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Progress in additive manufacturing, additive repair and fatigue evaluation of aviation titanium alloy blades

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ABSTRACT

The aviation industry is a key market that promote additive manufacturing (AM) technology since there are huge demands for precision manufacture of high-value complex structural parts and repair of local defects. Extensive research has been conducted on AM process, characterization, and fatigue evaluation of titanium alloy, but there are rare comprehensive reviews on fatigue evaluation methods used for AM aero-engine blades. Rigorous tests, evaluation, and certification are necessary before AM technology is applied in aero-engine blade repair, although it has shown great advantages in different engineering fields. This paper introduces the application of AM technology in the manufacturing and repair of aero-engine titanium alloy blades, summarizes the key factors affecting the fatigue performance of AM titanium alloys, thoroughly discusses the fatigue mechanism, research methods, and process optimizations of AM parts, and compares the differences among several prediction models in fatigue evaluation of AM titanium alloys.

Abbreviations: FOD: foreign object damage; LCF: low cycle fatigue; HCF: high cycle fatigue; LSP: laser shock peening; SP: shot peening; LP: low-pressure; HAZ: heat affected zone; AM: additive manufacturing; LAM: laser additive manufacturing; DED: directed energy deposition; PBF: powder bed fusion; LPBF: laser powder bed fusion; EPBF: electron beam powder bed fusion; LMD: laser metal deposition; LCD: laser cladding deposition; LENS: laser engineered net shaping; SLM: selective laser melting; EBM: electron beam melting; SEBM: selective electron beam melting; SLS: selective laser sintering; DMLS: direct Metal Laser Sintering; DMD-L: direct metal deposition by laser; DMD-P: direct metal deposition by plasma arc; LS: laser sintering; AB: as-built; LOF: lack of fusion; EVS: extreme value statistics; LEVD: largest extreme value distribution; VED: volumetric energy density; PD: probabilistic distribution; MRO: maintenance, repair & operations; STA: solution treatment & aging; BUS: broken-up structure; HIP: hot isostatic pressing; M&P: machining and polishing; SR: stress relief; AN: annealing; DAN: double annealing; PBG: prior β grain; TCT: thermochemical treatment; AC: air cooling; SMAT: surface mechanical attrition treatment; CT: computer tomography; SEM: scanning electron microscope; FCG: fatigue crack propagation; FCGR: fatigue crack propagation rate; SIF: stress intensity factor; EIFS: equivalent initial defect size; LEFM: linear elastic fracture mechanics; ML: machine learning; ANN: artificial neural network; FNN: feed forward neural network; CNN: convolutional neural network; PINN: physics-informed neural network; PPgNN: probabilistic physics-guided neural network; ANFS: adaptive network-based fuzzy system; SVM: support vector machine; SVR: support vector regression; RF: random forest; CDM: continuum damage mechanics.

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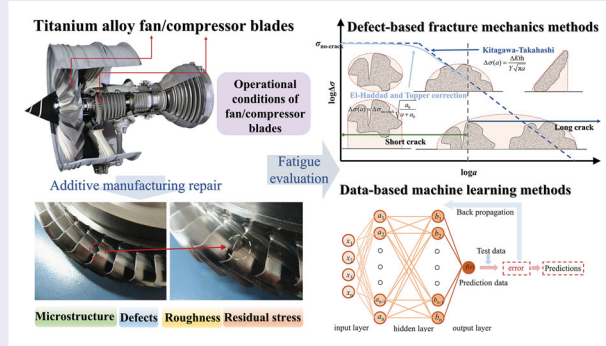
KEYWORDS

Aero-engine; titanium alloy; additive manufacturing; microstructure; damage mechanism; fatigue

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IMPACT STATEMENT

The fatigue performance of additively manufactured titanium alloys is influenced by a combination of microstructure, defects, surface roughness, and residual stresses. In the context of fatigue assessment, the role of defects is typically prioritized.

1. Introduction

Fatigue fracture caused by damage is a long-term problem to be faced during the whole service life of an aero-engine. Fan and compressor blades are key components of aero engines. Their fatigue performance is closely related to damages encountered during engine service life thereby becoming, an important factor causing aircraft “heart disease” [1]. During the long service life of an aero-engine that operates in harsh environments (including Gobi, desert, ocean, etc.), the fan and compressor may inhale hard objects such as sand, gravel, screw, nut, etc., which cause severe damage to blades named Foreign Object Damage (FOD) [2–4], as shown in Figure 1. Titanium alloy is very sensitive to defects and is prone to high-frequency fatigue fracture under the condition of air induced vibration. A crack of 0.1 mm can reduce the fatigue strength of the blade by about half [5,6]. Compressor blades will withstand an in-take air flow rate of roughly 1.2 tons/sec, a temperature of up to 540 °C, and a pressure of 600 psi during service [7]. Under these service conditions, extremely high centrifugal loads and vibrations caused by aerodynamic loads develop on the titanium alloy compressor blades. During flight, damaged blades are very easy to induce fatigue

crack initiation and propagation under the combined action of low cycle fatigue (LCF) loads and high cycle fatigue (HCF) loads, and then lead to fracture failure [8] or even non-containment accident [9,10], seriously threatening flight safety [11]. According to statistics, in the 20 years from 1996 to 2016, China’s major civil aviation companies recorded a total of 1765 engine FOD failures, involving 16 well-known engine models such as CFM56 series, Trent700, and V2500 [12], causing huge economic losses. What’s more, there are special requirements on military aviation engine models for special environmental conditions such as Gobi low altitude penetration. Thus the FOD failures of the fan and compressor blades of such engines have been more serious than those of civil ones.

