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Influence of Ultrasonic Surface Rolling Process and Shot Peening on Fretting Fatigue Performance of Ti-6Al-4V

Ning Wang*, Jinlong Zhu, Bai Liu, Xiancheng Zhang, Jiamin Zhang and Shantung Tu

Abstract

At present, there are many studies on the residual stress field and plastic strain field introduced by surface strengthening, which can well hinder the initiation of early fatigue cracks and delay the propagation of fatigue cracks. However, there are few studies on the effects of these key factors on fretting wear. In the paper, shot-peening (SP) and ultrasonic surface rolling process (USRP) were performed on Ti-6Al-4V plate specimens. The surface hardness and residual stresses of the material were tested by vickers indenter and X-ray diffraction residual stress analyzer. Microhardness were measured by HXD-1000MC/CD micro Vickers hardness tester. The effects of different surface strengthening on its fretting fatigue properties were verified by fretting fatigue experiments. The fretting fatigue fracture surface and wear morphology of the specimens were studied and analyzed by means of microscopic observation, and the mechanism of improving fretting fatigue life by surface strengthening process was further explained. After USRP treatment, the surface roughness of Ti-6Al-4V is significantly improved. In addition, the microhardness of the specimen after SP reaches the maximum at 80 μm from the surface, which is about 123% higher than that of the AsR specimen. After USRP, it reaches the maximum at 150 μm from the surface, which is about 128% higher than that of AsR specimen. It is also found that the residual compressive stress of the specimens treated by USRP and SP increases first and then decreases with the depth direction, and the residual stress reaches the maximum on the sub surface. The USRP specimen reaches the maximum value at 0.18 mm, about − 550 MPa, while the SP specimen reaches the maximum value at 0.1 mm, about − 380 MPa. The fretting fatigue life of Ti-6Al-4V effectively improved after USRP and SP. The surface integrity of specimens after USRP is the best, which has deeper residual compressive stress layer and more refined grain. In this paper, a fretting wear device is designed to carry out fretting fatigue experiments on specimens with different surface strengthening.

Keywords: Ti-6Al-4V, Fretting fatigue, Residual stress, Ultrasonic surface rolling process, Surface strengthening

1 Introduction

Fretting fatigue refers to small relative displacements in regions of contact between two parts while the contacting parts are subjected to vibratory load, as shown in Figure 1. Compared with uniaxial fatigue, fretting fatigue crack initiation mainly occurs at the geometric discontinuity of the contact zone, where the fretting damage is the most serious. In addition, fretting will accelerate the wear, occlusal and material loss of the surfaces in contact, which greatly reduces the mechanical properties of the material. At the same time, it will accelerate the initiation and propagation of cracks and even early fracture of the specimen. A large number of engineering cases [1, 2] show that fretting will greatly reduce the service time of components by 20%–50%, or even more. Among them, the reports about fretting fatigue leading to premature fatigue failure of the joints of aero-engine blades are particularly prominent [3–5].

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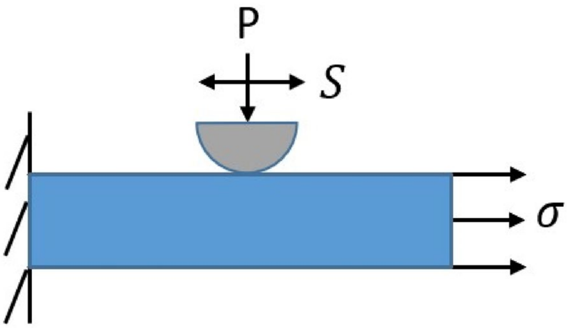

Figure 1 Schematics of the fretting fatigue

Titanium alloy is one of the materials that widely used in aerospace and other fields, which has a series of advantages such as high specific strength, stable high temperature performance, etc. However, due to the high friction coefficient and poor wear resistance of titanium alloy, it is particularly sensitive to fretting wear and crack initiation, which seriously affects the safety and service life of titanium alloy components. Therefore, it is necessary to adopt some surface strengthening methods to improve its fatigue and wear resistance. Surface strengthening refers to the process of changing the structure of the material surface by applying external force or heat treatment, so as to improve the surface strength, hardness, fatigue resistance, wear resistance, surface integrity. Some common surface strengthening processes in engineering mainly include wet shot-peening [6, 7], laser shock [8, 9], surface coating [10, 11], composite surface strengthening treatment [12, 13], etc. A large number of studies have shown that surface strengthening improves the fatigue resistance of materials mainly due to the introduction of residual compressive stress. The improvement of wear resistance is mainly shown in the improvement of material surface and sub-surface micro-hardness, smaller surface roughness, surface layer gradient nanostructures, etc. No matter what kind of surface strengthening process is used, the fundamental purpose is to avoid wear from appearing in the crack area of the fretting graph [14]. Ren et al. [15] studied the effects of different surface ultrasonic rolling process parameters on the fretting wear properties of high strength and high toughness titanium alloy, and the experiments showed that the process parameters had the best wear resistance when the rolling times were 30 times and the vibration amplitude was 7 μm. Li et al. [16] found that the improvement of surface strength after wet shot-peening (SP) can effectively resist local fatigue caused by fretting. At the same time, the residual compressive stress can also effectively hinder the crack propagation. Liu et al. [17] found that USRP effectively improved the surface hardness of Inconel 690TT by refining the surface and subsurface grains. Plasma nitriding (PN) improves the surface hardness by infiltrating nitrogen atoms into the surface of the material to change the chemical composition of the matrix. Through comparative analysis of USRP, USRP + PN and PN strengthening process, it is proved that USRP + PN makes Inconel 690TT have the best wear resistance and can effectively hinder the initiation and propagation of cracks. It is also found that the different surface treatments on Ti-6Al-4V can effectively improve the fretting fatigue life [18]. Compared with USRP, mechanical surface polishing would weaken the fretting fatigue performance of Ti-6Al-4V [19]. In terms of improving fatigue strength, the residual compressive stress produced by USRP is better than the surface gradient nanostructures produced by mechanical surface polishing. The fatigue strength is increased by 113.6%. The residual compressive stress is considered the key factor to improve the fretting fatigue life. Lu et al. [20] pointed out that high hardness would block the initiation of cracks. The coupling effect of the residual compressive stress and the plastic deformation layer will slow down the early growth of fretting fatigue cracks and the residual compressive stress plays a major role.

