Research on fatigue behavior of the flash welded joint enhanced by ultrasonic peening treatment

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Abstract

The flash welded joint of U75V steel has been widely used in high-speed railway. Considering the fact that fatigue failure is the main failure mode of high-speed railway, ultrasonic peening treatment (UPT) was used to improve the fatigue performance of the flash welded joint. Micro-structure, hardness, wear resistance, corrosion resistance and fatigue fracture mechanism of the flash welded joint before and after UPT were analyzed in detail. Results show that nanocrystals forms on the surface of the welded joint after UPT. Fatigue life, wear resistance and corrosion resistance of the welded joint were improved for the surface strengthening caused by UPT.

Keywords: Flash welded joint; Ultrasonic peening treatment; Nanocrystal; Fatigue

1. Introduction

High-speed railway has become a practical and reliable transportation way for its high speed and safety. Aiming to extend the service life of high-speed railway, some high-strength steels are adopted. U75V steel with a high mechanical strength has been widely applied in the present railway industry^[1]. Seamless docking technology

between the rails will determine the secure operation of the high-speed train. Flash butt welding with a high thermal efficiency, simple metallurgical process and small heat affected zone has become the principal method to connect U75V rail steel^[2, 3]. In addition, flash butt welding can get a high quality welded joint, because the filler metal is not needed in the welding process.

Welded joint of the high-speed railway is very important for the security of a running high-speed train. The qualities of welded joint directly affect the fatigue performance and service life of the high-speed railway. Most of literature about flash welding of the rail steel mainly discussed the welding residual stress or welding process. For example, Ma et al. studied the residual stresses in a rail steel flash-butt joint by an in-house finite element programme JWRIAN.^[4] Chvertko et al. made efforts to study the parameters of flash-butt welding in real-time mode by statistical methods, and the on-line monitoring system based on neural networks was used for prediction of possible defects in the welded joints^[5]. These efforts have enriched the research data of the flash butt welding. For the fatigue problem of the high-speed railway, researchers also did some discussions. Zhong et al. studied the crack growth conditions of the rolling contact fatigue in U75V rail steel and the relationship between the rolling contact fatigue and wear resistance^[6, 7]. Zhao et al. evaluated the fatigue fracture mechanism of the flash butt welded joint of U75V rail steel. Fatigue crack sources of the fractured specimens are at the surface or subsurface near the interface area^[8]. In view of the above-mentioned facts, we should take some methods to enhance the surface of the flash welded joint, which will effectively improve the

fatigue performance, wear resistance and corrosion resistance. Ultrasonic peening treatment (UPT) with the advantages of small noise, high efficiency, low cost and energy conservation has become an ideal method to strengthen the surface of welded joint^[9]. UPT is a severe plastic deformation process. As an effective method of surface treatment, a thin layer of nanocrystals can be formed on the surface of welded joint after UPT^[10, 11]. Huo et al. investigated the fatigue property of 16Mn steel after UPT. Results show that fatigue strength of 16Mn steel increases by 84% and fatigue life of 16Mn steel increases by 3.5-27 times under the constant amplitude loading^[12]. In the Literature^[13], fatigue testing of full-size fillet-welded doubling plates treated by UPT has been performed, and the paper also presents alternative *S-N* curves for improved details. Wang et al. analyzed and summarized a large numbers of fatigue testing results of welded joint after UPT. Conclusions show that material strength has a major effect on the fatigue performance of welded joint after UPT^[14]. Kleiman et al. concluded that UPT was an effective and economic technique to improve the fatigue strength of welded joint^[15]. The above research results fully proved that the flash welded joint can be strengthened by UPT.

In order to ensure an adequate service life of the high-speed railway, this work investigates the fatigue strength of the flash butt welded joint of U75V rail steel and analyzes the fatigue fracture mechanism including the corrosion fatigue before and after UPT by comprehensively considering the metallography characteristics, nano-enhancing mechanism, hardness, X-ray diffraction of the flash welded joints.