The mainstream engineering solutions for the deterioration of fatigue performance of fan and compressor blades due to FOD are divided into two types of processes: strengthening and repairing. Strengthening processes are usually carried out before engine service, including surface treatments by laser shock peening (LSP) [13,14] and shot peening (SP) [15,16], to improve the fatigue performance of fan and compressor blades. Repairing processes are often conducted after service, including processes of grinding, welding, and additive

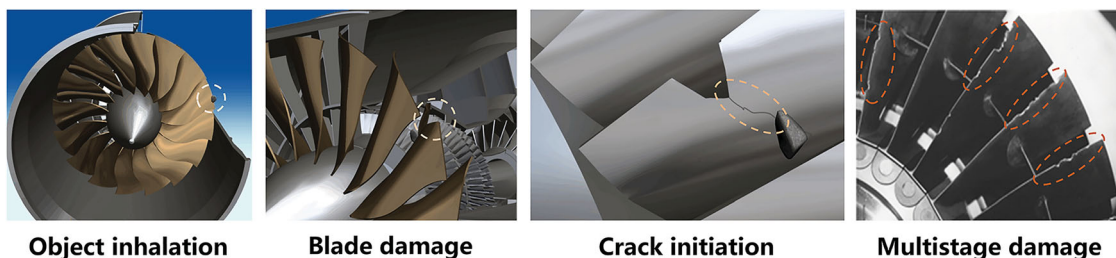


Figure 1. FOD failure of aero-engine fan blades.

manufacturing (AM) [17,18], aiming to improve surface conditions of damaged blades and reconstruct geometric dimensions, to restore the fatigue performance of the blades. As the fourth-generation fighters adopt integral titanium alloy blisk design in engine fans and low-pressure (LP) compressor blades (very different from former tenon-mortise assembly of blades and disk in material and constructure), the crack or fracture on a single blade would cause invalidation of the whole blisk, which not only seriously affect engine utilization, but also bring huge economic burden since expensive titanium alloy blisk has a long and complex manufacturing cycle. Conventional grinding and repairing methods could not solve problems such as angle drop, bulge, large gap, and large deformation occurring on titanium blisk blades, AM is used more widely in engine blade repair as the mechanical manufacturing concept and technology improved, mitigating the difficulties in the repair of damaged blades of the fourth-generation fighter engines.

AM repair can effectively restore the “shape” of the damaged components, but defects such as solidification cracking and microstructural changes formed during the repair process [19] would result in significantly worse fatigue performance as compared to the original ones, which is called “same shape with different performance” [20–22]. AM repair for titanium alloy stators of aero-engines has been partially realized, with the results of enhanced tensile strength and yield limit but worse plasticity [23,24] and insufficient fatigue strength [25,26] due to residual tensile stress, phase transformation in the repaired zone and heat affected zone (HAZ), and manufacturing defects. Therefore, AM repair has not been widely used on rotating parts of aero engines. Driven by the above problems, the aero-engine industry has been exploring technologies to improve the fatigue performance of AM repaired blades, and research on restoring fatigue properties of titanium alloy parts after AM repair is carried out in recent years from the aspects of heat treatment [27,28] and surface strengthening [29–31].

The working environment of an aero-engine is harsh. In contrast, the safe operation of an aero-engine is directly related to the life and property of everybody on board. Thus, safety becomes the core issue when fan or compressor blades are mounted back to service after AM repair. Tan et al. [32] reviewed the processing window, microstructure, material properties, and performance envelopes of aero-engine materials manufactured by laser additive manufacturing (LAM). Their work covered the three most widely used aero-engine materials, namely the advanced high-strength steels, nickel-based superalloys, and titanium-based alloys, but neglected practical issues about the operational environment of engineering structural components manufactured by LAM. Blakey-Milner

and his colleagues [33] conducted a comprehensive review on the issue of metal AM in the aerospace industry. Their work focused more on the commercial benefits and industrial application of AM components and structures, demonstrating numerous successful examples of metal AM in aerospace applications. They summarized many open research issues in the aerospace AM industry, including part certification, unique quality control requirements, post-processing challenges, potential reduced fatigue properties, and supply chain maturity issues required to produce functional components, and proposed prospects for future research and technological development in this field. But they did not discuss the specific issue of repairing aero-engine blades. Kanishka et al. [34] produced a comprehensive analysis of the foundational principles and prospective applications of AM restoration and repair. Their review focused more on reverse engineering, process parameters, and commercial applications rather than mechanical properties, emphasizing the application of AM technology in the repair process of different industrial products.

In addition to commercial benefits and engineering applications, there are also many comprehensive reviews on the fatigue properties of AM structural components. Liu et al. [35] introduced the latest research results about the fatigue properties of AM superalloys and titanium alloys. The LCF, HCF behaviors, and fatigue crack propagation (FCG) processes of these alloys under multi-field coupling and general testing conditions were compared. The effects of defects, microstructures, AM processes, post-treatments, and heat treatments on fatigue properties were highlighted. They also discussed the relevant fatigue mechanical models and the manufacturing defects and other parameters that should be emphasized in the models. Foti and collaborators [36] presented an overview of multiaxial fatigue in AM metallic components, provided insights into crack initiation sites and growth orientations, and related them to the fatigue failure mechanisms in these components. In addition, the development history of fracture mechanics models considering original defects was discussed, and the principal life prediction methodologies applied for the fatigue damage assessment of AM components under multiaxial fatigue loading were presented, with prediction accuracies of different models.

Although there are extensive reviews on the impact of AM repair process on fatigue performance [37–40] as well as the fatigue problems of titanium alloy components after AM repair [41–44], no comprehensive investigation has been conducted on the application of AM repair on titanium alloy blades, or the latest progress in fatigue performance evaluation methods used for AM

repaired titanium alloy parts. The purpose of this paper is to present a strict and special investigation on fatigue problems of AM repaired titanium alloy parts (especially aero-engine blades), to summarize an integral status of AM repair at present and to give suggestions on future research directions. Therefore, this paper makes an in-depth review of AM repair of titanium alloy parts from the aspects of technology development, fatigue performance evaluation methods, factors influencing fatigue properties, etc., aiming especially at the major demand for AM repair for damaged aero-engine blades. Methods widely used to repair aero-engine blades are described in the paper, key influencing factors of AM repair on the fatigue performance of titanium alloy blades are analyzed, fatigue evaluations on AM repaired titanium alloy parts are summarized, and research trends are forecasted. The purpose of this review is to provide the latest and complete information about AM repair for titanium alloy blades and promote the research and application of this technology in the aero-engine field.

2. Present status of aero-engine blades' manufacturing and repair

The titanium alloy fan and compressor blades require sufficient static strength reserve and fatigue strength reserve under the combined action of vibration stress and steady-state stress in service conditions. The static strength reserve requires that the blade's tensile stress and bending stress be controlled within the allowable range of materials, capable of continuously carrying out work without failure. The fatigue strength reserve requires that the transient value of the maximum vibration stress of the blade should be $\leq 60\%$ of the HCF limit of the blade (i.e. the HCF strength reserve ≥ 1.67). The titanium alloy's fatigue limit requires that the target number of cycles reach 10^9 . However, considering the test cost of conditioned fatigue limit, it is usually reduced to 10^8 cycles in practical engineering applications. In cases where HCF limit higher than 3×10^7 is not available, the HCF limit for 10^8 cycles can be temporarily calculated based on the 3×10^7 cycle test results and the SN curve fitting equation [3,45]. This strict blade generic performance requirement poses a challenge to the manufacturing and repair process of blades.

