

Review

Review on Anti-Fatigue Performance of Gradient Microstructures in Metallic Components by Laser Shock Peening

Fei Yang ¹, Ping Liu ², Liucheng Zhou ^{1,*}, Weifeng He ¹ , Xinlei Pan ¹ and Zhibin An ¹

¹ National Key Lab of Aerospace Power System Safety and Plasma Technology, Air Force Engineering University, Xi'an 710038, China

² Institute of Aviation, Chongqing Jiaotong University, Chongqing 400074, China

* Correspondence: happyzlc@163.com; Tel.: +86-133-2454-3606

Abstract: Laser-shock-peening technology is an international research hotspot in the surface-strengthening field, which utilizes the mechanical effects of laser-induced plasma shock waves to effectively improve the fatigue performance of metallic components by introducing the gradient microstructures and compressive residual stress into the surface layer of processed materials. The fatigue failure caused by high-frequency vibrations in aeroengines during service is the most important threat to flight safety, and this case is more prominent for military aeroengines because their service situation is harsher. The present paper focuses on components such as high-temperature components, fan/compressor blade, and thin-walled weldments, and it systematically introduces the researching findings about surface nanocrystallization and compressive residual stress formation mechanism in typical aeronautical metallic materials treated by laser shock peening. The contents mainly involve the characteristics, formation process, fatigue resistance mechanism, thermal stability of residual compressive stress, and nanocrystallization generated by laser shock peening.

Keywords: laser shock peening; aeroengine; gradient structure; residual compressive stress; anti-fatigue



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1. Introduction

The aeroengine service environment is complex and harsh, and its mechanical components are prone to vibration fatigue failure under the long-term coupling effect of airflow excitation, mechanical excitation, and acoustic excitation. For example, the high incidence of failures in fan/compressor blades, thin-walled weldments, and high-temperature turbine blades [1] greatly affects the safety and reliability of aircraft operations as shown in Figure 1. Understanding how to improve the fatigue performance of important components of aeroengines has become a vital technical problem that needs to be solved at home and abroad [2–4].



Figure 1. Typical vibration fatigue weak link of aeroengine (a) turbine blades; (b) fan/compressor blades; (c) thin-walled weldments.

Because fatigue cracks usually originate from the surface of the component [5,6], surface-strengthening techniques have become an important tool to improve the fatigue performance of components. Common surface-strengthening processes include shot peening (SP) [7], laser shock peening (LSP) [8], deep rolling (DP) [9], ultrasonic nanocrystal

surface modification (UNSM) [10], etc. LSP utilizes a high-energy laser with a pulse duration of several ns to irradiate the surface materials. The absorbing protective layer coated on the metal surface absorbs the laser energy and explosively vaporizes, producing plasma with high temperature ($>10^7$ K) and high pressure (>1 GPa). The force effect of high-pressure plasma shock wave causes plastic deformation of the material surface layer, forming gradient structure and gradient residual compressive stress field to improve fatigue performance [11–13]. It has the advantages of good effect, deep influence layer, controllability, adaptability, and a low cold-work-hardening rate. The effect of this technology on fatigue performance enhancement has been experimentally verified on a variety of commonly used metallic materials in aviation, such as aluminum alloys [14], magnesium alloys [15], titanium alloys [16–18], superalloys [19,20], and steels [21–23], which have been widely used in aviation equipment.

The mechanism of LSP improving the component fatigue performance is studied from two aspects, including residual compressive stress induced by laser and microstructure change, as shown in Figure 2. When the shock wave pressure is greater than a certain threshold, serious plastic deformation occurs on the surface material, forming defects such as dislocation and refining grains, and forming nanocrystals that gradually transition in the direction of laser gradient. Residual compressive stress can reduce the crack propagation rate and enhance the crack closure effect by balancing the working tensile stress and reducing the threshold stress intensity factor of the alternating tensile stress and crack so as to improve the fatigue strength of the material. However, metal parts in the aviation field usually work in harsh environments and residual compressive stress is easy to relax, thus affecting the effect of anti-fatigue strengthening. In contrast, gradient nanostructures require more energy to move grain boundaries per unit area per unit distance. Therefore, non-elemental nanomaterials generally have poor grain boundary activity and better stability under extreme use conditions and can still guarantee anti-fatigue effects after residual tensile stress relaxation.

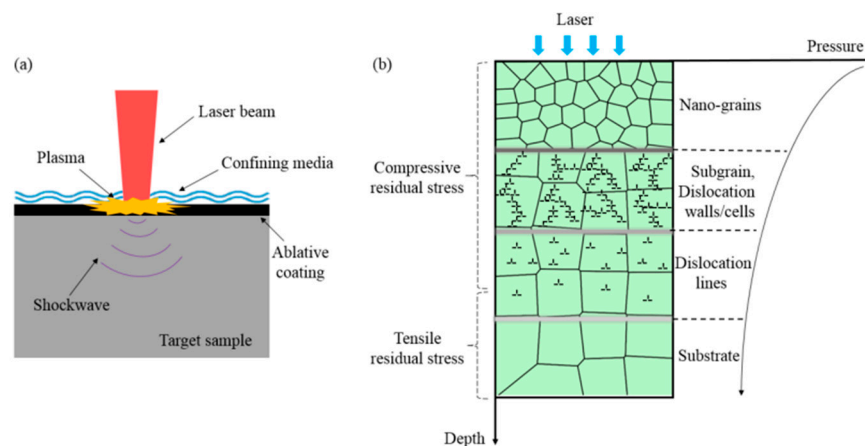


Figure 2. (a) Schematic of the laser-shock-peening (LSP) process. A high-energy laser pulse is generated to hit the target, the cooperation of ablative coating materials and confinement layer leading to the formation of high-pressure shock waves; (b) Schematic of gradient microstructures and residual stress induced by LSP. Gradient microstructures characterized by refined grains → dislocation cells (walls) → dislocation lines are formed along the depth direction; compressive residual stress is introduced in the surface region, while tensile residual stress is generated in the substrate. Reprinted with permission from Ref. [24]. 2022, Elsevier.

Laser-shock-peening equipment is a high-power pulse laser [25] because it requires a short amount of time to produce high-energy pulsed laser beams for material processing, which is commonly used models including Nd:Glass, Nd:YAG, etc., supporting the use of the constraint layer system, optical path system, monitoring system, and other auxiliary facilities. Table 1 shows the process parameters of LSP processing. For different materials, different conditions of use and obvious technical limitations, new technologies for

cryogenic LSP (CLSP) [26], electropulsing-assisted LSP (EP-LSP) [27], femtosecond LSP (FLSP) [28], and more new technologies for ultrashort-laser-enhanced processing [29] have been developed in recent years.

Table 1. Comparison of different process parameters in LSP.

LSP Process Parameter	Definition	The Effect on the Peening Process	References
Power density	Laser beam energy per unit area and per unit time	Induced shock wave intensity	[30]
Overlap ratio	Overlay area coverage of different laser pulses	Coupling of shock waves induced by different laser beams	[31]
Laser spot characteristics	Spot shape, spot size, distance between adjacent spots	Properties of the induced shock wave	[32]
Impact times	The number of laser processing times	Multiple shocks affect the residual compressive stress and the depth of action	[33,34]

This review takes titanium alloy, nickel-based superalloy, and other typical structural component materials as research objects, and engine fan/compressor blades, high-temperature components, thin-walled weldments, and other components with high failure rates as application cases. The research results on the application of LSP on aeroengine components are systematically summarized, focusing on the characteristics of LSP-induced surface nanocrystallization of metal materials, residual stress characteristics, formation principles, thermal stability, fatigue resistance mechanism, and process methods, etc. The effects of residual compressive stress and nanocrystals on the properties of common metals used in aeroengine components are reviewed, and the latest progress in LSP technology to enhance foreign object damage (FOD) performance and fatigue resistance is discussed. Figure 3 shows the research framework of the review.

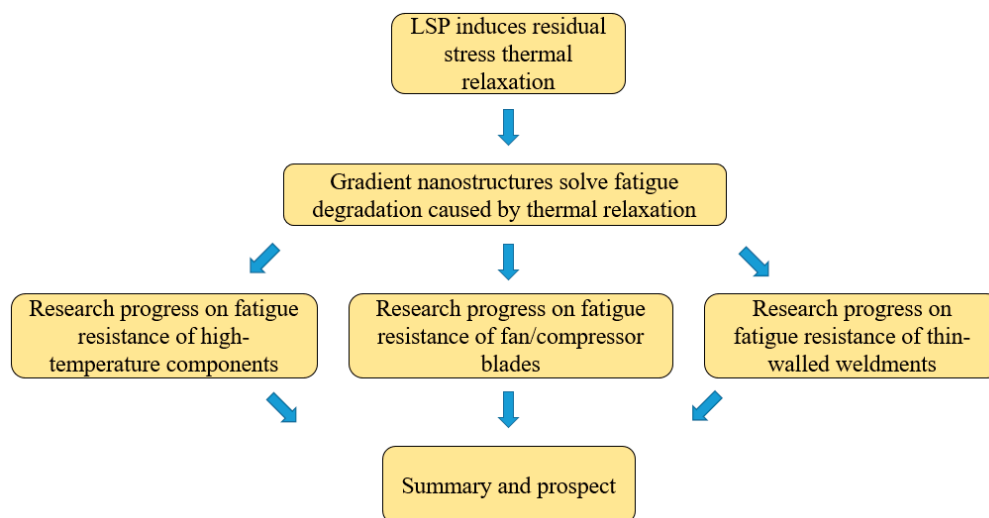


Figure 3. The review research framework.

