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A Critical Review of Laser Shock Peening of Aircraft Engine Components

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Many aviation accidents are caused by the failure of aircraft engine components, and engine blades are especially vulnerable to high-cycle fatigue fracture in severe working environments as well as to impact damage caused by foreign objects. To address this problem, the United States took the lead and has been successful in implementing laser shock peening (LSP) as a surface treatment for aircraft engine components to enhance their fatigue performance. This review provides an overview of the development of LSP for use in treating aircraft engine components over the past three decades, with a brief introduction to the development of high-energy pulsed lasers for LSP. A particular focus of this review is on the limitations and challenges associated with the application of LSP for treating critical aircraft engine components. It is hoped that this review serves as a reference for future research and development that can lead to better performance of these components.

1. Introduction

By introducing beneficial compressive residual stresses (CRS) in the near-surface regions of metallic components, laser shock peening (LSP) can significantly improve the fatigue performance of metallic components.[1–6] The deep, high-magnitude CRS produced by LSP can suppress the propagation of cracks caused by foreign object damage (FOD) and can mitigate fretting fatigue failure in aircraft engines (AEs).[7–10] These stresses effectively improved the serviceable damage tolerance of AE components treated by LSP, thereby reducing maintenance costs. Because of its beneficial effects, LSP is currently the most widespread advanced surface treatment used by the United States Air Force (USAF).[11]

Fatigue failure is a common failure mode of AE components. According to the statistics shown in **Figure 1**, fatigue-related failures account for 49% of typical engine failures, with high cycle fatigue (HCF) accounting for 24% of the failures and low cycle fatigue (LCF) accounting for 12%. Prior damage (such as FOD and microcracks),[12,13] resonant vibrations,[14,15] and fretting wear between the tenon joints[16,17] are major causes for the fatigue failure of the AE components.

Fatigue failures have caused numerous aviation accidents/incidents, including the midflight breakup of a USAF F111 fighter bomber in 1969. The worst single-aircraft accident to date, the 1985 crash of a Boeing 747 near Mount Takamagahara in Japan (Japan Airlines Flight 123), caused 520 casualties. It was later discovered that fatigue failure of the aircraft's aft pressure bulkhead due to improper maintenance was the cause of the crash. In 1987, four F/A18 flights experienced in-flight accidents due to HCF caused by FOD to the General Electric (GE) F404 engine blades. It was later determined that metal fatigue failure of the hollow-core fan blade was responsible for this accident. More recently, in February 2018, a United Airlines Boeing 777-200 flying from San Francisco to Hawaii experienced a similar engine failure. An investigation by the National Transportation Safety Board (NTSB) concluded that the incident was caused by damage to the engine fan blades due to fatigue failure. In December 2020, a Japan Airlines Boeing 777-200 suffered an in-flight engine failure, 20 min after takeoff from Naha, Japan. The Japan Transportation Safety Board found two damaged fan blades, one with a metal fatigue crack. In February 2021, a United Airlines Boeing 777 experienced a contained

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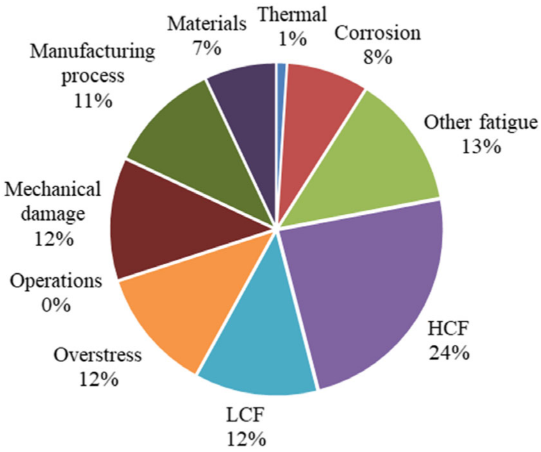

Figure 1. Representative failure mode statistics of engine components. Reproduced with permission.[230] Copyright 1996, Springer Nature.

engine failure only minutes after takeoff from Denver International Airport. Because of the aforementioned fatigue-related accidents/incidents, HCF of AE components has become a well-known problem in aviation. Fatigue-related accidents/incidents such as those mentioned earlier highlight the critical need to improve the fatigue performance of AE components.

Surface treatment technologies such as shot peening (SP), LSP, low-plasticity burnishing (LPB), and deep rolling (DR) have been widely used to improve the HCF resistance of AE components and prolong their service life.[18–25] While conventional SP can improve the fatigue resistance of components by introducing a large CRS on the target surface, the depth of the CRS layer is limited.[26–28] Other limitations of SP include poor thermal and mechanical stability of the CRS,[29–31] a significant increase in target surface roughness, and difficulty in realizing automatic control.[20] LPB and DR work similarly, and a stable layer of CRS introduced by LPB and DR has been demonstrated to improve the fatigue performance of various metallic materials.[24,25,32–36] LPB and DR not only result in better surface quality but also induce superior low-level work hardening as compared to SP and LSP.[20] However, the magnitude of CRS produced by LPB and DR is usually smaller in magnitude and shallower in depth as compared with SP and LSP.[20] Moreover, due to the limited pressure of LPB and DR, optimal results cannot be obtained for materials with high hardness. In addition, as LPB and DR equipment needs to be specially designed according to the shape of sample, it can result in poor flexibility, and this is particularly true for components having complex structures.

LSP has attracted considerable attention due to the following advantages: a higher magnitude and deeper depth of CRS, strong controllability and good adaptability, high processing precision, good accessibility for processing components with complex geometry, high processing efficiency, and a clean processing environment. Due to its excellent performance, the United States made LSP the first technological measure in the “High-cycle Fatigue Science and Technology Program” implemented in 1994. After the program demonstrated in the laboratory that LSP is highly effective for improving the HCF performance of AE components, LSP transitioned from the laboratory to industrial applications. LSP successfully mitigated the issue of HCF fracture of the fan blades of F110 AEs and F404 after burning turbofan engines as well as insufficient FOD resistance of the blisks in F119 turbofan AEs. Given these technological achievements, LSP was listed by the United States as one of the most critical technologies for the development of engines for fourth-generation fighter aircrafts. At present, LSP has been widely used to improve the fatigue performance of many critical components.

In the past two decades, several reviews about LSP have been published. In 1995, Peyre et al.[37] from the Laboratoire d’Application des Lasers de Puissance (LALP) in France provided an exhaustive overview of the physical mechanisms of LSP and how it affects fatigue performance. In 2002, Montross et al.[38] from the University of Sydney (Australia) compared the effects of LSP and SP and discussed the response of microstructure and mechanical properties of metallic materials after LSP. In 2005, Shepard et al.[11] at the Air Force Research Laboratory (USA) summarized the applications of LSP in USAF engine lines and commented on trends for future development. In 2016, Liao, Ye and Cheng[39] from Purdue University (USA) reviewed the state of the art for warm laser shock peening (WLSP) and discussed the primary mechanisms of the process in detail by establishing the relationship between process, microstructure, and performance. In 2019, Sundar et al.[40] at the Indira Gandhi Centre for Atomic Research (India) analyzed the influence of critical parameters such as laser energy, pulse width, and overlap rate on the strengthening effect of LSP. In the same year, Clauer[41] at LSP Technologies (USA) comprehensively reviewed the history of the development of LSP (including its origins, transition, and path to commercialization) and discussed the application status of LSP and its future directions. In 2020, the role of LSP in improving fatigue performance and stress corrosion cracking was discussed by Hamdy and Elbashar[42] at Cairo University (Egypt). The application of LSP in treating additively manufactured parts was discussed by Munther et al. In 2021, Zhang et al.[43] at Huazhong University of Science and Technology (China) presented a review that focused on the application of LSP in emerging fields and the development of innovative LSP processes. In the same year, Kattoura et al.[44] at LSP Technologies reviewed the development history of LSP and introduced the latest advances in LSP in terms of the laser equipment employed in the process, LSP parameter effects, material performance, and process simulation. In 2022, Glaser et al.[45] at the Council for Scientific and Industrial Research (South Africa) provided a summary of the local industrial use of LSP in South Africa for applications such as power generation, mining, and aerospace components. The above reviews have provided an overview of the history of the development of LSP, its property enhancement capabilities, and some innovative applications. However, considering the importance of LSP for mitigating fatigue failure in AEs, a review article dedicated to the use of LSP in treating AE components is still needed.

Herein, this review summarizes the historical development of LSP in the aviation field and discusses the limits and challenges when using LSP to treat AE components. We aim to provide a summary of the applications and limitations of LSP in the aviation field and, more importantly, provide a reference for future research and development.

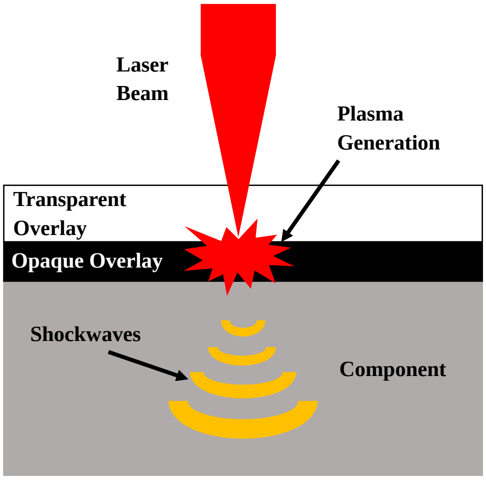

Figure 2. Schematic diagram of LSP treatment.

2. The Physics Mechanisms of LSP

A schematic view of the LSP process is shown in **Figure 2**. During the LSP process, a high-power-density (GW cm^{-2}) and short-pulse (ns) laser beam passes through a transparent overlay (water or glass) and is focused on an opaque overlay or a target surface in laser shock peening without absorbent coating (LSPwC). The opaque overlay or target surface is ionized to form a dense plasma with an elevated temperature (>10 000 °C) and high pressure (>1 GPa). The expansion of the plasma between the transparent overlay and the target surface induces a shock wave in the target material. Plastic deformation occurs when the strength of the shockwave pressure exceeds the Hugoniot elastic limit (HEL) of the material. As the shock wave propagates to the inner layer of the material, its strength is gradually attenuated. Once the attenuation falls below the HEL, elastic deformation occurs around the plastic deformation zone. Once the shock wave dissipates, the elastic deformation zone begins to recover and interacts with the plastic deformation zone during the recovery process to form a layer of beneficial CRS, as shown in **Figure 3**. Compared with the traditional SP, LSP can introduce a deeper residual stress field (of about 1–2 mm), suppress the fatigue crack initiation, and mitigate the growth of cracks.[37,46,47]

3. History of the Development of LSP

Laser-induced shock waves were discovered in the 1960s, and the United States began to adopt LSP for surface treatment in the 1970s.[48,49] Later on, the method attracted new attention for the treatment of aerospace components, when it was used to improve the fatigue strength and damage tolerance of AE blades.[50–52] Studies to date have demonstrated that LSP can be used to prolong fatigue life as well as to improve fretting fatigue resistance, corrosion resistance, and the FOD tolerance of AE blades without compromising their surface integrity.[53–55] In general, the development of LSP can be divided into two stages: early exploration and industrial application.

3.1. The Early Exploration Stages

The concept of LSP can be traced back to basic research that was conducted in the 1960s. One of the critical steps for laser peening after its invention occurred in 1962, when Gurgen Askar'Yan and E. M. Moroz at the P. N. Lebedev Physics Institute (USSR) discovered that the pressure exerted by a high-intensity laser beam on the surface of a metal target was much greater than the calculated value.[56] Later on, Joerg Neuman at Laser Zentrum Hannover e.V. (Germany) found in experiments that a short laser pulse can produce considerably more pressure than a regular pulse (with the peak pressure increasing with power intensity). Soon after, around this crucial discovery, more experimental and theoretical research was conducted, and experimental trials were carried out in vacuum to prevent dielectric breakdown in air.