SP is widely used in the aerospace field because of its mature technology, high processing efficiency, the ability to process the surface of various complex shapes, etc. While ultrasonic surface rolling process [21] (USRP) is an emerging technology that superimposes static pressure and ultrasonic vibration impact force as a combined load applied to the contact surface of the ball and the component. Compared with traditional surface strengthening technologies, it can make the material surface produce a denser plastic deformation layer [22], higher surface roughness, better wear resistance and introduce a deeper residual compressive stress layer [23–26]. The schematic diagrams of the two processes are shown in Figures 2, 3.

Based on the above research background, the surface of Ti-6Al-4V is strengthened by USRP and SP processes. The fretting fatigue experiments are carried out on different surface strengthened specimens by a designed fretting wear device and fatigue testing machine. The combined effects of residual compressive stress and surface roughness on fretting fatigue life of Ti-6Al-4V are studied, and the effect of strain on wear resistance of paper surface is studied.

2 Experiments

2.1 Material and Specimen

The material used in the experiments is a duplex alloy (Ti-6Al-4V, Figure 4), which is commonly used to make turbine blades of aeroengine. The heat treatment state is forging and annealing. The principal chemical

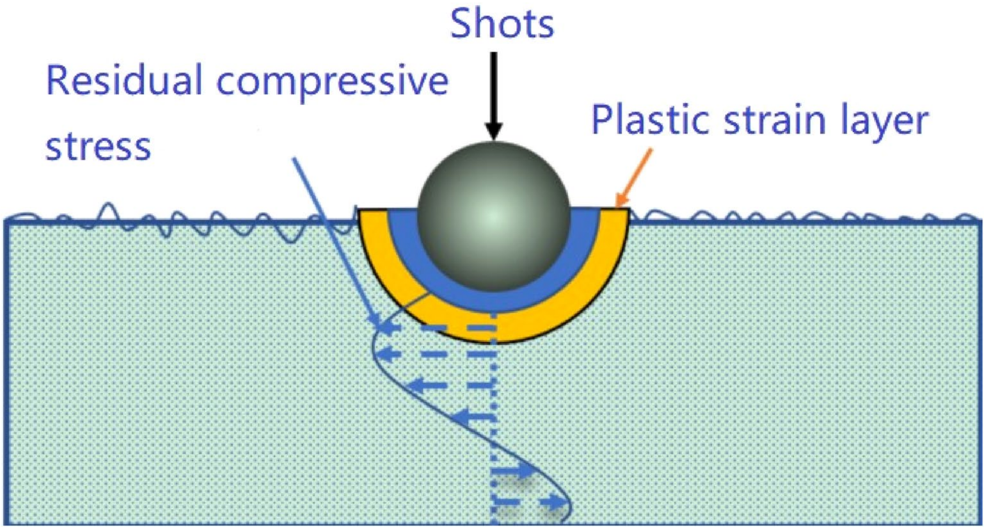

Figure 2 Schematics of SP strengthening process

composition of Ti-6Al-4V are given in Table 1. The main material properties at room temperature of Ti-6Al-4V are listed in Table 2.

Ti-6Al-4V specimens are prepared by wire cutting, grinding, and polishing. Figure 5 shows the geometrical details of the fretting fatigue plate specimen.

2.2 Different Surface Strengthening Processes

The surface strengthened by SP and USRP is two parallel end faces in thickness direction and the arc surface at 1.5 mm radian, as shown in Figure 6. It is aimed to prevent the specimen from breaking near the geometric discontinuity during the experiment.

USRP uses ultrasonic impact energy and static load rolling to treat the surface of metal parts. The machining head applies a certain amplitude of ultrasonic mechanical vibration along the normal direction of the workpiece surface. Under certain feeding conditions, the working head transmits the static pressure and ultrasonic impact vibration to the surface of rotating mechanical parts to produce extrusion, resulting in large elastic-plastic deformation of metal materials. To avoid overheating of the alloy ball during rolling, coolant needs to be added to cool down. In addition, the addition of coolant can also reduce the surface roughness of the specimen. Generally speaking, the processing parameters of USRP mainly include rolling pitch, feed speed, static pressure, number of processing passes and so on. According to the previous process exploration [27, 28] of the research group, the processing parameters selected in this experiment are shown in Table 3.