2.1. Manufacturing of blades

With the growth of the aviation industry, there has been a heightened demand for improved engine performance, which in turn necessitates better fan/compressor blades. Traditional casting, cutting and other methods are often inefficient when dealing with large integrated blisks or

turbine blades with film cooling holes, and achieving precise dimensional accuracy can be challenging, leading to significant material waste. In recent years, AM technology has garnered widespread attention due to its ability to offer new solutions for blade preparation in the field of aeroengines.

Based on the 3D model, AM process could form a metal part with fully dense and high performance in one step by in-situ metallurgy, rapid solidification and layer-by-layer stacking methods. In other words, AM presents an easier way to manufacture metal parts with complicated structures and realizes the well-known 'free manufacturing' [46]. In Standard F2792 [47] of the American Society for Testing & Materials (ASTM), AM process is divided according to their different additive processes into two types: direct energy deposition (DED) technology and powder bed fusion (PBF) technology.

Currently, there are several powder-based AM technologies for metal parts. Laser metal deposition (LMD), laser cladding deposition (LCD), and laser engineered net shaping (LENS) belong to DED. Selective laser melting (SLM), selective electron beam melting (SEBM), and selective laser sintering (SLS) belong to PBF [34]. Among them, LMD, SLM, and SEBM are widely used for additive manufacturing of components in the aerospace industry [48,49]. If divided according to the energy source used in AM process, both LMD and SLM use a laser as an energy source, while SEBM uses an ultra-high kinetic electron beam which is more effective and easily absorbed with larger action depth and smaller metal reflection compared to laser. Thus, SEBM has better forming efficiency than SLM. If divided according to material feeding modes in AM process, LMD is powder feeding type, and SLM and SEBM are powder spreading type. The powder spreading mode is more suitable for small and complex fine structure manufacturing since it is more stable and air controllable (or vacuum), and so the material powder can be self-supporting with high spatial accessibility during the manufacturing process. All the above AM processes have their own scope of application in metal part manufacturing due to their respective characteristics. Compared with LMD, the laser/electron beam size used by SLM or SEBM is smaller, and the forming accuracy of SLM and SEBM is higher, as shown in Figure 2. Zhao et al. [48] summarized the differences in technical parameters of the three commonly used titanium alloy AM processes, as shown in Table 1.

Based on the above analysis, the SLM process is suitable to manufacture small titanium alloy parts with porous material and complex geometry, and could present the best surface quality. But it has very high requirements on material powder particles and a rather low forming efficiency. The forming capacity of the

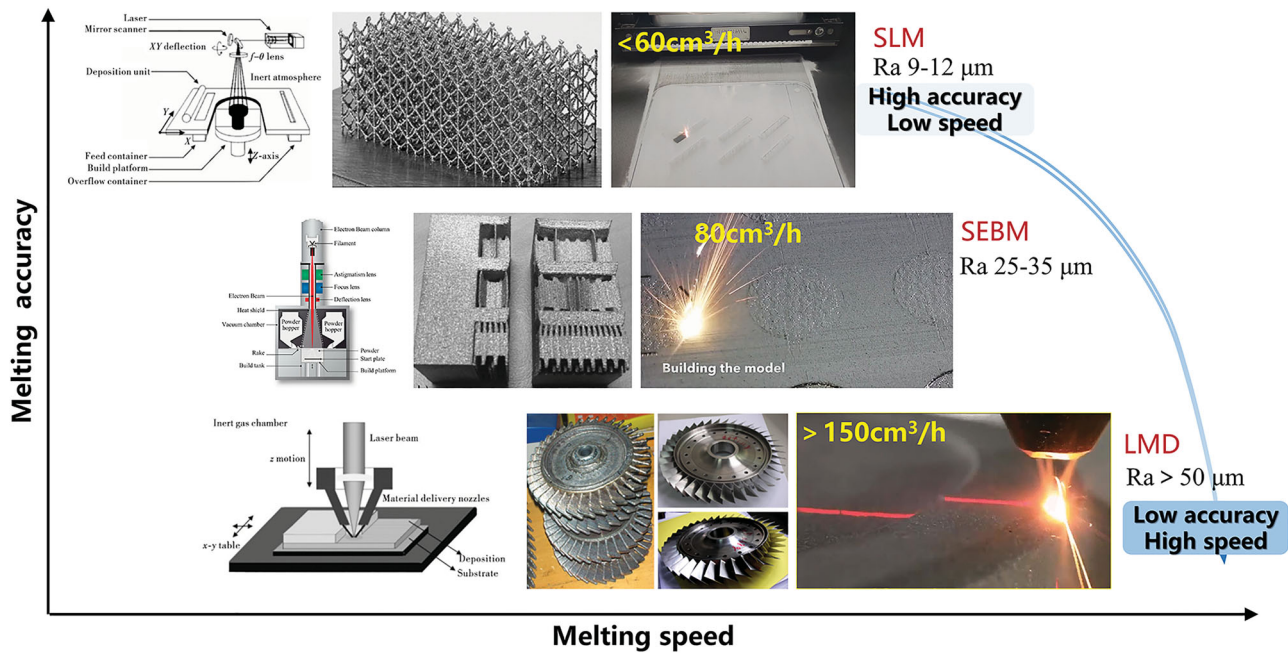


Figure 2. Comparison of three AM processes used for metal manufacturing [50–52].

Table 1. Comparison of three AM processes used for TC4 titanium alloy [48].

Process	Equipment	Energy	Parameter				
			Power / W	Scan rate / (mm s ⁻¹)	Spot diameter / μm	Layer thickness / μm	Powder diameter / μm
LMD	Trumpf-DLD	Laser	1200–1600	120–1560	4000	500–1000	50–150
SLM	EOS-M270	Laser	40–160	8.3–15.3	50–100	30–70	0–45
SEBM	Arcam-A2	Electron beam	210–630	300–900	100–500	70–100	45–105

SEBM process lies between LMD and SLM, and the SEBM processed parts have a smaller size compared to LMD processed ones. These three AM processes have been utilized for the manufacturing of aero-engine blades. However, when it comes to repairing damaged blades, the powder spreading mode, despite its advantages in stability and precision, faces challenges in accurately applying powder on damaged blades due to their varying damaged positions and dimensions. As a result, the presently adopted repair process for aero-engine blades and blisk is the powder feeding LMD [53]. Nevertheless, further process optimization and validation are necessary for the successful application of PBF in blade repair.