2. Research Progress on Fatigue Resistance of High-Temperature Turbine Blades Gradient Structures by Laser Shock

High-temperature turbine blades work in a harsh environment and are prone to fatigue damage under high temperatures and large loads, leading to many serious flight accidents [35]. However, there are certain technical difficulties in the application of LSP of turbine blades, mainly due to the turbine blades in service under high-temperature gas environments. The gradient residual compressive stress formed by LSP is easy to relax and recover under thermal action, resulting in a significant reduction in the anti-fatigue strengthening effect. Zhou [36] revealed a laser-induced residual-stress-relaxation model for K417 at 700 °C for 500 min as shown in Figure 4. The laser wavelength was 532 nm,

the pulse energy was 1000 mJ, the power density was 6.14 GW/cm^2 , and the impact spot diameter was 1.6 mm.

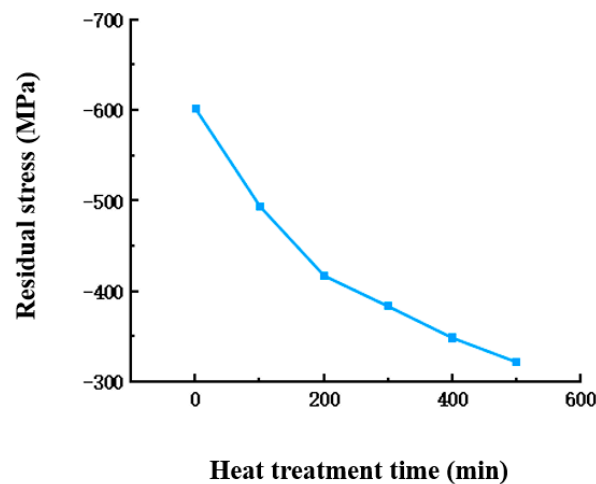


Figure 4. Stress relaxation for LSP of high-temperature turbine blades.

In order to solve the problem of the poor strengthening effect due to residual stress relaxation under high temperature environments, Zhou et al. [19] proposed to control the laser parameters to achieve the gradient structure of nanocrystal preparation on the surface layer and high-density dislocation on the subsurface layer of turbine blade, which can inhibit the crack initiation of turbine blades and improve the vibration fatigue performance through the compound effect of surface nanocrystal and residual stress.

To this end, Li, Zhou et al. [24] revealed the formation mechanism of surface nanocrystals induced by LSP through a combination of multi-scale simulations and experiments. The molecular dynamics model and finite element model of laser-shock-wave-compressed metal materials were mainly constructed and the details of the microstructure evolution of the shock wave front surface were described. Combined with synchrotron radiation and transmission electron microscope (TEM) observation of cross-sectional microstructure sections, the correspondence between shock wave profiles and microstructure evolution mapping was established. The mechanism of surface nanocrystal formation was revealed: the laser-induced shock wave pressure needs to be greater than the threshold of dislocation uniform nucleation; high-density dislocations are formed rapidly at the shock wave surface; and dynamic recrystallization occurs with higher shock wave pressure to form nanocrystals. Based on this, the optimized process parameters were proposed. LSP induced the largest plastic deformation in the surface layer and formed nanocrystals. As the shock wave pressure gradually decayed along the depth, only high-density dislocation structures were formed, so the cross-section was characterized by gradient changes.

Zhou et al. [20] also investigated the relaxation of surface nanocrystals formed by laser shock on nickel-based alloys under the effect of heat. They performed LSP on a type of engine turbine blade K417 nickel-based alloy and induced the formation of nanocrystals with sizes ranging from 30 nm to 500 nm and a thickness of $1 \mu\text{m}$ on the surface of the material. After 150 min of heat treatment at 900°C , the residual compressive stress induced by laser shock relaxed by 72%, while there was no significant change in nanocrystals as shown in Figure 5a,b. The analysis concluded that the cold-work-hardening rate of laser shock was only 5%, its deformation recovery energy was low, ultra-high-density dislocation defects delayed or prevented grain growth, and the pinning effect of the alloying elements biased at the grain boundaries inhibited the growth of nanocrystals. The fatigue test results showed that LSP improved the fatigue life of the nickel-based alloy by 1.1 times after the holding treatment, although the residual stresses were heavily relaxed as shown in Figure 5c. The thermal stability of surface nanocrystals was the reason for fatigue strength improvement. The team further strengthened nickel-based alloy components,

such as GH4133B [19] and DZ17 [37], all of which improved fatigue performance at high temperatures.

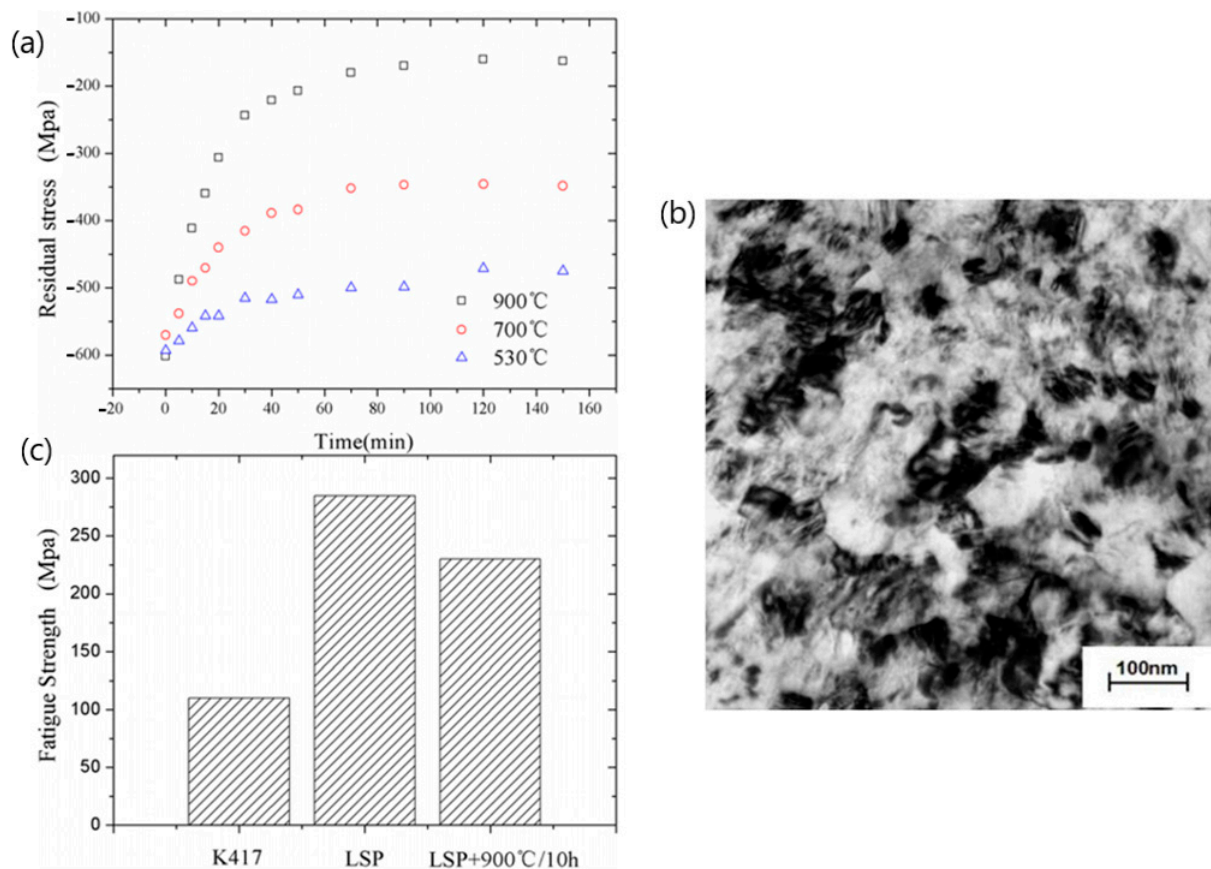


Figure 5. Stress relaxation and fatigue strength of K417 alloy after LSP: (a) Relaxation of residual compressive stress on the surface of K417 alloy; (b) TEM image of surface microstructure after heat treatment at 900 °C for 10 h; (c) Vibration fatigue strength of K417 alloy before and after LSP processing. Reprinted from Ref. [20].

He et al. [38] studied the nanocrystalline microstructure of a K417 alloy after annealing treatment and revealed the mechanism of thermal stability. They found that there is no change in grain size and grain boundary when the temperature increases to 0.38 T_m of 500 °C (T_m : melting point of the K417 Ni-based superalloy is 1300 °C) and 0.54 T_m of 700 °C. This indicates that the surface nanostructure induced by LSP has a higher critical growth temperature than the dynamic crystallization temperature, which is 0.36 T_m of 468 °C for original samples. Similar results were reported by Lewandowska et al. [39]. It is notable that the grain boundaries become blurred after 700 °C of 1 h annealing treatment, which reveals that the grain has a tendency to grow at this temperature. They also observed that the surface nanostructure has good thermal stability at 900 °C.