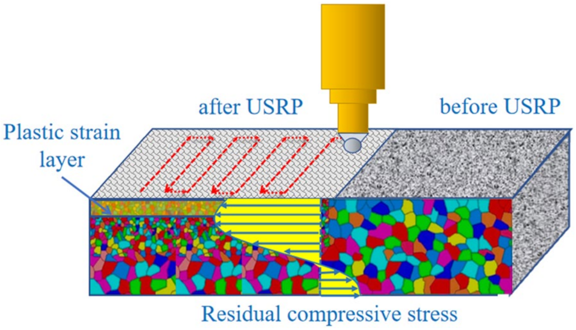

Figure 3 Schematics of USRP strengthening process

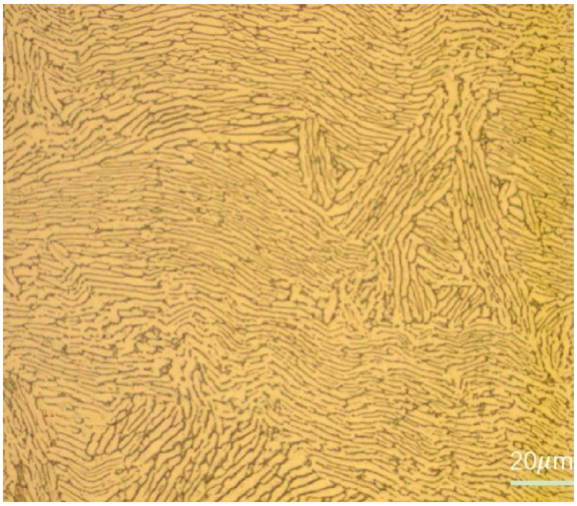

Figure 4 The microstructure image of specimen

Table 1 Chemical composition of Ti-6Al-4V (wt.%)

Fe	C	N	H	O	Al	V	Ti
0.1	0.012	0.009	0.004	0.09	6.08	4.1	Bal.

Table 2 Mechanical properties of Ti-6Al-4V

σ_b (MPa)	$\sigma_{0.2}$ (MPa)	*E* (GPa)	Elongation after fracture (%)	μ
820	740	120	11	0.34

2.3 Residual stress

The residual stress of specimen is measured by Proto-IXRD MG40P FS STD residual stress analyzer (Figure 7). The specimen is a cuboid with the size of 5 mm × 5 mm × 6 mm. Cu target is selected in the test. The X-ray generator tube voltage is 24 kV, tube current is 7 mA, diameter of collimator is 1 mm and the exposure time is 5 s. In order to accurately obtain the residual stress field along the depth direction after USRP, the residual stress is measured by electrolysis layer by layer. The ratio of perchloric acid to formaldehyde is 1:9. The polishing voltage is 15 V. When measuring the residual stress, three different positions are tested in the horizontal direction of each depth so that the test error can be reduced by calculating the mean value.

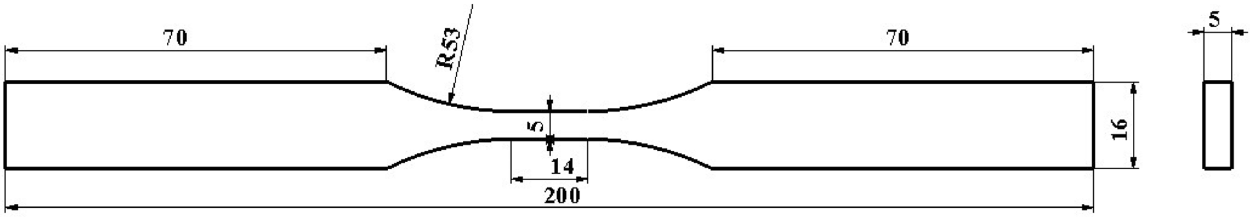

Figure 5 Geometric details of the specimen (units: mm)

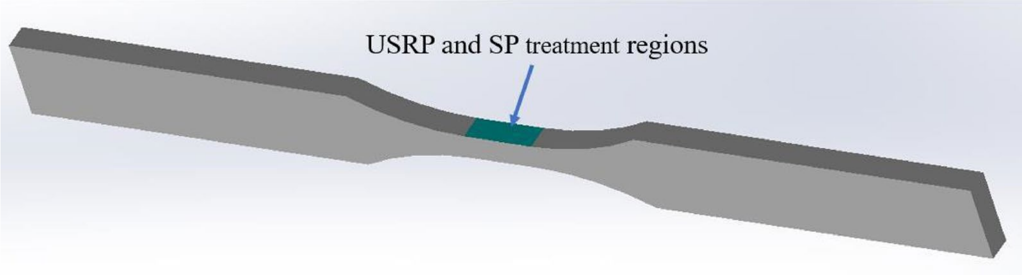

Figure 6 Schematics of USRP and SP treatment regions

Table 3 The parameters of USRP

Load (*N*)	Amplitude (μm)	Feed rate (mm·min^{-1})	Rolling pitch (mm)	Rolling passes	The diameter of ball (mm)
180	20	2000	0.05	25	10

Table 4 The parameters of SP

Pressure (MPa)	Flow rate(kg·min^{-1})	Shot distance (mm)	Shot time (s)	Coverage rate (%)	The diameter of ball (mm)
0.1	3	150	8	100	0.3

SP uses air pressure to obtain kinetic energy from the pellets to impact the surface of the specimen at a high speed, so as to introduce residual stress field and plastic strain layer to improve the fatigue resistance of the material. The processing parameters of SP mainly include shot peening flow rate, shot peening time, shot peening pressure, shot diameter and so on. The processing parameters selected in this experiment are shown in Table 4.

Figure 7 Residual stress analyzer

Figure 8 Microhardness tester

2.4 Microhardness and Surface Roughness

Microhardness is measured by HXD-1000MC/CD micro Vickers hardness tester, as shown in Figure 8. The load is 200 GF, and the holding time is 15 s. Five effective points were measured at the same depth and the average value was taken. The interval between each data point is 50 μm. The hardness value is measured every 50 μm in depth direction. This method can obtain enough data and minimize the influence of hardness indentation on adjacent positions. Since the measurement of microhardness requires good surface roughness, metallographic specimens are directly used for hardness measurement.