While it is feasible to use vacuum operation in the laboratory, it is challenging to achieve in industrial applications. Fortunately, in 1968, Nordin C. Anderholm at Sandia Laboratories (USA) demonstrated that with the aid of a transparent overlay, sufficient shock pressure could be generated at a power density that does not cause dielectric breakdown in air. This discovery allows laser-induced shock wave technology to break away from the limitation of the vacuum environment and bring the industrial application of lasers one step closer to reality.

In 1970, L. I. Mirkin at Moscow State University (USSR) first reported the influence of laser shock on the microstructure of metals, which helped to explain the property enhancement effect.[57] In 1972, Fairand et al. from the Battelle Columbus Laboratories (USA) used a high-energy, pulsed laser beam to shock 7075 aluminum alloy, which increased its yield strength by 25% and confirmed that the beneficial effect was due to a

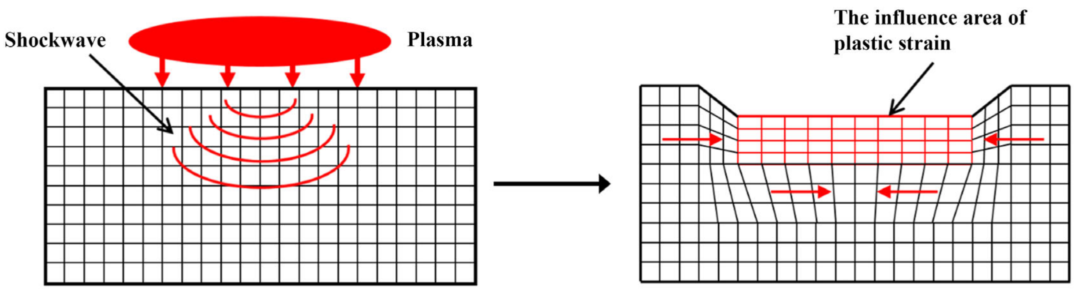

Figure 3. Schematic of the mechanism for generating compressive residual stresses during LSP. Reproduced with permission.[43] Copyright 2021, Wiley.

significant increase in the dislocation density.[58] In 1977, Clauer et al.[59] at the Wright Aeronautical Laboratories (later merged into AFRL) first proposed the typical LSP setup using a transparent confinement layer and a black coating, and they obtained a shock wave with a magnitude of several GPa. Since then, the commonly used reinforcement structure has incorporated a transparent confinement layer with an opaque absorption layer structure (Figure 2). In 1978, Clauer et al.[60] at Wright Aeronautical Laboratories used the reinforcement structure to conduct a study on improving the fretting fatigue life of fasteners. The results showed that the fatigue life of specimens treated using LSP was increased by two orders of magnitude under different stress levels.

These early researchers established the fundamental basics for the later industrial application of LSP. However, the LSP process stayed in the laboratory for a long time due to the low frequency (approximately one pulse every 8 min) of the laser systems available at the time.

3.2. Laser Systems for LSP

In 1968, Battelle Memorial Institute imported a large laser from France to conduct laser fusion (shown in **Figure 4**). Fairand et al. applied the device to metal modification and proved that laser-induced shock waves can improve the performance of materials in the laboratory.[58] This discovery pioneered material modification by laser-induced shock waves. From 1992 to 1994, the General Electric Aircraft Engine (GEAE) division used the laser systems at Battelle Memorial Institute to perform LSP treatment of fan blades, and they were able to restore the HCF performance and eliminate FOD sensitivity (**Figure 5**).[61]

The early laser systems delivered a beam with high energy (up to 100 J) but very low pulse frequency (<1 Hz). For example, the first-generation (GEN I) laser system was able to deliver 100 J in 30 ns at a frequency of 0.1 Hz. To increase the frequency and improve the stability of the laser, GEAE and LSP Technologies, Inc. (LSPT), developed a second-generation system (GEN II, shown in **Figure 6**) with a repetition frequency of 0.25 Hz. In 1997, USAF introduced GEN II technology for the B-1B Lancer heavy bomber aircraft and subsequently used it for various airfoils. While GEN II served as a stable production laser for many years, its operation and maintenance costs are relatively high due to its complex structure and its use of costly consumable components. A third-generation system (GEN III) has been developed; however, little information on this system is available in the open literature because it never replaced the GEN II for production.

With the further development of lasers in the mid-1990s, lasers with lower pulse energy and higher pulse frequency became available. To reduce the cost of the system, with the support of GEAE, LSPT developed the GEN IV, a pulsed laser system with a simple structure that is easy to maintain. The GEN IV delivers a 10 J laser pulse in 30 ns at 10 Hz; it can introduce a CRS layer with a depth of 1.5 mm, which is equivalent to the depth achieved by GEN I and GEN II.[61] Since then, the GEN IV system has gradually replaced GEN II system for LSP-related production and commercialization.

To meet the LSP requirements for treating integral blade rotors (IBRs) of Pratt & Whitney (PW) F119 and F135 engines, LSPT has further developed an image monitoring and RapidCoater system (**Figure 7**) based on the GEN IV. The operating principle of the RapidCoater system is to fix a jig on a

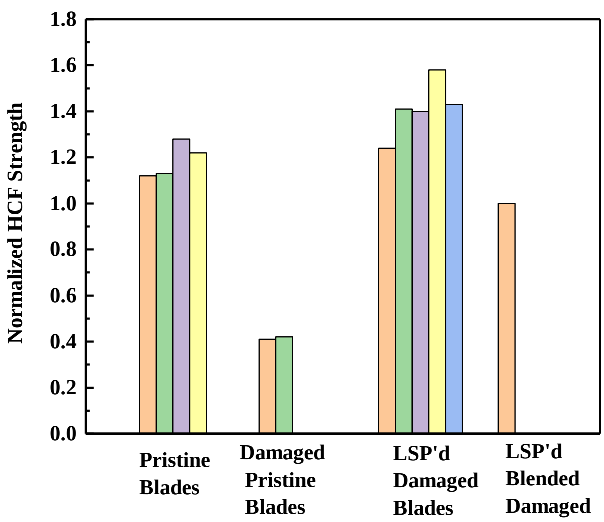

Figure 5. Typical fatigue capability comparison for Ti–6Al–4V fan blades using GEAE's Gen II system. Reproduced with permission.[61] Copyright 2004, AIAA.

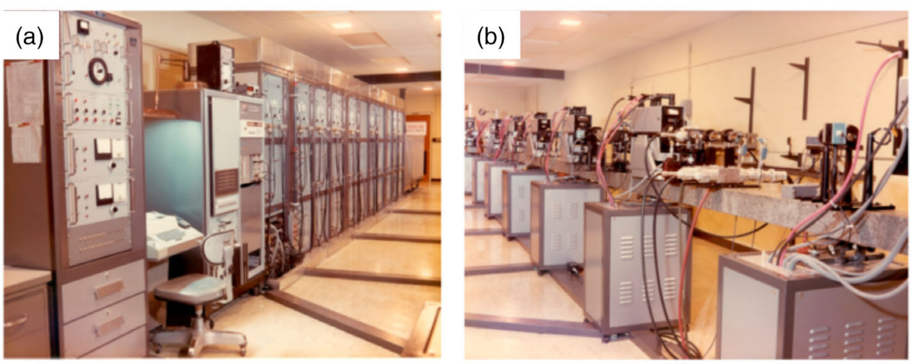

Figure 4. The Battelle Compagnie Gènèrale Electrique (CGE) VD-640 Q-switched laser: a) capacitor banks; b) laser rod amplifier. Reproduced with permission.[41] Copyright 2019, MDPI.

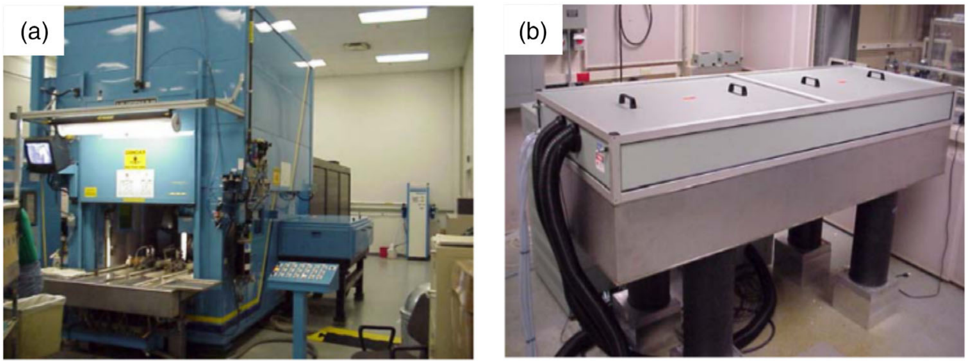

Figure 6. LSP systems developed by General Electric and LSPT: a) Gen II system; b) Gen IV system. Reproduced with permission.[61] Copyright 2004, AIAA.

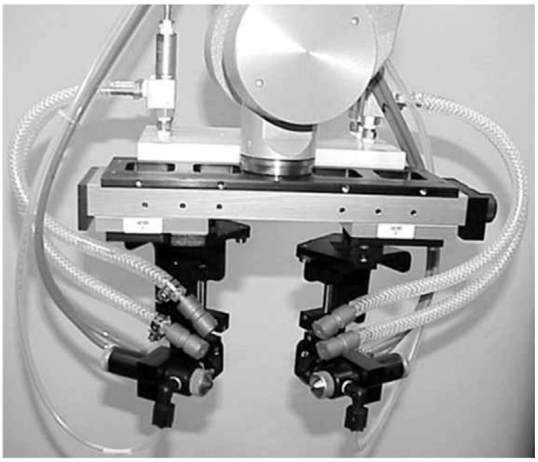

Figure 7. RapidCoater system developed by LSPT. Reproduced with permission.[231] Copyright 2002, Taylor & Francis.

spraying robot and equip the jig with spray nozzles, water spray nozzles, and air-jet nozzles. The spray robot and a joint robot in this system work cooperatively to apply and remove the absorbing layer and the protective layer on the surface of the workpiece. According to Sokol et al., the RapidCoater system reduced the cost of laser peening by 30–40% and increased the process throughput by 4–6 times as compared to conventional laser peening.[62]

The Procudo 200 Laser Peening System (**Figure 8**), which delivers a 10 J pulse and has a pulse width of 8–20 ns at 1–20 Hz, is a lower-energy laser that was recently developed by LSPT. It is the first commercially available laser system specially designed for LSP and can deliver either single or dual beams to the processing cell. This production-quality, turn-key system comes with fully integrated modules for laser beam delivery, diagnostics, and robotic part manipulation. In 2017, Guangdong University of Technology (Guangdong, China) imported a Procudo 200 Laser Peening System from LSPT to begin conducting LSP research.

3.3. The Industrial Application of LSP in the United States

During the late 1980s, the academic community had a basic understanding of the process for using laser-induced shock waves to achieve surface modification of materials, and laser-induced shock wave technology had developed to a stage that enabled industrial application. Since that time, it has become known as LSP. The United States took the lead in achieving large-scale applications of this technology in the aviation industry and has adopted LSP as one of the critical technologies for improving the resistance of HCF in AE components. GE, PW, Metal Improvement Company (MIC), and LSPT have already applied this technology for the blades of numerous engines (including F101, F110, F404, and F119, among others).

Dating back to 1991, F101 engines in the B-1B Lancer frequently suffered fatigue fractures resulting from FOD; these fractures seriously affected flight safety and even caused the USAF to ground the aircraft. To ensure the normal flight of the B-1B, USAF required its personnel to conduct a very detailed manual inspection of the engine fan blades before each takeoff—an inspection that is expensive and requires a high number of man-hours to conduct.

In response to this problem, the United States began implementing the "High Cycle Fatigue Science and Technology Program" (HCFSTP) in 1994. This program is divided into seven action groups. The first group is "component surface treatment", which had the goal of increasing the FOD resistance of the blade's leading edge by 15 times. The "component surface treatment" group tried many surface treatment technologies before focusing on LSP development. This group was a collaboration between national laboratories (including Lawrence Livermore and Los Alamos) and other units such as GEAE and MIC. Many tests were conducted, and LSP was proven to significantly improve the HCF performance of AE blades.[63] The promotion of LSP by the HCFSTP led to its application in industry.

