

Fretting wear mechanism of GH4169 dovetail joint specimens treated with hybrid laser shock peening

Xiuyang Fang^{a,*}, Zheng Wang^a, Magd Abdel Wahab^{c,d,e}, Jianen Gong^a, Xiong Liu^{f,g},
Xing Liu^g, Zhenbing Cai^{a,b,**}

^a School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, China

^b Tribology Research Institute, Key Lab of Advanced Technologies of Materials, Southwest Jiaotong University, Chengdu 610031, China

^c Soete Laboratory, Department of Electrical Energy, Metals, Mechanical Constructions, and Systems, Faculty of Engineering and Architecture, Ghent University, Ghent 9000, Belgium

^d College of Engineering, Yuan Ze University, Taiwan, China

^e Parallel and Distributed Systems Laboratory, Jožef Stefan Institute, Jamova cesta 39, Ljubljana SI-1000, Slovenia

^f DongFang Electric Machinery Co., LTD, Deyang 618000, China

^g State Key Laboratory of Advanced Electromagnetic Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China

ARTICLE INFO

Keywords:

GH4169 dovetail joint
Hybrid laser shock peening
Surface integrity
Fretting wear

ABSTRACT

Aero engine blade structure is prone to severe fretting wear under centrifugal forces and vibration loads, resulting in greatly reduced engine service life, which is a typical fretting damage problem. In this paper, without Absorbing layer Nanosecond Laser Shock Peening (wAN-LSP) and without Absorbing layer Nanosecond superimposed Femtosecond hybrid Laser Shock Peening (NF-LSP) are utilized to strengthen the surface of GH4169 dovetail joint specimens, which is a common material for engine blades, to explore its strengthening mechanism and fretting wear evolution law. The findings indicate that the surface roughness of the wAN-LSP specimen rises from 0.28 μm to 1.16 μm . The thermal effects of wAN-LSP lead to the formation of a molten layer roughly 10.97 μm thick on the surface, accompanied by numerous pits, ablation holes, and micro-cracks. In contrast, NF-LSP treatment effectively eliminates the surface oxidation defects made by the thermal effects of wAN-LSP, leading to a slight decrease in surface roughness. Both wAN-LSP and NF-LSP treatments enhance the surface hardness of the specimens, creating a plastic deformation layer roughly 400 μm deep, but the near surface hardness of NF-LSP treated specimen is further improved compared to that of the wAN-LSP specimen. The wear mechanism observed in the GH4169 dovetail joint specimens following wAN-LSP and NF-LSP treatment are identified as abrasive wear and oxidation wear. Initially, as the number of cycles raises, the wear volume of GH4169 specimen treated with wAN-LSP is higher than that of untreated specimen, but subsequently, it becomes lesser than that of the untreated specimen. This phenomenon results from the interplay between the molten layer and hardened layer. In the initial stage of wear, despite the surface strengthening of the wAN-LSP specimen, the presence of molten layer significantly diminishes the fretting wear resistance of the material. As wear progresses, the molten layer is removed, revealing the benefits of surface strengthening. Throughout the wear process, the wear volume of NF-LSP specimen remains consistently lower than that of other two specimens. In comparison to the wAN-LSP treatment, NF-LSP treatment can enhance the surface condition of the material, leading to improve resistance of fretting wear across various wear stages.

1. Introduction

Aeroengine is the source of aircraft power and one of the most important components of aircraft. As the key component of aero-engine,

the stable operation state and service life of engine blade affect the operation performance, safety, reliability and economic cost of aircraft [1–4]. The blades have been used in extreme environments such as cyclic alternating loads for a long time. Once defects and damages occur in

* Corresponding author.

** Corresponding author at: School of Mechanical Engineering, Southwest Jiaotong University, Chengdu 610031, China.

E-mail addresses: fangxiuyang@home.swjtu.edu.cn (X. Fang), czb-jiaoda@126.com (Z. Cai).

<https://doi.org/10.1016/j.triboint.2025.110740>

Received 20 January 2025; Received in revised form 18 April 2025; Accepted 20 April 2025

Available online 24 April 2025

0301-679X/© 2025 Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

the service process, serious safety accidents will occur, which seriously limit the operation and maintenance of aeroengines [5,6]. GH4169 superalloy is the main manufacturing material of Aeroengine Blades at present. Fretting wear often occurs under centrifugal force and vibration load during service, leading to blade failure [7–9]. In order to enhance the fretting wear performance of material and prolong the service life of Aeroengine Blades, surface deformation strengthening technique is a choice.

Currently, the prevalent surface deformation strengthening technologies include surface mechanical rolling, ultrasonic nano rolling, shot peening and laser shock peening(LSP), etc. [10–13]. Laser shock peening surface deformation technology irradiates the surface layer of metal materials by high-energy laser beams, leading to alterations in the surface microstructure of metal materials [14–16]. Compared with other surface deformation strengthening technologies, laser shock peening has the following advantages, including good surface quality, high control accuracy, the ability to process thin-walled and complex shaped workpieces and form deep hardened layers and CRS fields [17–19]. The laser energy of traditional LSP technology can reach the Joule level, while the laser energy of without absorbing layer nanosecond laser shock peening technology is usually between tens and hundreds of mJ. And compared with the traditional LSP technology, wAN-LSP has no absorption layer in the processing process, only a constraint layer [20,21]. The processing laser energy of Femto-Second Laser Shock Peening (FS-LSP) technology is usually at the micro focus level, with pulse durations reaching as short as 10^{-15} s. In comparison to wAN-LSP technology, FS-LSP technology has obvious advantages in machining geometric parts with strange and complex shapes because this technology has no absorbing layer and constraint layer [22,23].

Zhao et al. [24] conducted traditional LSP and wAN-LSP treatment on GH4169 superalloy respectively to research the effect on the microstructure and mechanical properties of GH4169 superalloy. The research revealed that LSP treatment resulted in an increase in the tensile strength of the GH4169 superalloy, while wAN-LSP treatment led to a reduction in tensile strength for the reason of the creation of an oxide layer and microcracks above the specimen's surface. However, once the oxide layer was removed, the ductility and strength of GH4169 superalloy strengthened by wAN-LSP showed significant improvement, surpassing that of the alloy treated with LSP alone. Dhakal et al. [25] treated 7075-T6 aluminum alloy with wAN-LSP with power densities of 4 GW/cm² and 6 GW/cm². The researchers thoroughly analyzed the alterations in the specimen's microstructure post wAN-LSP treatment and observed a significant 25 % increase in microhardness. Additionally, a work hardening layer measuring over 1000 μ m in depth was formed, with the maximum residual compressive stress at 100 μ m reaching 227 MPa. Nataraj et al. [26] treated SS 304 stainless steel with 9 GW/cm² wAN-LSP, as a result, the hardness level of the SS 304 stainless steel rose by 61 %, leading to the creation of a residual compressive stress layer that extended more than 200 μ m deep, and the highest residual compressive stress reached 230 MPa. Zhao et al. [27] conducted LSP treatment on GH4169 superalloy and carried out a fretting wear test at high temperature. They observed a notable enhancement in the wear performance of GH4169 post-LSP treatment, evidenced by a 12.7 % decrease in friction coefficient and a 67.0 % reduction in wear rate. This improvement can be the cause of the creation of a gradient microstructure caused by LSP treatment. Consequently, the mechanism of wear transformed from adhesive wear to abrasive wear. Praveenkumar et al. [28] conducted 9 GW/cm² wAN-LSP treatment on ALSI 304 alloy with one and five scanning times and carried out fretting wear tests under different loads (5 N, 10 N, 20 N). It was found that the wear performance of the alloy was sensibly enhanced after wAN-LSP treatment. Yang et al. [29] used FS-LSP technology to treat ALSI 9310 gear steel with different laser energy and spot spacing, and found that FS-LSP treatment led to a significantly enhancement in surface microhardness ranging from 9.4 % to 17.4 %, a significant increase in surface residual compressive stress by 30.5–103.1 %, and the development of a

hardened layer measuring 150–300 μ m in depth. Sano et al. [30] strengthened 2024 aluminum alloy with FS-LSP of different energies and found that FS-LSP would not produce a molten layer of the material, while would produce hardened layers of different depths.

Numerous scholars have conducted extensive studies on the wear properties and surface integrity of metal specimens following wAN-LSP and FS-LSP technology treatment. The findings indicate that wAN-LSP and FS-LSP technology can enhance material hardness, bring in residual compressive stress, and significantly decrease friction when enhancing wear resistance. But there remain additional problems to be further explored. At present, researchers at home and abroad generally use sliding wear tests to assess the friction and wear properties of LSP treated specimens, with minimal focus on fretting wear tests. Many researchers primarily focus on measuring wear amount changes, neglecting the impact of alterations in surface integrity on wear behavior. There is a lack of detailed explanation of the factors that enhance the wear resistance and the research on the evolution law of fretting wear of materials after LSP treatment. It is not enough for the research on the interaction effect of hybrid laser strengthening and the improvement effect on the abrasion resistance of materials. Investigating the fretting wear evolution of GH4169 dovetail joint specimens after wAN-LSP and wAN-LSP superimposed FS-LSP treatment is meaningful. It is essential for enhancing aero-engine turbine blade longevity through improved understanding of wear resistance enhancement mechanisms.

2. Methods and materials

2.1. Material

Table 1 lists the chemical composition of GH4169 nickel base superalloy material used in the test. The material is forged and processed, followed by solid solution and aging heat treatment, and finally processed into the required test specimens by machining. The microstructure of GH4169 nickel base superalloy is observed through scanning electron microscope after metallographic corrosion, as shown in Fig. 1 (a), annealing twins and numerous δ phases can be seen. In addition, the surface of GH4169 superalloy front and back LSP treatment is tested by XRD. According to Fig. 1(b), no new diffraction peaks appear on the material after wAN-LSP and NF-LSP treatment, indicating that wAN-LSP and CS-LSP treatment will not cause significant phase transformation of GH4169 superalloy. However, the diffraction peak shifts, which may be due to the introduction of a large number of dislocations by laser shock peening.

2.2. LSP processing

The laser processing equipment of Xi'an Tianruida company (YSM2000-C30A) is utilized to strengthen the material. The pulse width of wAN-LSP treatment is nanosecond, the value is 10 ns, and the laser power density is 3.98 GW/cm², the wavelength is 532 nm, the spot diameter is 0.4 mm. Other specific parameters are shown in Fig. 2. There is a water layer as a constraint layer, but no absorption layer. The NF-LSP treatment method is to perform wAN-LSP treatment on the surface of GH4169 specimen before FS-LSP treatment. The pulse width of FS-LSP treatment is femtosecond, the value is 290 fs, and the laser power density is 27.45 TW/cm², the wavelength is 1030 nm, the spot diameter was 40 μ m. Other specific parameters are also shown in Fig. 2. There is no binding layer and absorption layer. The spot is LSP processed along the "Z" path on the surface of the specimen to be processed, and the

Table 1
Chemical composition of GH4169 nickel base superalloy (wt%).

Si	C	Al	Ti	Nb	Mo	Cr	Fe	Ni
0.03	0.06	0.16	0.54	0.74	0.42	15.12	18.17	Bal.