Huang et al. [40] of Jiangsu University investigated the effect of LSP on the high-temperature fatigue behavior of an Inconel 718 nickel-based alloy. LSP could make the crack source transfer from the surface to the material interior, significantly improving the fatigue life of the specimen. The maximum improvement in fatigue life at room temperature and 700 °C was 47.4% and 107.3%, respectively. During the phase of fatigue crack steady growth, the high-temperature oxide film and precipitated phases hindered the smooth transition of the fatigue striations as shown in Figure 6, which made it difficult for fatigue crack propagation and consumed the driving force of the fast crack growth (FCG) zone.

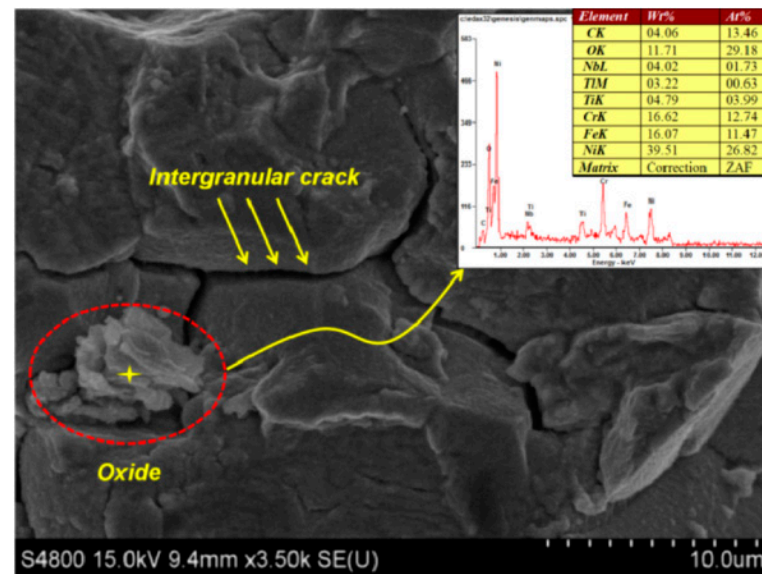


Figure 6. Oxide film on the intergranular crack path after fatigue at the temperature of 700 °C. Reprinted with permission from Ref. [40]. 2020, Elsevier.

Similar research ideas have also been put forward by relevant research units abroad. Bagherifard, Sara et al. [41] of Politecnico di Milano et al. applied different surface treatment techniques, such as shot peening, laser shock peening, and ultrasonic grinding, on Inconel 718 nickel-based superalloy fatigue specimens. The results showed that LSP improved the fatigue life of the Inconel 718 nickel-based alloy by 3.2 as shown in Figure 7, and the better thermal stability of the nanocrystals formed by laser shock was the main reason for the improved fatigue performance.

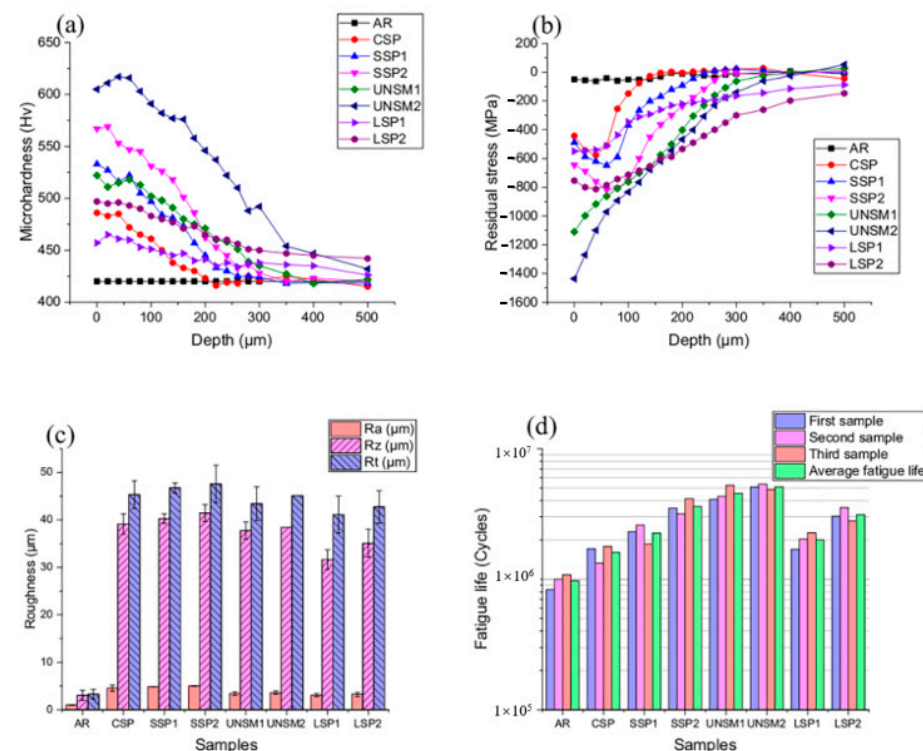


Figure 7. Effect of different treatment processes on mechanical properties of Inconel 718 superalloy. (a) Microhardness distribution; (b) Distribution of residual compressive stress; (c) Surface roughness; (d) Fatigue life at a maximum stress of 900 MPa. Reprinted with permission from Ref. [41]. 2021, Elsevier.

Kattoura et al. [42], University of Cincinnati, USA, studied the influence of LSP on the fatigue properties of an ATI 718Plus nickel-based alloy at high temperatures, which is similar to the idea of LSP of high-temperature components against fatigue by Li, Zhou et al. [43] at Air Force Engineering University. The relaxation behavior of residual stresses is susceptible to temperature effects, but the microstructure generated by laser shock strengthening is more stable and effective.

Tests conducted by the team showed that the residual compressive stresses formed by laser shock on a 718 Plus nickel-based alloy relaxed by 32% when held at 650 °C for 140 h, while the fatigue strength properties improved 4.5 times. The wavelength of the laser beam was 1064 nm, the frequency was 10 Hz, the laser energy was 3 J, the spot diameter was 2 mm, the pulse width was 20 ns, and the lap rate was 50%. Analysis suggested that the orientation of the grains around the crack and their boundaries indicate that the crack mainly propagated through the grain boundaries. The increase in dislocation density induced by laser shock led to the formation of dislocation entanglement and slip bands, and that the 30–50 nm nanocrystals on the surface layer provided an obstacle to the dislocation movement toward the surface, thereby retarding the generation of intrusion and extrusion and hindering the initiation and growth of surface fatigue cracks as shown in Figure 8.

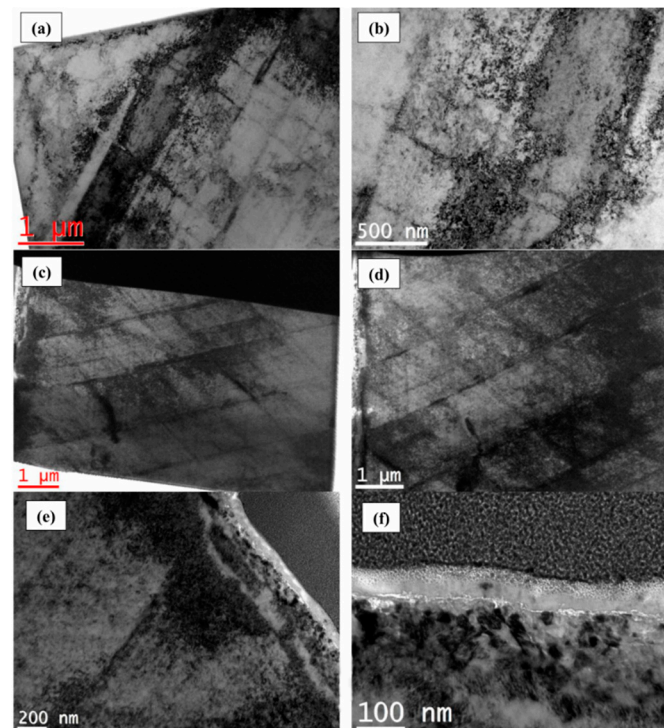


Figure 8. TEM images of fatigue samples of 718 Plus nickel-based alloy tested at 650 °C. (a) Uniform slip distribution; (b) fatigue cellular structure; (c,d) dislocation density increases greatly, resulting in dislocation entanglement and slip bands; (e,f) near-surface subgrain layers with subgrain sizes of 30–50 nm. Reprinted with permission from Ref. [42]. 2017, Elsevier.