In 1995, LSP technology entered production lines from the laboratory after approval from the USAF. Since 1995, the United States has been studying the problem of insufficient FOD resistance of the F101 engine during the Gulf War, basing its efforts on the research results from HCFSTP. GEAE conducted LSP on Ti–8Al–1V–1Mo blades of the first-stage fan of the F101 engine, as shown in **Figure 9**. A V-shaped notch was set into the leading edge of the LSP-treated blades with a chisel or electrical discharge machining to simulate FOD. From the fatigue results shown in **Figure 10**, it can be observed that the fatigue strength of the predamaged blades after LSP can

Figure 8. The Procudo 200 Laser Peening System developed by LSPT. Reproduced with permission.[232] Copyright LSPT.

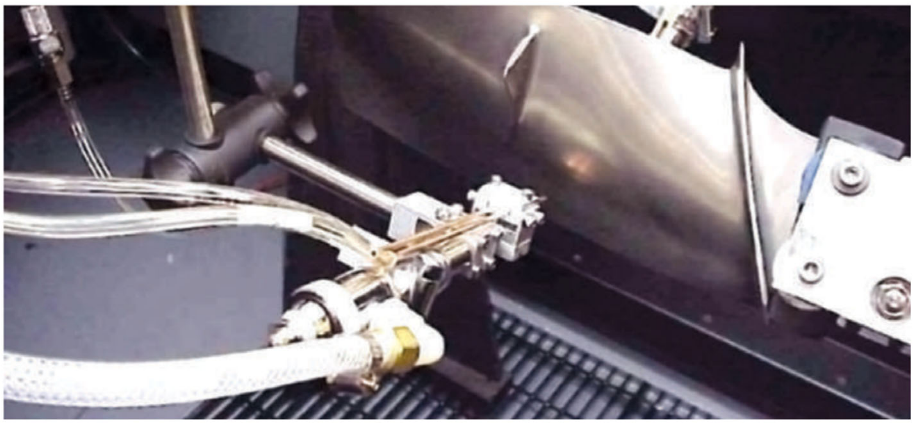

Figure 9. LSP Technologies' Rapid Coater system is positioned for processing an F101 engine blade. Reproduced with permission.[233] Copyright 2009, Springer Nature.

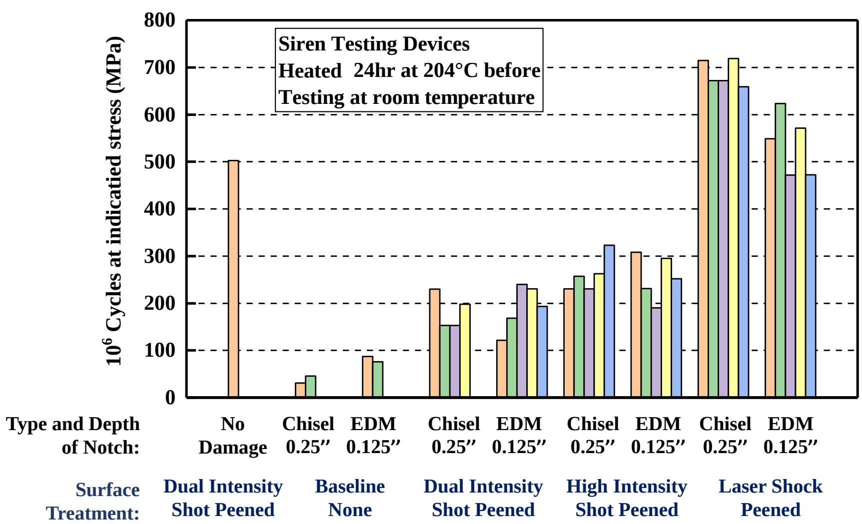

Figure 10. Fatigue strength of F101-GE-102 fan blades comparing the influence of various surface treatments for protecting against the loss of fatigue strength from FOD. Reproduced with permission.[63] Copyright 2003, The Amptiac Quarterly.

reach or even exceed the fatigue strength of new blades.[41] The findings of the study indicate that the tolerance of engine blades against FOD has been significantly improved by LSP. As a result, blades that experience FOD at some level can continue to operate safely.

GEAE became the first industrial user of LSP after the incorporation of LSP in the production line of F101 first-stage fan blades in 1997.[41] As the LSP-treated blades installed in the engine were no longer affected by ordinary FOD, it was no longer necessary to perform manual inspection of the blades before each flight. Application of LSP mitigated the problem of frequent HCF fracture of the B-1B Lancer's F101 engine resulting from FOD, and this significantly reduced costs. From 1998 to 2000, GE continued to apply LSP to F110 and F104 engine blades, and LSP successfully increased the damage tolerance against FOD by about 15 times.[64] Over the years, GE has continued to treat numerous types of aircraft or engine components using LSP.

In 1999, LSPT teamed up with PW to apply LSP to the IBR of the F119 engine used in the F-22 fighter aircraft. As shown in **Figure 11**, LSP increased the fatigue strength of the notched IBR by 100%.[62] However, at that time, industrial application was restricted due to the process efficiency and cost. Fortunately, soon after, the process for treating an F119 IBR by LSP was shortened from 40 h to 8 h, thanks to the efforts of the Air Force Man Tech project.[65] In 2003, USAF approved the use of LSP processing for IBR. As shown in **Figure 12**, LSPT used the laser processing unit developed by Man Tech to strengthen the turbine IBR of the F-119-PW-100 fighter jet. LSPT became the first commercial provider of laser peening services, and they gradually expanded production to other AE components. Since then, LSP has been widely used in the manufacture and maintenance of aviation components. Also in 2003, LSP was approved by the Federal Aviation Administration (in the USA) and by Japan Asia Airways as a technology for the maintenance of critical AE components for civil aviation.[66] In the same year, LSP was used in the manufacturing and maintenance of engine blades for Boeing aircraft.

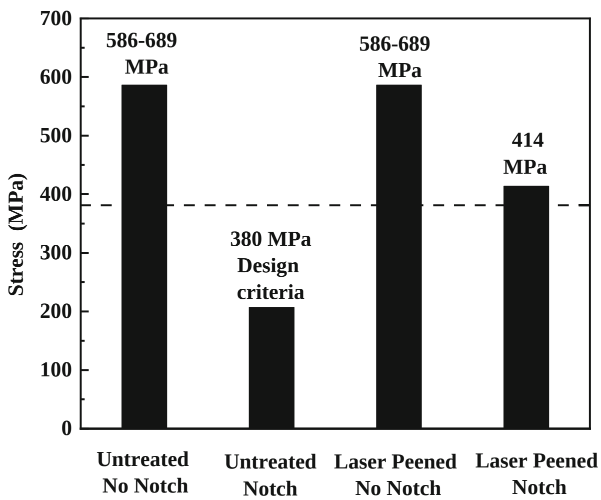

Figure 11. Effect of LSP on the fatigue performance of F119 IBR. Reproduced with permission.[62] Copyright 2005, Optica.

In the late 1990s, MIC joined the effort to study LSP. In 2003, MIC was approved by Federal Aviation Administration and Japan Asia Airways as the designated maintenance service station for LSP. After 2003, they established an LSP production line and entered the field as another provider, mainly for the LSP strengthening of Rolls Royce engine fan blades to improve their resistance to high-frequency fatigue and FOD. MIC has provided innovative laser systems and on- and off-site services, and they subsequently used LSP treatment for the wing skins of Boeing 747–8 aircraft.[67]

3.4. Global Research and Application of LSP

In addition to the USA, other countries and regions have also carried out research on LSP technology. In the 1990s, the mechanism of LSP was studied extensively in France, and researchers there have made significant contributions to laser-induced shock wave theory. In 1990, Fabbro et al.[68]—in a collaboration between LALP, Peugeot SA Etudes et Recherches, and Laboratoire de Physique des Milieux Ionisés—proposed a model to predict the shock pressure generated by confined plasma. In 1997, Berthe et al.[69] at LALP studied the plasma behavior of the transmission medium and the breakdown phenomenon in the confinement layer; they increased the shock wave pressure by reducing the wavelength. Since then, Peyre and Berthe et al.[70,71] at LALP adopted the Velocity Interferometer System

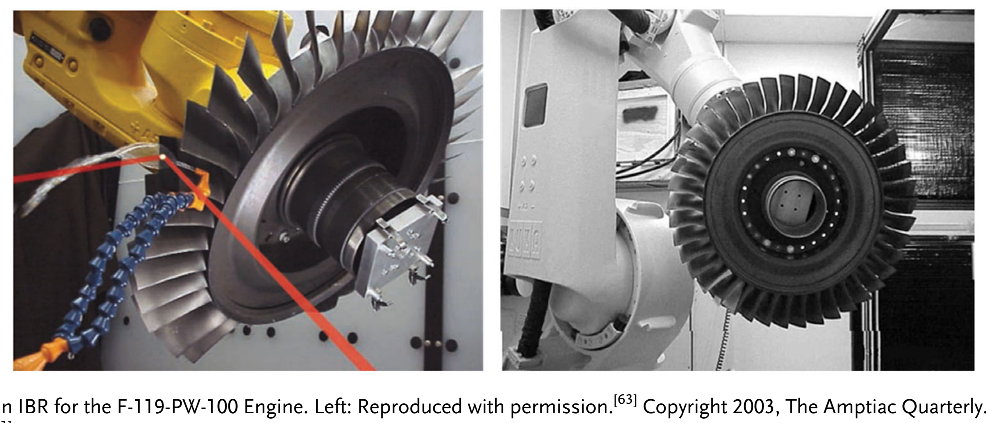

Figure 12. LSP of an IBR for the F-119-PW-100 Engine. Left: Reproduced with permission.[63] Copyright 2003, The Amptiac Quarterly. Right: Reproduced with permission.[231] Copyright 2002, Taylor & Francis.

for Any Reflector (VISAR) method, and polyvinylidene fluoride piezoelectric film (PVDF) enabled the measurement of laser-induced shock pressure with different pulse widths.

In the UK, Fitzpatrick et al.[72–76] studied the residual stress distribution and fatigue properties after LSP and the effect of overlap rate on the residual stress distribution for different types of aerospace aluminum alloys. Achintha and Nowell et al.[77–80] focused on the FE simulation of LSP. They developed an FE model to study residual stresses generated by LSP. Preuss, Withers, and Zabeen et al.[81–84] at the University of Manchester studied the effect on the residual stresses of FOD to a previously LSPed leading edge of the aerofoil-shaped specimen and found that different impacts angles of the foreign object caused different evolution of residual stress.