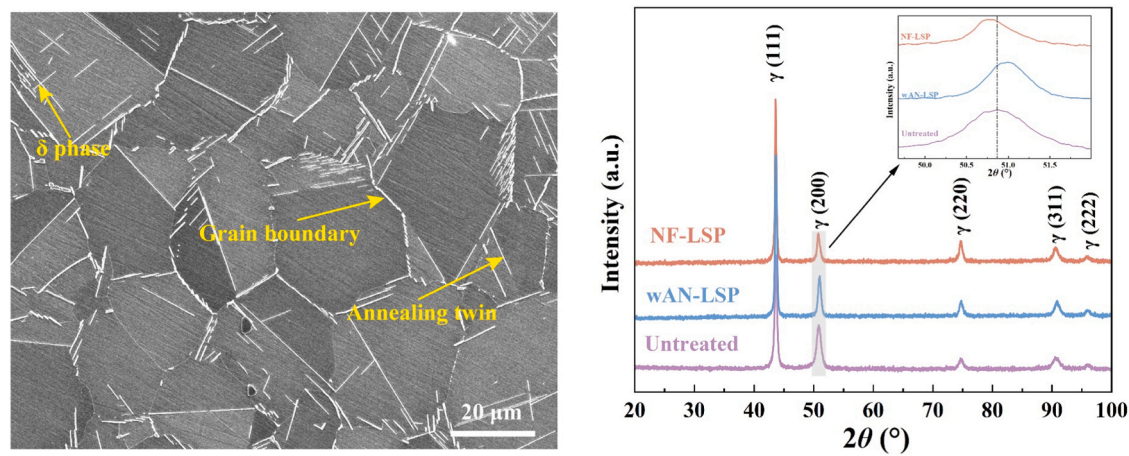


Fig. 1. Microstructure of GH4169 superalloy and XRD of GH4169 before and after different LSP treatments: (a) Microstructure and (b) XRD.

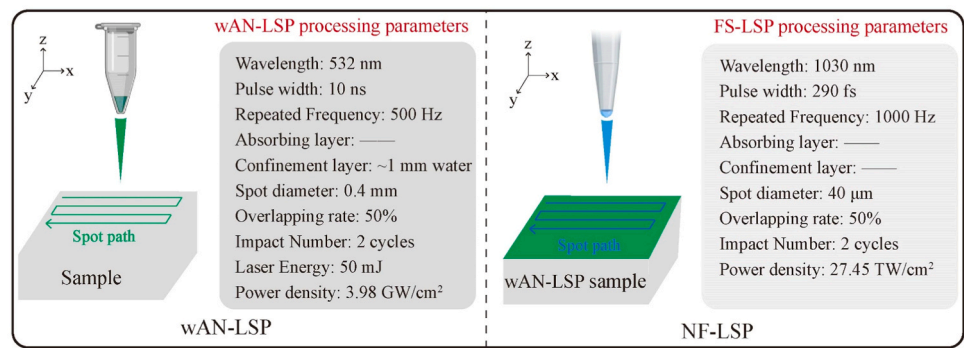


Fig. 2. Diagram of wAN-LSP and NF-LSP processing mode and processing parameters.

processing path is X-Y path.

2.3. Fretting wear test

The equipment is a self-developed tangential fretting wear test machine. Fig. 3 displays the schematic diagram of the equipment. The main components of the testing machine include lead screw, force sensor,

frame, voice coil motor, displacement sensor, guide rail, display and control system, as well as the upper clamp and lower clamp for fixing the specimen. The test in this paper adopts the ball plane contact mode. The size of the flat specimen is 10 × 10 × 6 mm, which is processed from GH4169 dovetail joint specimens. Al₂O₃ balls are used for the grinding pair and their diameter is 8 mm. The test parameters are listed in Table 2.

2.4. Morphology characterization

VHX-6000 super depth of field microscope (OM, Keyence, Japan) is utilized to watch the surface morphology of the specimen. White light interferometer (WLI, SuperView W1, Chotest, China) is utilized to observe the three-dimensional morphology of the specimen surface and measure its surface roughness. By field emission scanning electron microscope (SEM, Mira 3 XH, Tescan, Czech), the microstructure of the specimen is observed. The microhardness of the specimen section front and back LSP treatment is determined by the microhardness tester (KELITI-000ZB, Kerite, China). The test parameters used are load 200 g, pressure holding time 15 s. The phase composition of the GH4169

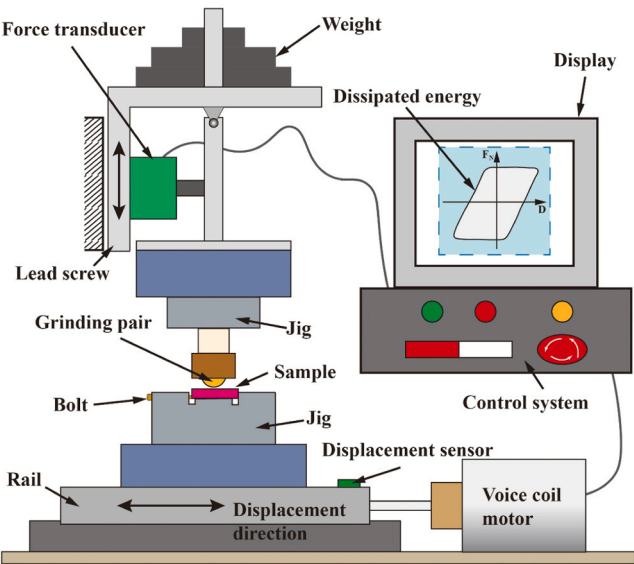


Fig. 3. Schematic diagram of fretting wear testing machine.

Table 2
Fretting wear test parameters.

Test parameters	Numerical values		
Specimen	Untreated	wAN-LSP	NF-LSP
Fretting cycle (×10 ⁴)	1	5	10 15 20
Normal load (N)	10		
Displacement amplitude (μm)	100		
Frequency (Hz)	10		
Temperature (°C)	RT		

surface before and after LSP strengthening treatment is tested by X-ray diffraction (XRD, Empyrean, Panalytical, Netherlands). The test parameters are shown as follows: the scanning angle range is 20–100 °, the step size is 0.02 °, and the Cu target is utilized as the X-ray source. To analyze the microstructural changes of specimen front and back wAN-LSP treatment, electron backscatter diffraction (EBSD, Bruker e-Flash^{FS}, Bruker, UK) is used to test the specimens, the Grain Average Misorientation (GAM) and inverse pole figure (IPFY) of plastic deformation layer were obtained.

3. Results

3.1. Surface morphology

Fig. 4 shows the three-dimensional surface morphology, OM and SEM morphology of GH4169 dovetail joint specimens before and after different LSP treatments. Since wAN-LSP treatment lacks absorption layer, the surface morphology has altered significantly by reason of the laser thermal effect. From the analysis of three-dimensional surface

morphology and OM morphology, wAN-LSP treatment makes the surface of the specimen rough, forming regular pits, and the surface roughness is found to have increased from 0.35 μm to 1.68 μm. Compared with wAN-LSP specimen, the surface of NF-LSP treated specimen is relatively flat and the roughness is reduced. Under the SEM morphology, there are obvious traces of wire cutting on the untreated specimen surface. The wAN-LSP treated specimen surface exhibits numerous molten layers, ablation holes and microcracks, resulting in a growth in surface roughness of GH4169 dovetail joint specimen. In Table 3, according to the statistics of surface chemical elements at point A and point B, the surface of wAN-LSP specimen is oxidized, the

Table 3
Content of chemical elements at point A - C (wt%).

Element	O	Ni	Fe	Cr	Nb	Mo
Point A	6.07	69.29	10.06	9.28	3.38	1.92
Point B	26.87	19.82	10.64	24.3	15.78	2.6
Point C	7.19	47.48	19.86	16.54	5.58	3.35

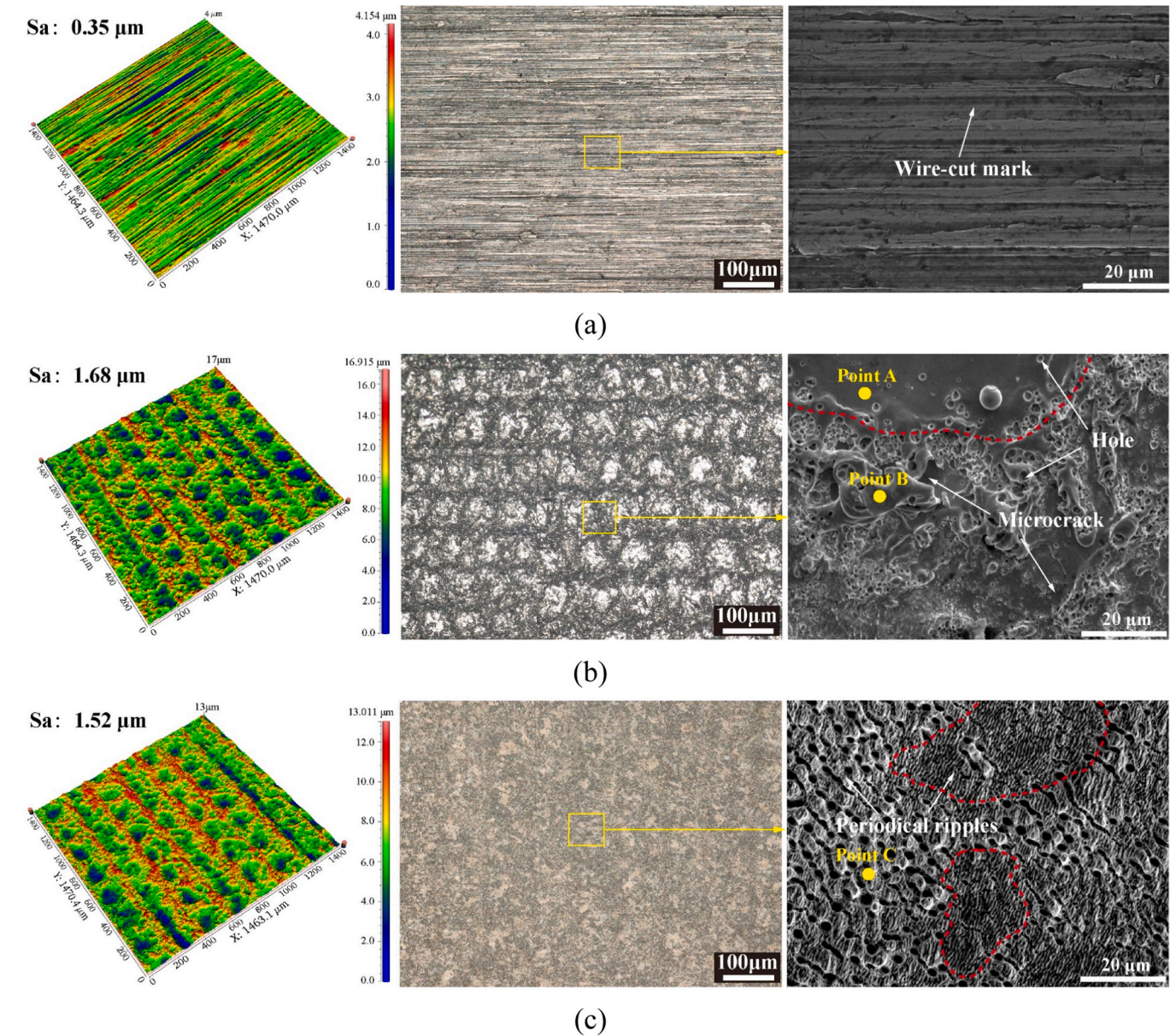


Fig. 4. Surface morphology of specimens: (a) Untreated, (b) wAN-LSP and (c) NF-LSP.

oxidation degree is unevenly distributed. The oxygen content of the smoother places is low, while the oxygen content of the molten layer was high. The NF-LSP specimen surface has no molten layer, ablation holes and microcracks, only regular periodic ripple structure, and the oxygen content in point C is also low. This indicates that the NF-LSP treatment can remove the surface oxidation defects produced by wAN-LSP.