In addition, in the study of single-crystal alloys, Tang et al. [44] of Xi'an Jiaotong University adopted warm laser-shock-peening (WLSP) technology for DD6 single-crystal nickel-based alloys to solve the problem of LSP-induced thermal relaxation of residual compressive stress in the work-hardened layer. WLSP is a thermo-mechanical surface treatment method that combines the advantages of LSP and dynamic strain aging (DSA). DSA is a strengthening mechanism that improves the multiplication of dislocations through the interaction between dislocations and diffuse solute atoms to obtain a unique structure with high stability and superior fatigue properties compared to LSP at room temperature. After WLSP strengthening, a large number of slip bands were observed on the grain

surface and stacking dislocations accumulated were also observed at the γ/γ' interface. Dislocations were disordered and irregularly distributed in the γ and γ' phases, with a large number of dislocation entanglements and dislocation walls. The WLSP-induced shock wave acted on the near-surface layer of the specimen and produced dense primary dislocations. Subsequently, further dislocation reactions occurred, and the two orthogonal dislocations continuously met in the motion and generated new dislocations and cross slipped along the crystal direction, forming a dislocation network as shown in Figure 9a–d. This hindered further dislocation movement and reduced the crack growth rate. The near-surface dislocation network and superlattice intrinsic stacking faults (SISFs) significantly extended the fatigue life of the materials as shown in Figure 9e. Some other scholars [45–47] have also obtained similar results in the study of TMS-138 single-crystal superalloy.

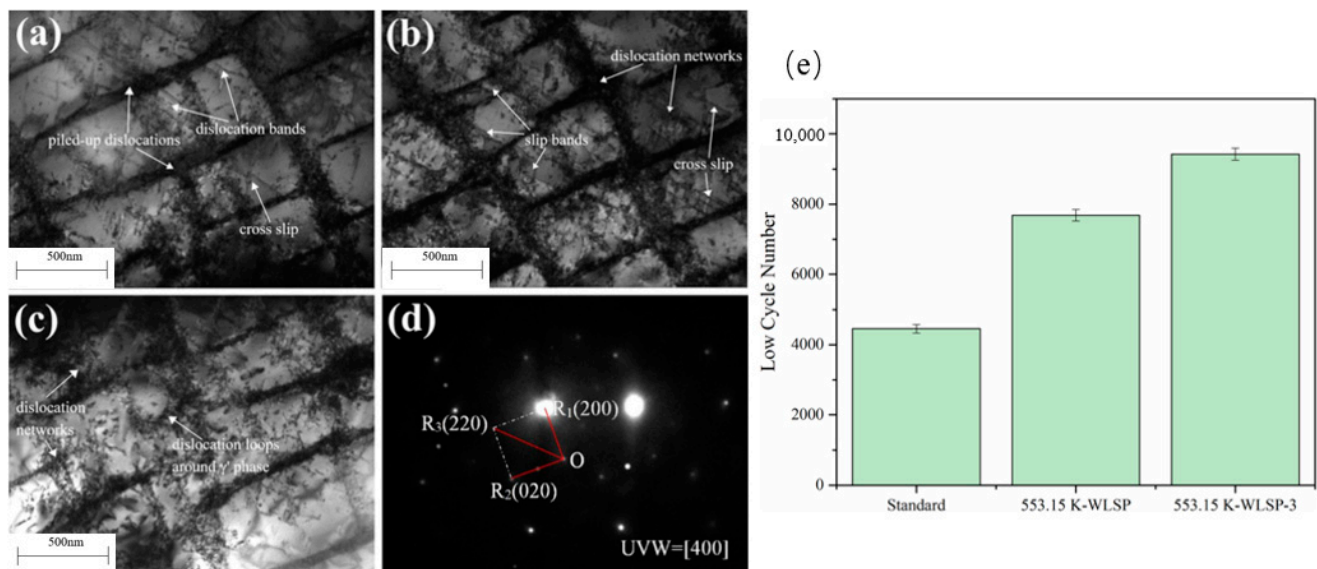


Figure 9. TEM bright-field images of the 553.15 K-WLSP specimen after low-cycle fatigue failure: (a) slip bands, piled-up dislocations, and cross-slips; (b) dislocation networks; (c) dislocation loops around γ' phase; (d) selected-area electron diffraction pattern; (e) low-cycle fatigue life. Reprinted with permission from Ref. [44]. 2021, Springer.

The surface nanostructure is the result of strong plastic deformation [48,49], which can cause high-density dislocation, grain boundary and other crystal defects in the deformed tissue, hinder the movement of dislocation in metal crystals, and make plastic flow of metal materials difficult to occur so as to improve the strength of metal. Moreover, the stress concentration caused by grain boundary dislocation accumulation is reduced. The small size and uniform nanocrystals share more driving force in cracks, the propagation direction of microcracks across the grain boundary is affected by the high-density dislocation, and propagation requires more energy.

3. Research Progress on Fatigue Resistance of Fan/Compressor Blades Gradient Structures by Laser Shock

Fan/compressor blades are widely used in titanium alloys, and typical materials include TC4, TC6, TC11, TC17, etc. [4]. Fan/compressor blades are a key part of aeroengines, and it is inevitable to inhale sand, metal, and other hard objects during the process of use. High-speed impact on fan/compressor titanium alloy blades leads to foreign object damage (FOD) [50,51], which weakens the fatigue performance of the blades. At the same time, the titanium alloy blades work to generate great centrifugal inertia force. Along with the vibration stress caused by the micro-vibrations of the airflow, FOD easily forms a fatigue weakening zone and leads to fatigue fracture. The fan/compressor is usually located at the front of the engine and a broken blade can cause overall engine damage or even induce

a non-inclusive flight accident. In the Gulf War, the US military learned a painful lesson. The blade was injured by hard objects, which resulted in more than 100 B-class accidents on F15 and F16 aircrafts [52]. For this reason, the United States Army and the United Kingdom jointly carried out a national research program on high-cycle fatigue, utilizing LSP technology to improve blade damage tolerance by 15 times.

Notch and residual stress fields are formed when hard objects damage titanium alloy blades. After a large number of high-speed ballistic impact simulation tests [53,54], it has been found that the general characteristics of FOD are as follows: The main manifestations are cracks/tears, notches, pits, local deformation, and axial or radial scratches on the macro. These macroscopic features are often accompanied by the stress concentrations from geometric mutations, and in addition, the fatigue strength of metals is very sensitive to surface integrity. Figure 10 reveals the stress simulation of titanium alloy blades damaged by a 2 mm steel ball with an impact angle of 30°. Tear damage occurred at an impact velocity of 170 m/s, and large notch morphology occurred at 200 m/s. Different from the previous anti-fatigue mechanism of the laser-shock-induced gradient structure to suppress crack initiation in high-temperature components, LSP research focuses on restraining the propagation of microcracks in titanium alloy blades damaged by foreign objects to a detectable range, as well as restraining the propagation of cracks caused by microcracks and residual tensile fields, to delay or prevent fatigue fracture.

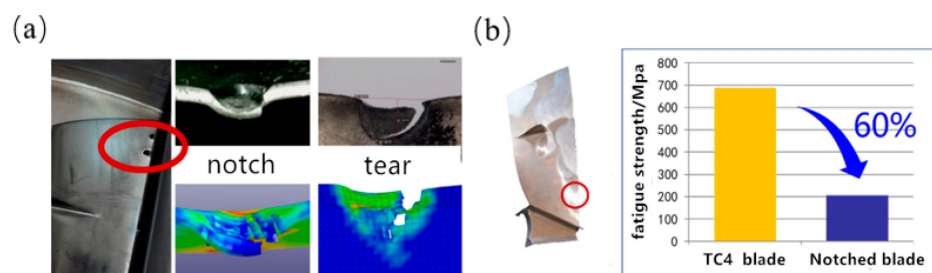


Figure 10. (a) Notch and tear damage; (b) Hard objects damage titanium alloy blades, resulting in notch, tear, etc., to reduce fatigue performance.

At present, research on LSP to improve the fatigue performance of blades injured by foreign objects are mainly conducted in Europe, the United States, China, and other countries. The University of Dayton, the United States Air Force Laboratory, and the University of Portsmouth et al. [55–57] have conducted relevant research on TC4 titanium alloy blades. It has been found that LSP can improve the damage tolerance and fatigue life of titanium alloy blades.

He et al. [58] of the Air Force Engineering University utilized LSP to surface treat TC4 titanium alloy specimens, and then simulated the impact of external objects on the edge of the specimen by using the air cannon test system. Finally, tensile–tensile fatigue tests were carried out. The results showed that LSP effectively improved the fatigue strength of TC4 titanium alloy specimens injured by a 2 mm diameter steel ball. The maximum tensile stress in the center of the pits decreased by 37.85% compared to before strengthening. LSP formed a certain thickness of the residual compressive stress layer, and the generated shock wave refined the surface organization of titanium alloy and produced high-density dislocations in the strengthened layer, making cracks less likely to initiate on the surface.