In Slovenia, Grum and Trdan et al. at the University of Ljubljana conducted LSP in the early 2000s.[85] They studied the effects of LSP on the macro-and microstructural evolution of metallic materials, as well as on the mechanical properties of specimens.[86–89] The influence of LSP parameters like laser beam diameter and pulse density per unit of area was established.[85]

In Spain, Ocaña et al. at the Universidad Politécnica de Madrid initiated LSP research in the late 1990s.[90] In the early 2000s, they carried an experimental project to study the effect of LSP on the fatigue and wear performance of aluminum alloy.[91–93] In their latest work, they investigated the thermal stability of residual stresses generated by LSP in Ti–6Al–4V.[94]

In Japan, LSP is mainly used to mitigate the corrosion of nuclear reactor components. In 1993, Yuji Sano at Toshiba Corporation developed a laser peening system to alleviate corrosion cracking of water-filled boiling water reactors and pressurized water reactors, and this system was different from the high-energy pulsed laser system used in the United States and Europe.[95]

In China, AVIC Manufacturing Technology Institute pioneered the implementation of LSP for treating integrated bladed rotors and other aircraft components in the early 2000s. In 2009, AVIC Manufacturing Technology Institute of China, in collaboration with Liming AE Company and AVIC Shenyang Engine Design Institute, conducted research on the LSP process of the blisk, which in turn provided several key breakthrough technologies for LSP treatment of titanium AE blisks. In 2005, Jiangsu University successfully developed a high-power LSP system. In 2008, Air Force Engineering University established an experimental base for LSP in Xi'an and began research on the LSP process for stainless steel blades; they later joined forces with Jiangsu University and other institutions to develop LSP processes and quality control methods for treating blades and other components. In 2011, the Shenyang Institute of Automation at the Chinese Academy of Sciences developed an LSP system for AE blisks that increased the service life of the blisks by four to six times.[96,97] In academia, Zhang et al. established the LSP research program at Nanjing University of Aeronautics and Astronautics in the 1990s.[98,99] Lu et al. from Jiangsu University carried out extensive studies of the grain refinement mechanisms in aluminum alloys,[100] stainless steel,[101] and pure titanium[102] subjected to LSP. Hu et al. from Shanghai Jiao Tong University utilized numerical simulation to study the boundary effects of circular and square spots and the effects of different overlap rates and peening sequences on the distribution of residual stress.[103,104] In 2017, the laser peening group lead by Y.K. Zhang at Guangdong University of Technology imported a Procudo 200 Laser Peening System from LSPT Inc.

In South Africa, research on LSP was initially academically oriented.[105–107] The National Aerospace Centre, the University of the Witwatersrand, the Council for Scientific and Industrial Research (CSIR), and AIRBUS Operations GmbH successfully collaborated to create the South African LSP initiative, which had the goal of creating local capability to support the advanced laser-based manufacturing industry. Driven by the needs of local industry, LSP has led to process research related to industrial applications—mainly in the power generation sector, the mining sector, and the aerospace sector.[45,108–110] Currently, CSIR has two LSP work cells. A laser system with a wavelength of 1064 nm is used for academic research, and a 532 nm laser system is being devised for industrial applications. As the components in the mining sector are too large and heavy to easily transport to a processing facility, there is also an urgent need for a mobile LSP system that can be used to refurbish these components.

4. Effect of LSP on the Resistance of Aircraft Engines to Fatigue and FOD

As mentioned in the introduction, fatigue failure is the main failure mode for AE components. FOD (**Figure 13**), a major accelerator of fatigue failure, occurs when small, hard objects (such as sand, stone, or metal fragments) are sucked into the engine at high speed and strike the fan blades or compressors during aircraft takeoff or landing.[111–113] The leading edges of aerofoils are particularly susceptible to such damage.

It has been shown that an FOD notch of less than 3 mm in depth can reduce the fatigue life of these blades by over 50%.[114] Under vibration and resonance service conditions, the dents, pits, or notches in the blades of fans and compressors caused by FOD may serve as initiation sites for fatigue cracks.[111] The edges of a dent are prone to form microcracks under the simultaneous action of a high-speed impact and high applied stress.[111,115–118] Robert O. Ritchie, Jan O. Peters, Joseph Hamrick II, and co-workers and Shankar Mall and co-workers[115–118] conducted a series of fatigue cracking experiments and found that the locations of crack initiation due to FOD are different at different levels of stresses. At low applied stress and a small load ratio, fatigue crack initiation is prone to occur below the surface and outside the crater rim, and in this case, the local tensile residual stress (TRS) induced by FOD is the main cause of fatigue cracking. In contrast, fatigue cracking is prone to occur at the crater base and is driven by the high concentration of stress caused by FOD. In addition, the microcracks and microstructure distortion (i.e., shear bands, local texturing) induced by FOD can also provide potential sites for fatigue crack initiation.

For active aircrafts in the USAF, the number of FOD incidents per 100 000 flying hours averages between 8 and 14 and results in a loss that exceeds $8 million per year. Thus, there is a need to

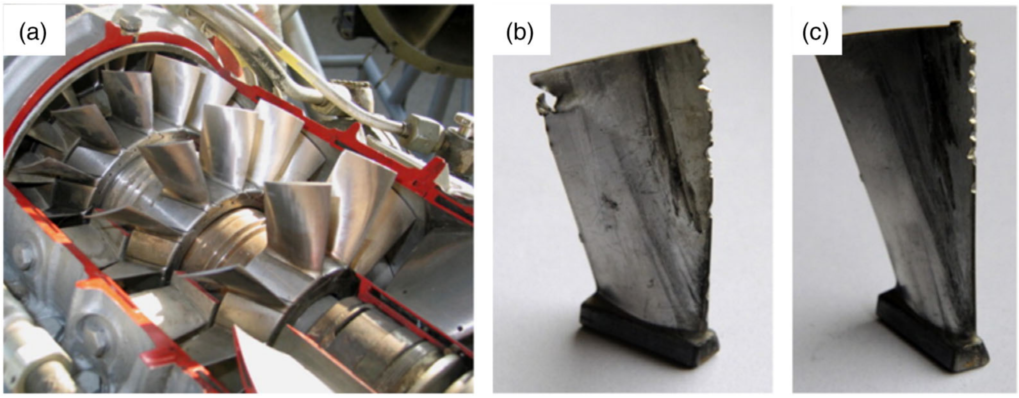

Figure 13. Photographs of a) the first stages of an aeroengine axial compressor and b,c) blades after FOD. Reproduced with permission.[13] Copyright 2011, Elsevier.

improve the FOD resistance of engine blades to mitigate fatigue failure in AEs.

4.1. LSP Improving the Fatigue Performance of Aircraft Engines

LSP can effectively extend the fatigue life of aircraft engines by producing CRS and inducing beneficial microstructure evolution.[50,84,119,120] The earliest investigation of the effect of laser peening on the fatigue behavior of thin sections was performed on F101-GE-102 aircraft gas turbine engine fan blades.[121] As shown in Figure 10, LSP significantly improved the fatigue life of F101-GE-102 fan blades that suffered FOD, and the LSP-treated blades were found to retain the fatigue strength of an undamaged blade. In 1997, GEAE began production of laser peening F101 first stage fan blades and adapted LSP in the production line.[122] Subsequently, it has been applied to improve the fatigue performance of various components for AEs, such as those used in F110 and F119 aircraft.

It has been proven that LSP can be used to improve the fatigue properties of various metallic materials, including magnesium alloys,[123–125] titanium alloys,[23,84,119,120] aluminum alloys,[2,92,126] and superalloys[127,128] that are used in aviation structures and components. Generally, the leading edges of fan or compressor blades made of titanium alloy are more vulnerable to FOD. Therefore, the published literature in this area mainly focuses on the fatigue performance of titanium alloys treated by LSP for aircraft components.[119,129]

For example, Ruschau et al.[114] at the University of Dayton (USA) studied the fatigue strength and fatigue crack growth of simulated TC4 leading-edge samples with prior FOD under different stress ratios. As shown in **Figure 14**, although LSP was found to significantly improve the fatigue performance of the notched TC4 sample at low-stress ratios ($R = 0.1$), no improvement was observed at higher-stress ratios. Hammersley et al.[47] reported a similar observation. In a study conducted at University of Portsmouth (UK), Spanrad et al.[8] studied LCF, HCF, and LCF + HCF behavior of TC4 aerofoil specimens under FOD and LSP + FOD conditions, and they reported that LSP could significantly reduce the fatigue crack growth rate after FOD.

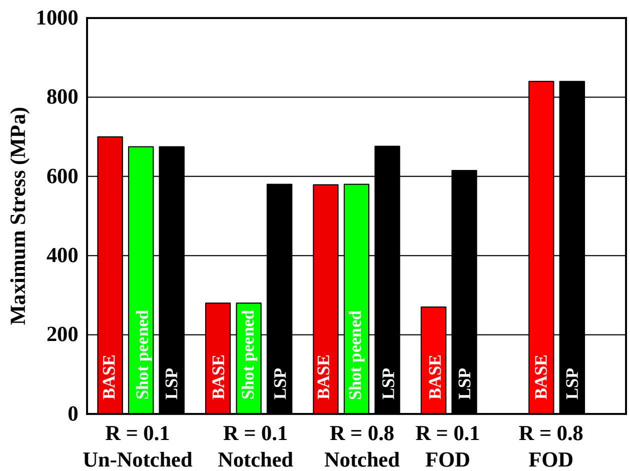

Figure 14. Fatigue strength of baseline samples and SP- and LSP-treated samples. Reproduced with permission.[114] Copyright 1999, Elsevier.

At the University of Manchester (UK), Philip Withers, Michael Preuss and co-workers[81,82,84] studied the effect of FOD on the residual field induced by LSP on the leading edge of a Ti–6Al–4V aerofoil-shaped sample through experiments and simulations. The results show that although the local TRS induced by FOD will promote crack initiation, the coupled CRS generated by LSP and FOD will inhibit the further propagation of cracks.

Yang et al.[130] at Jiangsu University (China) conducted experiments to study the effect of two different modes of double-sided LSP treatment on the FOD resistance of Ti–6Al–4V alloy samples. In one set of tests, the specimen is treated directly on the leading edge without a gap (LSP-D); in the other set of tests, the LSP-treated area is located 2 mm away from the leading edge (LSP-I). The results suggest that LSP-I can more effectively improve the resistance to FOD and fatigue than LSP-D, increasing the fatigue life of the specimens by 169% and 94%, respectively. The reason for this improvement is that the untreated area within 2 mm of the leading edge is a soft region with good plasticity that can resist the formation of cracks at the bottom of the induced notch, while the LSP-treated area is a hard region that can slow the growth rate of fatigue cracks.

The above research shows that LSP can significantly improve the FOD resistance of metallic specimens, thereby improving their fatigue performance. However, due to the complex shapes of AE components, the planar and simulated specimens used for research purposes may not be representative of the blades used in AEs. Thus, research that examines the effect of LSP on the fatigue performance of actual AE components is necessary. Although the large-scale production of LSP-treated AE fan/compressor blades was realized in the United States as early as the beginning of the 21st century, the open literature on the use of LSP to improve the fatigue strength of AE components is very limited. Therefore, this section mainly focuses on studies published by scholars in China.

In 2008, Ma and Li et al.[50] from the Air Force Engineering University (China) conducted LSP experiments on AE compressor rotor blades made from LY2 aircraft-grade aluminum alloy. It was found that LSP significantly improved the high-frequency fatigue life of AE compressor rotor blades, where the fatigue life of LSP-treated blades was found to be twice that of the as-received blade. Later, in 2011, He and Li et al.[131] at Air Force Engineering University (China) significantly improved the fatigue strength of a compressor blade made of 1Cr11Ni2W2MoV martensitic heat-resistant stainless steel by LSP, and the median vibration fatigue life of the blade increased by 70% at a stress level of 660 MPa.

In 2012, Wang et al.[132] from the Air Force Engineering University (China) carried out an LSP effect verification experiment with a fifth-stage rotor blade of an engine that was made from TC4 titanium alloy. The results showed that the fatigue limit of the blade after LSP was increased from 430 to 560 MPa; at 560 MPa, the median fatigue life of LSP-treated blades increased by more than 200%.

In 2018, Chen et al.[133] from Beihang University tested and verified the fatigue resistance of LSP on Ni-base superalloy turbine blades at high temperatures (530 °C). The HCF + LCF combined cycle fatigue test results showed that the life of K403 and GH4133B superalloy turbine blades was increased by 1.63 times and 1.32 times, respectively. In addition, it was found that while LSP can significantly prolong the vibration fatigue life of cast blades and forged blades, the effect on cast blades is more obvious.

Also in 2018, Zou et al.[134] from the AVIC Manufacturing Technology Institute (China) conducted LSP experiments on the first-order bending vibration nodal region of compressor blades made from titanium alloy Ti17. The results showed that the HCF vibration fatigue life of the LSP blades was improved by one order of magnitude as compared with the original blades.

