Effect of Ultrasonic Rolling on Properties of GCr15 Bearing Steel

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Abstract. The effects of ultrasonic rolling processing on the properties of GCr15 bearing steel were studied in this paper. The specimens were treated with different values of preload in ultrasonic rolling processing. The surface roughness, microhardness and rolling contact fatigue life of the specimens before and after ultrasonic rolling processing were analysed and compared. The index of power density was firstly introduced and combined with ultrasonic rolling parameters. The results show that the qualities of surface roughness and microhardness are improved after ultrasonic rolling treatment, and the friction coefficient is reduced. However, when the ultrasonic rolling power density exceeds 11.24 Gw/cm², the grain sizes of the specimens becomes larger, which leads to the increase of the internal stress, resulting in the initiation and propagation of crack. The propagation mode of fatigue cracks changes from transcrystalline to intergranular after ultrasonic rolling treatment, reducing the performances of wear resistance and rolling contact fatigue.

1. Introduction
Rolling contact fatigue (RCF) has been recognized as the prevailing failure in balling bearings [1], so it is of great significance to study the surface strengthening technologies of bearing steels.

Ultrasonic rolling treatment is a surface strengthening technology that combines traditional rolling with ultrasonic machining. It can significantly reduce the roughness of the material, improve hardness, and introduce residual compressive stress which is widely used to improve the surface properties of metal materials [2].

Many scholars have applied ultrasonic rolling technology to strengthen metal materials and the influences of ultrasonic rolling treatment on material properties were analyzed. It was obtained that ultrasonic rolling improves the microhardness, surface roughness and residual stress of 60Si2CrVAT spring steel [3], AZ31B magnesium alloy [4], steel of 45# [5], C53 steel [6] and GCr15SiMn bearing steel [7] etc.

Liu [8] found that the preload of ultrasonic rolling has the greatest influence on the residual stress of specimen, and the residual stress increases with the increase of preload within a certain range. Through theoretical calculation and experimental analyses, Zhou [9] obtained that the grain size of Aluminum alloy 7075 was mainly affected by the preload and amplitude.
However, many studies showed that improper setting of ultrasonic rolling parameters reduces the properties of materials. For example, micro-cracks was produced in the surface of SUS304 austenitic stainless steel when the preload was too large, resulting in the reduction of fatigue strength \[10\]. In addition, Li \[11\] found that the fatigue life of TC4 was reduced after the treatment of ultrasonic rolling. The reason was that the surface grain of TC4 material was reconstructed, resulting in uneven material properties and reduced fatigue life. Huang \[12\] proposed that un-uniform distribution of grain size generated by ultrasonic rolling causes stress concentration at the boundaries of grains and therefore reduces the fatigue life of rolling contact. Zhu \[13\] found that the high ultrasonic rolling energy would cause internal defects, such as micropores and cracks, resulting in reduction of corrosion resistance.

Up to now, there is little research on the processing of ultrasonic rolling applied to GCr15 steel, and the effects of ultrasonic rolling on GCr15 steel are unclear. In this paper, the roughness, microhardness and amount of indentation of GCr15 steel were obtained after ultrasonic rolling treatment with different values of preload, and the test of RCF was carried out to analyse the effects of ultrasonic rolling on the fatigue life of GCr15 steel.

2. Material and Methods

2.1. Material and preparations

GCr15 bearing steel was selected as the material of specimen in experiment. The raw material was a rolled rod with a diameter of 65 mm. After spheroidizing annealing, the rod was machined into annular specimens. The outer diameter was 52 mm, the inner diameter was 30 mm, and the height was 8 mm. The specimens were kept at 845 °C for 16.5 min and quenched in oil. Then, they were kept at 150 °C for four hours and cooled until to room temperature by air. After the heat treatments, the surface hardness (HRC) of the specimens was up to 62 ± 1. Finally, the oxide layer on surface was removed by grinding.