2. Experimental procedure

2.1. Experimental material and welding method

2.1.1. Experimental material

Experimental material is U75V rail steel of 60Kg/m. The chemical composition (wt.%) is: C=0.72-0.8, Si=0.56-0.64, Mn=0.89-0.98, S $\leq$ 0.035, P $\leq$ 0.035, V=0.47-0.58, which indicates that the content of C element and Si element are higher than the plain carbon steel. As an important element, Si element is beneficial to improve the hardness of U75V rail steel. But Si element and O element are easy to form SiO₂ with a high melting point, high viscosity and poor mobility, which may promote the generation of slag defects in welding process. Slag defects may go against fatigue performance of welded joint. Mn element as a kind of deoxidizer solubilizes in austenite, which can refine pearlite structure through reducing the transition temperature of pearlite and improve the strength of U75V rail steel. V element also can improve the strength and toughness of U75V steel by refining grain. S element and P element is favorable for the formation of cracks, which should be avoided as much as possible. The mechanical properties of U75V steel include the yield strength of 510-665MPa, tensile strength of 1000-1100MPa, elongation of 10-12% and hardness value of 285.8-315HB. In a word, U75V steel has a good plasticity and toughness, but its weldability is just common level. So this study is meaningful to improve the fatigue performance of welded joint by surface strengthening.

The metallographic structure of U75V steel is shown in [Fig. 1](#), which contains a large amount of black lamellar pearlite and a small amount of white ferrite.

2.1.2. Welding method

The flash welding is used to ensure the seamless docking of U75V steel. In this experimental study, welded joint is made up of two pieces of cuboid U75V steel with the same size. The size of each cuboid U75V steel is 120mm×30mm×10mm. In order to avoid the influence of stress concentration caused by surface scratch on fatigue performance of welded joint, all specimens were ground carefully by sandpaper. The flash welding of U75V steel was carried out by a small flash welding machine. The parameters of flash welding are shown in [Table 1](#).

2.2. Surface strengthening method

In order to improve fatigue life, wear resistance and corrosion resistance of the flash welded joint. HJ-III type ultrasonic peening equipment produced by Tianjin University in China was used to treat the surface of welded joint. After UPT, the defects on the surface or sub-surface of welded joint can be eliminated, and the surface roughness also can be significantly reduced. The parameters of UPT are shown in [Table 2](#). The macrophotograph of welded joint before and after UPT is shown in [Fig. 2](#).

2.3. The method of corrosion

The high-speed railways in coastal areas are often subjected to the erosion of ocean environment. Corrosion behavior is poisonous to fatigue property of welded joint. In order to simulate the service environment of high-speed railway, some welded specimens were soaked in corrosive liquid for 450 hours. The best time of 450 hours is obtained through experimental study. If the corrosion time is more than 450 hours, the surface state of specimens will be bad. Especially, the surface of welded

joint shows many corrosion pits, and the weight of welded joint reduces a lot, which will not reflect the actual working condition. In order to improve the corrosive speed, five times of chemical composition of corrosive liquid was used in this experiment. The composition of corrosive liquid is in accordance with reference^[16](see Table 3).

2.4. Wear experiment

Rails are long-term subjected to the wear of wheel. It is necessary to study the wear resistance of welded joint before and after UPT. DC-100 type wear tester made in Jinan Jingcheng testing technology Co., Ltd was adopted to take wear test. For the testing accuracy, 3000# fine sandpaper material was used as the abrasive and a low rotation rate was taken. The parameters of wear test are as follows: pre-pressure is 10N and wear time is 2min.

2.5. Fatigue test

Fatigue tests of welded joints were performed. All tension-tension fatigue tests were carried out under constant amplitude loading with stress ratio $R=0.1$ at room temperature. Tests were conducted on 200kN high frequency fatigue testing machine with static load error within a full measuring range between $\pm 0.2\%$ and dynamic load error between $\pm 2\%$. The frequency was resonance frequency determined by the fatigue specimen and high frequency fatigue testing machine. The value of frequency in fatigue tests is about 100-120Hz. In this study, fatigue tests of three kinds of welded joints (as-welded joint, welded joint after UPT and corrosion joint after UPT) were carried out. Where, the corrosion joint after UPT refers to the joint first is treated by UPT, then UPT-joint is penetrated into the corrosive liquid.