4.2. The Mechanism of Fatigue Performance Improvement by LSP

As mentioned before, TRS, stress concentrations, microcracks, microstructure distortion induced by FOD, and other factors are the main causes of fatigue crack initiation. Early studies suggest that LSP improves the fatigue life of materials by inducing beneficial CRS. Specifically, CRS can improve the fatigue strength of a material by reducing the average stress of the component, changing the stress field at the crack tip, mitigating the crack propagation rate, and even making the crack close. In 1996, Peyre and Fabbro et al.[2] at LALP (France) described the formation mechanism of CRS induced by LSP and asserted that CRS was the main reason for the better fatigue performance. Ruschau[114] and Montross[38] et al. also attributed the improvement in fatigue performance to the CRS introduced by LSP.

More recently, in 2018, Luo et al.[55] from Air Force Engineering University (China) combined experiments and finite-element (FE) simulations and found that both LSP and FOD induced stress redistribution and generated similar stress fields, including tensile and compressive stress regions. Prior to this, Zabeen et al.[82,84] from the University of Manchester and Open University (UK) reported experimental observations showing that, as compared to the tensile stress area of untreated notched specimens, no tensile stress area around the notches of specimens previously treated using LSP is evident; this finding explains why LSP is able to improve the fatigue resistance to FOD. In 2021, van Aswegen et al.[135] from the University of the Witwatersrand (South Africa) applied LSP to a precracked aluminum panel and found that the propagation of cracks along the LSP-treated area was significantly retarded.

It can be concluded that the beneficial effect of CRS on fatigue performance is recognized. With further research and development work on LSP, researchers have increasingly found that, in addition to CRS, the microstructure evolution (surface grain refinement, high-density dislocation, etc.) caused by LSP is another key factor to improving the fatigue performance of metallic materials.[136–138] According to Meyers' dislocation nucleation theory,[139] under the action of a shock wave, the dislocation nucleates uniformly on or near the shock wave front. With further action of the shock wave, coordinated plastic deformation such as slip, accumulation, interaction, entanglement, annihilation, rearrangement, and other processes will occur, enabling the formation of nanocrystals through dislocation movement under the continuous action of the shock wave.

During the crack initiation stage, the crack driving force acts on the fine and uniform nanocrystals formed on the surface by LSP. Since the stress concentration is small, cracks are not easy to initiate.[140,141] In the crack growth stage, due to high-density dislocation produced by LSP, additional energy is needed for crack growth in the surface region, and the rate of crack growth is reduced. In addition, some researchers report that surface nanocrystallization is also beneficial for mitigating the rate of crack propagation.[142–144] Because of the high grain boundary volume fraction of the nanocrystalline structure, microcracks will be hindered at the grain boundary. However, other researchers report that nanocrystalline materials tend to exhibit inferior fatigue crack growth behavior as compared to their coarse-grained counterparts due to the absence of crack closure effects.[141,145]

Considering the effects of LSP on the microstructure of metallic materials, an increasing number of studies have considered the improvement of fatigue performance of metallic materials by LSP as a synergistic effect of CRS and microstructure evolution.[130,136,137,145,146] However, the CRS introduced by LSP tends to relax at elevated temperatures, thus weakening or even eliminating the strengthening effect of LSP treatment, whereas the nanocrystals induced by LSP have good thermal stability[22,147,148] (the relaxation mechanism of CRS at elevated temperature will be described in greater detail in Section 5.4). Altenberger et al.[22,147,148] studied the stability of CRS and surface nanostructure induced by LSP in AISI 304 stainless steel and Ti64 titanium alloy, and they observed that although CRS is completely relaxed at 550–600 °C, the microstructure (highly tangled, dense dislocations, and nanocrystalline structure) still plays a role in extending the fatigue life. Kattoura et al.[149] pointed out that the increased fatigue life of alloy 718Plus at 650 °C is a result of the combined action of CRS and microstructure. Yinghong Li et al.[144] proposed that CRS and nanocrystals simultaneously improve the fatigue performance of metals at low temperatures, while nanocrystals play a major role in extending fatigue life for high-temperature components.

5. Challenges Associated with the Application of LSP for Treating Aircraft Engine Components

Even though LSP is already a mature process, there exists many challenges. Although the United States has achieved large-scale production of LSP-treated AE blades as early as the 2000s, LSP-related technologies for the treatment of some critical AE components are still classified and are not available to the public. The discussion in this section is based on information from the open literature.

5.1. Stability of Absorbing and Confinement Overlays

Absorbing and confinement overlays are typically needed in the LSP process, as previously discussed. While the absorbing layer can protect the target metals from thermal damage and the confinement layer can enhance the shock wave pressure, they also bring issues to the LSP process. The integrity of the absorbing overlay is one factor that has a direct impact on the effectiveness of LSP. Once the absorbing overlay bulges or ruptures, the surface of the target metal may become damaged, necessitating an interruption to the LSP process. Flaws such as bubbles and pockmarks in the original aluminum foil used as an absorbing overlay will lead to damage to the overlay during LSP, thereby forming defects on the blade surface (**Figure 15**). An absorbing overlay of smooth aluminum foil can be obtained by tool rolling or repeated pasting. Additionally, absorbing layers can also be damaged by unstable laser power density and excessive LSP treatment. Thus, a reasonable match between the LSP parameters and the aluminum foil is required to enhance the stability of the absorbing layers.

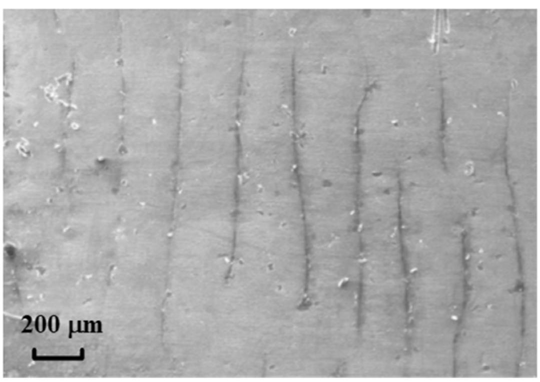

Figure 15. Pockmarks on the surface of blade. Reproduced with permission.[234] Copyright 2010, Springer Nature.

Water confinement can better match the geometry of the workpiece as compared to solid overlays (e.g., glasses). However, the water confinement could become unstable and fluctuate after each peening, and it requires a certain amount of time to recover before a subsequent laser pulse can be fired. This limits the frequency of LSP treatment. Moreover, the thickness of water confinement is not stable, particularly at the edges of a blade. Uneven water confinement may lead to high power density at a local location (the lens effect) or even damage to the absorbing overlay or the target surface. As shown in **Figure 16**, in order to stabilize the water overlay around the blade edge during LSP, the absorbing overlay can be extended beyond the edge of the blade to provide drainage.[150] Additionally, the blades are often positioned vertically during treatment, and gravity can create a uniform water overlay as water flows over the blade. AVIC Manufacturing Technology Institute developed an oblique jet pattern that also creates a consistent water overlay.

To improve the consistency of the LSP process, the application of the paint and overlay water needs to be monitored during processing and subsequently controlled to ensure that the thickness and/or uniformity of the paint and overlay water is the same for each laser pulse. The real-time nondestructive monitoring technology used during LSP treatment has become the focus of development in recent years. LSPT Inc. monitored the thickness and uniformity of the water overlay by a detection laser. The detection laser irradiates the water confinement layer at a certain angle, and the thickness of the water film is calculated through the reflection optical path difference between the upper and lower surfaces of the water film. The laser is not fired until the measured value is within a specified range.[151] In addition, as the natural frequency of the blade changes after LSP treatment,

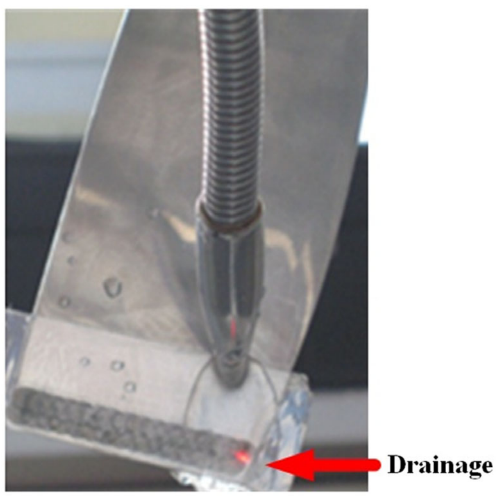

Figure 16. Drainage through extended absorbing overlay resulting in a stable water overlay. Reproduced with permission.[150] Copyright 2021, National Defense Industry Press (China).

GE monitored the quality of LSP in real time by observing the change in the natural frequency of the blade during LSP.[122]

Other techniques for real-time monitoring of the LSP process include acoustic monitoring and the use of polyvinylidene fluoride (PVDF) film. In the acoustic method, the acoustic emission signal from each peening pulse is monitored and processed using a sensing system. A quality assessment is then made by comparing the processed signal to a standard signal.[152–154] PVDF film can also be used for real-time monitoring. In this approach, a PVDF piezoelectric film is placed on the back side of the workpiece. Next, the shock wave pressure is translated into an electrical signal using the piezoelectric film. The electrical signal is then used to determine the quality of the LSP treatment. However, after the PVDF film is used for a certain amount of time, its qualities will deteriorate, and this can affect the monitoring reliability. In addition, the use of PVDF film is also inaccurate for workpieces with complex shapes. It should be noted that while a significant amount of empirical data is needed for the majority of the approaches mentioned above, real-time nondestructive monitoring of the LSP process is still worthy of continued research.

As mentioned before, LSP can be conducted without coatings (LSPwC).[95,155–157] At the University of Cincinnati, Vasudevan and co-workers performed LSPwC on AISI 304 austenitic stainless steel, Inconel 718, and AA5083 aluminum alloy.[158–160] The results showed that LSPwC significantly improved the pitting resistance of the specimens and contributed to the extended fatigue life. Note that although LSPwC increases the surface roughness of the specimen, the surface roughening is controlled, so the increase within a certain range does not affect the corrosion resistance of the specimens. In addition, according to a recent study by Kaufman and Vasudevan, LSPwC significantly reduced the intergranular corrosion rate compared with LSP.[159] Wang et al.[155] also found that although LSPwC improved the surface roughness of NiTi alloy, its wear resistance was also imoroved. LSPwC is appealing for industrial applications because it can significantly increase process efficiency. Since LSPwC was found to improve the stress corrosion resistance of boiling water reactors, it has been used to prevent stress corrosion cracking in Japanese nuclear power reactors since 1999.[161] However, LSPwC is not applicable for materials that can be easily ablated such as titanium alloys. Once severe ablation occurs, it will be detrimental to the fatigue performance of the material.

5.2. LSP of Thin Blades

AE blades are generally designed to be thin in order to improve their thrust-to-weight ratio. As a result, AE blades are more susceptible to FOD, thereby compromising their fatigue performance. LSP is able to improve the fatigue performance of AE blades by generating CRS throughout the entire thickness section of the thin blades.[162,163] However, as shown in **Figure 17**, the amount of geometrical deformation of the thin plate is sensitive to laser power density.[164] Thus, single-sided LSP can cause local bending at the leading and trailing edges of the blades.[134,164]

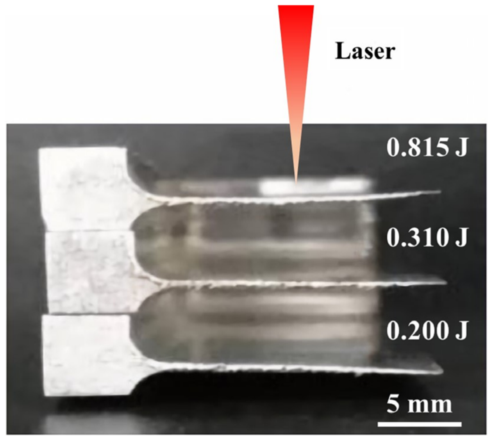

Figure 17. Distortion to blades after single-sided laser peening when using different laser pulse energies. Reproduced with permission.[163] Copyright 2018, Elsevier.