Zhou et al. [59] investigated the improvement effect of LSP, SP, and a combination of both treatments on resistance to foreign object damage (FOD) by hardened steel balls of Ti-6Al-4V alloy airfoil specimens. They also discussed the effects from the perspective of microhardness, residual stress field distribution, and tissue characterization. The results show that the microhardness and residual compressive stress of the specimens treated with the combination of LSP and SP had the deepest effect depth and the greatest amplitude. TEM observations of the cross-sections of the composite-treated specimens revealed a large number of dislocations and deformed twin crystals. The surface grains were effectively

refined, and nanocrystals were produced. Figure 11 shows the surface microstructure of the titanium alloy treated with a combination of LSP and SP. Figure 11a shows the location of the composite peening treatment of the specimen. From Figure 11b,c, it can be seen that the dislocation distribution inside the strengthened material was not uniform, and the original coarse grains were subdivided into many subgrains or fine grains. High-density dislocations were clustered around the grain boundaries, forming dislocation entanglements and dislocation cell structures as shown in Figure 11d. Under the effect of high-pressure shock waves, grain boundary orientation difference further increased, forming a small-angle grain boundary. With the progress of deformation, large-angle grain boundaries were eventually formed under the effect of dynamic recrystallization, and grain refinement was achieved. The corresponding selected-area electron diffraction (SAED) diagrams, as shown in Figure 11e, of the specimen surfaces after LSP and SP treatments showed that the diffraction spots were elongated and showed a ring trend, indicating the formation of mosaic-structured nanocrystals on the surfaces. The three peening processes improved the high-cycle fatigue strength of FOD specimens, among which the best enhancement effect was 24–35% by composite strengthening, 16–22% by LSP, and 9% by SP. The residual stress field introduced in the subsurface reduces the local tensile stress intensity and delays crack initiation. Meanwhile, the increased hardness and strength of the material improved the low-energy impact resistance.

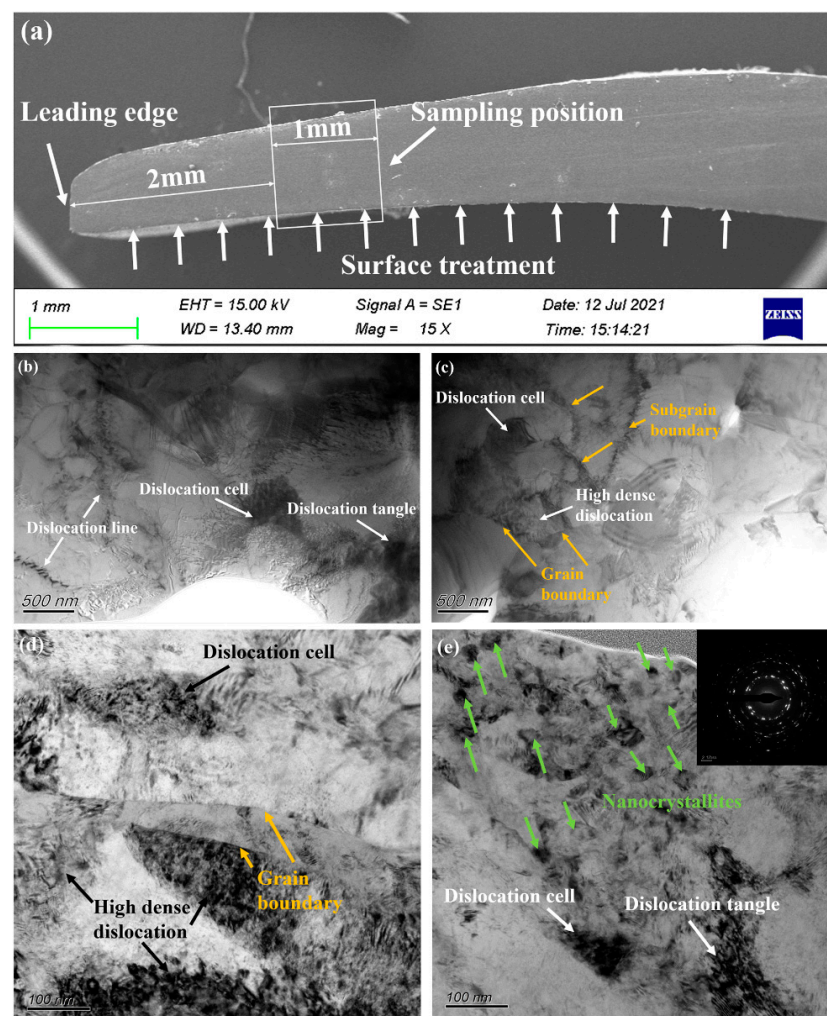


Figure 11. SEM and TEM images on the superficial layer of LSP+SP-treated specimens. (a) Sampling position of TEM images; (b,c) Typical deform-induced microstructures; (d) Annihilation and rearrangement of high-density dislocations; (e) Nanocrystalline characteristics. Reprinted with permission from Ref. [59]. 2022, Elsevier.

Luo et al. [60] from the same team also investigated how to improve the resistance to FOD of 2 mm harden spheres (GCr15 steel) by combining the introduction of the residual stress of preloading into TC4 through LSP with alterations to the microstructure. NIE et al. [61] verified the anti-fatigue effect of TC17 LSP under different FOD conditions by numerical simulation, FOD simulation test analysis, and high-cycle fatigue test.

Tong, J. et al. [55] of the University of Portsmouth, UK processed Ti-6Al-4V-alloy-simulated fan blades utilizing LSP, followed by FOD tests with 3mm hardened steel cubes with impact angles of 0° and 45°. The results showed that FOD led to the formation of micro-notches, shear bands, and other characteristics of titanium-alloy-simulated blades, which weaken the fatigue strength of the components. Different FOD loading methods had different damage characteristics and brought different damage to the fatigue performance. Loss of materials, material folding, and pile-up are more typical for head-on impacts. Whilst for 45° impacts, shear bands associated with the shearing action and LOM during impact are more relevant to crack initiation and growth. After LSP treatment, the fatigue strength of the simulated blade increased, the maximum initial stress of crack initiation increased, and the fatigue crack growth rate of the material decreased as shown in Figure 12.

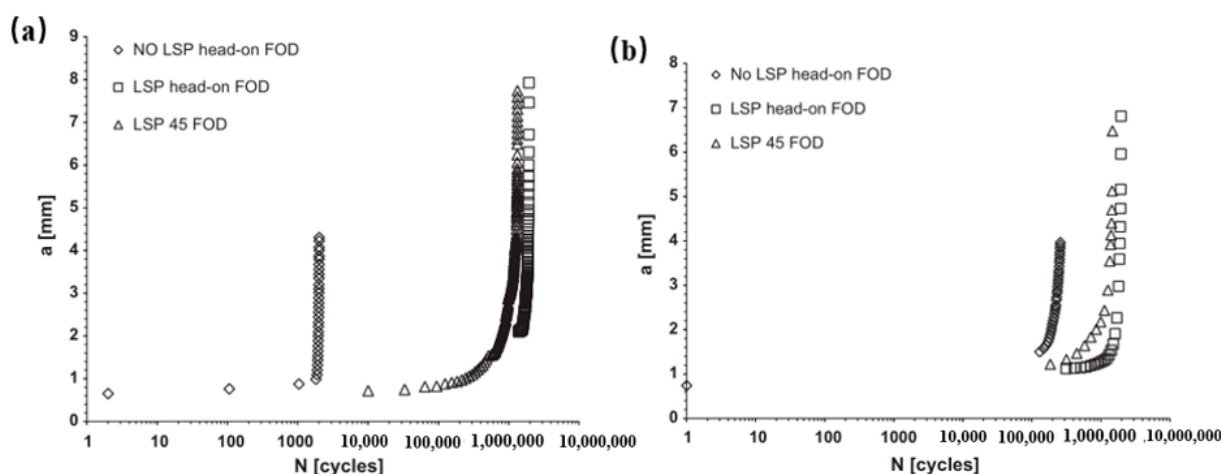


Figure 12. The crack length of 0° and 45° impact samples changes with the number of cycles, and the comparison of the results of LSP and non-LSP samples under the following conditions: (a) high–low-cycle-combined loading; (b) High cycle loading. Reprinted with permission from Ref. [55]. 2011, Elsevier.

Withers, P.J. et al. [62] of the University of Manchester, UK investigated the influence of LSP on the residual stress field of Ti-6Al-4V-titanium-alloy-compressor-simulated leading-edge blades after FOD by hardened steel cubes. LSP adopted a power density of 10 GW/cm², using a spot size of 3 × 3 mm², a 50% overlap and 200% coverage, and a pulse duration of 27 ns. The processing area extends 6 mm from the leading edge and over 65 mm along it. The residual stress distribution of simulated blades subjected to 0° and 45° FOD before and after LSP was tested using synchronous X-ray diffraction. The results showed that LSP produced residual compressive stress of about 0.5 times the yield strength in the longitudinal direction (crack opening direction) of the specimen as shown in Figure 13. Compared with the simulated blade without LSP, LSP can improve the resistance to FOD of the simulated leading-edge blade.

Frija, M. et al. [63] of the University of Sousse, Tunisia used finite element numerical simulations to simulate the effect of LSP on the resistance of Ti-6Al-4V titanium alloy blades to FOD with a square impact region and carried out experimental verification. The results showed that the surface residual compressive stress introduced by LSP significantly improved the high-cycle fatigue performance of titanium alloy fan blades. The fatigue life of strengthened blades with a laser shock wave with a maximum pressure P_{max} between 3–7 GPa was increased by 48–120%.

