Effect of ultrasonic surface rolling on surface characteristic of Mn13 high-Mn steel

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Abstract. In order to improve the surface quality and wear resistance of Mn13, increase its service life, Mn13 was strengthened by ultrasonic surface rolling (USRP). The effects of ultrasonic rolling parameters (rolling pressure and rolling times) on surface roughness and surface hardness were studied. A set of surface roughness instrument and micro Vickers hardness instrument were used to analyze the samples. Moreover, the surface quality of Mn13 before and after ultrasonic rolling was compared and analyzed. The results show that increasing the rolling times can reduce the surface roughness significantly, but excessive rolling times are liable to produce microcracks. Increasing the static pressure, the surface hardness and the depth of strengthening layer will increase. And the roughness can be reduced below 0.06 μm after ultrasonic rolling. The surface hardness can reach up to 741 HV, and the depth of strengthening layer is 700 μm.

1. Introduction
As a wear-resistant material, Mn13 is widely used in the harsh environment such as shot blasting machine, jaw crusher and tank track because of its excellent work hardening performance. Due to the low initial hardness of Mn13, its wear resistance is based on full work hardening. And it can be fully hardened only under high stress. However, under actual working conditions, the proportion of high stress working conditions don’t exceed 5%[1]. Most of the time it is filled in the condition of medium and low stress. So it is difficult for high-Mn steel to be work hardened and give full play to its wear resistance. In addition, the work hardening layer is not formed on the surface of high-Mn steel during work. It is liable to produce scratches and damage. Therefore it is necessary to pretreat the high-Mn steel to form work hardening layer on its surface before service[2].

Scholars at home and abroad have carried out many studies on the strengthening of high-Mn steel. Yan et al.[3] strengthened high-Mn steel by shot peening and forms a work hardening layer of 20μm on the surface of the material with a sharp increase in hardness. Yuan et al.[4] carried out plasma coating on high-Mn steel, analyzed the microstructure, morphology and phase composition of the cladding layer, and tested its wear resistance. It was found that the coating can improve the hardness and wear resistance of the matrix significantly. Meng et al.[5] strengthened the surface of high-Mn steel by laser impact. By analyzing the metallographic structure, microhardness and tensile properties of samples before and after laser impact hardening, the influence of laser impact on the micro-morphology and mechanical properties of high-Mn steel was discussed.
However, shot peening and laser impact increase the surface roughness, and ion coating is liable to produce defects such as bubbles[6-7], which has certain limitations in application. Ultrasonic rolling is a new processing technology. The combination of high-frequency energy impact and static pressure can greatly reduce the static pressure required for rolling, improve the surface microhardness of the workpiece, reduce the roughness and obtain good surface integrity effectively. In this study, ultrasonic rolling strengthening technology is applied to the surface strengthening of high-Mn steel. The comparative tests of surface hardness and surface roughness of high-Mn steel before and after ultrasonic rolling strengthening under different process parameters are carried out to explore the effect of ultrasonic rolling strengthening on the surface quality of high-Mn steel.

2. Ultrasonic rolling strengthening technology

Ultrasonic rolling reinforcement is a new surface strengthening technology, which combines ultrasonic processing with traditional rolling reinforcement. Under the combined action of ultrasonic vibration and static pressure provided by air pump, the tool head causes plastic deformation of workpiece surface, thus rolls and smoothes the micro-bumps on the workpiece surface and improves the surface quality of the workpiece processed. Essentially, it is a cold-plastic processing technology. The principle of ultrasonic rolling reinforcement is shown in Figure 1.(a) [8].

![Figure 1. (a) Schematic diagram of ultrasonic rolling; (b) Ultrasonic rolling equipment](image)

3. Ultrasonic rolling strengthening test

3.1. Test materials

Mn13 is an austenitic high-Mn steel, mainly composed of C and Mn. C improves the wear resistance of steel, and Mn promotes the formation of austenite in steel. The high-Mn steel plate is cut into specimens with a size of 45mm×16mm×8mm by wire cutting. Grind with 80 mesh, 160 mesh, 240 mesh and 400 mesh sandpaper in turn. Measure the unreinforced surface roughness and hardness of the sample. The main chemical composition of Mn13 is shown in Table 1.

| w/% | C      | Mn (11.0 ~ 14.0) | Si (0.03 ~ 1.00) | S (0.04) | P (0.07) |
|-----|--------|-----------------|------------------|--------|--------|
|     | 0.90 ~ 1.35 |     |               |        |        |

3.2. Experimental scheme

This experiment is carried out on HVM1260 HawKing CNC milling machine (as shown in Figure 1.(b)). The static pressure of ultrasonic rolling can be adjusted by controlling the air pressure. The influence of static pressure and rolling times on surface quality (surface roughness and hardness) of high-Mn steel is studied by single factor test with static pressure and rolling times as independent variables. The experimental scheme is shown in Table 2.
Table 2. Table of ultrasonic rolling test scheme

| Parameter Number | Static force(N) | Amplitude(μm) | Rolling times (cycle) |
|------------------|-----------------|---------------|-----------------------|
| 1                | 800             | 7             | 6                     |
| 2                | 1300            | 7             | 6                     |
| 3                | 1800            | 7             | 6                     |
| 4                | 800             | 7             | 1                     |
| 5                | 800             | 7             | 3                     |
| 6                | 800             | 7             | 9                     |

The surface hardness and gradient hardness in depth direction after strengthening were measured. Vickers hardness was measured at 5 points on each sample, and its average value was taken as the hardness of the sample. The roughness is measured by SJ-410 surface roughness tester. The sampling length is 8mm. The average of the roughness is taken as the sample roughness by 5 measurements at different positions parallel to and perpendicular to the scratch direction. The surface morphology before and after ultrasonic rolling strengthening was observed with VHX-2000C super depth-of-field microscopy system, and the 3D morphology was compared and analyzed.