3.2. Hardness and cross-sectional morphology

Fig. 5 shows the cross-section profile and cross-section hardness of specimens front and back different LSP treatments. Apparently, the cross-section of untreated specimens is relatively flat. After wAN-LSP treatment, the cross-section profile of GH4169 dovetail joint specimens have changed significantly, and the height difference of specimen cross-section has reached 8.14 μm . After NF-LSP treatment, the height difference of specimen cross-section is 6.21 μm , indicating that NF-LSP treatment can reduce the pit depth generated by wAN-LSP treatment. This results in an enhancement of surface quality and reduction of roughness. From Fig. 5(b) it can be apparently seen that a hardened layer roughly 400 μm deep is created on material surface of specimens following wAN-LSP and NF-LSP treatment. As the increase of depth, the microhardness gradually decreases until it is close to the matrix hardness, and in the hardened layer, the hardness value changes in a stepped distribution. The hardness in the hardened layer of NF-LSP specimen is slightly higher than wAN-LSP specimen, this phenomenon is more obvious at the depth of 100 μm , indicating that NF-LSP treatment can further enhance the surface microhardness without significantly increasing the depth of the hardened layer [31]. Because the laser wave induced by femtosecond laser can further produce plastic deformation and dislocation on the material surface, it will decay quickly inside the material and cannot affect the deeper part of the material [32].

Fig. 6 shows the SEM morphology of cross-sectional of GH4169 dovetail joint specimens after different LSP treatments. A molten layer approximately 10.97 μm thick appears on the surface of wAN-LSP specimen. Distinct boundary between the molten layer and the matrix, and there are holes and microcracks in the molten layer. This indicates that the thermal effect produced by wAN-LSP will only promote the appearance of the surface molten layer, holes and microcracks, but will not have more impact on the matrix [33]. The results of EDS show that numerous oxygen elements are found in the molten layer, indicating that this molten layer is consists of numerous oxides. The NF-LSP specimen section has a wavy shape, no molten layer and low oxygen content,

which further indicates that NF-LSP can remove the surface defects caused by surface oxidation after NF-LSP treatment.

3.3. Microstructure of cross-section

In order to analyze the geometric dislocation density and deformation layer depth in GH4169 dovetail joint specimens after LSP treatment, the wAN-LSP specimen is selected for EBSD test, and the GAM diagram and IPF diagram about 1200 μm along the section depth direction are obtained. Based on Fig. 7, the GAM map shows noticeable difference in orientation at the specimen surface, suggesting the occurrence of plastic deformation in this area [34–36]. Fig. 7(c, d) shows the statistical results of the kernel average misorientation (KAM) at the depth of 1000–1200 μm and 0–100 μm respectively. The value of KAM can represent dislocation density. The results show that the average KAM value at the 0–100 μm strengthened area is higher than that at the 1000–1200 μm un-strengthened area. wAN-LSP treatment introduces massive dislocations within the surface layer of GH4169 superalloy, leading to the development of a plastic deformation layer. The hardness of the material increases in proportion to the rising dislocation density [37]. Approximately 400 μm of plastic deformation layer is produced on the GH4169 superalloy surface by wAN-LSP treatment. The IPF diagram can reflect the change of grain size of GH4169 superalloy. Fig. 7(b) illustrates the existence of a plastic deformation layer above the GH4169 superalloy surface after wAN-LSP treatment, shows that the grain size of GH4169 superalloy has no significant change. Fig. 7(e, f) shows the grain size distribution statistics at the depth of 1000–1200 μm and 0–100 μm respectively. It can be seen that the grain size after strengthening has little difference from that of the un-strengthened region, this indicates that wAN-LSP treatment will not have a significant impact on the grain size of GH4169.

3.4. Fretting wear behavior

Fig. 8 shows the F-D-N and COF curves of different specimens after fretting wear test under different cycles. Under different cycles, the shapes of F-D-N curves both wAN-LSP and NF-LSP display a parallelogram shape, suggesting that the fretting mechanism is complete slip. This indicates that the number of fretting wear cycles and wAN-LSP and NF-LSP treatments does not affect the fretting mechanism of GH4169 dovetail joint specimens. The change trend of friction coefficient of GH4169 dovetail joint specimens after untreated and wAN-LSP, NF-LSP

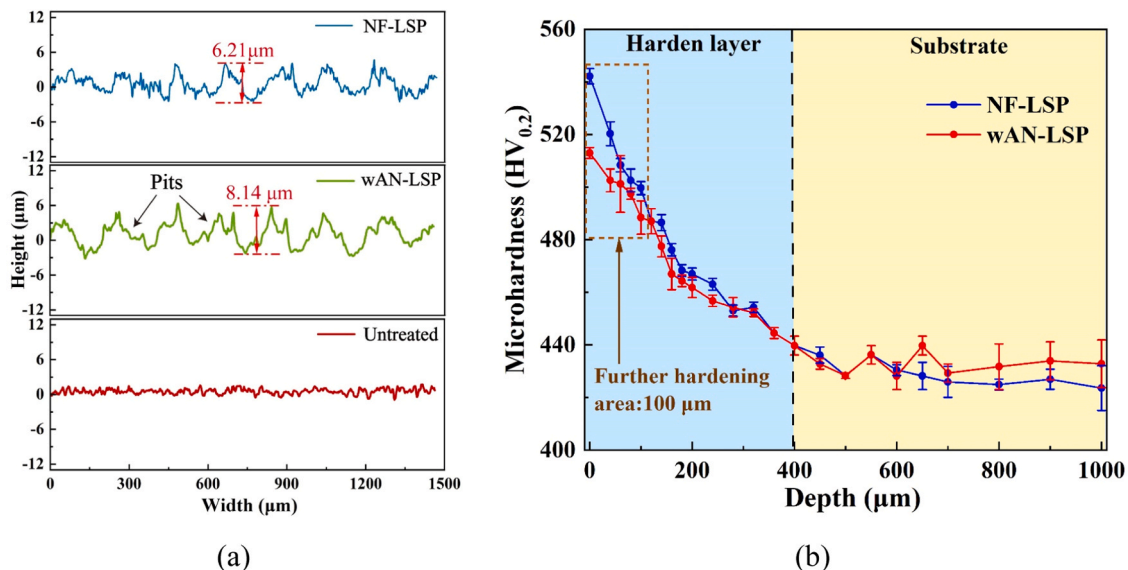


Fig. 5. Cross-section profile and Cross-section hardness of specimens before and after LSP treatment: (a) Cross-section profile and (b) Cross-section hardness.

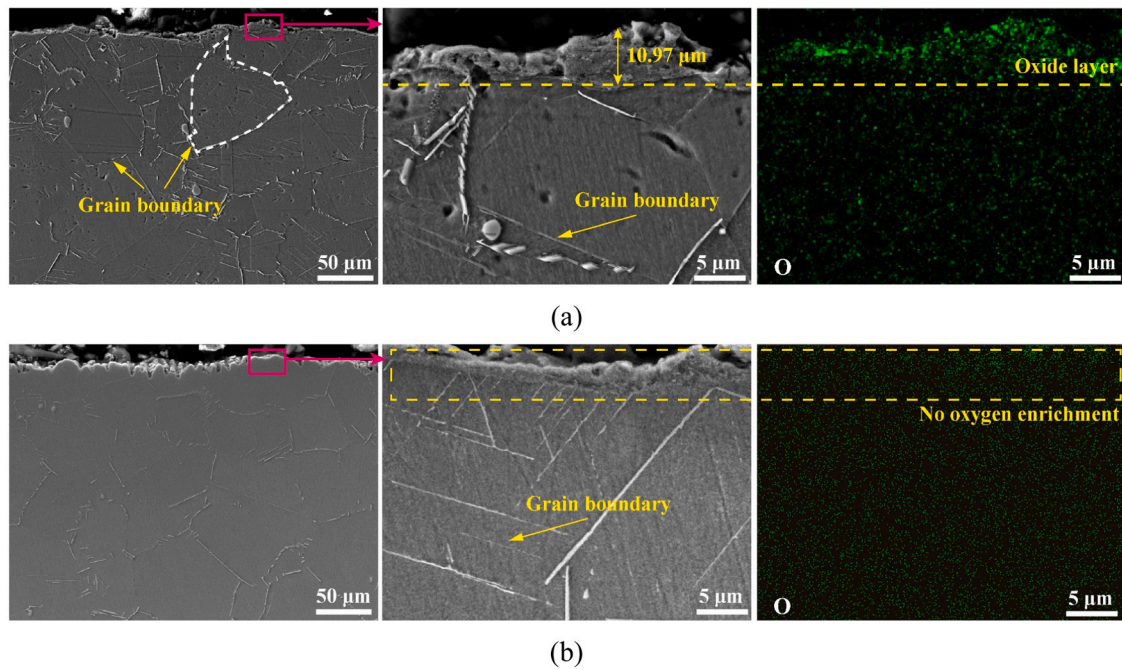


Fig. 6. Cross-section SEM morphology of specimens after LSP treatment: (a) wAN-LSP and (b) NF-LSP.

treatment is basically the same, and the change rule of friction coefficient curve is: at the beginning of wear, the friction coefficient rose rapidly. However, it eventually levels off as the fretting wear cycles increase, the cycle number and different LSP treatments have little effect on the coefficient of friction of GH4169 dovetail joint specimens for fretting wear.

Fig. 9 shows the three-dimensional morphology, cross-sectional profile and maximum wear depth of wear scar after fretting wear tests of three specimens under different cycles. The wear scar cross-sections of untreated, wAN-LSP and NF-LSP specimens under different cycles are all "U" shaped, indicating that GH4169 dovetail joint specimens will not change the fretting wear mechanism with the change of cycles and LSP treatment. The depth and width of wear scar of the three specimens gradually increase in the wake of the number of cycles increases. At 1×10^4 cycles and 5×10^4 cycles, the wear depth of the untreated and the wAN-LSP specimen is similar, but the width of the wAN-LSP specimen is marginally greater than that of the untreated specimen, which is more obvious when the number of cycles is 5×10^4 . The findings illustrate that the wear of GH4169 dovetail joint specimens after wAN-LSP treatment is more severe when the number of cycles is 1×10^4 and 5×10^4 . As the number of cycles increased to 1×10^5 , 1.5×10^5 and 2×10^5 , the wear depth of the untreated specimen and wAN-LSP specimen exceeded 11 μm, and the wear depth of wAN-LSP specimen is less than that of untreated specimen. However, the wear depth of NF-LSP specimen has a smaller wear depth compared to both the untreated and wAN-LSP specimens at varying cycles.

Fig. 10 shows the statistical results of the wear area and volume of three specimens behind fretting wear tests with different cycles. As the raise of wear cycles, both the wear area and wear volume of untreated, wAN-LSP and NF-LSP treated specimens also increase. However, there are some differences in these two aspects when the cycle times are different. As the increase of fretting wear cycle times, when the wear is in stage I before point A in Fig. 10, the wear area and volume of wAN-LSP specimen are higher than those of untreated specimen. When the wear is in stage II after point A in Fig. 10, the wear area and volume of wAN-LSP specimen exceed those of the untreated specimen. However, in the same stage, the wear area and wear volume of NF-LSP specimen are found to be lower than those of untreated and wAN-LSP specimen. This difference may be attributed to the ablation layer and hardening layer

formed on wAN-LSP treated specimen surface, along with the removal of oxidation defects and the subsequent enhancement of microhardness on the NF-LSP treated specimen surface.

4. Discussion

4.1. Wear scar analysis

Fig. 11 displays the OM morphology of wear scar. From morphology results, there are numerous debris and furrows on the scar surface along the fretting direction. In the wake of the rises of fretting wear cycles, the wear scar size of the three specimens increases gradually. When the number of cycles is 1×10^4 and 5×10^4 , the wear scar size of the wAN-LSP specimen is similar to that of the untreated specimen, while the NF-LSP specimen is smaller than two other kinds of specimens. When the number of cycles raises to 1×10^5 , 1.5×10^5 and 2×10^5 , the wear scar size of the specimen following wAN-LSP treatment is lesser than that of the untreated specimen, while the wear scar size of the NF-LSP specimen is still lesser than that of the untreated specimen and wAN-LSP specimen, which is conforming to the above alteration rule of wear area and wear volume.