The surface roughness of Ti-6Al-4V before and after SP and USRP process are measured by IFM G4 3D surface topography instrument, as shown in Figure 9. The mean deviation Ra of profile arithmetic is taken as the surface roughness characterization parameter.

2.5 Fretting Fatigue Experiment

Fretting fatigue experiment is completed by installing fretting wear device on INSTRON fatigue testing machine. The fatigue load provided by Instron fatigue testing machine is sinusoidal load. The experiment frequency is 10 Hz and the stress ratio is 0.1. The single chuck fretting wear device designed is mainly used to provide stable and fixed normal load. The normal load is mainly applied by real-time digital display torque wrench. The four symmetrical screws on the stress ring are mainly connected with the bottom plate to ensure that the whole mechanism can be horizontally and stably fixed on the tray. The fixing bolts on both sides are used to fix and support the bolt rod and prevent excessive vibration of the bolt rod during the experiment, as shown in Figures 10, 11.

The experiment conditions are shown in Table 5. In order to achieve the purpose of comparison, fretting fatigue experiments are carried out on untreated specimens (As Received, AsR), SP and USRP specimens under each operating conditions. A total of 32 groups of experiments were carried out, and there were 3 specimens in each condition.

3 Results and Discussion

3.1 Surface Roughness, Microhardness and Residual Stress

The surface roughness distribution of different specimens is shown in Figure 12. It can be seen that the surface roughness of Ti-6Al-4V is significantly improved after USRP. The surface roughness (Ra) of AsR specimen is 0.217 μm. After USRP, it reduces to 0.143 μm. However,

Figure 9 Three-dimensional non-contact optical profilometer

Figure 10 Fretting fatigue experiment machine

compared with the AsR specimen, the surface roughness increases after SP, which is 1.279 μm.

It also can be seen from Figure 12 that the surface asperities of the specimen under different surface treatments are not the same. For the AsR specimen, the highest point of the asperity reaches 0.9 μm. The distance between asperities on the left side of 1.5 mm is relatively close while on the right side is larger and the distance can be up to 0.3 mm in width. The whole two-dimensional contour map is small and sharp. The gap between two adjacent asperities is likely to be a potential microcrack. The larger the gap, the more likely it is to become a crack. However, the distance between the two asperities of the specimen after SP is relatively large and the maximum point can reach 0.4 mm. Throughout the overall trend in Figure 12b, almost every two asperities have different sizes of spacing and even have obvious characteristics similar to pits. The whole two-dimensional contour map is wide and high. The more the gap between the asperities, the wider the gap spacing, which means that the material is more likely to initiate microcracks on the surface and more likely to be damaged under the same working conditions. The height of the asperities of the USRP specimen is mostly about 0.4 μm and the height tends to be horizontal. The asperities are relatively tightly connected and do not have obvious gap. The whole two-dimensional contour map is dense and sharp. By comparison, the number of asperities of specimen after SP has increased significantly, while it greatly reduced after USRP.

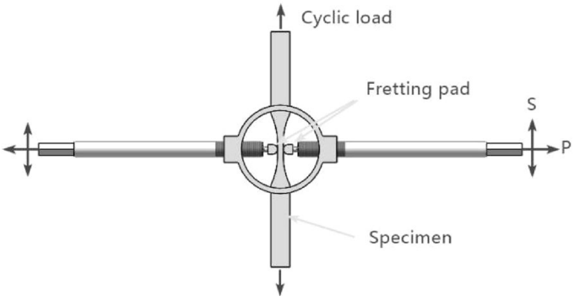

Figure 11 Schematic of fretting wear arrangement

The microhardness distribution of different specimens is shown in Figure 13. The microhardness of USRP and SP specimen are obviously greater than AsR specimen at the same depth. USRP specimen reaches the maximum value of 374 HV at the depth of 150 μm. SP specimen reaches the maximum value of 368 HV at the depth of

Table 5 Fretting fatigue experiment conditions

Surface treatments	Stress level	
	Axial load/MPa	Normal load/MPa
AsR	550	Constant
	600	
	625	
	650	
USRP	550	Constant
	600	
	625	
	650	
SP	550	Constant
	600	
	625	
	650	

80 μm. It can also be seen from Figure 13 that the microhardness of USRP specimen is greater than that of SP specimen. The microhardness of SP specimen is basically the same as the as received specimen at the depth of 450 μm, while the USRP specimen at the depth of 550 μm. Therefore, USRP has a deeper influence on the hardness of specimen than SP. The main reason for the increase in microhardness is grain refinement [29]. At the same time, because the microhardness distribution results of the specimens can objectively reflect the distribution trend of the plastic strain of the material [30], the plastic strain layer thickness of the specimen after USRP is also deeper.

The residual stress distribution of different specimens is shown in Figure 14. The residual compressive stresses of specimens after USRP and SP are first increase and then decrease in the depth direction and all reach the maximum value on the subsurface. Wohlfahrt [31] used Hertzian contact theory to explain this phenomenon. He believed that it was mainly caused by the competition mechanism between Hertzian dynamic pressure and surface plastic deformation. When the subsurface strain is dominant in the competition with surface plastic deformation, the maximum residual stress is located in the subsurface layer. The residual stress of the specimen that strengthened by USRP reaches the maximum of − 550 MPa at the depth of 0.18 mm, while the SP-strengthened specimen reaches the maximum of − 380 MPa at the depth of 0.1 mm. In addition, the influence