The application of AM technology in the field of engine blades has primarily focused on turbine blades. Siemens, for instance, has developed and tested functional prototypes of gas turbine blades by utilizing AM techniques. They have also successfully printed turbine blades of a 13-megawatt SGT-400-type industrial gas turbine using DMLS (direct Metal Laser Sintering) technology and completed full load testing [54]. The use of AM technology has significantly reduced the development and validation time for these components. The Boeing 777X and Comac C919 are powered

by GE's massive GE9X engine, which features EBM-printed TiAl low-pressure turbine blades [55]. These blades were manufactured by melting TiAl powder using an Arcam EBM machine and building it into 40 cm long blades, resulting in a weight reduction of 50% compared to traditional nickel-based alloy blades. The successful commercial applications of AM turbine blades demonstrate their strong market competitiveness. Furthermore, AM technology also plays a crucial role in the repair of aviation industry components.

2.2. Repairing of blades

Several methods such as mechanical grinding, welding, and AM are used for the repair of fan and compressor blades [18]. For repaired blades, their structural strength performance requirements must be met before being put into service. The higher the recovery degree of the repaired blade's mechanical and fatigue properties, the easier it is to meet its structural strength performance requirements of the blades. It is generally agreed that grinding could be used for light damage or damaged area which bears lower working stress since grinding could reduce the stress concentration factor of the damaged area and restore fatigue resistance. However, for large

damage or damaged area bearing large working stress, for example, blade tip drop, large blade body gap, large deformation, blade root gap, etc., welding or AM repair is usually selected to restore the geometric shape.

Mechanical polishing is a common method used to repair damaged fan or compressor blades of aero-engines. The typical mechanical process generally includes cutting, grinding, and polishing, to locally remove the materials in the damaged area of blades, and to form a gap with specific dimensional characteristics (width/depth ratio), thus reducing the stress concentration factor at the damaged location, and restore the fatigue performance to a certain extent. After the mechanical process, the repaired blades could meet the operation requirements. The mechanical repair process has been used on both military and civil aero-engines for many years because its principle is simple and its operation controllable. In the operation and maintenance manuals of main engine products in service (such as LEAP-1A and CFM56), the requirements for mechanical repair are stipulated, and strict standards and specifications are given for fan and compressor blades' grinding and repair. For example, the division of repair areas and specification of repair dimensions are shown in Figure 3.

However, mechanical grinding repair is a material reduction process that limits the recovery of fatigue performance in the damaged area. It is good enough for small-size blade damage and damage at low stress areas, but it could not solve the problem of large-size blade damage or damage at high stress areas. In addition, the grinding repair only reduces the stress concentration factor in

the damaged area but the damage remains, which has an inevitable impact on the aerodynamic performance of the engine.

Repairing based on welding is a widely used and economically beneficial technology for aero-engine blades [59]. Welding technology has successfully been applied to repair engines' compressor and turbine blades made of various materials such as titanium alloy, aluminum alloy, superalloy, and single crystal. For example, Zhang et al. [59] studied a turbine blade which was made of DS GTD111 material and repaired by arcwelding and discussed the failure issues of the repaired blade. Sayilgan et al. [60] used powder surfacing to repair the tip wear and cracks of a Ni-based single-crystal turbine blade. They successfully restored the initial geometry of the blade and created a single-crystal microstructure. Patriarca et al. [61] studied the mechanical behavior characteristics of Alloy625 wire-arc deposition alloy under LCF loads, discussed the LCF crack propagation characteristics, and provided guidance for damage tolerance design of repaired components.

Sometimes, it is difficult to define between welding and AM repair processes. Sikan et al. [7] studied the repair of a Ti-8Al-1V-1Mo compressor blade using electron beam wire-feed technology, which can also be considered as a use of welding technology. However, welding repairs face challenges such as uncontrollable geometry shape [62,63], nonuniform mechanical properties in the welded area [64,65], and safety concerns for the repaired blades.

In order to solve the damage problems that mechanical grinding and welding could not repair, AM has been

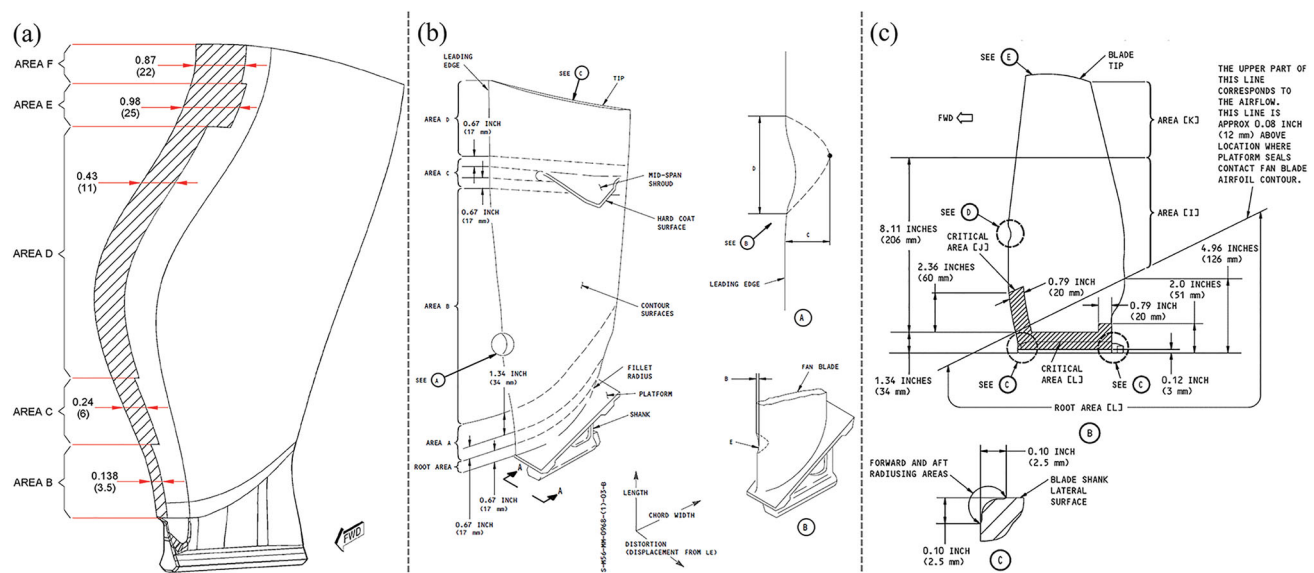


Figure 3. Maintenance specifications on aero-engine blades. (a) CFM-LEAP-1A engine fan rotor blade maintenance [56]; (b) CFM56-3 engine fan rotor blade maintenance [57]; (c) CFM56-7 engine fan rotor blade maintenance [58].

introduced into the field of aero-engine repair. The conventional repair scheme for damaged titanium alloy compressor blades includes several sequential operations, which are, inspecting and removing the FOD, preparing and sending powder to damaged areas for melting and depositing, namely LCD, stress relief (SR), and machine the repaired components [66]. After the material powder is shaped in forms, both the geometric dimensions and mechanical properties of the damaged blade are restored [67]. With the development of titanium alloy AM technology, many research works have been conducted on AM repair for aero-engine fan and compressor blades. Some achievements have been applied in industries, partially solving the blade repair problems caused by in-service damages [68,69]. A variety of blade repair processes and optimization methods have been put forward to restore the geometry and dimensions of damaged blades.