Fig. 12 shows EDS results and SEM morphology of wear scar of untreated GH4169 dovetail joint specimens after fretting wear tests with different cycles. During ball-plane contact in fretting wear, the highest stress at the contact center causes wear and debris formation. As the raise of the number of cycles, cracks form on the larger debris, breaking them into smaller pieces. The fine debris will be discharged with the fretting direction. The debris will lead to furrow formation in the process of discharge, and finally the debris will be gathered at the margin of the wear scar. Debris generation, cracks, debris fragmentation and debris discharge, which is a cycle process [38]. According to the EDS results, under different fretting wear cycles, oxidation is evident on the wear scar's surface in varying degrees, with oxygen enrichment indicating oxidative wear. Alongside, the wear surface shows numerous debris and furrows, with cracks forming on the debris, a common characteristic of abrasive wear [39]. These findings suggest that oxidation wear and abrasive wear are the principal fretting wear mechanism of untreated GH4169 dovetail joint specimens.

Fig. 13 shows EDS results and SEM morphology of wear scar of

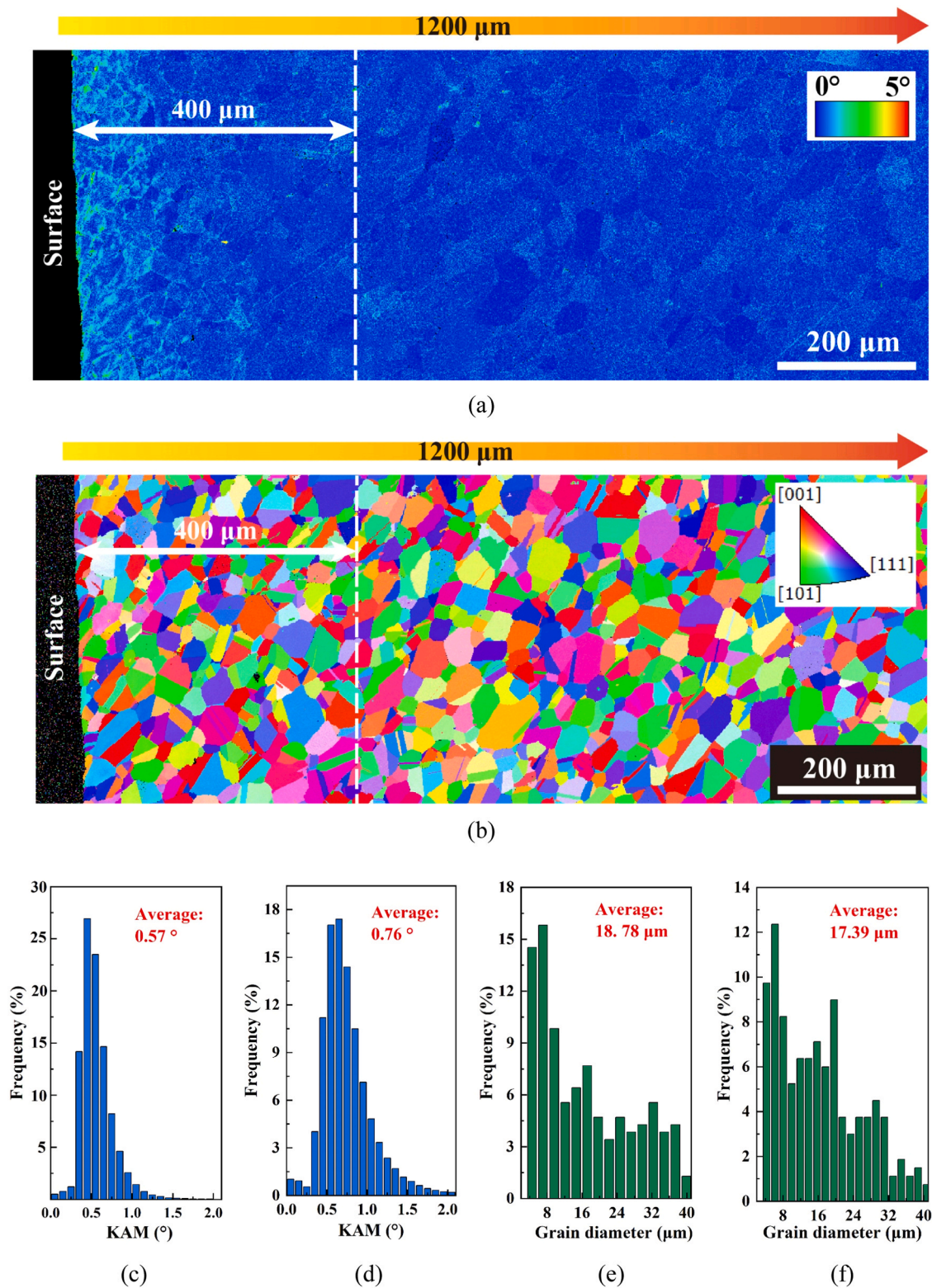


Fig. 7. GAM maps, IPF maps, KAM and grain size distribution statistics of GH4169 after wAN-LSP treatment: (a) GAM; (b) IPF; (c) KAM at 1000–1200 μm; (d) KAM at 0–100 μm; (e) grain size distribution at 1000–1200 μm; (f) grain size distribution at 0–100 μm.

GH4169 dovetail joint specimens after fretting wear test with different cycles after wAN-LSP treatment. The wear scar surface is oxidized to varying degrees, and there are furrows and numerous debris under all cycles. As the number of wear cycles reaches 1×10^4 and 5×10^4 , the oxygen content in the central area of the wear scar is low, while the edges show an abundance of oxygen. In addition to furrows and debris

on the surface of the wear scar, microcracks and holes are also appeared on the substrate, resulting from the molten layer created by wAN-LSP treatment. At this time, fretting wear occurs within this molten layer. After 1×10^5 cycles, the oxygen content in the central area of the wear scar increases, the holes and molten layer from wAN-LSP treatment on the surface of the wear scar disappear, leaving only minor furrows and

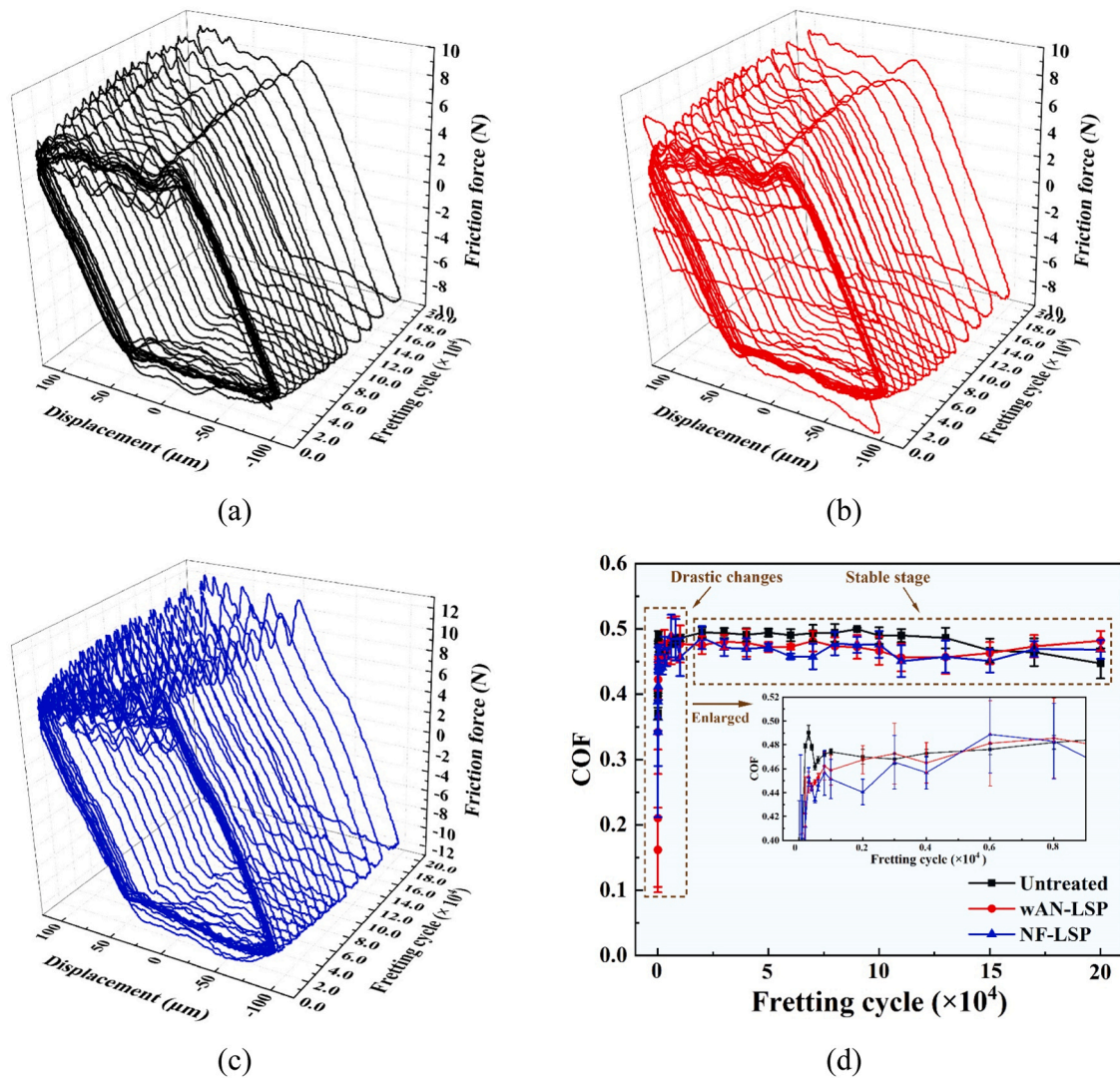


Fig. 8. F-D-N and COF curves of specimens: (a) F-D-N curves of untreated, (b) F-D-N curves of wAN-LSP, (c) F-D-N curves of NF-LSP and (d) COF.