2.2. Test method

The ultrasonic rolling equipment is mainly composed of lathe, rolling head and ultrasonic emission device, as shown in figure 1. Because the preload acted on the specimen surface by the ultrasonic head has a great influence in ultrasonic rolling processing \[8\], different values of preload were applied, i.e., 320 N, 800 N, 1280 N. The amplitude of ultrasonic vibration was 10 μm, the rotation speed of specimen was 173 r/min, the feed speed was 0.1 mm/r, and the ultrasonic frequency was 23.55 kHz.

The type of ball-disk RCF test device was adopted to test the RCF performance after ultrasonic rolling treatment, as shown in figure 2. The speed of spindle was 1000 r/min, the axial load was 5200 N, and the maximum contact stress acted on the surface of specimen by the balls was 6 GPa.

Wear resistance of the specimens was tested by a friction and wear device (RTEC, MFT-50, San Jose), as shown in figure 3. The load acted on the specimen was 50 N, the stroke of movement was 4.5 mm, the frequency was 4 Hz, and the test time was 30 min. A GCr15 steel ball was selected as the counterpart of friction.
The surface morphology and roughness of the specimen were measured by a white light interferometer (USP-Sigma, Saint Louis, MO, USA), the hardness was measured by a Vickers hardness tester (402MVD, Wilson, USA), and the grain size was observed by a metallographic microscope (4XC, Shanghai optical instrument factory, China).

3. Results and discussion

3.1. The amount of indentation

Under the conditions that the preload of ultrasonic rolling was 320 N, 800 N and 1280 N, the average indentation was 6 μm, 17 μm and 22 μm, respectively. The amount of indentation of specimens increases with the preload, because the degree of plastic deformation increases with the preload.

Because the elastic deformation in the contact area does not consume power in the reciprocating impact process of ultrasonic head, the plastic deformation of specimen consumes the most power of ultrasonic rolling, as shown in figure 4. Therefore, the power density formula of ultrasonic rolling can be obtained by

\[
J \approx \frac{2F\delta}{\pi Tr^2}
\]

where \(J\) represents the power density of the ultrasonic head acting on the specimen, \(F\) is the preload of ultrasonic rolling, \(\delta\) is the amount of indentation, \(T\) is the period of ultrasonic vibration time, and \(r\) is
the radius of contact area. When the value of ultrasonic rolling preload equals to 320 N, 800 N and 1280 N, the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², respectively. The power density of the rolling head acting on the specimen increases with preload, which is consistent with the law of indentation amount.

### 3.2. Surface roughness

Figure 5 shows the micro-surface morphology of the specimens after ultrasonic rolling treatment with different values of power density. The specimen untreated has obviously higher surface roughness, i.e., Ra=1.998 μm. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the roughness of Ra reduces to 0.510 μm, 0.469 μm and 0.386 μm, respectively, about 25.5 %, 23.5 % and 19.3 % of the untreated specimen. Surface roughness gradually decreases with the increase of ultrasonic rolling power density, because severe plastic deformation occurs in the contact area and many micro peaks disappear due to the impact of ultrasonic head. Noted that a few pits appeared in the surface when the ultrasonic rolling power density increases to 11.24 Gw/cm², as shown in figure 5 (d). The surface of specimen was damaged when the ultrasonic rolling power density was too large, so the power density of ultrasonic rolling cannot be too large.

### 3.3. Microhardness

The surface hardness of specimens before and after ultrasonic rolling was measured, and the position of hardness measurement is as shown in figure 6. The surface microhardness of specimens treated under different power density conditions are displayed in figure 7. The surface hardness after ultrasonic rolling is significantly higher than that of untreated specimens. The average microhardness of the untreated specimens was HV 789.97. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the average value of microhardness was HV 827.42, HV 875.21 and HV 903.48 respectively, which was about 4.7 %, 10.8 % and 14.4 % higher than the untreated one. And the microhardness increases with the ultrasonic rolling power density in a certain range.
The increase of hardness is mainly due to plastic deformation and grain refinement in the surface microstructure under high-frequency impact of ultrasonic head. Meanwhile, the increase of dislocation resistance makes the specimens after ultrasonic rolling more hard [14]. However, excessive plastic deformation of the material will lead to coarse grains and decrease of the hardness, when the ultrasonic rolling power density exceeds a certain range [15].