In addition to undesirable deformation, there also exist other adverse effects of using LSP on thin AE blades. First, to ensure the internal equilibrium state of the material, TRS will be generated along the direction of the CRS when LSP is carried out from one side, which will decrease the depth of CRS generated by LSP.[165,166] Secondly, LSP will produce a dimple on the peened side and a bulge on the reverse side of a thin AE blade[166] and will cause an uneven distribution of the RS field. More importantly, spalling and fracture can also occur when the intensity of the laser is too high.[167] Due to the thinness of the blade, it can also be challenging to constrain the laser-induced plastic deformation, and the CRS easily relaxes under HCF loads.

To address this problem, materials with the same acoustic impedance can be attached to the back of the AE blade to guide the wave and reduce the reflection amplitude.[168–170] It is also possible to use materials with high acoustic impedance to form compression waves and, thus, prevent the emergence of reflected

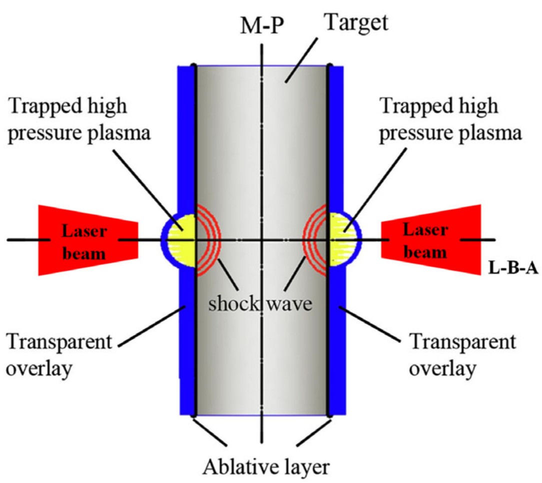

Figure 18. Schematic diagram (where M–P is the midplane axis and L–B–A is the laser beam axis). Reproduced with permission.[10] Copyright 2020, Elsevier.

tensile waves. However, to date, no further studies in this direction are available in the open literature.

Double-sided LSP is another option for preventing reverse deformation of the specimen during the LSP process. As shown in **Figure 18**, in double-sided LSP, the laser beam is split into two beams to induce laser peening on both sides of the component simultaneously.[130,163,171] For components with a symmetrical structure, double-sided LSP can generate symmetrical pressure loads by simultaneously peening both sides of the target region (such as the leading and trailing edges of the blade) to obtain a symmetrical residual stress field, thereby mitigating the deformation of thin blades,[10,107,172] as shown in **Figure 19**.

The mechanism for residual stress formation in double-sided LSP is more complicated than that for single-sided LSP. Up to now, the research on the evolution of local stress induced by double-sided LSP has mainly been based on FE simulations, and the mechanism of fatigue life improvement is yet to be analyzed in detail. Braisted et al.[173] built the first double-sided LSP FE model in 1999. Later, Ding and Ye[174,175] developed the first 3D simulations and found that TRS is present in the midplane of a metal sheet after double-sided LSP. The FE studies conducted to date suggest that the CRS is distributed on the front side, the back side, and the middle plane of the specimen, while TRS is distributed under the CRS layer.[176–178] A symmetrical M-shaped stress distribution field is obtained, and the magnitude of the residual stress depends on the thickness of the sheet.[172,174,175,179]

In double-sided LSP, it is typically necessary to ensure not only that the simultaneous laser shocks occur from both sides of the sample but that they also focus on the same position, which can be challenging for components with asymmetric structures, such as the tenon joint of an AE blade. The complicated structure of such components makes it difficult to adjust the laser beam path. Moreover, there are different opinions on whether to implement double-sided LSP: some researchers believe that double-sided LSP can easily lead to spallation due to reflected tensile waves from both sides arriving at the middle of the cross section simultaneously, and this can double the amplitude of tensile stress intensity.[168,175,180] While double-sided LSP has been proven to reduce component distortion in the laboratory, its implementation in the field is rare.

Other methods have been suggested to mitigate the undesirable effects of double-sided LSP. Hu et al.[162] proposed that alternating double-sided laser peening could reduce the risk of spallation, but no further studies in this direction have been published in the open literature. The experimental research on the evolution of local stress induced by double-sided LSP is limited, and the mechanism for fatigue life improvement has yet to be studied in detail. Using a small spot/scanning shock also seems to be a feasible solution. A smaller spot will induce a shallower shock wave propagation depth, which can prevent blade deformation. However, this will also reduce the depth of the CRS layer.[181]

5.3. LSP of Integral Blade Rotors

Traditionally, the rotor blades of compressors and fans in AEs are connected to the rotor, with the tenons and rabbets locked to each other. This traditional tenon joint structure is bulky, has many parts, and is inefficient; as such, it is not conducive to cost optimization and reliability improvement. In the early 1960s, the integral blisk, a blisk that incorporates the rotor blades and the wheel in one body, was introduced to address this issue. The tenon joint device was omitted from the design, which greatly simplified the structure of the integral blisk and prevented failures caused by the fretting fatigue between the tenon joints. **Figure 20** shows the IBRs used in the HF-120 turbofan engine.

At present, IBRs are mainly used in AE fans and high-pressure compressor rotors, and the primary materials used in their construction are titanium alloys and high-temperature alloys. An IBR is light in weight, simple in structure, high in efficiency, and very reliable. Research by Rolls Royce shows that the IBR structure can reduce the weight by 50% as compared to a traditional structure.[182] However, once the blade on an IBR becomes irreparably damaged, the entire blade/rotor component must be replaced. Because of this, it is of utmost importance that surface treatment such as LSP be carried out on the blade of an IBR prior to use.

It is very challenging to use LSP to treat an IBR due to its complex structure. For example, the blades in an IBR shield each other, and it can be difficult to treat the concealed surfaces. In 2003, the United States realized the application of LSP engineering for the IBR of the F119 engine and applied for several patents. These patents include double-sided peening technology to prevent deformation, high-inclination LSP technology to treat the concealed surface, quality control technology to improve reliability, and automatic coating technology to save time.

Figure 19. Deformation of the LSP-treated specimen. Reproduced with permission.[107] Copyright 2011, Springer Nature.

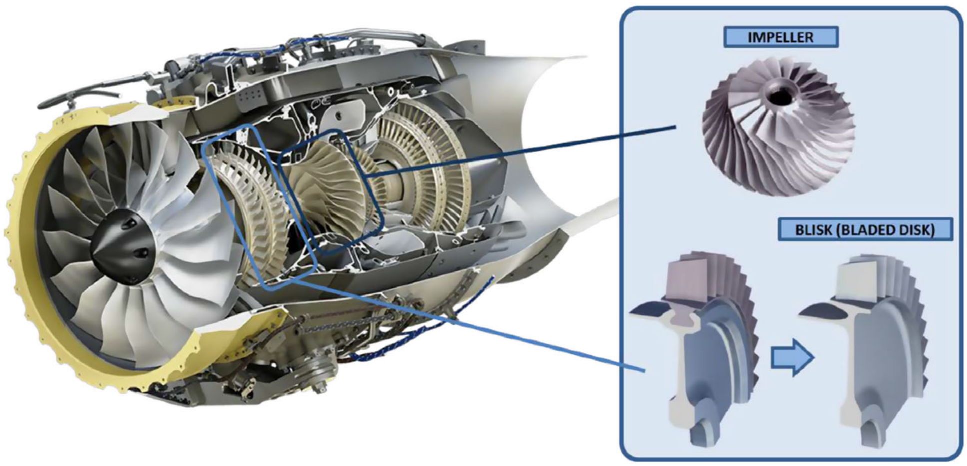

Figure 20. HF-120 turbofan engine produced by GE-Honda, with details showing the blisk and impeller. Reproduced with permission.[235] Copyright 2020, MDPI.

Zou et al.[183] pointed out that some technical challenges remain in the implementation of LSP on IBRs. The first is how to conduct LSP on a concealed surface. Unlike an open surface, it is difficult to shock the concealed surface of an IBR.[183] At the current time, the presence of a concealed surface has become the most important factor restricting the efficiency of LSP when treating IBRs. When using high-inclination laser incidence technology, the inclination angle (i.e., the angle between the laser beam and the normal direction of the area to be strengthened) is generally set to an angle of 60° or less, as an excessive tilt angle will cause serious distortion of the light spot and will result in energy loss. Thus, it is necessary to compensate by adjusting the laser pulse energy or the peened area at any time. Laser optics can also be used for dynamic correction of the light spot to round the distorted light spot. Light guiding technology has extremely high requirements for the control of the light path, and optical path pollution may occur during processing.

The second challenge relates to the requirement for high processing quality of the intake and exhaust edges of an IBR. It is difficult for LSP to induce favorable CRS at the edge of the blade of an IBR that is less than 1 mm thick without inducing excessive deformation. Therefore, it is necessary to strictly control the energy distribution of the laser spot and the overlap between spots. The third challenge is the stability of the water confinement overlay (which was mentioned in Section 5.1). When using LSP treatment for the blades of an IBR, the position of the water nozzle needs to be adjusted frequently due to the compact position of the blades and the large angle change. As a result, the stability of the water overlay cannot be ensured for each adjustment, making it challenging to ensure process consistency.

5.4. LSP of High-Temperature Components

While an AE has low-temperature components such as a fan and compressor blades, some components in the engine are designed to work at elevated temperatures, such as turbine blades, gears, and rotors. The high-temperature components are vulnerable to fatigue failure under the combined effects of mechanical and thermal loading.

LSP is the most effective method for improving the fatigue resistance of materials under normal temperature conditions.[18,38] Numerous studies show that the improvement of the fatigue strength for targets treated using SP and LSP is mainly attributed to the creation of CRS and nanograins.[38] However, the CRS and the work-hardened layer induced by room-temperature surface treatments (LSP, SP, deep rolling, etc.) become unstable during cyclic loading,[184–187] especially at elevated temperatures.[29,188,189] Fortunately, LSP-treated materials have relatively better thermal stability than those subjected to other surface treatment methods due to the lower cold working rate.[190,191] For example, Chin et al.[190] found that the CRS on the surface of an SP-treated Inconel 718 specimen relaxes by 45% after 1 h at 600 °C, whereas it relaxes by only 20% for an LSP-treated specimen.

The Aerospace Material Specifications (AMS) 2546 standard for LSP limits the working temperature of treated nickel-based superalloy components to 538 °C.[192] With the development of aviation technology, the working temperature of titanium alloy blades of a high-pressure compressor can reach temperatures

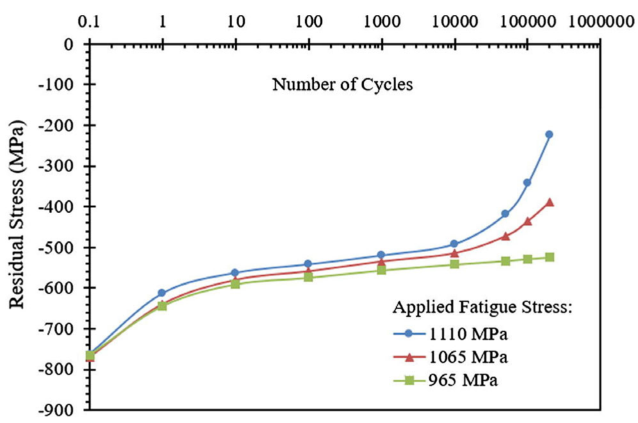

Figure 21. LSP residual stress relaxation with number of cycles at 650 °C for samples tested at applied maximum fatigue stresses of 965, 1065, and 1110 MPa. Reproduced with permission.[149] Copyright 2017, Elsevier.

of 600 °C. However, the maximum working temperature of turbine blades/disks can reach 800 °C.[193] Shepard et al.[194] found that the CRS introduced by LSP on the surface of a titanium alloy specimen was almost completely relaxed at 565 °C. As shown in **Figure 21**, Kattoura et al.[149] observed significant stress relaxation in the thermomechanical fatigue test of 718Plus alloy. Thus, the thermal relaxation of residual stress is a critical factor that limits the further development of the industrial application of LSP.