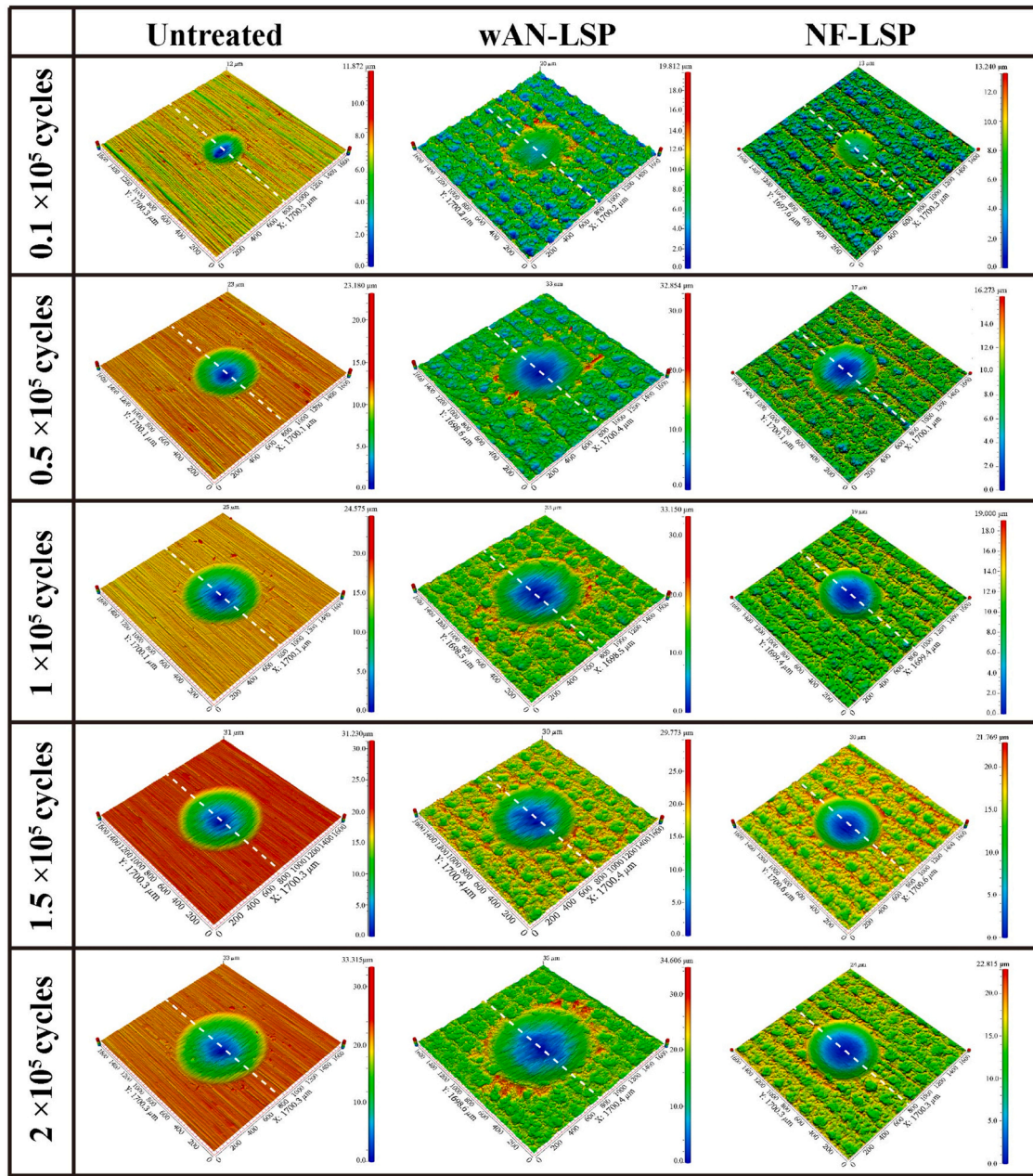
debris. By 1.5×10^5 cycles, the content of oxygen in the central increased further, and the wear debris increases. Cracks are observed on the wear debris. After 2×10^5 cycles, a significant buildup of oxygen is evident throughout both the central and edge areas of the wear scar. It is found that as holes and molten layers disappeared on the wear scar, numerous wear debris are generated and there were numerous cracks on the wear debris. The alternation of wear scar morphology may be related to the melted layer and hardened layer is formed by wAN-LSP treatment [39]. The findings illustrate that the mechanism of fretting wear of wAN-LSP treated GH4169 dovetail joint specimens has not changed, and it is still dominated by oxidation wear and abrasive wear.

Fig. 14 shows EDS results and SEM morphology of wear scar of GH4169 dovetail joint specimens after fretting wear test with different cycles after NF-LSP treatment. Uneven oxidation and oxidative wear occur in the wear process which is reason for oxygen enriched on the surface of the wear scar. At low cycle times, furrows and some wear debris appear on the surface, and microcracks are generated on the wear debris. Since no oxidation defects such as a molten layer were created on the surface of specimens following NF-LSP treatment, fretting wear occurred in the hardened layer at this time. When the number of cycles rises, numerous cracks begin to appear on the wear debris until it fell off. The peeled wear debris act as a solid lubricant to slow down the wear and improve wear resistance [40,41]. The mechanism of fretting wear of NF-LSP treated specimens is still dominated by oxidation wear and

abrasive wear.

4.2. Fretting wear mechanism

The mechanism of fretting wear of GH4169 dovetail joint specimens is shown in Fig. 15. Molten layer, microcracks and holes are formed on the GH4169 dovetail joint specimens after wAN-LSP treatment. In Fig. 6 (a) it is observed that the thickness of molten layer reaches $10.97 \mu\text{m}$, and the oxidation defects formed on the GH4169 dovetail joint specimens after NF-LSP treatment are removed, and the surface state is improved. The wear depth is less than the thickness of the molten layer when the fretting wear cycles reaches 1×10^4 and 5×10^4 , and there are phase microcracks and holes on the wear scar's surface, suggesting that the molten layer of wAN-LSP specimen is worn before 5×10^4 cycles. Due to the existence of microcracks and holes in the molten layer, the wear will be more intense, the material removal degree will be greater, and the wear will be more serious. Therefore, the wear volume of GH4169 after wAN-LSP treatment is slightly larger than that of untreated specimen. However, the degree of wear of NF-LSP specimen at this stage is slowed down due to its better surface state, and the wear volume is less than that of wAN-LSP specimen and untreated specimen. When the number of cycles rises further and the wear depth exceeds $11 \mu\text{m}$, the molten layer of wAN-LSP specimen is removed by wear. As shown in Fig. 5(b), both wAN-LSP and NF-LSP treatments are created a



(a)

Fig. 9. 3D morphology, cross-sectional profile and maximum wear depth of wear scar: (a) 3D morphology, (b) cross-sectional profile of Untreated, (c) cross-sectional profile of wAN-LSP, (d) cross-sectional profile of NF-LSP and (e) Maximum wear depth.

hardened layer approximately 400 μm deep on the GH4169 surface, which has the effect of resisting fretting wear [42,43]. The introduction of residual compressive stress is also one of the important contributions of laser shock peening. The plastic deformation of the contact area in the wear process will promote the increase of adhesion, and make the material surface and sub-surface form fatigue cracks. The residual compressive stress can offset the tensile stress in the wear process, inhibit the formation and propagation of micro cracks caused by friction, and reduce the wear damage [44,45]. Both the residual compressive stress and the hardened layer originate from the dislocation structure caused by laser shock peening. Consequently, as the raise of the number of cycles, the hardened layer begins to take effect, resulting in lower wear depth and volume for GH4169 specimens treated with

wAN-LSP and NF-LSP compared to untreated specimens. However, because NF-LSP treatment further enhances the microhardness of the surface layer, even if the molten layer of wAN-LSP specimen is removed by wear, the wear depth and wear amount of NF-LSP specimen are still less than wAN-LSP specimen, and NF-LSP specimen has better resistance to fretting wear. The authors have previously studied the wear performance difference between high-energy laser shock peening with absorber layer (HE-LSP) and wAN-LSP. It was found that the wear resistance of GH4169 superalloy was improved by HE-LSP treatment more than wAN-LSP treatment [39]. However, because the laser energy of HE-LSP is too large, it is easy to cause deformation for the processing of thin-wall and other workpieces, so the scope of application is limited. Some scholars have also studied the performance difference of

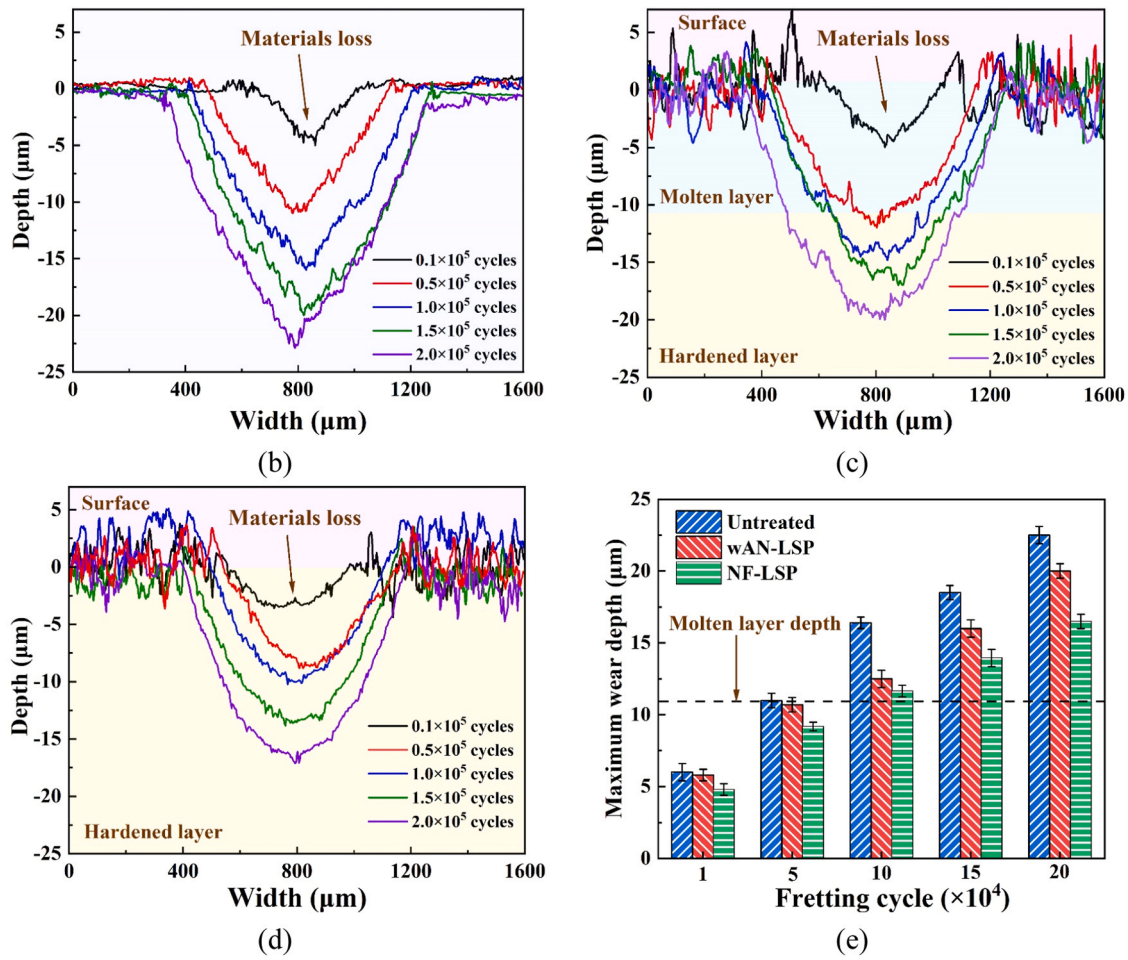


Fig. 9. (continued).

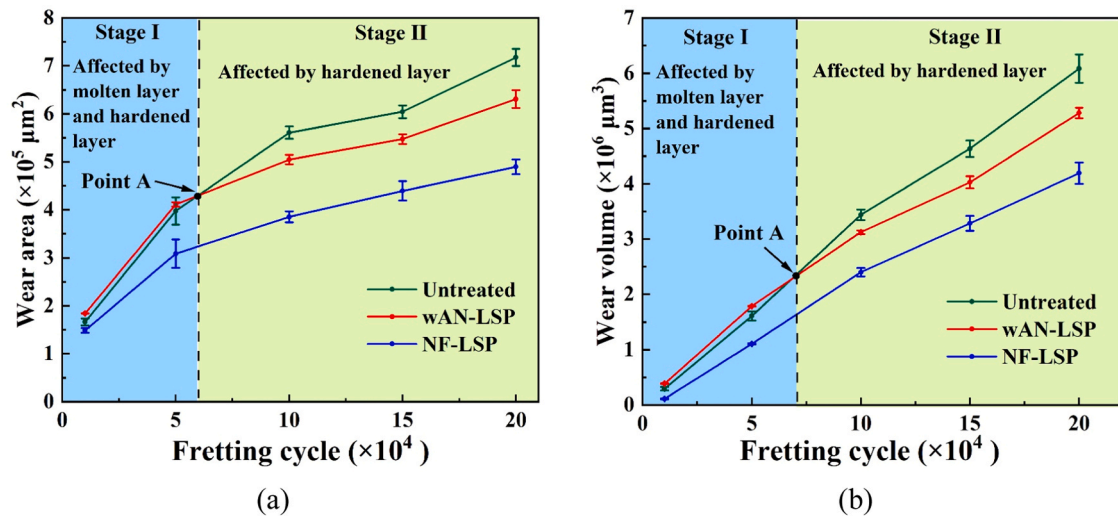


Fig. 10. wear results of specimens before and after LSP treatment: (a) wear area and (b) wear volume.

nanosecond laser shock peening with an absorption layer (LSP) and wAN-LSP. After LSP treatment, there is no surface molten layer, and the surface state is better than wAN-LSP. However, the microhardness of LSP treated specimen is generally less than wAN-LSP, and the refinement degree of LSP on the material is not as good as wAN-LSP [46–48]. Therefore, it is worth studying to maintain the plastic deformation

degree caused by wAN-LSP and remove its surface ablation defects.