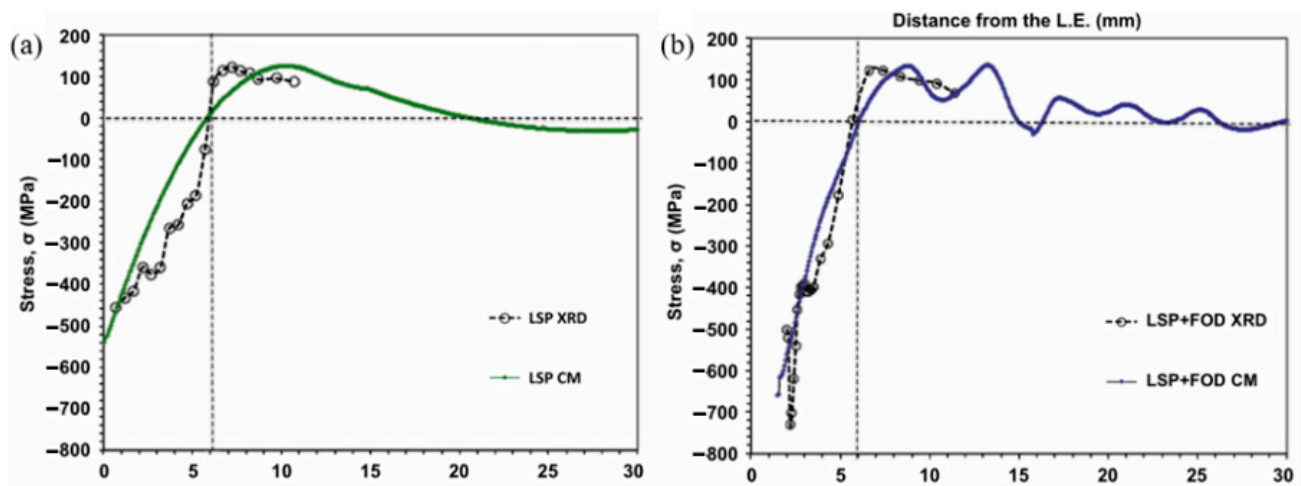


Figure 13. The longitudinal residual stress distribution parallel to the leading edge of the blade: (a) in laser shock strengthening state; (b) laser shock strengthening with +0° FOD. Reprinted with permission from Ref. [62]. 2013, Elsevier.

Sun et al. [64] of Southeast University investigated the influence rule of LSP on the fatigue performance of simulated TC17 blade leading-edge components with FOD of u-notch. The penetration residual compressive stress was introduced into the TC17 notched simulation, strengthened by double-sided single LSP, and the high-cycle fatigue strength increased by 55.6%. The fatigue strengthening mechanism of TC17-notched fatigue specimens led to the introduction of residual compressive stresses and the formation of surface nanocrystals.

Ren et al. [65] of Jiangsu University investigated the fatigue behavior of thin Ti-6Al-4V blades strengthened by double-sided LSP after damage by foreign objects with a 3 mm diameter hardened bearing steel ball (GCr15SiMn alloy with a hardness of HRC 62–64). The test results showed that the bilaterally homogeneous, high-strength residual compressive stresses introduced by the double-sided LSP counteract the tensile stresses introduced by the raised tip of FOD as shown in Figure 14. The fatigue crack growth caused by high shear force and shear band was slowed down by increasing the fatigue crack growth threshold, and the effect of LSP to improve the fatigue resistance of FOD was more significant under a lower stress ratio.

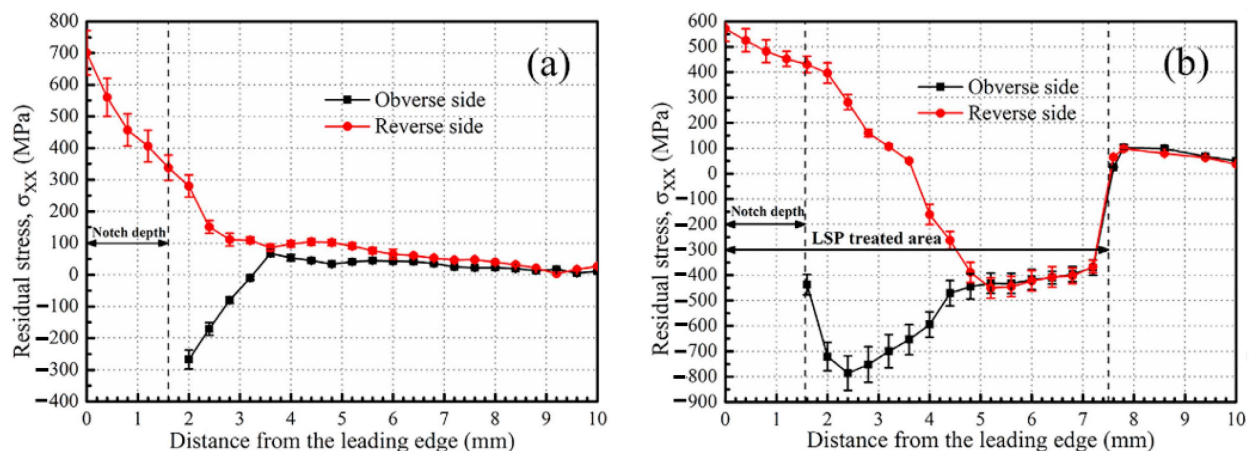


Figure 14. Comparison of residual stress distribution along the notch ($x = 0$) direction in front FOD impact. (a) No LSP processing; (b) Double-sided LSP processing. Reprinted with permission from Ref. [65]. 2020, Elsevier.

When the shock pressure exceeds the dynamic yield strength of the titanium alloy, dislocation slip occurs in the titanium alloy. When the shock wave pressure increases beyond the threshold value of nanocrystals, dislocation accumulation, interaction, and entanglement occur, as well as high-density dislocation annihilation and rearrangement, and finally nanocrystals are formed. Grain refinement disperses the same volume of deformation [64], increasing grain boundary resistance and reducing stress concentration. At the same time, grain refinement makes it easier for fatigue cracks to enter adjacent grains, consumes more energy to change the direction of fatigue crack growth, and effectively reduces the crack growth rate. Many scholars [66,67] have also analyzed and studied the performance improvement of titanium alloy blade surface caused by nanoization.

4. Research Progress on Fatigue Resistance of Thin-Walled Weldments Gradient Structures by Laser Shock

There are a large number of thin-walled welded parts on aeroengines, such as casing, actuator barrel, ducts, etc. However, due to the thermal influence of the welding process, the heat-affected zone of the weld forms welding tensile stress, coarse grain, and the embrittlement phase. Inevitably, there are defects such as thermal cracking, thermal tearing and porosity, heat-affected zones, etc., which are prone to producing vibration fatigue cracks. Laser shock treatment of thin-walled weldments can eliminate weld tensile stresses in the weld zone and heat-affected zone and form residual compressive stresses with a larger amplitude and deeper impact layer, regulate the brittle phase in the heat-affected zone of thin-walled weldments, and improve fatigue performance.

Zhou et al. [68,69] of Air Force Engineering University utilized the WLSP technique to strengthen thin-walled titanium alloy casing weld components of aeroengines. The test results showed that the residual compressive stresses introduced by WLSP in the weld zone and heat-affected zone affected into depths of 1700 μm and 1750 μm (1300 μm and 1500 μm for LSP at room temperature). In addition, WLSP exhibited higher load stability under external cyclic loading, with only 14% residual stress relaxation introduced after 1 million fatigue load cycles (32% for LSP at room temperature). WLSP generated surface nanocrystal structures with random orientation, as shown in Figure 15. Multi-grain boundary nanocrystallines enhanced the strength of the material by inhibiting strain localization and dislocation motion, effectively delaying crack initiation and improving resistance to high-cycle fatigue. The wavelength of WLSP technology was 1064 nm, the lapping rate was 50%, the spot diameter was 2.2 mm, the laser energy was 4 J, the laser impact was 1, and the processing temperature was 300 °C. The laser beam pulse duration was 20 ns. The high-cycle fatigue limit of weldments after WLSP treatment increased by 42.3%.

Shi et al. [70] studied the preparation of 3 mm thin-walled Ti-6Al-4V alloy-welded plates by using the tungsten inert gas (TIG)-welding method. The major grain size in the weld zone decreased from 3.2 μm (99.33%) to 0.6 μm (72.77%) after LSP treatment, and the Vickers hardness in the weld zone and heat-affected zone increased by 8.56% and 3.79%, respectively. The residual tensile stress was converted to compressive stress as shown in Figure 16a,b, and the high-pressure laser shock wave resulted in significant grain refinement. Fatigue crack initiation (FCI) shifted from surface to subsurface and the specimens exhibited better ductile fracture characteristics. Figure 16c,d revealed the loading force details and fatigue strength. The high-cycle fatigue strength of the specimens increased by 19.82%, which was similar to the result of a 26% increase in the fatigue life of TIG-welded pure titanium [71]. Zhou et al. [33] investigated multiple LSP treatments on welded joints of 316 L stainless steel, and the introduction of residual stresses improved the pitting resistance of the specimens. NIE et al. [72] investigated a double-sided LSP-treated TA15 TIG head to solve the problems of welding penetration depth and fatigue degradation after double-sided welding.