According to various studies, the magnitude of residual stress relaxation of a specimen exposed at elevated temperatures is related to a number of factors including the exposure time,[148,195] exposure temperature[195,196] initial stress,[196] and cold working rate.[190,197] Most stress relaxation on the surface occurs in the initial stage of thermal exposure. Ren et al.[196] reported that temperature has a more significant influence on stress release than exposure time. In addition, the relaxation of residual stress is closely related to the degree of cold working.[197] The initial CRS of highly cold worked surfaces might be relaxed in 10 min for either a titanium or a nickel-based alloy, even at the moderate AE temperatures (400–500 °C).[39,197]

The mechanism of residual stress relaxation is complex. Work conducted to date indicates that the thermal relaxation of CRS can mainly be attributed to the annihilation and reorganization of metastable crystalline defects induced by LSP, creep-controlled dislocation rearrangement, material softening at high temperatures, and uneven distribution of residual stress in the as-peened component, among other factors.[189,190,198] Numerous studies have focused on the prediction of the residual stress induced by LSP,[58–60] but research on the residual stress relaxation mechanism under thermomechanical loading is very limited. In addition, the failure mechanism of long-term service components in a high-temperature environment is quite complicated.[199–201] Most existing studies on fatigue failure are focused on the materials used for cold-end components, such as titanium alloys (particularly Ti–6Al–4V).[22,29] The research on other turbine splicing materials that are used in AEs, such as the nickel-based superalloys that are commonly used in turbine blades, is relatively limited.

To improve the CRS and microstructural stability of the material in LSP, Ye & Cheng at Purdue University proposed WLSP technology.[4,5,202–204] WLSP is a thermal-mechanical technique in which LSP is conducted on a prewarmed target surface. This thermal-mechanical process combines the advantages of LSP and dynamic strain aging: it has highly dense dislocations and better thermal stability due to the dislocation pinning effect induced by the interaction between dislocations and nanoprecipitates.[202,205] Since WLSP was first proposed in 2009, researchers have conducted WLSP experiments on aluminum alloys,[203,205] carbon steel,[4,206] titanium alloys,[23,207] and a nickel-based superalloy.[208] Compared with traditional LSP, WLSP treatment results in high strength and more stable surface CRS. While WLSP is a promising method for improving the effectiveness of the LSP for components that operate at elevated temperatures, the method used to preheat the target sample is difficult to implement in industrial applications.

5.5. LSP of the Tenon Joint Structure

The blades of the fans, compressors, and turbines in AEs are mostly integrated with the disc using a tenon joint splicing structure. Two types of tenon joint splicing structures are commonly used in AEs: the fir-tree type shown in **Figure 22**a, which is normally employed in the hot, smaller stages of the engine, and the dovetail joints shown in Figure 22b, which are normally found in the fan and colder stages of the engine. Since the tenon joint structure is not a rigid connection, local stress concentration and vibration conditions can lead to cracks or fractures caused by fretting fatigue (as shown in Figure 22), which become the primary failure mode for the spliced structure of the tenon joint.[16,209]

One study found that 16.7% of HCF failures in USAF military AEs are closely related to fretting fatigue of the tenon joint structure.[210] In addition, titanium alloys, which are widely used in the tenon joint structure of compressors and fans, have high sensitivity to fretting fatigue. Thus, to improve safety and extend the service life of an AE, fretting fatigue failure between the mating surfaces of the disc and blade root is a significant concern that must be addressed.

LSP has proven to be an effective surface enhancement process for improving the fretting fatigue of components in service,[3,18,53] and it has a better enhancement effect than SP because it induces a deeper layer of RS and a lower relaxation of thermal stress.[3,17,211] Good accessibility also makes LSP more suitable for strengthening complex structural parts.

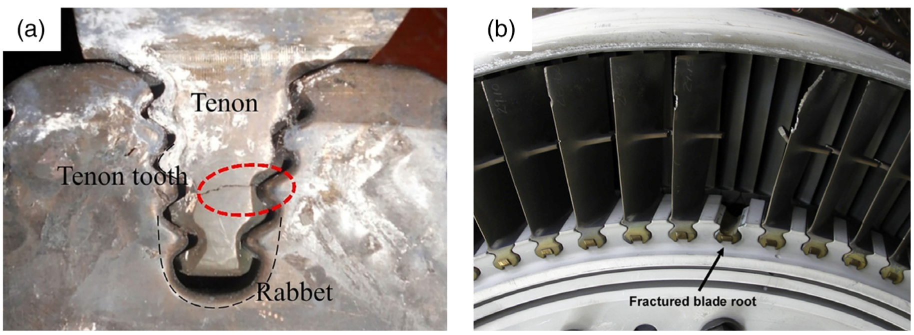

Figure 22. a) Fracture failure of the contact area in the fir-tree tenon joint structure of an aeroengine. Reproduced with permission.[18] Copyright 2019, Taylor & Francis. b) Dovetail attachment region of a bladed disk and the associated damage. Reproduced with permission.[236] Copyright 2008, Elsevier.

Golden et al.[17] conducted fretting fatigue tests on Ti–6Al–4V alloy dovetail specimens and found that the fatigue life after LSP was more than six times that of the as-received alloy. They claimed that although LSP treatment cannot prevent crack initiation, the CRS induced by LSP can mitigate the propagation of any cracks that form. This finding is consistent with the conclusions of Srinivasan.[212] More recently, Kumar et al.[146] and Lu et al.[18] noted that the improvement of the fretting fatigue life of LSP results from the synergistic effect of the increase in surface hardness, the refinement of the surface grain, and the formation of CRS.

As shown in **Figure 23**, the region near the transition section of a turbine blade and the first groove of the tenon tooth is vulnerable to cracking under the alternate stresses and high temperatures it experiences during service. Therefore, these regions are critical areas to treat using LSP. It should be noted that the ablation layer is difficult to cover in this area, and the water confinement layer is prone to uneven thickness due to the narrow region and the large curvature of the tenon tooth. In this case, LSP without coating (LSPwC) can be conducted. However, for some materials, especially titanium alloys, the material surface is easily ablated during LSPwC. Once ablation occurs, it will be detrimental to fatigue performance.

In addition, the narrow base of the tongue and groove structure make it difficult for a laser beam to reach all areas of the groove and tenon. Once the laser beam has irradiated the sidewall of the groove to generate plasma, the bottom of the groove cannot be peened, and this reduces the effectiveness of the LSP treatment. To accomplish LSP treatment, the path of the laser beam needs to be constantly adjusted. Adjusting the vertical incidence and the large inclination angle of the laser allows different positions of the tenon structure to be treated.

It should also be noted that the size of the tenon tooth/groove in a turbine blade is small, and the curvature of the transition region changes significantly. If the same laser power density is used to process all areas, it is easy for stress to concentrate at the upper and lower edges of the R rabbet. Moreover, the ablation layers at the upper and lower edges of the R rabbet are easily torn. This problem can be prevented by adopting the "unequal stress distribution impact method," in which the groove bottom and the transition zone are strengthened using different energy parameters in the treatment to control the stress distribution (see **Figure 24**).

5.6. Spallation-Like Phenomenon (Internal Cracking)

The enhancement effect of LSP on materials has been widely reported,[4,5,8] but few researchers have studied the detrimental effects of laser shocks. In 2002, a spallation-like phenomenon in an aluminum alloy after LSP was reported by Ding et al.[213] During LSP, the unloading (release) wave inside the solid body interacts with the waves reflected from the back of the target to form dynamic tensile stress. When the intensity and duration of tensile stress reach a certain threshold, dynamic fracture will occur inside the metal target, producing a spallation-like phenomenon (**Figure 25**). In the process of spalling, a substrate layer is peeled from its original plane to form a bump at the surface, while the actual spallation plane is buried underneath the surface of the material. Therefore, some studies refer to spallation as internal cracking. The micromechanism of spallation can be attributed to the nucleation, growth, and coalescence of microvoids.[214,215]

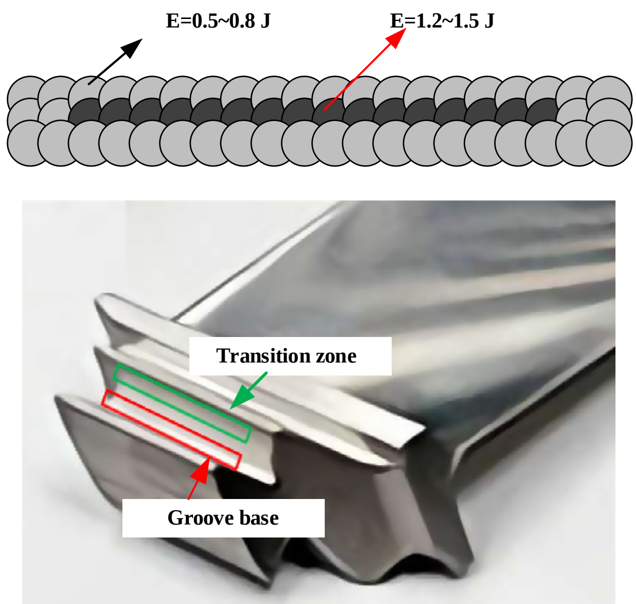

Figure 24. Laser shock peening areas at the center of the groove and the transition region of a blade root. Reproduced with permission.[238] Copyright 2020, Gas Turbine Experiment and Research (China).

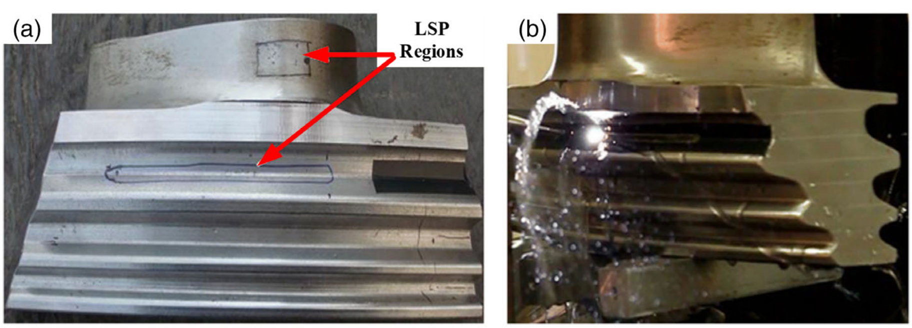

Figure 23. a) Laser-peened regions at the root of the turbine blade. b) LSP processing. Reproduced with permission.[237] Copyright 2014, Springer Nature.

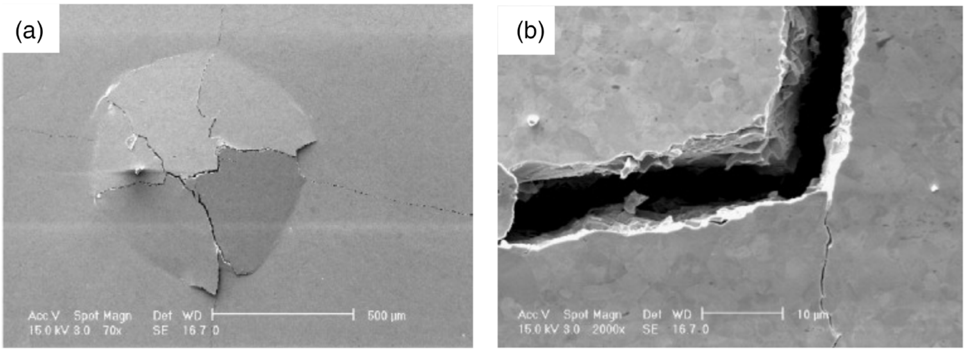

Figure 25. a) Spallation and cracking observed on a 0.2 mm-thick tungsten substrate; b) enlarged view of an in-plane crack. Reproduced with permission.[217] Copyright 2009, Elsevier.