In conclusion, oxidation wear and abrasive wear are the primarily mechanism of fretting wear of GH4169 dovetail joint specimens before and after wAN-LSP and NF-LSP treatment, and wAN-LSP and NF-LSP treatment will not affect this mechanism. As wear progresses, the wear volume of GH4169 dovetail joint specimens after wAN-LSP treatment

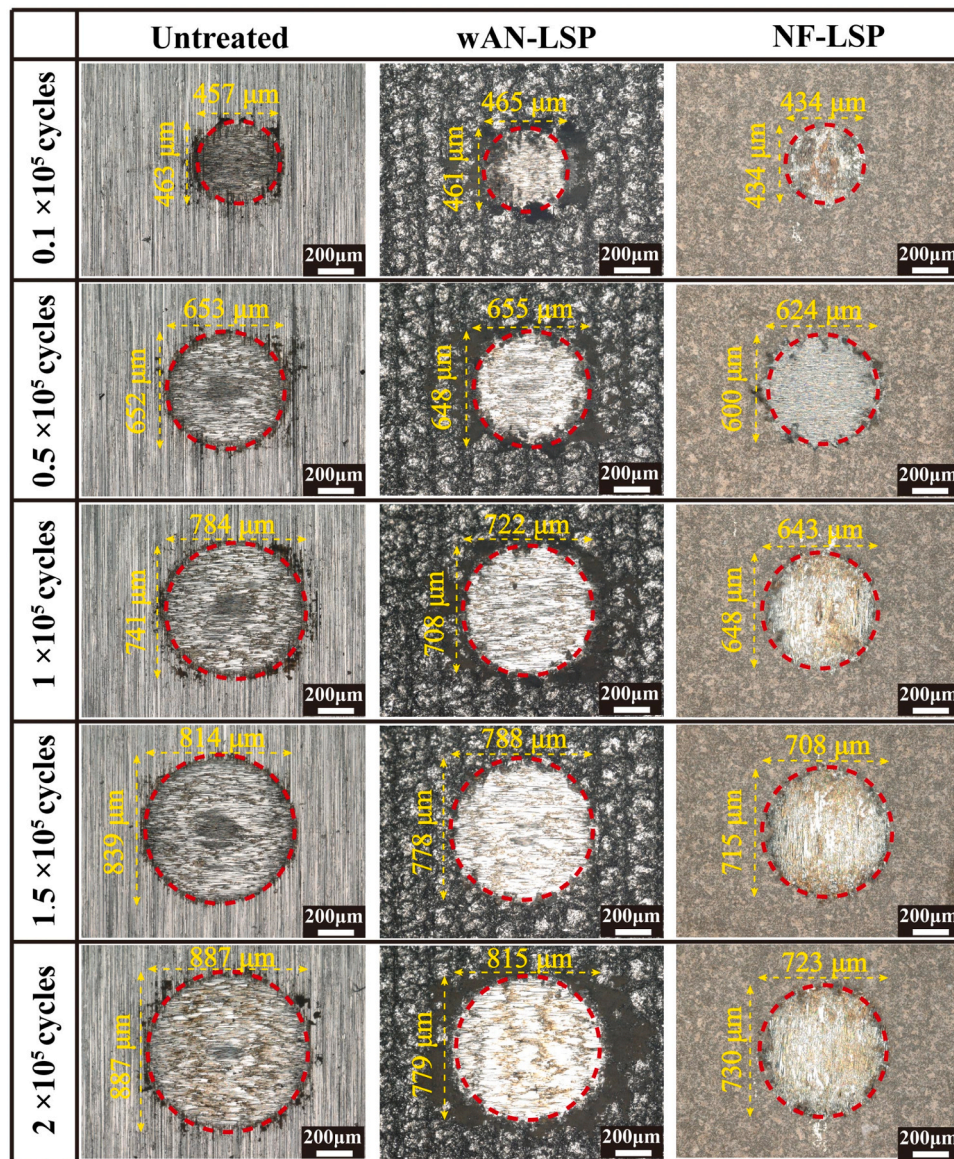


Fig. 11. OM morphology of wear scar.

surpassed that of untreated specimen at first, and then lesser than that. This is attributed to the impact of molten layer and hardened layer respectively. However, the wear volume of GH4169 dovetail joint specimens after NF-LSP treatment is always lesser than that of other two specimens. This is reason for the combined effects of enhancement in surface quality and further improving the hardness in hardened layer. The use of wAN-LSP treatment is proven to enhance the material surface's resistance to fretting wear. Nonetheless, this treatment can sometimes lead to the creation of a slight molten layer (approximately $10 \mu\text{m}$) on the surface of the strengthened layer. This molten layer exists in the form of ablative holes and microcracks, resulting in the materials have weak resistance of fretting wear at the initial stage of wear, which requires a certain running in period in actual engineering service. After the thin molten layer on the surface is removed, the parts will show excellent fretting wear resistance. Therefore, how to remove the surface molten layer caused by without absorbing layer nanosecond laser shock peening has become a key problem. Without absorbing layer nanosecond superimposed femtosecond hybrid laser shock peening can effectively improve this problem and make the surface of parts obtain more excellent fretting wear resistance.

5. Conclusion

In this paper, GH4169 dovetail joint specimens are treated with wAN-LSP and NF-LSP. The effects of molten layer and hardened layer on fretting wear evolution are analyzed by fretting wear tests under different cycles. The fretting wear evolution of GH4169 after wAN-LSP and NF-LSP treatment is revealed. The conclusions are as follows.

- 1) Both wAN-LSP and NF-LSP treatments change the surface state and created a plastic deformation layer. The thermal effect of wAN-LSP treatment creates a molten layer, as well as a high number of ablation holes and microcracks on the specimen surface. However, NF-LSP treatment completely eradicates these effects.
- 2) The fretting wear mechanism of GH4169 superalloy is not altered by the treatment of wAN-LSP and NF-LSP and the change of cycle times. The fretting mechanism is all gross slip and the mechanism of fretting wear is primarily the abrasive wear and oxidative wear.
- 3) The existence of molten layer and hardened layer leads to different wear properties of GH4169 specimen treated by wAN-LSP in the early and late stages of wear. After NF-LSP treatment, the wear properties of GH4169 specimen are always better than other

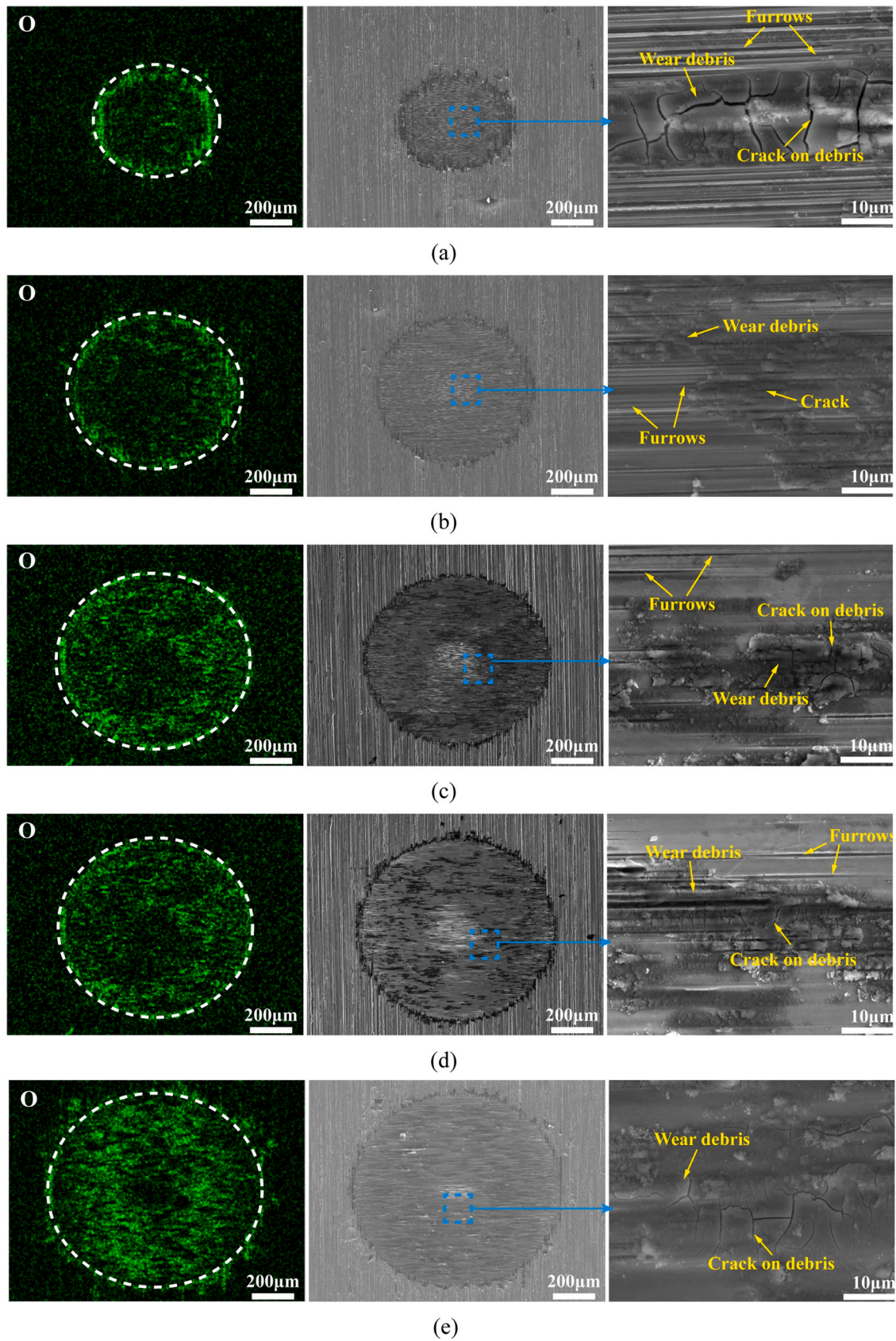


Fig. 12. EDS surface scan and SEM morphology of wear scar of untreated specimen: (a) 0.1×10^5 cycles, (b) 0.5×10^5 cycles, (c) 1×10^5 cycles, (d) 1.5×10^5 cycles and (e) 2×10^5 cycles.