3. Results and discussion

3.1. *Microstructure of the flash welded joint*

The OLS3000 laser confocal microscope was adopted to observe the microstructure. Microstructures of the welded joint before and after UPT are shown in [Fig. 3](#) and [Fig. 4](#). Except for the base metal (BM), welded joint can be divided into four areas: interface area (IA), overheated zone (OZ), recrystallization zone (RZ) and incomplete recrystallization zone (IRZ).

In the interface area, there is no obvious boundary and macroscopic defects, and the eutectic structure has already formed. The microstructure of interface area is the same as that of base metal (lamellar pearlite+a small amount of ferrite), but many bulky grains exist. The basic microstructure of overheated zone is the large lamellar pearlite (black)+ferrite (white). In addition, the net-like ferrite exists in the grain boundary and grows in transgranular direction, which has the characteristics of westergren structure. The microstructure of recrystallization zone is lamellar pearlite and reticular ferrite. The recrystallization process is equivalent to the normalized process of base metal, which reduces the size of chunk and the layer spacing of pearlite as well as refines grains. For the incomplete recrystallization zone, the microstructure is between recrystallization zone and base metal, mainly includes pearlite and a small amount of ferrite. In view that the bulky grains of interface area and westergren structure of overheated zone, fatigue damage is easy to occur in the interface area and overheated zone of coarse structure.

In [Fig. 4](#), the specimens after UPT present three areas: severe deformation layer

(SDL), transition layer (TL) and matrix (M). Among them, the severe deformation layer is the area affected directly by the high speed ultrasonic peening. It can be observed from Fig. 4 that the thickness of the deformation layer is about 50-70 μm . In view that nanocrystals layer is formed on the surface of welded joint, the size of grain and layer spacing of pearlite are refined to nanoscale, which will significantly improve the strength, hardness and wear resistance of welded joint.

3.2 Surface strengthening mechanism of UPT

The stacking fault energy is the key factor to determine the mode of plastic deformation. The mode of plastic deformation usually affects the way of grain refinement. The plastic deformation mode of the high stacking fault energy material and the low stacking fault energy material is dislocation glide and mechanical twinning, respectively. In view that the welding materials are not added during the flash welding process, the plastic deformation mode of welded joint and U75V steel is consistent. Because U75V steel has a high stacking fault energy, the plastic deformation mode of welded joint tends to be dislocation glide. JEM-2100F type TEM was undertaken to obtain more detailed microstructural informations of the deformation layer. Fig. 5 is TEM photograph of the plastic deformation layer (distance from the ultrasonic peening surface is about 20-30 μm) of welded joint after UPT.

From Fig. 5, nanocrystallization process of grains on the surface of the welded joint is as follows: the coarse grains are refined to the small-sized dislocation cells under the action of UPT. Dislocation tangling and dislocation wall are formed as a

result of the dislocation aggregation at grain boundaries. Then, the high dislocation density can be generated in the grains when a further plastic deformation occurs. Thus, there is a high energy in the grain boundary. In order to keep the stability of grain boundary, the phenomenon of dislocation annihilation and recombination happens in the region of dislocation tangling and dislocation wall. Next, dislocation tangling and dislocation wall turn into the small-sized subgrains by absorbing dislocations. As the strain energy increases gradually, a large number of dislocations appear in the grains. Meanwhile, the annihilation phenomenon of dislocations also occurs in the subgrain boundary, which results in the dislocations slip along the subgrain boundary. With further increasing of strain energy, dislocation tangling and dislocation wall are formed again in refined subgrains and grains. The above microstructural evolution is repeated in refined subgrains and grains, which bring further refinement of those grains. The dislocation walls evolve gradually and form nanocrystals by absorbing the high density dislocations, as shown in Fig. 6.