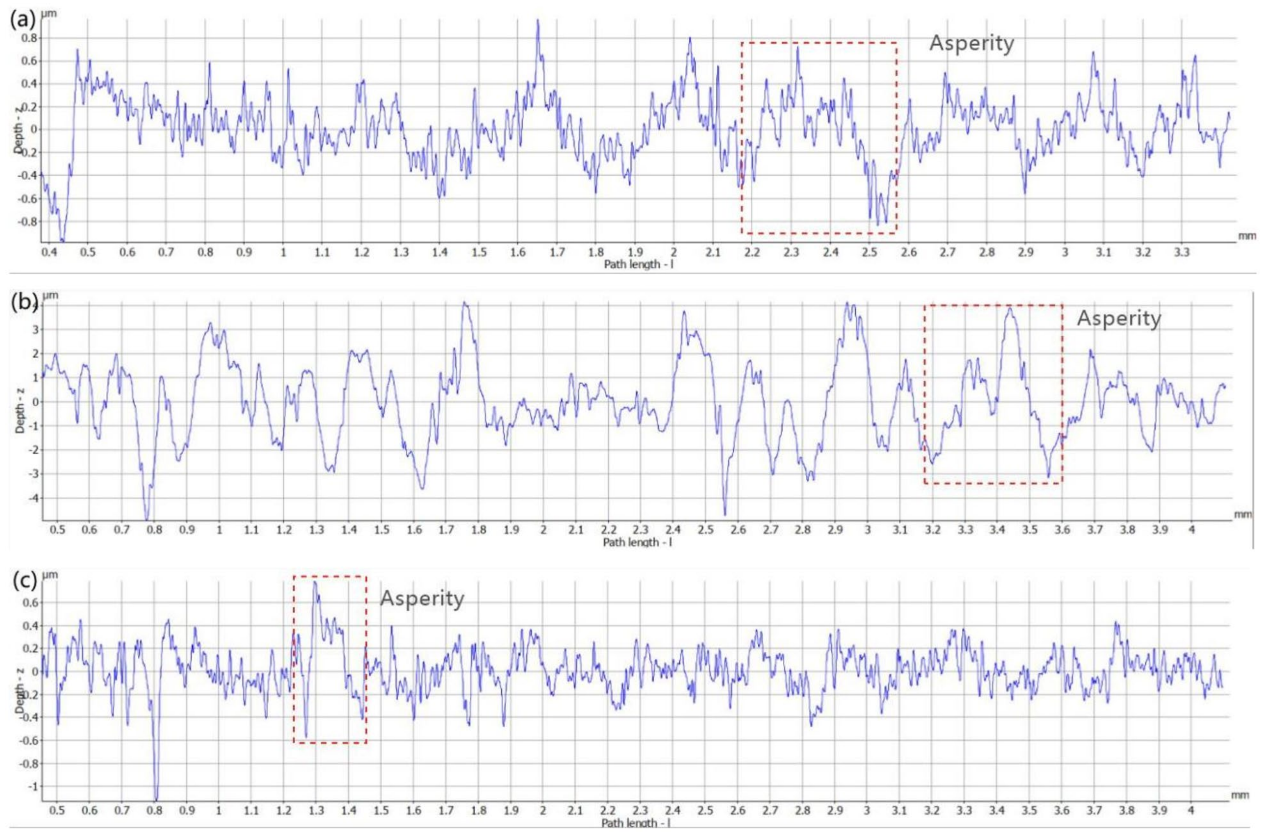

Figure 12 The surface roughness of the **a** AsR, **b** SP and **c** USRP specimens

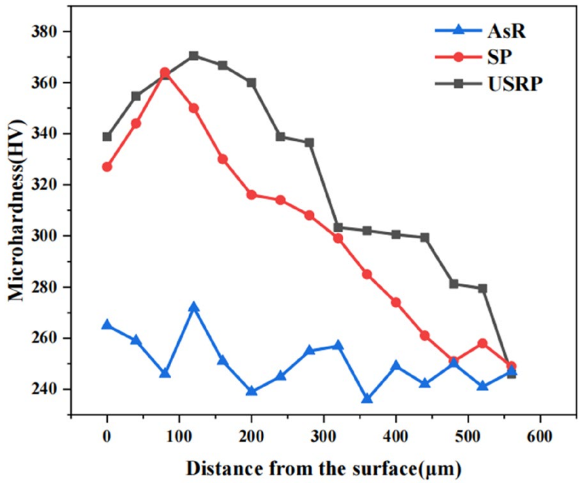

Figure 13 The Microhardness distribution of the AsR, SP and USRP specimens

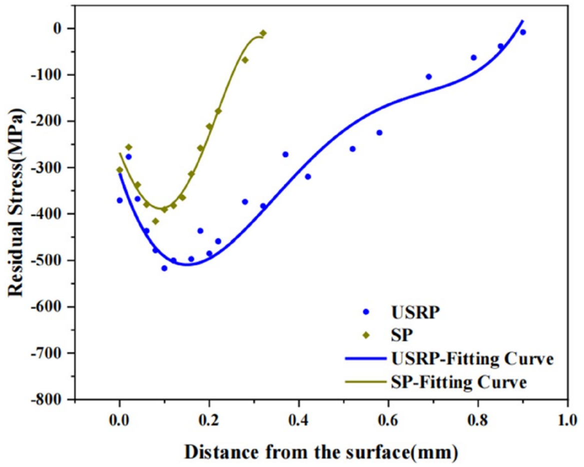

Figure 14 The residual compressive stress distribution of the AsR, SP and USRP specimens

range of residual compressive stress field and residual compressive stress value at the same depth after USRP are greater than those after SP strengthening. The surface residual compressive stress of the AsR specimen is between 35 MPa and 72 MPa and the affected layer is very shallow, about 20 μm. Some scholars believed that a deep residual compressive stress layer is beneficial to prolong the propagation life of cracks, because it can effectively delay the propagation rate of cracks. In addition, the high residual compressive stress can well offset the external load on the surface, which has a positive effect on the resistance to crack initiation [32]. Therefore, USRP has better effect than SP on the improvement of fretting fatigue life of Ti-6Al-4V.