The laser AM repair technology applied for aero-engine fan and compressor blades and blisks is rather mature in the United States and Germany. The Sandia National Laboratory of the U.S. developed LMD technology in the 1990s [70]. Optomec Design Company popularized the LMD process and then developed LENS technology in cooperation with the Laboratory [71]. The LENS process has been used to repair worn parts of U.S. Navy T700 engines (as shown in Figure 4(a) [33]), realizing rapid and low-cost remanufacturing of damaged aero-engine parts.

What's more, H&R Technology Company of the U.S. has repaired the blisk of the T700 engine with LCD technology. Huffman Company also used LCD technology to repair both nickel base superalloy and titanium alloy aero-engine blades. The "Mobile Repair Station" developed by the U.S. military also used LCD technology to realize rapid processing and remanufacturing of

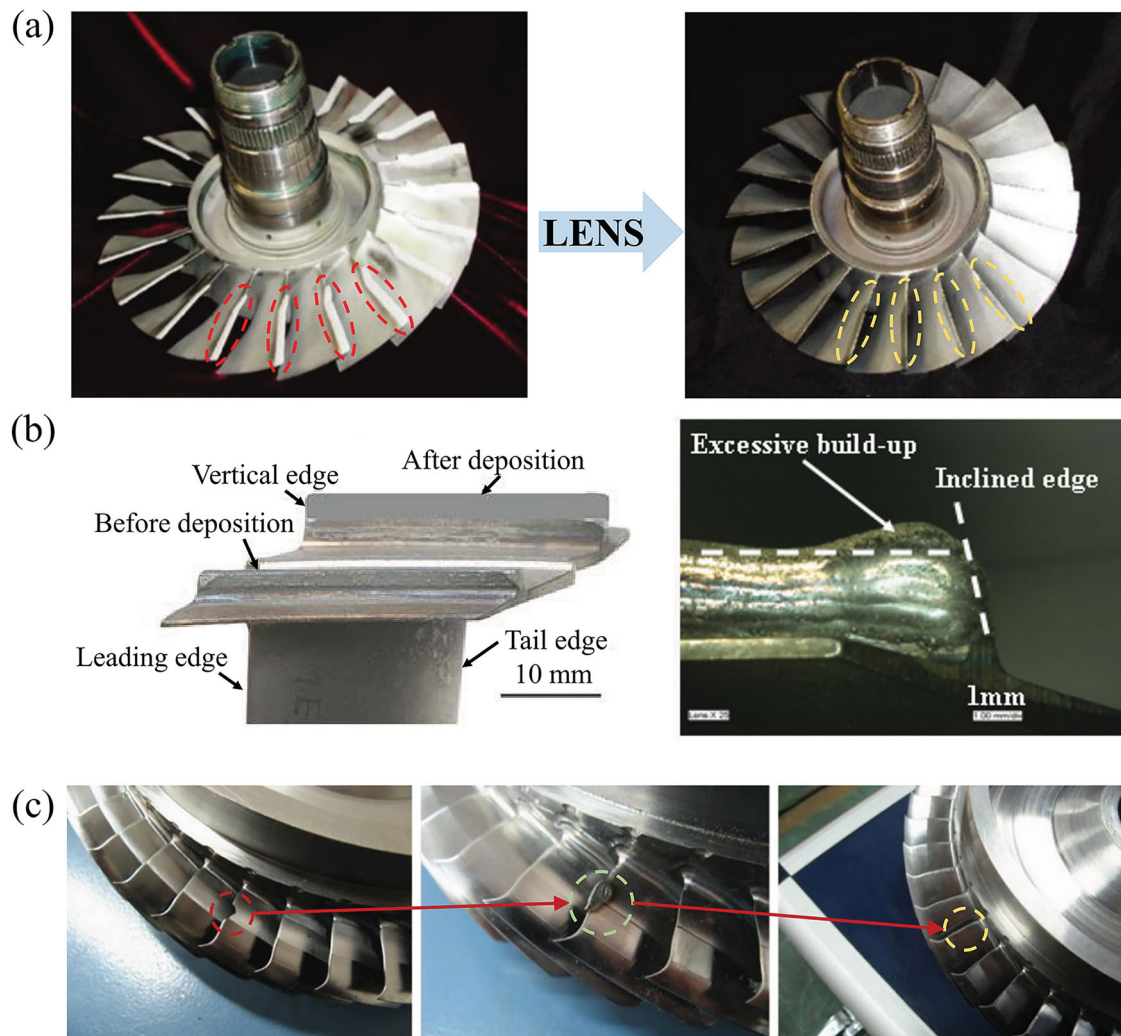


Figure 4. LMD repair technology used for aero-engine blades. (a) Titanium alloy blisk blade repaired by LENS process of Optomec Design Company; (b) Nickel-base turbine blade knife-edges repaired by Fraunhofer Laser Technology Association; (c) Titanium alloy blisk blades repaired by Northwestern Polytechnic University.

metal parts. It has already entered service in U.S. Navy and Army, and played an important role in the Afghan battlefield.