Fig. 6 is TEM photograph of the nanostructured surface layer of welded joint after UPT. The average size of grains is about 20nm, and the grains are equiaxed shape. The crystallographic orientation of the grains is random for the ring-shape diffraction pattern. All these characteristics demonstrate that the grains have been refined and the surface of the specimen has been strengthened after UPT.

3.3. Hardness analysis

Models for MH-3 vickers hardness tester was adopted to measure the hardness values of welded joint. The hardness values of welded joint before and after UPT

were measured along the direction of thickness (from surface to interior). The loading is 300g and the lasting time is 10s. The hardness values are shown in Fig. 7. The hardness values on the surface of welded joint after UPT become larger. Hardness values will decrease with the depth increased, then the hardness values will tend to be a stable level. The hardness values on the surface of welded joint before and after UPT are about 1388 HV and 340 HV, respectively. The hardness values after UPT increased by 308% comparing with that before UPT. The increasing of hardness values is caused by both grain refinement and work-hardening. The improvement of hardness values indicates that the surface of welded joint can be strengthened by the formation of nanocrystals.

3.4. X-ray diffraction analysis

D/Max 2500PC type X-ray diffractometer was adopted to measure the changing of phase and intensity of welded joint before and after UPT. Fig. 8 is X-ray diffraction pattern of welded joint. There is no new diffraction peak on the surface after UPT, which indicates that there is no changing of phase in the welded joint after UPT.

The highest value of X-ray diffraction peaks of the front surface before and after UPT are about 700 counts and 500 counts, respectively, while the highest value of X-ray diffraction peaks of the side surface after the front surfaces are treated by UPT is about 600 counts, which indicates that the work-hardening has occurred on the front surface of welded joint after UPT. The Bragg diffraction peak of X-ray is broadened after UPT as a result of grain refinement and micro strain increasing.

3.5. Wear resistance analysis

The wear resistance of welded joint is analyzed by comparing the wear loss and wear morphology of the specimens. The relative wear resistance of material refers to the ratio of wear loss of two materials under the same external conditions. The electronic balance of 1/10000 precision was adopted to measure the weight of specimens including welded joint before and after wear test. The wear loss and relative wear resistance of welded joint are shown in Table 4. The hardness values of welded joint are significantly improved after UPT, so the wear loss decreases a lot and the relative wear resistance increases by 29%.

Fig. 9 is the wear morphology of welded joint observed by OLS3000 laser confocal microscope. From Fig. 9, the wear scars become deeper and the distance between wear scars gets narrower after UPT compared with those before UPT under the same wear condition, which illustrate that the wear resistance is better after UPT.

3.6. Fatigue *S-N* curve

The stress level and fatigue life together determine the fatigue performance of the specimen. The relationship between applied stress and fatigue life is represented in equation (1). The curve based on the equation (1) is the traditional *S-N* curve.

$$N = \frac{C}{\Delta\sigma^m} \quad (1)$$

According to *S-N* curve, the fatigue strength corresponding to a cyclic number can be obtained. Fatigue testing data should be analyzed according to the principle of statistical method established in IIW (International Institute of Welding)^[17]. The authorized surviving fraction is 50%, while the confidence is 75%. In this study, we only require to compare the differences of three *S-N* curves. Therefore, the

surviving fraction and confidence do not affect the comparison of $S-N$ curves.

Nominal value is calculated as the following process:

1. Calculating all the stress range $\Delta\sigma$ and the cycle index N (in logarithm with the base-number 10) of fatigue testing data points.

2. Calculating the exponent m and the constant $\log C$ regressively, using the power function model:

$$m\log\Delta\sigma + \log N = \log C \quad (2)$$

Three $S-N$ curves representing as-welded joint, welded joint after UPT and the corrosion joint after UPT are shown in [Fig. 10](#).