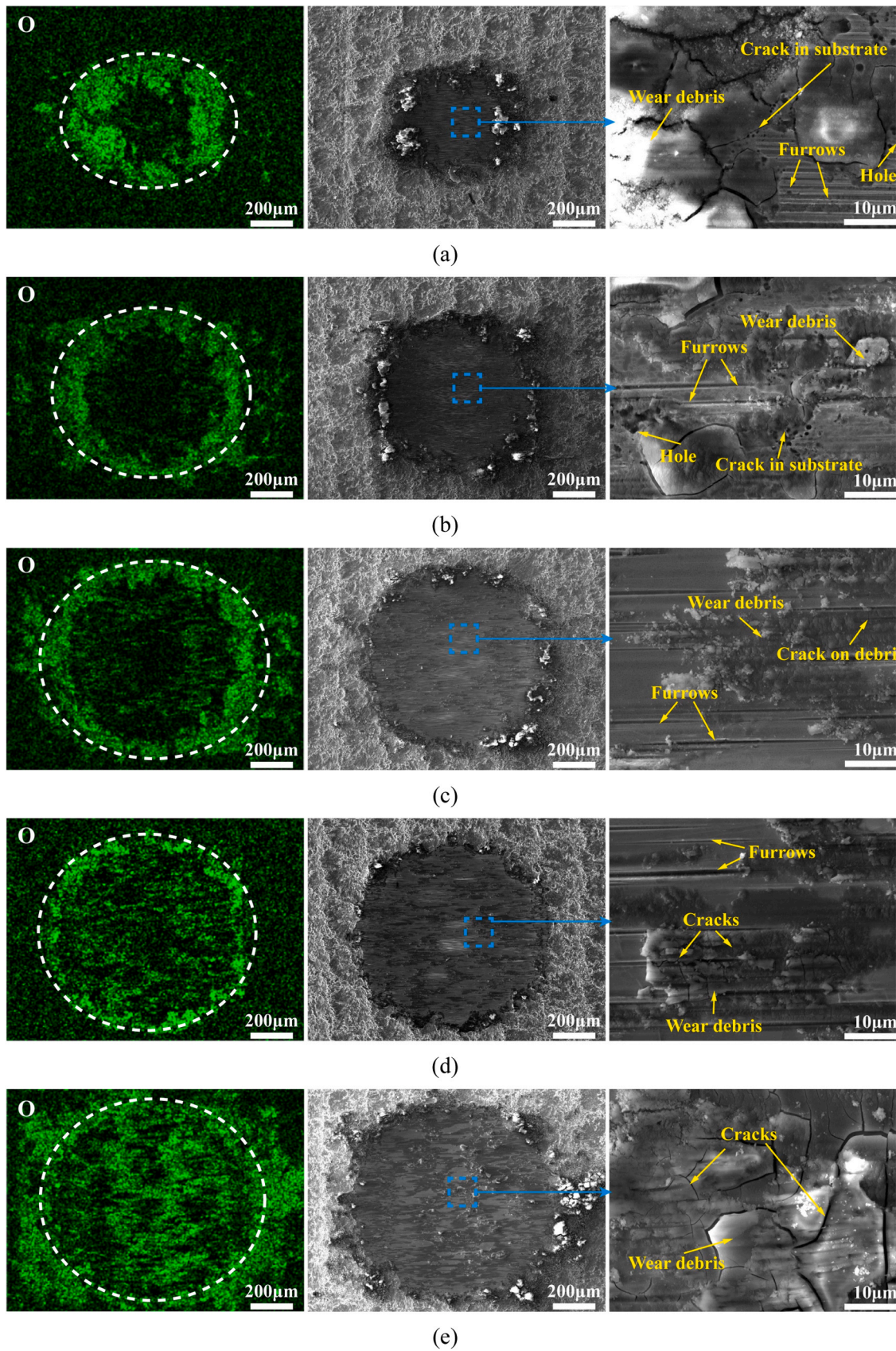


Fig. 13. EDS surface scan and SEM morphology of wear scar of wAN-LSP specimen: (a) 0.1×10^5 cycles, (b) 0.5×10^5 cycles, (c) 1×10^5 cycles, (d) 1.5×10^5 cycles and (e) 2×10^5 cycles.

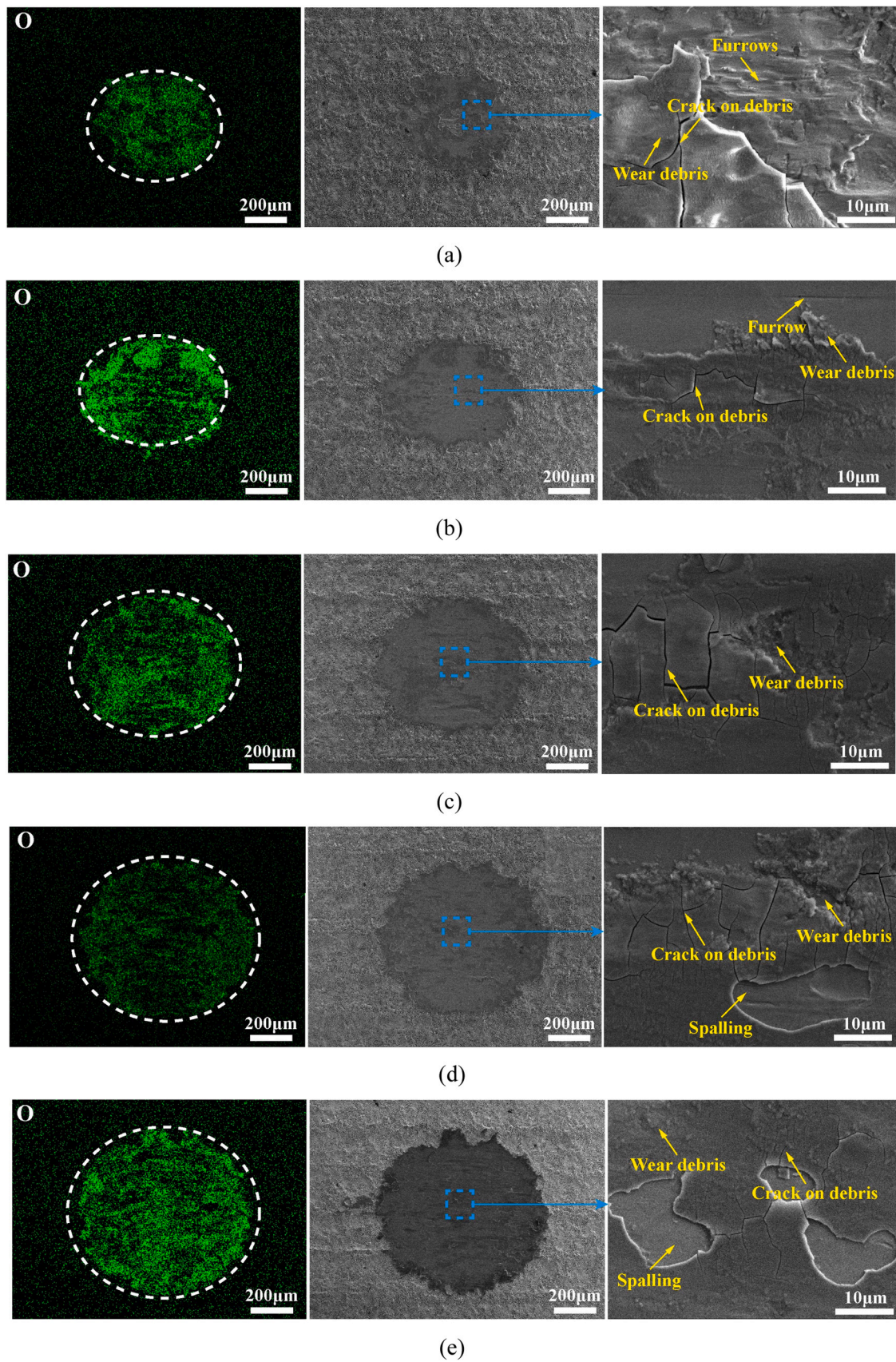


Fig. 14. EDS surface scan and SEM morphology of wear scar of NF-LSP specimen: (a) 0.1×10^5 cycles, (b) 0.5×10^5 cycles, (c) 1×10^5 cycles, (d) 1.5×10^5 cycles and (e) 2×10^5 cycles.

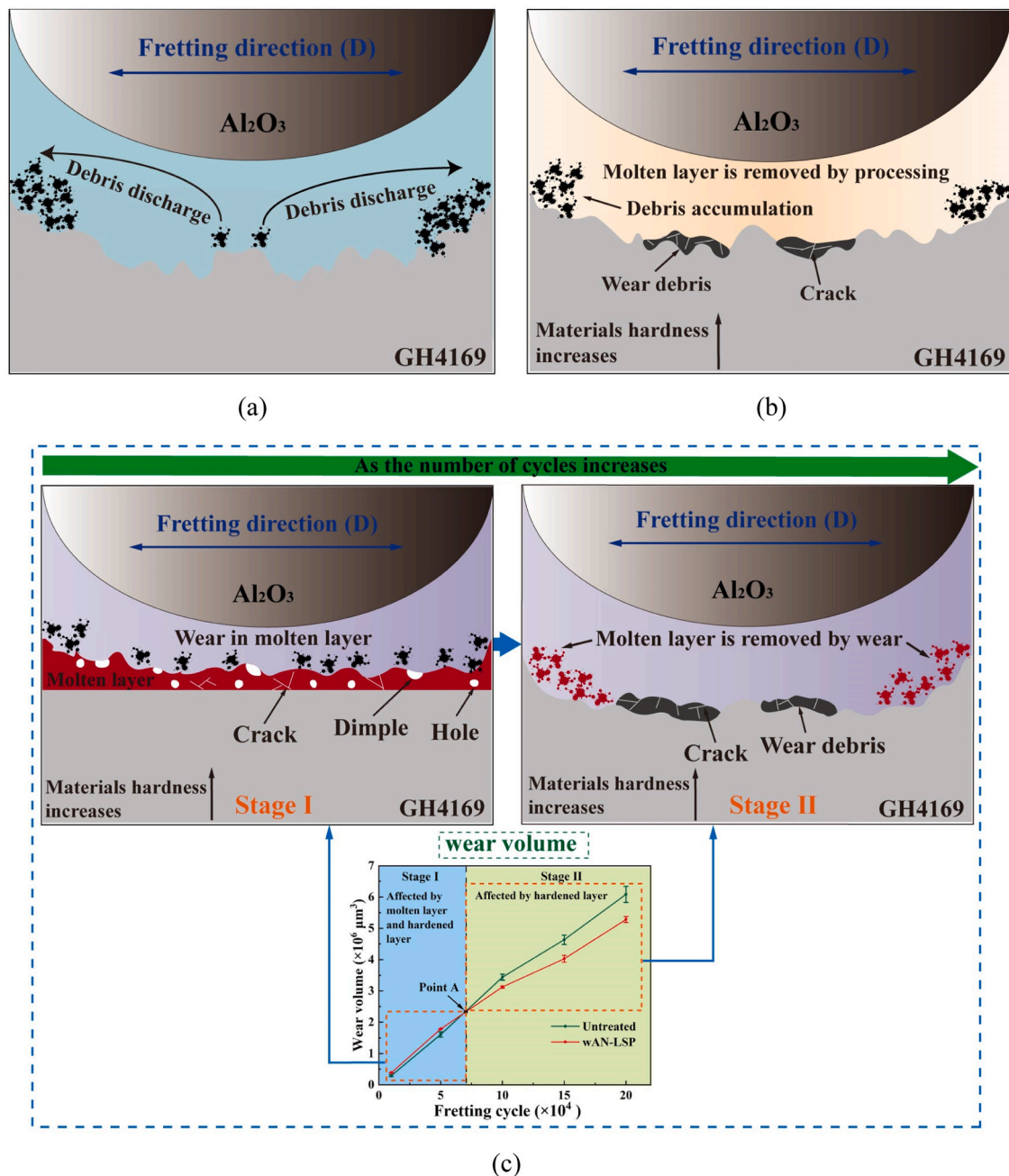


Fig. 15. Wear mechanism: (a) Untreated, (b) NF-LSP, (c) wAN-LSP.

specimens, which is the reason for the combined action of the enhancement in surface quality and the further increase of the hardness.