3.2 Wear Profile

The morphology of fretting areas on the surface of specimens after fretting fatigue experiment are shown in Figure 15. The locations of fracture failure are all located in the fretting area. Observing the fretting area, the specimen has a certain degree of elastic and plastic deformation. It can be seen from Figure 15a, b that there are large areas of slip marks in AsR specimens, mainly adhesion and a small amount of delamination. The SP specimen (Figure 15c, d) has obvious flaking of massive material at the fracture position, which may be caused by the initial collection of microcracks under the combined action of axial fatigue load and contact stress. In the fretting area, there are slight wear marks, delamination and a few micro-cracks and the surface also appears embrittlement. This is probably because a large amount of shots bombards the surface of the specimen during the SP process, the surface grain of the specimen is refined but not uniform. In contrast, only slight delamination and smaller wear pits exist on the USRP specimen (Figure 15e, f). This is because the surface and sub-surface grains are refined and relatively uniform, the wear resistance is improved. In addition, no cracks can be found in the wear area and only a few wear pits exist. It is possible that the specimen is in a global slip state during the fretting process. Similar to the results of Mohd [33], cracks initiate at the boundary between the adhesion zone and the sliding zone in the local sliding zone, while only accumulated debris is found in the overall sliding zone. It means fretting wear is dominant in the competition mechanism with fatigue during the fretting process. The wear rate is greater than the crack initiation rate so that the initiating microcracks are worn away.

3.3 Fracture Analysis

Through the fretting fatigue experiment, the crack initiation and fracture failure of all specimens are located on the side of the lower edge of the fretting contact area. The wear marks on the surface of the fretting contact area is a typical fretting fatigue failure. The macroscopic view of the fracture surface after fretting fatigue failure are shown in Figure 16. The fatigue crack originates close to the contact surface of the specimen. Because the normal load is applied through the micro-motion pad and the contact form between the micro-motion pad and the specimen is "cylindrical-planar" contact. According to Hertz contact theory, there is serious stress concentration in the contact area. Thus, the main crack source must be formed in the contact area. Regardless of whether there are defects in the crack source area, fatigue cracks are initiated from

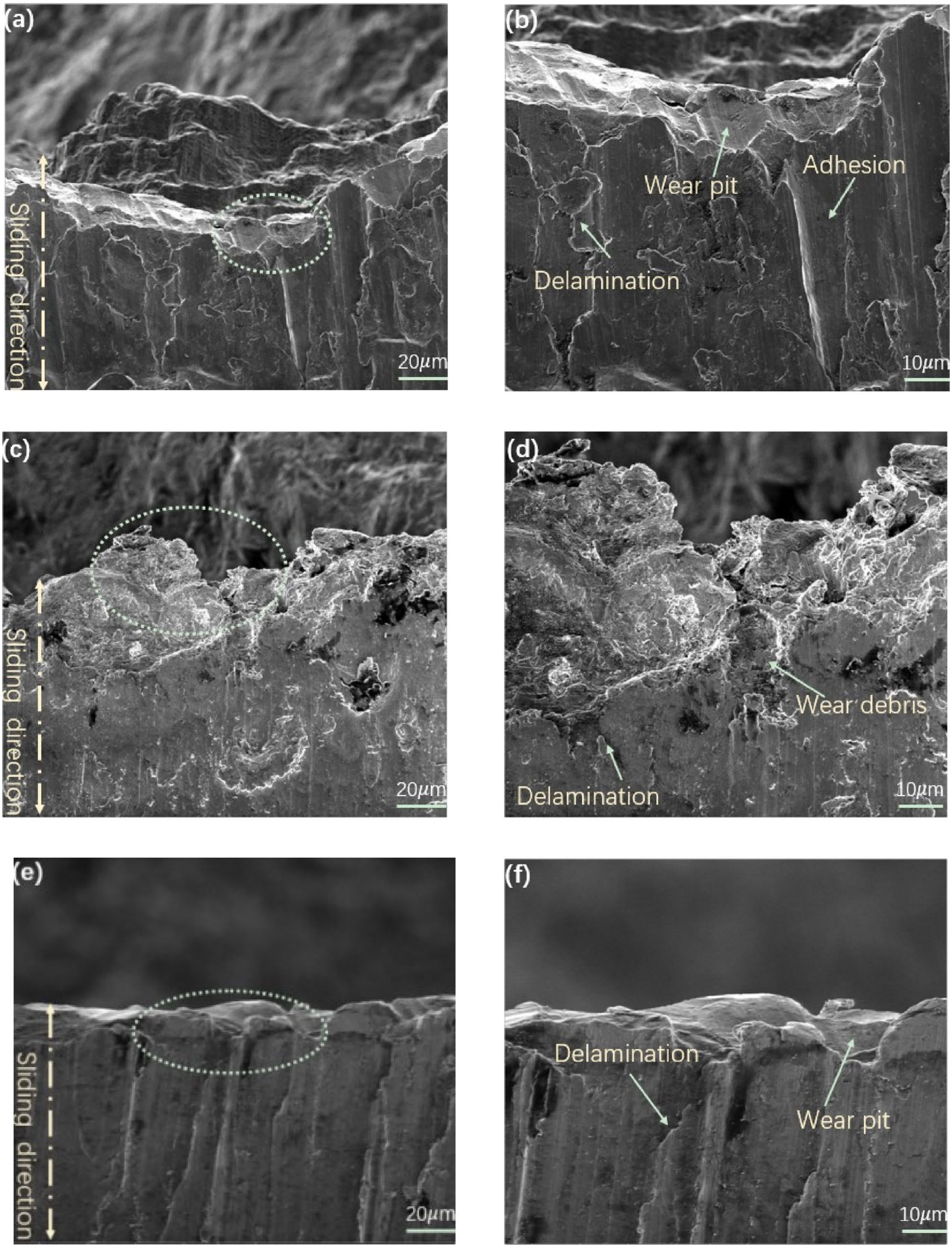

Figure 15 SEM images of the typical wear morphologies of **a**, **b** AsR specimen, **c**, **d** SP specimen and **e**, **f** USRP specimen