$S-N$ curve of welded joints after UPT is higher than that of as-welded joints, which indicates that fatigue performance of welded joint can be increased by UPT. In addition, fatigue strength of welded joints before and after UPT corresponding to 2.0×10^5 cycles is 256MPa and 314MPa, respectively. Fatigue strength of welded joints after UPT increases by 23%. In addition, fatigue strength of the corrosion joints after UPT to 2.0×10^5 cycles is 290MPa. Fatigue strength of the corrosion joints decreases by 8% as compared with the welded joints after UPT. However, fatigue strength of the corrosion joints is still higher than as-welded joints, which indicates that UPT enhanced the corrosion resistance of welded joint.

[Fig. 11](#) shows the fatigue fracture locations of as-welded joints, welded joints after UPT and corrosion joints after UPT. The fracture locations of three kinds of welded joints are all at welding seam center, which shows that although the fatigue

life of welded joints can be significantly improved by UPT, welded joints are still the weakest position in.

3.7 Fatigue fracture mechanism of the flash welded joint before and after UPT

Fig. 12 is the macroscopic morphology of fatigue fracture for the welded joints before and after UPT. Comparing Fig. 12a with Fig. 12b, fatigue fracture began at the horizontal surface for the as-welded joint and at vertical surface for the welded joint after UPT. The detailed mechanisms of crack initiation, propagation and instantaneous fracture region were examined on the failed specimens using EVO-18 type SEM. Fig. 13 is SEM photograph of the fatigue crack sources of welded joints before and after UPT.

Fatigue crack sources of both two kinds of welded joints present the transgranular fracture mode. Fig. 13a is SEM photograph of fatigue fracture for the welded joints before UPT. It can be concluded from Fig. 13a that fatigue crack initiates at the horizontal surface with self-defect. Fig. 13b is SEM photograph of fatigue fracture for the welded joints after UPT. It shows that fatigue crack initiates at the corner between horizontal surface and vertical surface. This is due to that the self-defects and stress concentration on the horizontal surfaces are eliminated by UPT, which effectively prevents the crack initiation on this surface. The self-defects exist on the vertical surfaces since these surfaces have not been treated by ultrasonic peening and fatigue crack forms on these surfaces.

Fig. 14 is SEM photograph of fatigue crack propagation region for the welded joints before and after UPT. Fig. 14a shows that a lot of micro-level striations which

are parallel to each other, slightly curved and perpendicular to the direction of crack growth. Fatigue striation is a typical characteristic of fatigue crack propagation region. Fig. 14b shows that there is no obvious fatigue striations, which may be caused by UPT. The surfaces treated by UPT have residual compression stress. The existence of residual compression stress makes the crack propagation not fully be completed.

Fig. 15 is SEM photographs of instantaneous fracture region for the welded joints before and after UPT. Comparing Fig. 15a with Fig. 15b, SEM photographs of instantaneous fracture region for the welded joints before and after UPT have almost no difference. As Fig. 4 shows that the plastic deformation layer is only about tens of microns, while the fracture dimension of the instantaneous fracture region under the effect of tensile loads is much larger than the thickness of the deformation layer. Thus, UPT has almost no influence on the SEM photographs of instantaneous fracture. The fan-shaped cleavage pattern exists in the instantaneous fracture region.

3.9 Fatigue fracture mechanism of the corrosion joint

Fig. 16 is SEM photograph of the fatigue fracture for the corrosion joint after UPT. This fatigue fracture still contains three regions, which are crack source region, crack propagation region and instantaneous fracture region. As the horizontal surface of welded joints has been treated by ultrasonic peening, fatigue crack initiates at the vertical surface (see Fig. 16a). The microscopic defect becomes larger under the effect of corrosion. The extension direction of fatigue crack can be clearly observed (see Fig. 16b). Crack begins at certain point and expands into specimen interior. The reason is that the horizontal surface has been treated by ultrasonic peening, where the residual

compression stress formed and prevented the crack extension. The direction of crack propagation is indicated by arrow marks.