3.4. Rolling Contact Fatigue

Figure 8 shows the surface morphology of spalling pits after rolling contact fatigue tests. The propagation of cracks can be observed clearly around the spalling pits of specimens, which was observed in the direction of rolling. The cracks propagate mainly from surface to interior, and therefore the failure is mainly due to the stress concentration and defects near the surface [16].

![Figure 8](image)

Figure 8. The morphologies of spalling pits and cracks: (a) the surface without ultrasonic rolling treatment; (b) the cross section without ultrasonic rolling treatment; (c) the surface with ultrasonic rolling treatment; (d) the cross section with ultrasonic rolling treatment.

The rolling contact fatigue life of specimens are listed in table 1. Unexpectedly, the rated life ($L_{10}$), median life ($L_{50}$), and characteristic life ($V_s$) of the specimens after ultrasonic rolling treatment are all lower than the untreated ones. The characteristic life ($V_s$) of specimens after ultrasonic rolling treatment reduced by 24.1 %, 34.5 % and 62.1 % compared to the untreated ones respectively.

![Table 1](image)

| Power density / Gw/cm$^2$ | Rated life ($L_{10}$) /Times | Median life ($L_{50}$) /Times | Characteristic lifetime ($V_s$) /Times |
|---------------------------|-------------------------------|-------------------------------|--------------------------------------|
| Untreated                 | 323039                        | 477499                        | 515218                               |
| 11.24                     | 201909                        | 313939                        | 391212                               |
| 42.90                     | 123428                        | 310363                        | 337440                               |
| 64.92                     | 101304                        | 181238                        | 195302                               |

It was proved that the high-frequency vibration energy during ultrasonic rolling treatment can result in the initiation and propagation of micro cracks [17, 18]. Excessive power density will lead to excessive energy transfer and accelerate crack propagation. Higher energy can increase the internal stress of specimens and reduce the bonding force between organizations. Meanwhile, the increase of hardness after ultrasonic rolling treatment generates brittleness of microstructure. Under the load of cyclic rolling contact, high-stress concentration occurs easily near the surface defects after ultrasonic rolling treatment, leading to the earlier fatigue failure and decrease of RCF life. This is the primary cause of GCr15 steel RCF life reduction when the ultrasonic rolling power density exceeds 11.24 Gw/cm$^2$.

The cross sections of spalling pits along the direction of rolling are as shown in figure 9. It can be seen from figure 9 (a) that the crack of untreated specimens is straighter, and its propagation is mainly transcrystalline. The cracks of the specimens after ultrasonic rolling treatment are branched, and their propagations are mainly intergranular. The reason of the phenomenon is that the increase of hardness after ultrasonic rolling treatment leads to the increase of material brittleness, which reduces the force between grains, and therefore the crack propagation along the grain boundary become easier, resulting in the decrease of RCF life.

The metallographic structure before and after ultrasonic rolling treatment are as displayed in figure 10. The untreated specimen has the smallest grain size, with the average value of 14.256 μm. After ultrasonic rolling treatment, the grain size increases. When the power density is 11.24 Gw/cm$^2$, 42.90
Gw/cm² and 64.92 Gw/cm², the average value of grain size is 15.247 μm, 16.274 μm and 16.768 μm. The reason is that when the power density exceeds a certain value, the degree of strain near the surface is intense, and the excessive dislocations lead to the re-winding and fusion of microstructure at the sub-grain boundary and the formation of large grains. The increase of the grain size can reduce the life of RCF.

Figure 9. The cross sections of spalling along the direction of rolling: (a) without ultrasonic rolling treatment; (b) the ultrasonic rolling power density is 11.24 Gw/cm²; (c) the ultrasonic rolling power density is 42.90 Gw/cm²; (d) the ultrasonic rolling power density is 64.92 Gw/cm².