A lot of research have been carried out on laser repair technology for aero-engine blisk by German institutes. Singapore Institute of Manufacturing Technology and German Fraunhofer Laser Technology Association [72] conducted laser AM repair on nickel-base turbine blade knife-edges according to a pre-designed technological path which applied multi-layer laser deposition, and successfully restored the dimensions and mechanical properties of blades, as shown in Figure 4(b). The LMD repair technology [73] developed cooperatively by Laser Zentrum Hannover e.V. and Leibniz University Hannover can be used in depositing and remelting single-crystal structures on substrates of the nickel-based superalloys CMSX-4 and turbine blade tips of PWA 1426, restoring original geometric dimensions. The Fraunhofer Institute of Laser Technology [74] in Germany developed a special nozzle to carry out LCD repair for titanium alloy blades which needs no atmosphere protection chamber, realizing local repair of the leading edge of Ti-17 blisk blades. Furthermore, Germany has launched the “Integrative Production Technology for Energy-efficient Turbo-engine Project (TurPro)” in recent years. The first research of the Project is AM technology which aims to achieve local repair of the edge and tip of blisk blades by LAM and then strives for direct replacement of damaged blades or even direct manufacture of blisk through the combination of initial design, manufacture process, and LAM technology.

In addition, explorative research on AM repair for aero-engine blades have been carried out in universities as well as enterprises in China. Professor Huang Weidong’s team from Northwestern Polytechnic University conducted LMD repair tests on damaged blades and blisks made of TC4 [75], TC11 [76], and TC17 [77] titanium alloys or GH4169 [78,79] and K418 [80] superalloys. They studied the microstructure evolution rules and performance control methods for small laser molten pool solidification of different materials, and characterized the microstructure and hardness distribution rules in different areas (repaired zone, HAZ, and forged substrate zone) of LMD repaired titanium alloy parts. The performance of repaired parts has been evaluated, and several batches of repaired parts have entered service, as shown in Figure 4(c). The research on LMD technology by Professor Wang Huaming’s team of Beihang University focuses on the application in large-scale main load-bearing titanium alloy structural parts [81] and high-performance material gradient structural parts [82] of aircraft, as well as directional solidification

of refractory metal materials [83]. They have formulated a complete set of technical specifications on LMD technology used for aircraft titanium alloy structural parts.

Some specific achievements in AM repairing titanium alloy blades are listed below. Paydas et al. [84] investigated the mechanical properties of repaired samples by LCD processes on a Ti-6Al-4V substrate. The deposition regions showed higher hardness and tensile strength. LCD can be considered as an adequate repair technology for restoring the mechanical properties of Ti-6Al-4V alloy. Shrestha et al. [85] used two different Ti-6Al-4V feedstocks (metal powder and wire) to repair the Ti-6Al-4V alloy substrate through DED processes. Subsequently, dog bone specimens for fatigue testing were machined with a bond line at the center of the specimen gauge. DED repaired samples could obtain mechanical properties comparable to those of conventional Ti-6Al-4V alloy, but exhibited a decrease in fatigue performance, which was more obvious in the samples repaired by metal wire. They also evaluated the fracture toughness and fatigue crack growth rate of the two types of repaired samples [86,87]. The results showed that the fracture toughness of the repaired samples was slightly lower than that of annealed Ti-6Al-4V specimens, and the fatigue crack growth rate was slightly higher than that of conventional specimens.

There are relatively few cases of AM repair research for actual aero-engine blades. Sikan et al. [7] discussed the surface residual stress distribution of the Ti-8Al-1V-1Mo blade after 20,000 h of in-service thermo-mechanical loading cycles. The residual stresses on the blade basin side are mainly compressive, with magnitudes ranging from -300 to -500 MPa, and no obvious tensile region can be observed. The compressive residual stresses are distributed in a gradient from the periphery to the center. The measurements on the blade’s backside indicate higher compressive residual stresses (-600 to -700 MPa) around the tip and the leading edge, while the magnitudes are lower on the tail edge. Tensile residual stresses (200 MPa) are apparent near the root section of the blade tail edge. A gradient distribution in residual stresses is noticeable along the diagonal direction from the tip of the leading edge to the root of the tail edge. This stress state gradually evolved from the initial residual stress introduced by surface strengthening (such as SP, LSP) during the service operation. The complex local stress distributions of compressor blades can have adverse effects on the AM repair process, causing local deformation and large residual stresses in the repair region. This is a huge challenge for the repair of aero-engine blades.

Pre-processing and post-processing are critical for pushing AM repair technology to Maintenance, Repair & Operations (MRO) applications. Currently, almost all studies on AM repaired titanium alloy blades are carried out by directly depositing repair layers on substrate samples [85–88] or by prefabricating grooves on substrate samples for depositing repair layers [84,89,90]. In research on the AM repair of substrate, the pre-processing methods generally involve sandpaper polishing and alcohol cleaning as well. During the actual maintenance process, it is essential to comprehensively consider parameters such as damage location, size, and morphology when performing AM repair on damaged blades. Firstly, a repair plan should be developed based on the damage situation, and the geometric parameters of the repair area should be determined. Then, an appropriate mechanical processing method must be selected to locally remove the damaged material and obtain the desired geometric morphology. Finally, the area to be repaired should be polished and cleaned to ensure that its surface condition meets the repair requirements [66,67].

After completing the repair, post-processing methods such as Solution treatment & aging (STA), Broken-up structure (BUS), Hot isostatic pressing (HIP), Machining and polishing (M&P), SR, etc. are applied to AM repaired blades [91–96]. These post-processing methods mainly affect the microstructure, defects, surface roughness, and residual stress of AM components through heat treatment and mechanical processing, in order to obtain better physical and mechanical properties. The specific influences caused by these post-processing methods are described in Tables 2–5 in Section 3 of this review.

However, it is important to note that aero-engine blades repaired in the outfield usually do not have the necessary conditions to perform most of the post-processing. For instance, a suitable heat treatment furnace cannot be easily found in remote locations for blisk due to its large volume. As a result, the fatigue performance of AM repaired blades typically falls short of that of forgings. Therefore, further improvement of the AM repair process is required to enhance the comprehensive performance of the blades in the As-built (AB) state. Ensuring the safe use of aeroengines loaded with AM repaired blades poses a significant challenge, particularly in terms of fatigue evaluation.

Relevant AM processes used to manufacture large titanium alloy structural parts (such as corner boxes and abdominal fin joints), titanium alloy special coatings and high-temperature alloy structural parts are mature enough to satisfy demands. Aero-engine blades work under complex and severe conditions, and bear multiple axial loads. Present LMD repaired aero-engine blades have problems such as insufficient dimensional accuracy

and stability, large surface roughness, and deteriorated fatigue performance. It is difficult to accurately evaluate the fatigue performance of LMD repaired blades since the evolutionary law of stress and microstructure is not clear and the fatigue failure mechanism under the working state is difficult to master. These directly limit the safe use of AM repaired blades. Recent research has paid more attention to the fatigue performance improvement of LCD structural parts from the perspectives of the manufacturing process, microstructure evolution, residual stress, additive defects, and so on. However, due to experimental conditions, most studies were conducted on AM standard specimens, which can guide the performance of AM repaired blades but require further verification in actual structural components. Furthermore, no systematic fatigue assessment methods and criteria have been established for LMD repaired titanium alloy structural parts, and uncertain risks still exist in engineering application. Therefore, future AM repair research for titanium alloy blades should focus on establishing comprehensive fatigue assessment methods and criteria for AM repaired structural parts.