- 4) Oxidation defects occur on the surface of GH4169 dovetail joint specimens treated only by nanosecond laser shock peening, leading to the weakening of the fretting wear resistance during the initial wear stage. However, the use of nanosecond superimposed femto-second hybrid laser shock peening can effectively eliminate the oxidation defects, resulting in significantly improved fretting wear resistance on the specimen's surface.

Statement of Originality

This manuscript has neither been published nor been submitted elsewhere for review.

To the best of my knowledge and belief, the manuscript contains no

material previously published or written by another person except where due reference is made in the thesis itself.

CRediT authorship contribution statement

Cai Zhenbing: Supervision, Conceptualization. **Liu Xing:** Data curation. **Liu Xiong:** Investigation. **Gong Jianen:** Methodology, Investigation. **Abdel Wahab Magd:** Writing – review & editing, Supervision. **Wang Zheng:** Writing – review & editing, Resources. **Fang Xiuyang:** Writing – review & editing, Writing – original draft, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the financial support from the National Key R&D Projects (2022YFB3401900), Sichuan Science and Technology Program (2025YFHZ0163), and Fundamental Research Funds for the Central University (2682024GF004).

Data availability

The authors do not have permission to share data.

References

- Chen X, Lin Y, Wen D, Zhang J, He M. Dynamic recrystallization behavior of a typical nickel-based superalloy during hot deformation. *Mater Des* 2014;57: 568–77.
- Dong Y, Zeng D, Wu P, Lu T, Zhao H, Li Y, et al. Study on fretting fatigue crack initiation of scaled railway axles in consideration of fretting wear. *Wear* 2023;512–513. :204545–204545.
- Mishra D, Maurya R, Verma V, Balani K, Krishna K, Srivastava D, et al. Understanding the influence of graphene-based lubricant coating during fretting wear of zircaloy. *Wear* 2023;512–513. :204527–204527.
- Schafrik R, Sprague R. Superalloy technology-a perspective on critical innovations for turbine engines. *Key Eng Mater* 2008;380:113–34.
- Rajasekaran R, Nowell D. Fretting fatigue in dovetail blade roots: experiment and analysis. *Tribol Int* 2006;39(10):1277–85.
- Kumara C, Wang R, Lu R, Deck C, Gazza J, Qu J. Grid-to-rod fretting wear study of SiC/SiC composite accident-tolerant fuel claddings using an autoclave fretting bench test. *Wear* 2022;488:204172.
- Yang J, Liu D, Ren Z, Zhi Y, Zhang X, Zhao R, et al. Grain growth and fatigue behaviors of GH4169 superalloy subjected to excessive ultrasonic surface rolling process. *Mater Sci Eng A* 2022;839:142875.
- Qin Z, Li B, Chen C, Chen R, Zhang H, Xue H, et al. Crack initiation mechanisms and life prediction of GH4169 superalloy in the high cycle and very high cycle fatigue regime. *J Mater Res Technol* 2023;26:720–36.
- Liu L, Gao Y, Du J, An T. Oxidation damage zone formed in creep fatigue crack growth of GH4169 alloy at 650°C. *J Iron Steel Res Int* 2023;30:2582–92.
- Sano Y, Akita K, Sano T. A mechanism for inducing compressive residual stresses on a surface by laser peening without coating. *Metals* 2020;10(6):816.
- Yuan T, Dou M, Liu L, Li L, Sun S, Hu C. Improving high temperature fretting fatigue performance of nickel-based single crystal superalloy by shot peening. *Int J Fatigue* 2023;171:107563.
- Yang J, Liu D, Fan K, Liu Y, Ren Z, Liu D, et al. Designing a gradient structure in a Ni-based superalloy to improve fretting fatigue resistance at elevated temperatures through an ultrasonic surface rolling process. *Int J Fatigue* 2023;168:107397.
- Tang G, Sun S, Yang J, Pan Y, Liu Z, Liang Z. Fabrication and tribological properties of WC-reinforced Inconel X-750 alloy at elevated temperature. *J Manuf Process* 2024;131:1321–33.
- Geng Y, Mo Y, Zheng H, Li G, Wang K. Effect of laser shock peening on the hot corrosion behavior of Ni-based single-crystal superalloy at 750°C. *Corros Sci* 2021; 185:109419.
- Digonta H, Fatemi A. Laser shock peening and its effects and modeling on fatigue performance of additive manufactured metallic materials. *Theor Appl Fract Mec* 2024;130:104281.
- Park C, Jung D, Chun EJ, Ahn S, Jang H, Kim Y. Effect of laser shock peening without coating on fretting corrosion of copper contacts. *Appl Surf Sci* 2020;514: 145917.
- Pan X, Zhou L, Wang C, Yu K, Zhu Y, Yi M, et al. Microstructure and residual stress modulation of 7075 aluminum alloy for improving fatigue performance by laser shock peening. *Int J Mach Tool Man* 2023;184:103979.
- Chen X, Li K, Lin Y, Xu Z, Guo B, Chen J, et al. Effect of laser shock peening uniformity on bending fatigue life of 20CrNiMo. *Opt Laser Technol* 2024;175: 110704.
- Gu C, Wang C, Zhao J, Wang Y, Tian Z. Crystal and dislocation characteristics of Ti-6Al-4V alloy under effect of laser shock peening. *Materials* 2025;18(2):378.
- Prabhakaran S, Kalainathan S, Shukla P, Vasudevan V. Residual stress, phase, microstructure and mechanical property studies of ultrafine bainitic steel through laser shock peening. *Opt Laser Technol* 2019;115:447–58.
- Lu Z, Xu F, Tang C, Cui Y, Xu H, Mao J. Stress Corrosion cracking susceptibility of 304 stainless steel subjected to laser shock peening without coating. *J Mater Eng Perform* 2021;30(10):7163–70.
- Li Y, Ren Z, Jia X, Yang W, Nassreddin N, Dong Y, et al. The effects of the confining medium and protective layer during femtosecond laser shock peening. *Manuf Lett* 2021;27:26–30.
- Wang H, Jurgensen J, Decker P, Hu Z, Yan K, Gurevich E, et al. Corrosion behavior of NiTi alloy subjected to femtosecond laser shock peening without protective coating in air environment. *Appl Surf Sci* 2020;501:144338.
- Zhao W, He W, Zhu D, Liang X, Pang Z, Song J, et al. Comparative investigation on microstructure and mechanical properties of GH4169 superalloy after laser shock peening with and without coating. *J Mater Res Technol* 2024;29:276–85.
- Dhakal B, Swaroop S. Mechanical properties and deformation dependent microstructural aspects of laser shock peened 7075-T6 aluminum alloy without coating. *Mater Charact* 2022;183:111620.
- Nataraj M, Swaroop S. Deformation-induced phase transition and nanotwins in SS 304 steel during cryogenic laser shock peening without coating. *J Mater Res Technol* 2022;19:2611–22.
- Zhao W, He W, Liang X, Huang Z, Zhou Q, Pang Z, et al. Enhancing elevated-temperature fretting wear performance of GH4169 by tuning wear mechanism through laser shock peening. *Tribol Int* 2024;192:109215.
- Praveenkumar K, Swaroop S, Manivasagam G. Effect of multiple laser peening on microstructural, fatigue and fretting-wear behaviour of austenitic stainless steel. *Surf Coat Tech* 2022;443:128611.
- Yang F, Zhao T, He P, Zhou L, Pan X, Liang X, et al. Effect of pulsed femtosecond laser shock peening surface modification on anti-wear failure properties of AISI 9310 gear steel. *Eng Fail Anal* 2024;159:108146.
- Sano T, Eimura T, Kashiwabara R, Matsuda T, Lsshiki Y, Hirose A, et al. Femtosecond laser peening of 2024 aluminum alloy without a sacrificial overlay under atmospheric conditions. *J Laser Appl* 2017;29:012005.
- Sun R, He G, Bai H, Yan J, Guo W. Laser shock peening of Ti6Al4V alloy with combined nanosecond and femtosecond laser pulses. *Metals* 2021;12(1):26.
- Guo W, Wang H, He G, Peng P, He D, Han G, et al. Comparison of mechanical and corrosion properties of 7050 aluminum alloy after different laser shock peening. *Opt Laser Technol* 2022;151:108061.
- Nikitin I, Altenberger I. Comparison of the fatigue behavior and residual stress stability of laser-shock peened and deep rolled austenitic stainless steel AISI 304 in the temperature range 25–600 °C. *Mat Sci Eng A* 2007;465(1–2):176–82.
- Li Z, Guo X, Yu S, Yu S, Ning C, Jiao Y, Cai Z. Influence of laser shock peening on surface characteristics and corrosion behavior of zirconium alloy. *Mater Charact* 2023;206:113387.
- Bazarbayev Y, Kattoura M, Mao K, Song J, Vasudevan V, Wharry J. Effects of corrosion-inhibiting surface treatments on irradiated microstructure development in Ni-base alloy 718. *J Nucl Mater* 2018;512:276–87.
- Kattoura M, Mannava S, Qian D, Vasudevan V. Effect of ultrasonic nanocrystal surface modification on elevated temperature residual stress, microstructure, and fatigue behavior of ATI 718Plus alloy. *Int J Fatigue* 2018;110:186–96.
- Liu Y, Wang L, Yang K, Song X. Mechanism for superior fatigue performance of warm laser shock peened IN718 superalloy after high-temperature ageing. *J Alloy Compd* 2022;923:166340.
- Zhao W, He W, Liang X, Huang Z, Zhou Q, Pang Z, et al. Enhancing elevated-temperature fretting wear performance of GH4169 by tuning wear mechanism through laser shock peening. *Tribol Int* 2024;192:109215.
- Fang X, Gong J, Yu Y, Yu S, Zhou L, Zhang Z, et al. Study on the fretting wear performance and mechanism of GH4169 superalloy after various laser shock peening treatments. *Opt Laser Technol* 2024;170:110301.
- Yuan X, Li G, Zhang X, Pu J, Ren P. An experimental investigation on fretting wear behavior of copper-magnesium alloy. *Wear* 2020;462:203497.
- Zhang S, Liu L, Ma X, Zhu G, Tan W. Effect of the third body layer formed at different temperature on fretting wear behavior of 316 stainless steel in the composite fretting motion of slip and impact. *Wear* 2022;492:204220.
- Kumar S, Raman S, Narayanan T, Gnanamoorthy R. Influence of counterbody material on fretting wear behaviour of surface mechanical attrition treated Ti-6Al-4V. *Tribol Int* 2013;57:107–14.
- Kumar S, Sai S, Raman S, Gnanamoorthy R. Fretting wear behaviour of 304 stainless steel fretted against different counterbody materials. *Tribol-Mater Surf In* 2013;7(4):168–74.
- Cao Z, Cui L, Luo S, Su H, Pang Z, Zhao W, et al. Superior fretting wear resistance of titanium alloys from stable gradient nanostructures induced by laser shock peening. *Int J Plast* 2025;188:104293.
- Li G, Hong B, Song D, Ma Y, Yuan C. Effect of pulsed current coupled ultrasonic rolling on surface fretting friction and wear properties of Ti-6Al-4V alloy 2025;568–569:205959.
- Tong Z, Jiao J, Zhou W, Yang Y, Chen L, Liu H, et al. Improvement in cavitation erosion resistance of AA5083 aluminium alloy by laser shock processing. *Surf Coat Tech* 2019;377:124799.
- Zhao W, He W, Zhu D, Liang X, Pang Z, Song J, et al. Comparative investigation on microstructure and mechanical properties of GH4169 superalloy after laser shock peening with and without coating. *J Mater Res Technol* 2024;29:276–85.
- Luo K, Sun M, Lu J, Zhang Q, Jiang X, Wang C, et al. The effect of laser shock peening with and without coating on microstructure and electrochemical corrosion behavior of AZ31b magnesium alloy. *Surf Coat Tech* 2025;496:131709.