Figure 10. Grain morphology of specimens: (a) without ultrasonic rolling treatment; (b) the ultrasonic rolling power density is 11.24 Gw/cm²; (c) the ultrasonic rolling power density is 42.90 Gw/cm²; (d) the ultrasonic rolling power density is 64.92 Gw/cm².

3.5. Friction and wear resistance

The friction coefficient curves are as plotted in figure 11. At the beginning of wear, the dry friction coefficients of the specimens are generally high. After the running-in period, the dry friction coefficients of the specimens decrease and enter the stage of stable wear. The dry friction coefficient of the untreated specimen is 0.3589. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the dry friction coefficient is 0.3448, 0.3429 and 0.3136, respectively. It is obtained that the friction coefficients after ultrasonic rolling treatment are generally lower than that of untreated specimens. In addition, the friction coefficient decreases with the increase of power density within a certain range, because the friction coefficient is proportional to the roughness value under the same test load, and the surface roughness of specimens decreases with the increase of power density as shown in figure 5.

The wear morphology of the specimens is as shown in figure 12. The dry wear amount of the untreated specimen is 4.49 × 10⁻² mg. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the dry wear amount is 7.12 × 10⁻² mg, 7.87 × 10⁻² mg, 7.95 × 10⁻² mg, respectively. It is known that the wear amount of specimens after ultrasonic rolling is higher than that of untreated specimens. And the wear amount increases with the power density of ultrasonic rolling, which is consistent with the change of RCF life in Tab.1. Because the high hardness of the peeled particles produces high contact stress on the friction surface during the wear process of the specimens after ultrasonic rolling treatment, which accelerates the wear of the specimens.
Figure 11. The curves of friction coefficient: (a) without ultrasonic rolling treatment; (b) the ultrasonic rolling power density is 11.24 Gw/cm²; (c) the ultrasonic rolling power density is 42.90 Gw/cm²; (d) the ultrasonic rolling power density is 64.92 Gw/cm².

Figure 12. Wear morphology: (a) without ultrasonic rolling treatment; (b) the ultrasonic rolling power density is 11.24 Gw/cm²; (c) the ultrasonic rolling power density is 42.90 Gw/cm²; (d) the ultrasonic rolling power density is 64.92 Gw/cm².

4. Conclusions

i) Ultrasonic rolling treatment can produce plastic deformation of surface material. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm², 64.92 Gw/cm², the average indentation of specimens was 6 μm, 17 μm, 22 μm, respectively.

ii) Ultrasonic rolling treatment can reduce the value of surface roughness of GCr15 after quenching and tempering. The specimens untreated has obviously higher surface roughness, i.e., Ra=1.998 μm. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the value of Ra reduces to 0.510 μm, 0.469 μm and 0.386 μm, respectively, about 25.5 %, 23.5 % and 19.3 % of the untreated specimen. The surface was damaged when ultrasonic rolling power density was too large, so the power density of ultrasonic rolling cannot be too large.

iii) Ultrasonic rolling can improve the surface microhardness of GCr15 after quenching and tempering. The average microhardness of the untreated specimens was HV 789.97. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the average microhardness increases to HV 827.42, HV 875.21 and HV 903.48 respectively, which was about 4.7 %, 10.8 % and 14.4 % higher than the untreated ones.

iv) After ultrasonic rolling processing, the dry friction coefficient of the specimen decreased, while the wear amount increases with power density. When the ultrasonic rolling power density is 11.24 Gw/cm², 42.90 Gw/cm² and 64.92 Gw/cm², the dry friction coefficient decreases from 0.3589 to 0.3448, 0.3429 and 0.3136, respectively. The wear amount increases from 4.49 × 10⁻² mg to 7.12 × 10⁻² mg, 7.87 × 10⁻² mg, 7.95 × 10⁻² mg, respectively.

v) The RCF life of GCr15 decreases when ultrasonic rolling power density exceeds 11.24 Gw/cm². After ultrasonic rolling treatment, the propagation mode of cracks changes from transcrytalline to intergranular in the experiments.

Acknowledgments

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