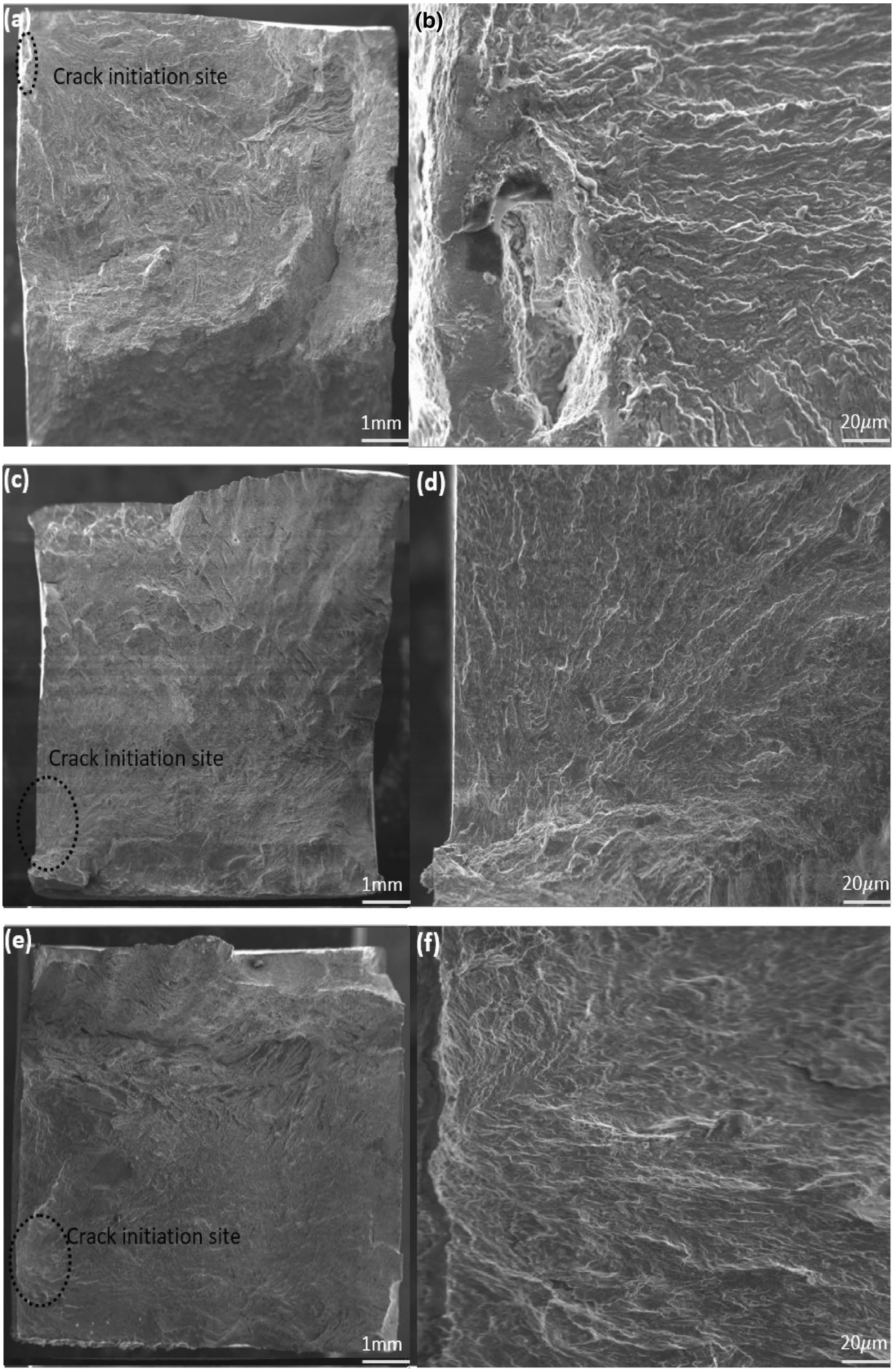

Figure 16 SEM fracture surface morphologies of **a**, **b** AsR specimen, **c**, **d** SP specimen and **e**, **f** USRP specimen

the maximum stress concentration area because the initiation of cracks must undergo repeated slippage processes to form [34]. Moreover, the form of crack propagation is radial expansion with the main crack source as the center, similar to "ripple" diffusion. Eventually, the fracture failure occurred in the transient area. In addition, there are wear pits in the crack source area of the AsR (Figure 16a, b) specimen. This is due to the low hardness and poor wear resistance, the titanium alloy is easy to be affected by fretting wear during the fretting process [35]. While after SP process, the surface hardness of the specimen is improved, and the subsurface also has a certain degree of nano gradient structure, which can effectively resist fretting wear. However, due to the surface embrittlement and the increase of roughness, the wear resistance will be weakened to a certain extent. As a result, the traces of wear damage can be found in the crack source area. However, the surface hardness of the specimen after USRP is improved, and the surface roughness is greatly reduced. Therefore, the specimen after USRP can better resist fretting damage.