3. Effect of AM on fatigue performance of titanium alloy blade

Extensive research results show that the effect of AM process on titanium alloy fatigue performance mainly depends on microstructure, manufacturing defects, surface roughness, and residual stress [49,122,123]. The four factors play different roles (mostly negative) in affecting the fatigue performance of AM repaired titanium alloy, as shown in Figure 5.

3.1. Microstructure

LAM manufactured parts are certain to have different microstructures caused by rapid cooling and solidification of alloy within the molten pool since the LAM process is accompanied by rapid heating and rapid cooling. This is similar to rapid quenching in the heat treatment process. AM process with a single layer or few layers usually leads to the generation of a fine metastable phase, while multi-layer cladding manufacturing will seriously affect the microstructure of AM processed parts since the repeated heating and cooling of the deposited layer brings about a complex thermal cycle. In addition, repeated multi-layer AM process presents a unique mesostructure influenced mainly by filler spacing, powder layer thickness, and scanning mode. These complex characteristics across the micro- and meso-scales determine that the fatigue dispersion of AM processed titanium alloy is much more complex than that of forged or cast alloys.

Table 2. Effect of microstructure on HCF strength of AM manufactured titanium alloy.

Material	Progress	Post processing	Microstructure	Test status	Cycles	σ_e /MPa	Refs.
TC4	SLM, Z	AN, 650°/3 h	Columnar PBGs in Z, grain size 140 μm , fine needle HCP α/α' lath	Tension, $R = 0.1$	10^7	340	[97]
			Columnar PBGs in Z, grain size 120 μm , fine needle α/α' lath			453	
		/	Columnar PBGs in Z, grain size 140 μm , fine needle HCP α/α' lath	Rotating bending, $R = -1$	10^7	340	[98]
			Columnar PBGs in Z, grain size 120 μm , fine needle α/α' lath			453–475	
		DAN (920°/0.5 h FC, 700°/2 h AC), M&P	Columnar PBGs in Z, grain size 140 μm , fine needle HCP α/α' lath			375–400	
		DAN (920°/0.5 h FC, 700°/2 h AC), M&P	Columnar PBGs in Z, grain size 120 μm , fine needle α/α' lath			453–475	
	LMD, X/Y	/	Columnar PBGs, ultra-thin layer with a width of 200–800 nm $\alpha+\beta$ structure, needle α' lath	Tension, $R = 0.1$	10^6	500	[99]
	LENS, Z	AN, 600°/1 h	Column and basket $\alpha+\beta$ grain in Z, needle α' lath	Tension, $R = 0.01$	10^6	482	[100]
	EPBF, Z	HIP, 920°C/103 MPa/2 h	$\alpha+\beta$ phase	Tension, $R = 0.1$	5×10^6	155	[101]
	LPBF, Z	AN, 730°/2 h	$\alpha+\beta$ phase, needle α' phase			265	
	SLM, Z	AN, 500°/2 h	A mixture of β and fine needle α	Tension, $R = 0.1$	10^7	430	[102]
	SLM, Z	/	$\alpha+\beta$ phase, needle α' phase	Tension, $R = -1$	10^7	290	[103]
			$\alpha+\beta$ phase, needle α' phase			370	
		HIP, 900°C/120 MPa/2 h	Lamellar $\alpha+\beta$ phase			580	
	SLM, Z	/	Columnar PBGs in Z with α colonies	Tension, $R = 0.2$	2×10^5	100	[104]
	LPBF, 45° to Z	AN, 700°/1 h	Interrupted columnar PBGs, result in stray grains, needle α' phase	Tension, $R = -1$	10^7	75–100	[105]
	SLM, Z	AN, 800°/2 h	Hexagonal α phase and minor amounts of β phase	Tension, $R = -1$	10^7	250	[106]
	SLM, Z	HIP, 920°C/100 MPa/2 h	Hexagonal α phase and less amounts of β phase			420	
	EBM, Z	/	Hexagonal α lamellae			410	
	SLM, Z	AN, 700°/1 h, HIP, 900°C/100 MPa/2 h	Elongated α grains embedded in α/β -phase grain boundaries with a column size of up to 3 μm width	Tension, $R = -1$	10^7	200	[107]
		AN, 700°/1 h, HIP, 900°C/100 MPa/2 h, M&P	Elongated α grains embedded in α/β -phase grain boundaries with a column size of up to 3 μm width			350	
	SLM, Z	/	Fine needle α/α' phase	Tension, $R = 0.1$	10^7	100	[108]
	EBM, Z	/	Lamellar $\alpha+\beta$ phase			60	
	SLM, Z	AN, 670°/5 h	Fine needle α' martensitic α -platelets interspersed in the β matrix	Tension, $R = -1$	3×10^7	221	[109]
		DAN (670°/5 h, 920°/2 h)	α -platelets interspersed in the β matrix			191	
	SLM, Z	AN, 670°/5 h, HIP, 920°C/200 MPa/2 h	α -platelets interspersed in the β matrix	Tension, $R = 0.1$	10^7	369	[110]
		/	Complete martensitic α' in PBGs			550	
	EBM, Z	/	Lamellae α phase and a small amount of β within PBGs			300–340	

(continued)

Table 2. Continued.

