenching (Unquenched-URT) in grain refinement, hardness and corrosion resistance. When the static loads and rolling times are small, the process quenched-URT is better than the process Unquenched-URT in the roughness as well as magnitude and depth of residual compressive stress. The increase in static load and rolling time has little effect on hardness, but is favorable to residual compressive stress and unfavorable to roughness. Therefore, the proposed process plan is to carry out ultrasonic rolling on the GCr15 steel after quenching by the small static load and rolling time, where the proposed static load and rolling time are 1000N and 3 times, respectively.

5. Conclusion

Two new surface strengthening process Unquenched-URT and Quenched-URT were investigated on the GCr15. The surface integrity and corrosion were tested and ABAQUS simulation was conducted, and the following conclusions are obtained:

(1) The surface integrity and corrosion resistance of GCr15 can be improved by ultrasonic rolling. The proposed process is to carry out ultrasonic rolling on the GCr15 steel after quenching by the small static load and rolling time, where the proposed static load and rolling time are 1000N and 3 times, respectively.

(2) The interlacing distribution of martensite, the existence of microcracks in martensite, the irregular distribution of bainite and polygonal austenite grains make the quenched sample more prone to dislocation and slip, resulting in better grain refinement effect in comparison with the unquenched sample. The unquenched sample has a thicker refining layer, which has obvious rheological structure resulting from the large plastic deformation.

(3) When the static loads and rolling times are small, ultrasonic rolling has a good peak-cutting and valley-filling effect on the quenched sample surface, which leads to the roughness of the quenched samples less than that of the unquenched samples. When the static loads and rolling times are great, the roughness of quenched samples is larger than that of unquenched samples. Due to the high hardness and poor plasticity of the quenched samples, the plastic deformation caused by the subsequent impact cannot fill the vacancies generated by the previous impact to result in the formation of bulge and gully, which increase the surface roughness.

(4) The initial residual compressive stress in the quenched sample due to heat treatment is greater and deeper than that of the unquenched sample due to large plastic deformation under small static loads or rolling times. With the increasing of static loads and rolling times, the residual compressive stress in the unquenched sample due to large plastic deformation greater and deeper than that in the quenched sample due to heat treatment and plastic deformation.

(5) The hardness of the unquenched samples is much lower than the quenched samples, owing to better grain refinement effect in quenched samples. The corrosion resistance of quenched samples is better than unquenched samples.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Authorship contribution statement

Yongchen Wang: Methodology, Investigation, Writing - original draft. Jianghai Lin: Writing - review & editing. Yanshuang Wang: Methodology, Data curation, Writing - review & editing. Xiuli Fu: Writing - review & editing.
Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal or ethical reasons.

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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References

[1] Maoguang Chen and Zhongkui Zhang 2020 Comparison and analysis of heat treatment process and properties of G8Cr15 and GCr15 bearing steels Hot Working Technology 49 135–8

[2] Hui Li and Zhen-li Mi 2014 Nano-scale carbides precipitation in GCr15 bearing steel during heat treatment. Materials and Heat Treatment 55 54–8

[3] Ali M, Ali H, Kamran A, Farzad A and Reza A 2021 Molecular modeling of Ti-6Al-4V alloy shot peening: the effects of diameter and velocity of shot particles and force field on mechanical properties and residual stress Model. Simul. Mater. Sci. Eng. 29 065001

[4] Amini K 2021 The effect of silicon percentage and shot peening operation on mechanical properties of hadfield steel containing 17% manganese Protection of Metals and Physical Chemistry of Surfaces 57 589–96

[5] Perai L B, Quintero Amado, Vielma A T, Barbés María Florentina and Fernández-Pariente L 2021 TEM evaluation of steel nanocrystalline surfaces obtained by severe shot peening Surface & Coatings Technology 418 127328

[6] Heydari Astaraee Ashgar, Sara Bagherifard, Stefano Monti and Mario Guagliano 2021 Evaluating the homogeneity of surface features induced by impact-based surface treatments Materials (Switzerland: Basel) (https://doi.org/10.3390/MA14135476.)

[7] Liangshun Huang X P, Lan Luo X R and Yuhai Jing Y L 2020 Microstructure evolution and mechanical properties of AZ31 alloy with accumulative roll bonding Mater. Trans. 61 5

[8] Zhang Q, Hu Z, Su W and Qi X 2017 Microstructure and surface properties of 17–4PH stainless steel by ultrasonic surface rolling technology Surface & Coatings Technology 321 64–73

[9] Liu C, Liu D, Zhang X and Zhao W 2017 Effect of the ultrasonic surface rolling process on the fretting fatigue behavior of Ti-6Al-4V Alloy Materials 10 833

[10] Yihong Z et al 2021 Effect of rolling process on microstructure and wear properties of high carbon equivalent gray cast iron Journal of Wuhan University of Technology(Materials Science) 06 903–10

[11] Amine O, Sebastien L, Dyke Pierre V, Sebastien L, Sattarpanah K S and Lamine D 2021 Fretting fatigue life assessment of overhead conductors using a clamp/conductor numerical model and biaxial fretting fatigue tests on individual wires Fatigue Fract. Eng. Mater. Struct. 44 1498–514

[12] Ting Wang and D-po Wang 2009 4Cr nano-crystallization by ultrasonic surface rolling extrusion processing Chin. J. Mech. Eng. 45 177–83