3.4 Fretting Fatigue Life

Residual stress and surface roughness are considered the most critical factors affecting fretting fatigue life. The residual stress introduced by surface and sub-surface layers of the specimen after surface strengthening is compressive stress, which can effectively reduce the average stress caused by the applied load and reduce the stress ratio, thereby preventing the initiation of fatigue cracks and reducing the crack growth rate. Therefore, residual stress is often considered to be the average stress. The effect of surface roughness on fatigue is usually attributed to the stress concentration effect. Lower roughness helps the specimen avoid surface stress concentration during the fretting fatigue experiment and prevent crack initiation that caused by surface defects, especially for low-cycle fatigue experiment under high stress levels. This is mainly because the residual stress is prone to relaxation under high stress levels [32]. For the fretting fatigue damage with the coupling effect of fretting wear and fatigue damage, the importance of surface hardness cannot be ignored, especially in the overall sliding state. According to the Archard wear equation, the wear volume is proportional to the surface hardness of the material. Therefore, the higher the surface hardness is, the stronger the wear resistance is and the longer the fretting fatigue life is.

The fretting fatigue life curves are shown in Figure 17. The fretting fatigue life under three different test conditions are all decrease with the increase of stress level. For the dispersion of fretting fatigue lifetime, this is mainly because the dispersion of fatigue data itself is relatively large, coupled with the effect of wear. Moreover, the lower the stress level, the more obvious the strengthening effect. Among two strengthening methods, USRP has a more significant effect on the improvement of fretting fatigue life, especially under the stress level of 600 MPa. Some studies have shown that in the early fretting fatigue crack propagation stage, compressive residual stress can significantly decrease tensile stress at the crack tip [36]. Similar to clamping stress, compressive residual stress can also close up fretting fatigue cracks in the early stages of fretting fatigue crack propagation [18]. At the same time, the surface roughness and surface microhardness have also been greatly improved, which can well improve the wear resistance and stress concentration of the specimen. The coupling effect of the above three parameters greatly increases the fretting fatigue life. In the stress range of 600–650 MPa, SP does not significantly improve the fatigue life of Ti-6Al-4V. The research on the effect of SP on the fatigue strength of cast iron structure shows that higher residual compressive stress and nanocrystalline structure help to improve the fatigue strength, but the high roughness caused by SP will greatly weaken the above effect [37]. Generally speaking, parts with larger friction coefficients are more susceptible to fretting damage, especially titanium alloys that are more sensitive to fretting wear. In addition, some researchers [38–40] proved that SP will change the surface morphology and increase the roughness of the material while introducing residual stress. The increase of roughness will cause some unfavorable results like surface stress concentration, microcracks, etc. In the study of the effect of different SP treatments on the fretting fatigue life of 7075-t7351 aluminum alloy, it is found that laser SP can increase the fatigue life of 7075-t7351 aluminum alloy at

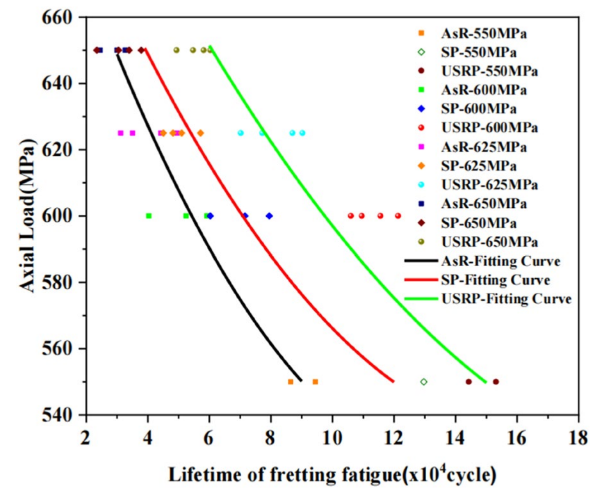

Figure 17 Fretting fatigue life of AsR, SP and USRP specimens

the early and late stages of crack propagation by 7 and 3 times respectively. However, SP can only increase by 2 to 3 times. The main reason is that the SP process can easily cause embrittlement and roughening of the material surface. In addition, in the process of SP, the surface of the material will form a region which is easy to promote the rapid propagation of cracks. These will greatly weaken the beneficial effect of residual compressive stress. The surface brittleness and roughness caused by SP can also aggravate the fretting wear of the material, which makes the surface of the material easy to fall off, delamination and even appear pits or microcracks. Moreover, under the action of high strain amplitude, the residual compressive stress will relax, which weakens the ability of residual compressive stress to resist crack initiation.

4 Conclusions

(1) The surface hardness of specimens strengthened by SP and USRP increased by 38.4% and 46.2%, respectively. The surface roughness of USRP specimens are reduced by 34.1%.

(2) During the long-term fretting process, the material loss and no crack nucleation can be observed as fretting damage for this gross sliding cases, which is due to the domination of the mechanisms of adhesion and surface delamination.

(3) Compared with SP specimens, USRP specimens have a better improvement in the fretting fatigue lifetime, which means lower surface roughness can effectively mitigate the undesired effects that fretting wear has on specimens.

(4) Both SP and USRP specimens show better fretting fatigue resistance, owing to the beneficial effects of the enhanced hardness, the strain hardening layer and the compressive residual stress.

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Authors' Contributions

NW was in charge of the whole trial; JZ wrote the manuscript; BL, JZ assisted with sampling and laboratory analyses. XZ and ST were responsible for providing idea and revising the manuscript. All authors read and approved the final manuscript.

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Competing Interests

The authors declare no competing financial interests.

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