4. Experimental results and discussion

4.1. Effect of ultrasonic rolling on microhardness

The surface of workpiece is plastic deformed after ultrasonic rolling. During the deformation process, many additional dislocations occur through the original dislocation movement. The interaction between dislocations results in that the movement of any dislocation is hindered by other dislocations, so the hardness of the surface of workpiece will be increased. Explain the work hardening Taylor model [9] from the dislocation point of view as follows:

\[
\sigma = k_c \left( \frac{b}{R} \right)^{\frac{1}{2}} \varepsilon^{\frac{1}{2}}
\]

(1)

Where, \(\sigma\) is the material stress; \(k_c\) is a constant; \(b\) is the modulus of the Burgers vector; \(R\) is the radius of dislocation ring; \(\varepsilon\) is the material strain.

It can be seen from Figure 2.(a) that the effect of ultrasonic rolling on surface hardness is obvious when the number of rolling is less. The surface hardness of workpiece increases from 300 HV to 536 HV after 1 roll, and the depth of hardening layer is about 600 μm. The surface hardness increases at a slower rate with increasing rolling times. The surface hardness reaches 663 HV, which is 121% higher than that of the matrix, and the depth of the hardening layer can reach 700 μm after 9 rolls. This is nearly double the strengthening effect of 60-minute shot peening[10]. The influence of rolling times on surface hardness of workpiece is shown in Figure 2.(b). The hardness distribution in the hardening layer decreases from the surface to the inside of workpiece. The hardness gradient distribution is uniform and has no obvious gap with the matrix. It is bonded firmly with the matrix during the service and use of the workpiece without shedding and has a good fatigue life. Within the depth of 100 μm, the number of rolling times has a significant influence on hardness, and the hardness decreases rapidly with the increase of depth. This is because the hardening layer formed on the surface of workpiece by initial roll-pressing hinders the ultrasonic impact. The thicker the hardening layer, the greater the resistance. When the depth exceeds 400 μm, the hardness decreases slowly and approaches the hardness of the matrix, and the strengthening effect of ultrasonic impact is greatly reduced.
4. Effect of ultrasonic rolling on roughness

Ultrasound rolling surface hardening is a continuous pulse impact hardening method, which presses the surface crest of the workpiece into the trough, thereby reducing the surface roughness of the workpiece. Because the impact is not continuous, wrinkles and scratches on the workpiece surface during the rolling process are avoided[11]. Surface roughness has an important influence on the wear resistance of mechanical parts. Lower surface roughness can reduce wear effectively. As shown in Figure 4.(a), ultrasonic rolling reinforcement can reduce the surface roughness value of workpiece effectively, and the surface finish can be improved better when the number of ultrasonic rolling is less. The roughness basically remains unchanged after 3 rolls. It can be seen from Figure 4.(b) that different static pressures reduce the roughness by more than 50% for 6 rolls and reach the roughness below 0.06μm after rolling.

The surface morphology of workpiece before and after ultrasonic rolling is shown in Figure 5.. Before rolling, the surface of workpiece is markedly scratched and uneven. After 1 ultrasonic roll, the surface of workpiece becomes flat, but the scratches are still visible clearly. After 3 ultrasonic rolls, the scratches on the surface of the workpiece disappear and become smoother. When ultrasonic rolling is carried out 9 times, obvious micro-cracks appear on the surface of the workpiece. This is due to the decrease of plasticity after full work hardening of the surface. And the micro-cracks are liable to occur when the surface is rolled again by ultrasonic rolling.
Figure 4. Effect of ultrasonic rolling on roughness: (a) Effect of rolling times on roughness; (b) Effect of different static pressure on roughness

As can be seen from Figure 6., the surface quality of the workpiece under 200 times super depth-of-field microscopy system is poor without ultrasonic rolling, and there is obvious height difference on the surface, with a maximum height difference of 51.59 μm. From the 3D morphology of the sample after ultrasonic rolling, it can be seen that the plastic deformation effect caused by ultrasonic rolling basically eliminates the surface pits and scratches, improves the surface quality significantly and reduces the maximum height difference of 3D morphology to 28.12 μm.

Figure 5. Effect of different rolling times on surface morphology

Figure 6. 3D morphology before and after ultrasonic rolling: (a)Before USRP; (b)After USRP
5. Conclusion
1) It is found that ultrasonic rolling can improve the surface hardness of Mn13 significantly. Proper rolling parameters can increase the surface hardness to 741 HV, 147% higher than that of the matrix, and the depth of the hardening layer can also reach 700 μm. The transition from the base metal hardness to the hardness is smooth and there is no delamination;
2) Increasing the number of ultrasonic rolling appropriately can eliminate the scratches caused by the previous step and reduce the surface roughness of the workpiece to 0.06 μm or so, and reduce the height difference of workpiece surface. Continuous increase of rolling times has little effect on surface roughness and will cause micro-cracks on the surface, while different static pressures have little effect on surface roughness.

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