[13] Ting Wang and D-po Wang 2009 Effect of ultrasonic surface rolling processing parameters on 4Cr surface roughness Journal of Tianjin University 42 168–72

[14] Huuki J, Hornborg M and Juntunen J 2014 Influence of ultrasonic surface burning technique on surface quality and change in the dimensions of metal shafts Journal of Engineering 2014 124237

[15] Xuarte I F et al 2020 Surface modification of additively manufactured 18% nickel maraging steel by ultrasonic vibration-assisted ball burnishing J. Manuf. Sci. Eng. 142 071008

[16] Huuki J and Ullah R 2019 Effect of tangential misalignment in ultrasonic burnishing Procedia Manufacturing 38 1540–6

[17] Ziyi Cui, Xiaoyu Hu, Shengjian Zhu, Fuqian Tang, Xuehui Zhang and Xiaoxian Li 2021 Effect of ultrasonic surface rolling treatment on microstructures and properties of cemented carbide China Tungsten Industr 01 35–40

[18] Wagner I 1999 Mechanical surface treatments on titanium, aluminium and magnesium alloys Materials Science & Engineering A 263 210–6

[19] Lin-jin Li and Yong-wei ZHU 2017 Modeling and testing on material removal mechanism of rotary ultrasonic machining.(eds Proc. of 2017 2nd Int. Conf. on Advanced Materials Science and Environment Engineering(AMSEE2017) 167–72 DEStech Publications (https://kns.cnki.net/kcms/detail/detail.aspx?FileName = LRCM2017060902033&DnName = IPFD2018)

[20] Jian Z et al 2021 Characterization of microstructure and mechanical properties for Ti-6Al-4V processed by rotary ultrasonic roller burnishing Mater. Charact. 178 111288

[21] Lei Zhu, Gaofeng Pan, Xiaoli Hao, Shengli Guo and Zewei Yuan 2021 Influence of ultrasonic rolling process parameters on surface quality of TCA titanium alloy Journal of Henan Institute of Science and Technology (Natural Science Edition) 05 78–84

[22] Jun LEI 2020 Gray correlation analysis of surface integrity of ultrasonic-assisted rolling Gcr15 bearing steel J. Mech. Strength 42 545–50

[23] Li-qin C, Bin X, Xue-chong Ren, Xin-gui L and Guo-biao L 2014 Influences of surface ultrasonic rolling processing parameters on surface condition of axle steel used in high speed trains China Surface Engineering 27 96–101

[24] Xinhuan G, Jinzhi P, Chunhuan C, Zhi C and Ruiming R 2021 Analysis of surface microstructures and properties of GCr15SiMn bearing steel processed by ultrasonic rolling technology Surface Technology 51 262–70

[25] Bing X, Shihong C, Yongsheng R, Fengshi Y, Teng S and Minghao S 2021 Effect of tempering heat treatment on microstructure and mechanical properties of GCr15 bearing steel Journal of Shandong University of Technology (Natural Science Edition) 02 73–6

[26] Liu M, Cui Z, Shang X and Zhou S 2018 Comparative study on the microstructure characteristics and enhanced mechanical properties of spray formed GCr15 bearing steel Steel Res. Int. 89 170529

[27] Wu K et al 2017 Improved resistance to hydrogen embrittlement by tailoring the stability of retained austenite Mater. Sci. Technol. 33 1497–504
[28] Li N et al 2018 Structure and properties of GCr15 modified by multiphase ceramic nanoparticles/Fe-C composite inoculants Materials Science & Engineering A 738 63–74

[29] Guo-song Z, Hong-zhi C and Gui-qin C 2016 Friction and wear behaviors of gas nitriding and quenching compound treatment of GCr15 steels China Surface Engineering 06 30–7

[30] Su H, Shen X, Xu C, He J, Wang B and Su G 2020 Surface characteristics and corrosion behavior of TC11 titanium alloy strengthened by ultrasonic roller burnishing at room and medium temperature Journal of Materials Research and Technology 9 8172–85

[31] Changsheng Z, Xuehui S, Jiatian W, Chonghai X, Jianqun H and Xiaolan B 2021 Improving surface properties of Fe-based laser cladding coating deposited on a carbon steel by heat assisted ultrasonic burnishing Journal of Materials Research and Technology 12 100–16

[32] Li G, Qu S, Xin Xie M and Li X 2017 Effect of ultrasonic surface rolling at low temperatures on surface layer microstructure and properties of HIP Ti-6Al-4V alloy Surface & Coatings Technology 316 75–84

[33] Teimouri Reza and Amini S 2018 Analytical modeling of ultrasonic surface burnishing process: Evaluation of through depth localized strain Int. J. Mech. Sci. 151 118–32

[34] Lan J, Feng S and Hua L 2017 The residual stress of the cold rolled bearing race Procedia Engineering 207 1254–9

[35] Unal Fatma, Kaya F and Kazmanli K 2021 Synthesis, characterization and radioluminescence properties of erbium-doped yttria phosphors Int. J. Miner. Metall. Mater. 12 118–32

[36] Topolski K and Garbacz H 2018 Manufacturing of nanostructured titanium grade2 using caliber rolling Materials Science & Engineering A 739 277–88

[37] Tian W C, Long M Q, Hao C F, Hong W J, Ran Z Y and Rong W Z 2021 Corrosion resistance of industrial pure titanium and its alloys under high temperature and different cooling methods Key Eng. Mater. 891 3–9