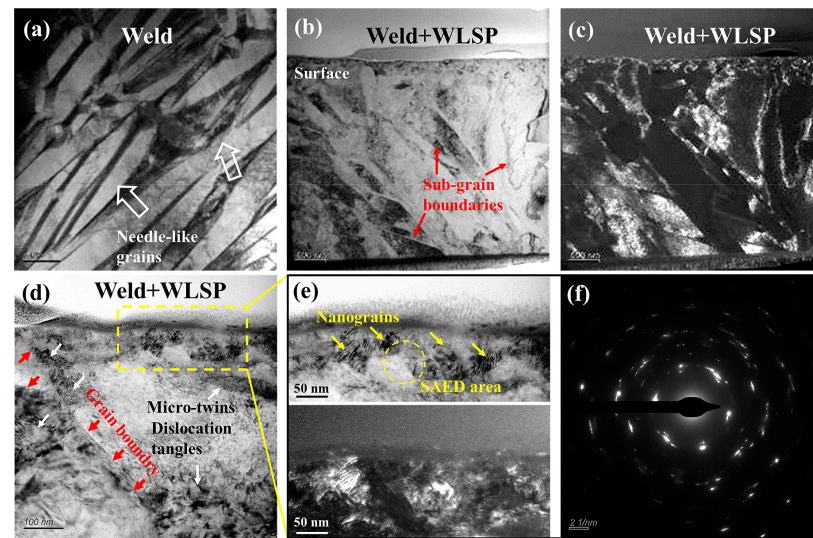


Figure 15. Grain morphologies of the weldment with and without WLSP: (a) As-welded; (b) WLSP; (c) Corresponding dark-field image to (b). Nanostructures on the top surface after WLSP characterized by TEM; (d) Cross-section TEM image at the shock surface of weldments after WLSP; (e) Magnified bright-field image of selected region in (d). Corresponding dark-field image to (e); (f) selected-area electron diffraction (SAED) of targeted region in (e). Reprinted with permission from Ref. [68]. 2021, Elsevier.

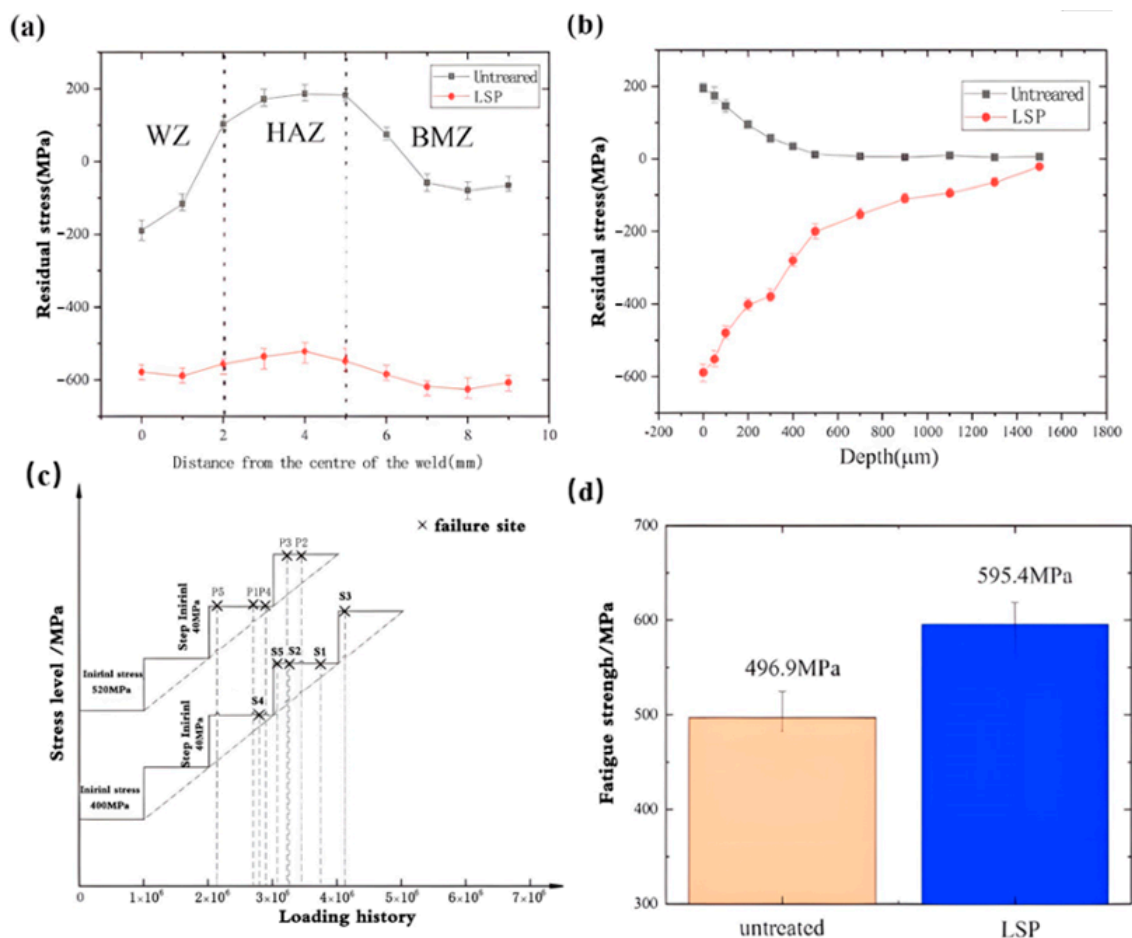


Figure 16. Residual stress: (a) Residual stress field of surface; (b) Residual stress field of depth; High-cycle fatigue test results: (c) loading history; (d) fatigue strength. Reprinted with permission from Ref. [70]. 2021, Elsevier.

Hatamleh et al. [73] of Nasa Johnson Space Center proposed the application of LSP technology to welded parts and verified its feasibility. By comparing LSP with SP, he found that three-layered LSP could significantly reduce the fatigue crack growth rate of 7075-T7351 stir-friction-welded specimens as shown in Figure 17a. LSP induced deeper compressive residual stresses, resulting in the smallest fatigue stripe spacing as shown in Figure 15b, and the same conclusion was obtained in the subsequent verification of welded specimens of different materials [74,75].

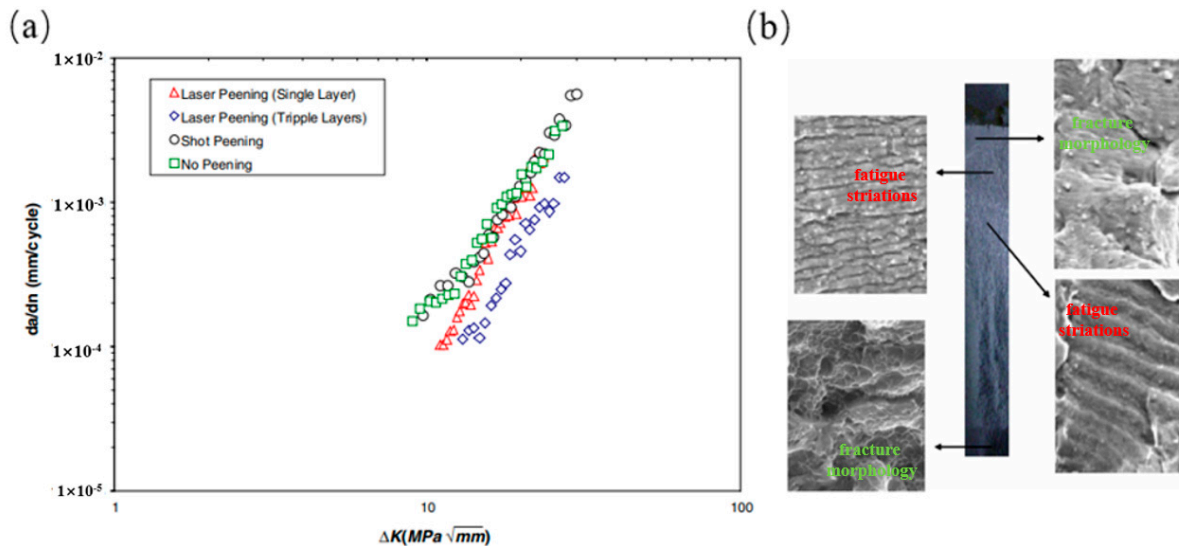


Figure 17. Crack propagation behavior and morphology. (a) Crack growth rates for configuration II (L-T) specimens in FSW 7075-7351; (b) Fractographic images for the fracture surface for configuration two in FSW AA 7075-T7351. Reprinted with permission from Ref. [73]. 2007, Elsevier.

Manikandan, M. et al. [76] of Vellore Institute of Technology, India investigated the effect of LSP on 3 mm thick commercial pure titanium TIG arc weldments. LSP helped to refine the microstructure of the fusion zone, converting harmful tensile stresses into beneficial compressive stresses as shown in Figure 18, and the high residual compressive stresses formed helped to avoid tensile failure in the fusion zone. The residual compressive stress induced by laser shock improved the mechanical properties of welded joints. Compared with the untreated weld condition, the strength of the weldments increased by 12% and the grain size of the welded area after LSP reduced by 12%.