4. Conclusions

The ultrasonic peening treatment was proposed to improve fatigue performance, wear resistance and corrosion resistance of the flash welded joint of U75V rail steel. Surface nanocrystallization is the main reason to enhance welded joint. The nanocrystallization mode is the process of dislocation annihilation and recombination caused by UPT. The formation of nanocrystal layer on the surface of the flash welded joint after UPT can prevent the crack initiation and improve fatigue performance, wear resistance and corrosion resistance of the flash welded joint effectively. Fatigue strength of the flash welded joints increases by 23% after UPT. Fatigue strength of the flash welded joints treated by UPT after corrosion only decreases by 8% with that before corrosion. The wear resistance of the flash welded joints after UPT improved by 29% for the increasing of hardness and surface nanocrystallization. Therefore, UPT will be widely applied in the strengthening field of welded joint.

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Tables

[Table 1.](#) The parameters of flash welding

[Table 2.](#) The parameters of ultrasonic peening treatment

[Table 3:](#) The composition of artificial seawater

[Table 4:](#) Wear loss and relative wear resistance of the flash welded joint

Table 1. The parameters of flash welding

Voltage/V	Flash allowance /mm	Upset pressure /MPa	Upset allowance /mm	Flash rate /mm/s
3.76	7-7.5	25	2.5-3	0.18

Table 2. The parameters of ultrasonic peening treatment

Current /A	Frequency /KHz	Amplitude /μm	Time /min	Impact needle	Impact area /mm ²	coverage rate
3.76	17±2	48	20	Circular	10mm×30mm	100%

Table 3. The composition of artificial seawater

The types of salt	The concentration of salt in artificial seawater/(g/L)
NaCl	105.00
MgCl ₂	12.70
MgSO ₄ ·7H ₂ O	7.70
CaSO ₄ ·2H ₂ O	12.15
CaCO ₃	0.5

Table 4. Wear loss and relative wear resistance of the flash welded joint

Pre-pressure	Wear time	Weight before experiment	Weight after experiment	Wear loss	Relative wear resistance
10N	120s	1.5321g	1.5186g	0.0125g	1
10N	120s	1.5418g	1.5321g	0.0097g	1.29

Figures

Fig. 1. Metallographic structure of U75V rail steel

Fig. 2. The macrophotograph of welded joint before and after UPT

Fig. 3. Microstructures of the flash welded joint before UPT (IA: interface area; OZ: overheated zone; RZ: recrystallization zone; IRZ: incomplete recrystallization zone)

Fig. 4. Microstructures of the flash welded joint after UPT (SDL: severe deformation layer; TL: transition layer; M: matrix)

Fig. 5. TEM photograph of the plastic deformation layer with the distance from the ultrasonic peening surface is about 20-30 μm

Fig. 6. TEM photograph of the nanostructured surface layer

Fig. 7. The hardness values in the through-thickness direction before and after UPT

Fig. 8. X-ray diffraction pattern of the flash welded joint before and after UPT

Fig. 9. Wear morphology of the flash welded joint before and after UPT

Fig. 10. *S-N* curves of welded joints under three conditions

Fig. 11. Fatigue fracture locations of three kinds of flash welded joints

Fig. 12. The macroscopic morphology of fatigue fracture for the failed specimen

Fig. 13. SEM photograph of fatigue crack sources for the flash welded joints before and after UPT

Fig. 14. SEM photograph of crack propagation region for the flash welded joints before and after UPT

Fig. 15. SEM photograph of instantaneous fracture region for the flash welded joints before and after UPT

Fig. 16. SEM photograph of fatigue fracture for the corrosion joint after UPT

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Graphical Abstract

Nanocrystallization process is that the coarse grains are refined to the small-sized dislocation cells under the action of ultrasonic peening treatment (UPT). Dislocation tangling and dislocation wall are formed as a result of dislocation aggregation at grain boundaries. Dislocation tangling and dislocation wall were turned into the small-sized subgrains by absorbing dislocations. With further increasing of strain energy, dislocation tangling and dislocation wall are formed again in the refined subgrains and grains. The above microstructural evolution is repeated in refined subgrains and grains, which bring further refinement of those grains. Surface nano-enhancing will effectively improve fatigue performance of the flash welded joint.