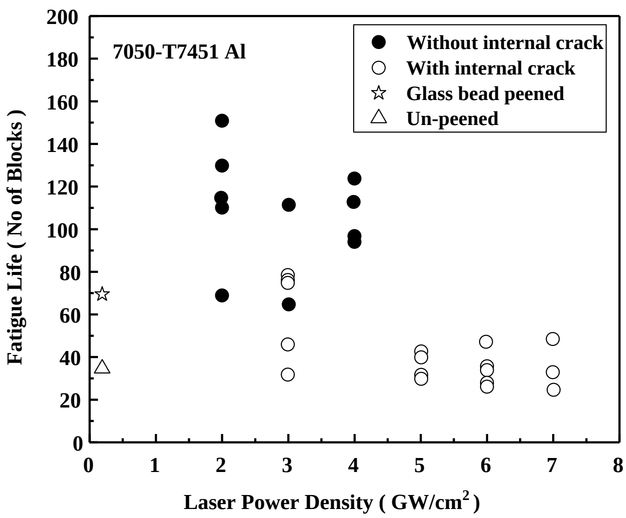

Figure 26. Fatigue life as a function of laser power density on LSP-treated 7050 Al specimens under spectrum loading at an applied peak stress of 390 MPa. Reproduced with permission.[218] Copyright 2004, Balkema.

Liu et al.[216] further studied the influence of laser power density on the fatigue life of 7050 aluminum alloy, and the results are shown in **Figure 26**. It can be seen in this figure that when the laser density reaches a certain threshold (5 GW cm^{-2} in this case), the fatigue life of the alloy is significantly reduced. Liu et al. attributed this decrease in fatigue life to the formation of internal cracks (spallation). Hu et al.[215] also observed in-plane cracking and spallation in tungsten when the stress waves had sufficiently high amplitudes. More recently, Jarmakani et al.[216] studied the spalling and fragmentation behavior in polycrystalline and monocrystalline vanadium induced by laser shocks. They found that the laser energy, target thickness, and microstructure have an effect on the spalling strength of vanadium, and the monocrystalline specimen has a higher spalling strength than the polycrystalline specimen.

It is noted that a high laser power density is required for LSP treatment of AE blades and that the blades are generally very thin. For example, the laser power density required to strengthen titanium alloy blades is more than 6 GW cm^{-2}, and it can even go as high as 9 GW cm^{-2}.[44,217] As a result, LSP is likely to cause spallation on the back side of the blade (especially at thin wall edges). For example, Wu et al.[217] found that LSP induced a spallation-like phenomenon on the rear side of a blade made from TC17 titanium alloy, and other studies have also shown that LSP can lead to spallation.[216,218] Double-sided LSP is more vulnerable to spallation due to the doubling of TRS.[175] To alleviate spalling, aluminum foil can be pasted on the rear side of blade and covered with water overlay, as shown in **Figure 27**.[219]

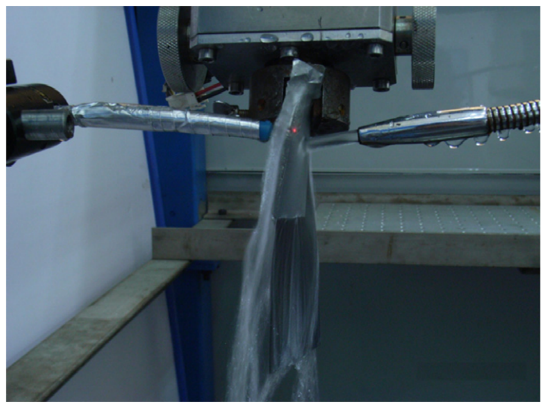

Figure 27. The rear side of the blade is covered with aluminum foil with flowing water to mitigate spallation. Reproduced with permission.[221] Copyright 2011, Rare Metal Materials and Engineering (China).

In recent years, researchers have studied the spalling phenomenon in various materials (such as titanium alloy, aluminum alloy, vanadium, and tungsten) that result from LSP treatment.[214–216,220] However, research on how to avoid spallation during the process of blade edge strengthening is fairly limited.

5.7. Effect of Peening Region and Geometric Discontinuities

To reduce costs, in actual engineering practice, only the critical regions of the blade surface are typically treated, and this process is known as selective LSP. As shown in **Figure 28**, Fu et al.[165] found that LSP can effectively suppress the deflection of the

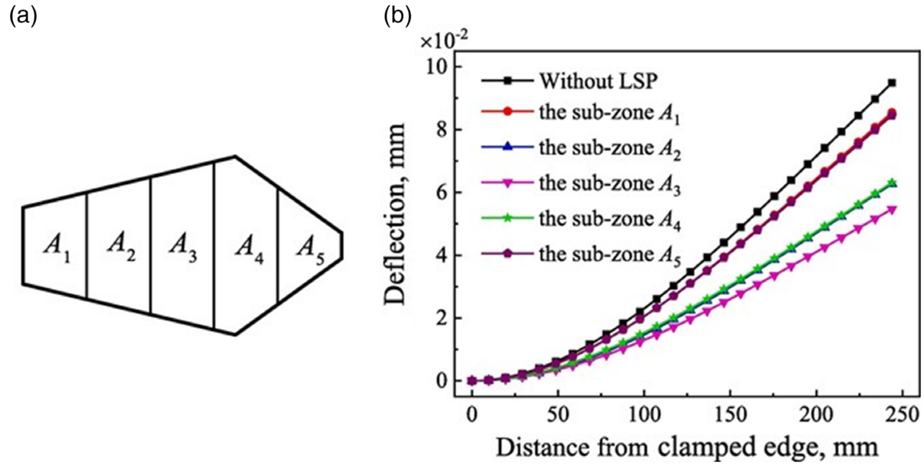

Figure 28. a) Schematic showing five strengthened zones on a blade surface. b) Blade deflection responses observed when different positions are strengthened. Reproduced with permission.[165] Copyright 2020, Elsevier.

blade; in other words, it effectively suppresses the forced vibration response of the blade. In addition, the different peened areas of the specimen (the regions labeled as A1–A5 in Figure 28a) have different degrees of deflection of the blade. That means the peening region influences the enhancing effect.[165] Therefore, vibration deflection can be used as an optimization objective when selecting the region to strengthen, and this provides helpful guidance for optimizing the LSP process parameters.

In addition to the peening region, geometric discontinuities are also known to have an influence on the effectiveness of LSP. Previous studies have shown that discontinuities at the edges of components are likely to form during processing.[73,221,222] These geometric discontinuities are susceptible to large plastic deformation and even local collapse, resulting in local stress relaxation and strain concentration, which will reduce the fatigue life of the component. Sun et al.[223] performed LSP treatment on three specimens having the same structure but where different regions were treated using LSP and found that when the peening area covers the discontinuous edge of the specimen, the edge becomes a weak point. Dorman et al.[73] found that the fatigue life declined by 10% when a scratch having a depth of 150 μm was made on the edge of the specimen.

In the LSP process, the interaction between the laser shock wave and the edge of the specimen can easily create discontinuities at the edge. As the geometry of engine blades is complex, once an edge effect occurs, it will weaken the effects of LSP and can even decrease the fatigue life of the specimen. In addition, Praveenkumar et al.[138] found that the residual stress induced by LSP is also related to the geometry or curvature of the blade. Therefore, studies using plane specimens to simulate AE blades with complex curvatures may not be informative.

5.8. Finite-Element Simulation of Residual Stress Distribution Induced by LSP

The CRS introduced by LSP is an important factor for improving fatigue performance. To obtain an ideal residual stress distribution, it is necessary to explore the optimal LSP parameters and scanning paths. FE simulation is widely used to predict the residual stress distribution of LSP due to the complexity of experimental studies of LSP. The first FE analytical model for LSP was developed by Braisted and Brockman,[173] who successfully predicted the residual stress distribution induced by LSP in carbon steel.

Since then, FE simulations have been applied to construct the residual stress fields induced by LSP in a wide range of materials. Fang et al.[51] used numerical simulation to analyze the effects of different LSP parameters and ways on the residual stress of TC4 alloy blades. Their results show that the CRS in the blade surface direction increases significantly with increases in the spot radius and the laser pulse width. Yan et al.[224] used FE to evaluate the residual stress field in a TC4 titanium alloy blade treated by LSP. They found that the depth of the maximum value of residual stress and the depth of the plastic deformation layer increased after several passes of LSP. Li et al.[225] established an FE model of residual stress and energy distribution for TC4 titanium alloy blades under various power densities during LSP, and they validated the models by comparing the simulation results with results obtained from experiments.

FE simulations have also been used to study the effect of overlap between laser spots on the distribution of residual stress for various materials. Xu et al.[226] studied the effect of different scanning paths and overlap between laser spots on the residual stress distribution of 316L stainless steel turbine blades through FE simulation and compared the results with experimental results. It was reported that when the overlap was 30%, varying the scanning path had no obvious effect on the residual stress field distribution. As the percentage of overlap increased, the residual stress field became more uniform. To simulate processes that involve multiple passes of LSP, Wang et al.[227] developed two different types of 3D FE models—one based on a plate model and the other on a model of a blade made from TC4 titanium alloy—to thoroughly study the effect of the percentage of overlap. The results demonstrate that the CRS depth and grain refinement both increase with the percentage of overlap.

Although some simulation work has been performed in an attempt to construct residual stress distributions for LSP-treated engine blades, the majority of simulation studies are based on a flat plate model,[228,229] which may not be representative of the impact response of actual AE components, which have curved surfaces. More simulation work on models that use actual blade geometries is needed to effectively optimize the process parameters.

6. Conclusion

LSP originated from basic research conducted in the 1960s and was developed for industrial application in the 1980s. With the continuous improvement of laser systems in the mid-1990s and the impetus of the "High Cycle Fatigue Science and Technology Program" implemented in the United States in 1994, LSP has been successfully applied to many different AE components. Over the years, significant progress has been made in the use of LSP for treating these components. In this review, the application of LSP for treating AE components was considered, with a focus on the possible obstacles to the practical application of LSP in AE blades. The development of LSP for treating AE components over the past three decades was presented, including the early exploratory stages and industrial application at later stages. In addition, the mechanisms of LSP and their effect on the fatigue resistance to FOD of AEs were briefly introduced.

Based on the results of the studies presented in this review, the following conclusions and recommendations can be made. 1) Further development of LSP for treating aviation components is closely tied to advances in the development of high-energy pulsed laser systems. The need for LSP treatment of critical locations on large and complex structural components has created a niche for lasers with relatively lower pulsed laser energy and higher frequency. As lasers that are smaller in size and more portable become available, larger and more complex components can be treated on site rather than having to be transported to a processing facility at another location. 2) Some innovative applications of LSP have only been verified in the laboratory, and additional work is required before industrial implementation of these LSP technologies can be realized. For example, although WLSP can improve the stability of compressive residual stresses and microstructure, further work is needed before the process is considered to be ready for industrial application. 3) LSP studies need to take into account the complex geometries of various aeroengine components. The planar samples used in some existing studies may not be representative of the blades used in AEs, and some processes that are already in use in the aircraft industry require further optimization to be suitable for treating these components. For example, while double-sided LSP can resolve issues of excessive distortion that are created during LSP treatment of thin-walled components, it can easily result in spallation, and it is challenging to apply double-sided LSP to AE components having complex geometries. 4) While LSP has been found to significantly improve the FOD resistance of metallic samples, thereby improving their fatigue performance, it is difficult to precisely determine the degree of improvement in the fatigue performance. Additional research on fatigue life prediction is still needed to incorporate any relevant fatigue life benefits from LSP into damage tolerance design. Moreover, to improve the quality of LSP-treated components, the support of a theoretical framework and more experimental data is needed. To promote the further development of LSP in the field of aviation, it is necessary for academia and industry to closely collaborate on future research.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

aircraft engines, engine blades, fatigue, laser shock peening

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