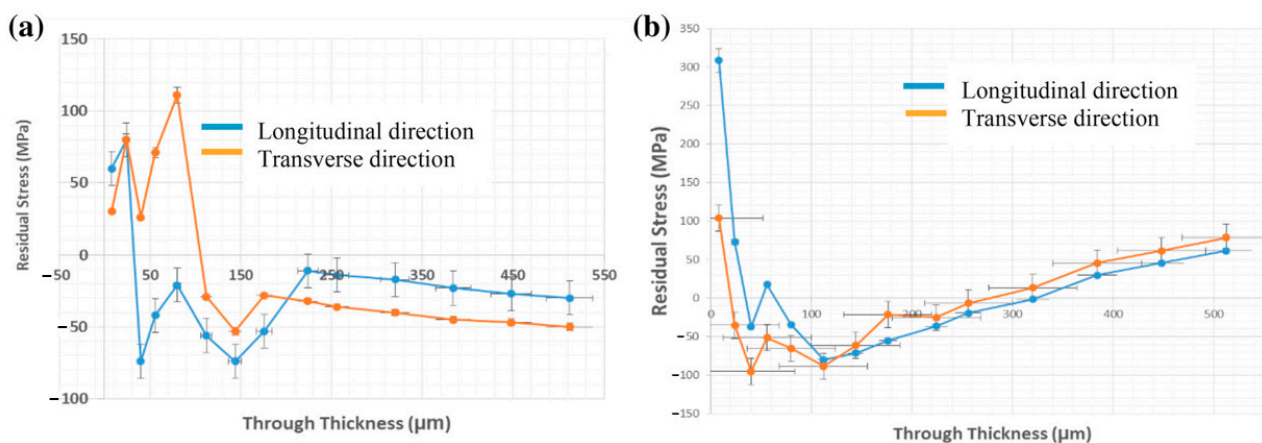


Figure 18. Residual stress distribution before and after LSP treatment. (a) Residual stress in untreated fusion zone; (b) Residual stress in fusion zone treated by LSP. Reprinted with permission from Ref. [76]. 2019, Springer.

Fomin, Fedor et al. [77] of the Helmholtz Association, Germany studied the effect of milling, laser surface remelting, and LSP to improve the fatigue properties of Ti-6Al-4V thin-walled laser-welded joints and analyzed the influence of different processes on the high-cycle fatigue properties of welded joints. The study revealed that welding porosity determines the internal crack initiation of surface-treated weldments. LSP treatment significantly improved the fatigue performance of welded joints, resulting in an increase in the fatigue limit to 380–400 MPa, which was close to the fatigue limit of machined joints as shown in Figure 19. Residual stresses around the weld induced by LSP could mitigate the notch effect caused by the weld underfill and increase the material fatigue life by three times.

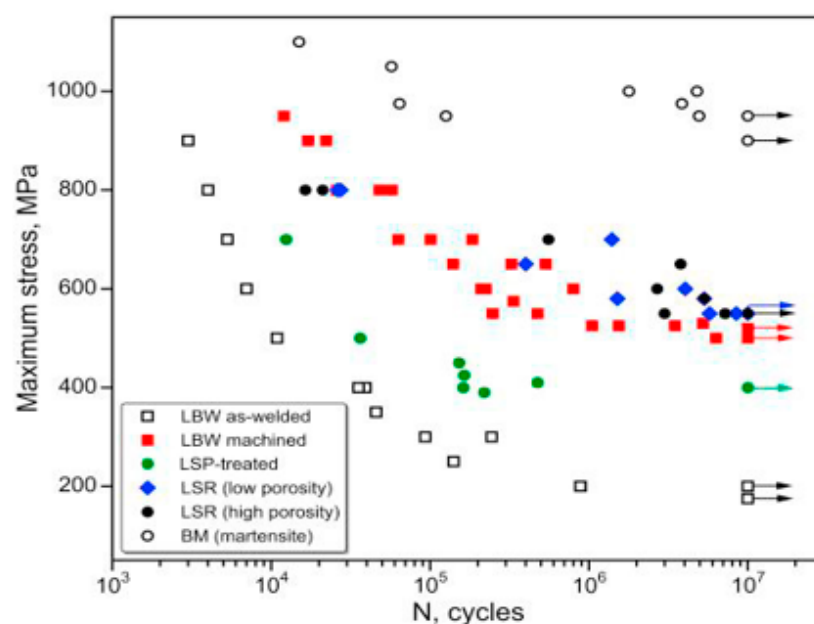


Figure 19. S–N curves of laser-welded Ti-6Al-4V butt joints and effects of different post-treatment methods on fatigue properties (welded with $P = 7$ kW, $v = 4$ m/min, no filler material). Reprinted with permission from Ref. [77]. 2018, Springer.

Cao et al. [78] of the Institute of Manufacturing Technology of AVIC used Nd:YAG laser beams to perform laser shock surface treatment on thin-walled Ti6Al4V-titanium-alloy-welded plates with two different surface conditions: single-sided remelting and double-sided remelting. For the welded joints of double-sided laser remelting, the source of fatigue cracking after LSP was transferred from the weld spatter zone on the weld surface to the air gap zone inside the weld. The fatigue test results showed that residual compressive stress played a key role in reducing the stress concentration effect. Under LSP conditions, the median fatigue life was 6.7 times higher for single-sided remelting than for non-laser shock peening and 9.6 times higher for double-sided remelting than for non-laser shock peening. The fatigue data of laser shock specimens fluctuated widely, a phenomenon that could be explained by the random defect characteristics on the surface of the laser-welded specimens.

LSP further refined the original strip grain in the weld area. The multi-grain boundary nanocrystalline grain on the surface enhanced the strength of the material by inhibiting strain localization and dislocation movement, effectively postponing crack initiation and improving resistance to high-cycle fatigue. The defects with higher density and a more complex structure, such as dislocation and twins, were introduced on the subsurface, which made crack initiation and propagation more difficult by restraining plastic flow [11].

Table 2 summarizes the processing characteristics of different engine components by LSP.

Table 2. Comparison of the strengthening effects of LSP on different engine components.

LSP of Engine Components	Reinforcement Mechanism	Advantage	Disadvantage
High-temperature turbine blades	At the microstructure level, the slip length decreases and the crack nucleation resistance increases [38]	The nailing effect of nanocrystals makes the surrounding dislocation structure more stable [20]. The nanocrystals can solve the thermal relaxation problem of residual compressive stress at high temperatures	It is difficult to control the uneven stress distribution in complex structures, such as monolithic disks
Fan/compressor blades	Prefabricated residual compressive stress on the surface layer of blades can improve the local stress field caused by FOD, form a coupling stress field, and inhibit fatigue crack propagation [4]	LSP-induced residual compressive stress and microscopic nanocrystalline structure contribute to the resistance to both fatigue and FOD	In thinner parts, stress waves can easily penetrate and form reflections on the back
Thin-walled weldments	The tensile stress state of the welding zone is improved to a compressive stress state and the coarse grains are refined [4]	Improve the overall mechanical properties (deep residual stress layer, work hardening layer) and microstructural properties (low surface roughness) of weldments [79]	When the same laser peened material is subjected to different environmental conditions based on its applications, the nature of stress (stability) is changed. In addition, there is a lack of technical parameter standards under different conditions

5. Conclusions

Facing the critical problem of fatigue fracture resistance of aeroengine components, this paper systematically introduces the characteristics, formation mechanism, thermal stability mechanism, and process method of gradient structure formed by laser shock induction, and it investigates the related research progress at home and abroad. The relevant research results have been applied to high-temperature turbine blades of aeroengines, titanium alloy blades of fan compressors, thin-walled weldments, etc., which have played an important role in ensuring safety in service.

The problems in LSP processing are as follows:

- (1) The study of LSP mainly focuses on the influence of different process parameters on surface integrity and fatigue performance. However, the LSP-induced gradient structure contains microstructure characteristics of multiple scales, such as nanocrystalline, high-density dislocation, and coarse matrix, and it involves multiple disciplines of laser, materials, mechanics, and plasma, and has strong intersections. It is urgent to develop a multi-scale mechanical theory of the relationship between microstructure and macroscopic properties of materials.
- (2) The laser duration is short, and the material response process is fast. It is difficult to monitor and correct the strengthening quality problems caused by deviation in the process parameters.
- (3) There is a lack of unified technical specification for the reinforcement effect of complex structures, such as thin-wall structure, gear structure, and irregular welding structure.

Therefore, we forecast the development prospect of LSP as follows:

- (1) In order to achieve a better strengthening effect, the strengthening technology is developed from a single technology to multiple different processing technologies.

- (2) The strengthening mechanism changes from a single residual stress to the interaction between residual stress and the microstructure. A deeper understanding at the microscopic scale is possible in the future.
- (3) The quality of laser processing is guaranteed by real-time monitoring and intelligent automatic control in the strengthening process.
- (4) With the advancement of science and technology, as well as the emergence of lasers with higher performance, ultrashort lasers attract people's attention due to their extreme physical properties, and the interaction with matter in the microstructure level is paid more attention and studied.

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