Material	Progress	Post processing	Microstructure	Test status	Cycles	σ_e /MPa	Refs.
TC17	SLM, X/Y	/	α' martensitic	Tension, $R = 0.1$	4×10^4	400	[111]
		AN, 400°/2 h	Ultra-fine lamella $\alpha + \beta$ phase		3×10^6		
	DMLS, Z	AN, 710°/2 h	Columnar PBGs perpendicular to Z, fine needle α/α' phase	Tension, $R = 0.1$	5×10^6	500	[112]
	EBM, Z		Columnar PBGs perpendicular to Z, needle α/α' phase		10^7	280	
	DMD-L, Z		Columnar PBGs perpendicular to Z, needle α/α' phase		10^7	580	
	DMD-P, Z		Columnar PBGs perpendicular to Z, lamella α phase		3×10^7	500	
	EBM, Z	/	Needle $\alpha + \beta$ phase with α lath thickness of 0.7 μm	Tension, $R = 0.1$	10^7	200	[113]
		AN, 650°/5 h	Needle $\alpha + \beta$ phase with α lath thickness of 0.6 μm			250	
		HIP, 900°C/100 MPa/2 h	Thick lath $\alpha + \beta$ phase with α lath thickness of 1.6 μm			540	
	DMLS, X/Y	AN, 650°/2 h	Lamellar $\alpha + \beta$ colonies distributed in equiaxed α grains	Rotating bending, $R = -1$	10^5	60	[114]
TA15		HIP, 900°C/102 MPa/2 h, M&P	Lamellar $\alpha + \beta$ colonies distributed in equiaxed α grains, with thick α lath		10^7	405	
	DMLS, Z	AN, 650°/2 h, M&P	Lamellar $\alpha + \beta$ colonies distributed in equiaxed α grains		2×10^4	60	
		HIP, 900°C/102 MPa/2 h, M&P	Lamellar $\alpha + \beta$ colonies distributed in equiaxed α grains, with thick α lath		10^7	400	
	DED, X/Y	/	Ultra-fine α basketweave structure in columnar β grains	Tension, $R = 0.1$	2×10^5	365	[29]
TA15	DED, Z	DAN (950°/2 h FC, 600°/4 h AC)	Columnar PBGs in Z, needle α grains dominated	Tension, $R = 0.06$	1.6×10^5	720	[115]

Notes: σ_e – the fatigue limit, Z – the load direction is parallel to the deposition direction, X/Y – the load direction is perpendicular to the deposition direction, R – the stress ratio, FC – Furnace cooling, EPBF – Electron beam powder bed fusion, SMAT – Surface mechanical attrition treatment, DMLS – Direct Metal Laser Sintering, DMD-L – Direct metal deposition by laser, DMD-P – Direct metal deposition by plasma arc.

For titanium alloy, the rapid heating and cooling cycle of AM process leads to fine microstructure consisting of metastable martensite α' phase within prior β grain (PBG), most of which could be observed as obviously layered microstructure [97]. Eylon et al. [91,92] studied the effect of microstructure on the properties of powder metallurgy Ti-6Al-4V alloy. They used BUS or Thermochemical treatment (TCT) to obtain a fine α flake structure. The result is that the grain size of α reduces by an order of magnitude compared with the reference, and the cluster structure is removed. The tensile strength and fatigue strength of Ti-6Al-4V alloy are significantly improved by adjusting the microstructure, and the fatigue strength of TCT processed samples is the highest. Liu et al. [124] repaired Ti-6Al-4V alloy parts by DED and EBM (Electron Beam Melting) processes and obtained fatigue limit improvement in the repaired area at the cost of a lower crack growth threshold. This

is due to the high-density dislocations of α' Martensitic phase generated during the AM process. That is, the significant dislocation strengthening effect improves fatigue performance [124].

Hagiwara et al. [93] also studied the effect of different microstructure characteristics on the fatigue strength of Ti-6Al-4V alloy. They used several heat treatments including HIP, BUS, and STA to refine and regulate the microstructure of fully densified materials, and obtained a bimodal lamellar structure. In addition, they applied cold rolling before HIP to regulate the columnar microstructure into an equiaxed shape. This kind of bimodal microstructure has the highest fatigue strength with better performance than most cast titanium alloys. Crack generation and propagation in the whole structural part could be prevented by refinement of the microstructure whose effect is similar to a single crystal. Joshi et al. [125] also validated the excellent fatigue properties

Table 3. Effect of manufacturing defects on HCF strength of AM processed titanium alloy.

Material	Progress	Post processing	Defects	Test status	Cycles	σ_e /MPa	Refs.				
TC4	SLM, Z	/	$\sqrt{\text{area}} = 68.6\text{--}71.3\ \mu\text{m}$	Rotating bending, $R = -1$	10^7	340	[98]				
		/	$\sqrt{\text{area}} = 36.4\text{--}43.1\ \mu\text{m}$			453–475					
		DAN (920°/0.5 h FC, 700°/2 h AC), M&P	$\sqrt{\text{area}} = 68.6\text{--}71.3\ \mu\text{m}$			375–400					
		DAN (920°/0.5 h FC, 700°/2 h AC), M&P	$\sqrt{\text{area}} = 36.4\text{--}43.1\ \mu\text{m}$			453–475					
	LMD, X/Y	/	$\sqrt{\text{area}} = 126\ \mu\text{m}$	Tension, $R = 0.1$	2×10^5	500	[99]				
		/	$\sqrt{\text{area}} = 63\ \mu\text{m}$			10^6					
	EBM, X/Y	/	Diameter = 328 μm	Tension, $R = 0.1$	5×10^6	150	[116]				
		HIP, 920°C/100 MPa/2 h	Diameter = 328 μm			140					
	LPBF, X/Y	HIP, 920°C/100 MPa/2 h, M&P	/	Rotating bending, $R = -1$	10^7	650	[117]				
		AN, 710°/2 h	Diameter = 44 μm			200					
		AN, 710°/2 h, HIP, 920°C/100 MPa/2 h	Diameter = 44 μm			185					
		AN, 710°/2 h, HIP, 920°C/100 MPa/2 h, M&P	/			650					
		SLM, Z	AN, 500°/2 h			Diameter = 30 μm		Tension, $R = 0.1$	10^7	430	[102]
		SLM, Z	/			Diameter = 34 μm		Tension, $R = -1$	10^7	290	[103]
	EBM, Z	HIP, 900°C/120 MPa/2 h	/	Rotating bending, $R = -1$	10^7	370	[117]				
		HIP, 900°C/120 MPa/2 h, SMAT	/			580					
	DMLS, Z	HIP, 920°C/100 MPa/2 h, M&P	Diameter = 50–120 μm	Tension, $R = 0.1$	10^7	590	[118]				
	SLM, 45°to Z	HIP, 920°C/100 MPa/2 h, M&P	Diameter = 30–50 μm			610					
	SLM, Z	AN, 650°/3 h	Diameter = 30–80 μm	Tension, $R = 0.1$	10^7	210	[108]				
		AN, 650°/3 h, M&P	/			510					
	EBM, Z	/	Porosity = 1%	Tension, $R = 0.1$	10^7	100	[108]				
		/	Porosity = 5%			280					
	SLM, Z	/	Porosity = 1%	Tension, $R = -1$	3×10^7	400	[109]				
		/	Porosity = 5%			60					
	SLM, Z	/	Porosity = 1%	Tension, $R = -1$	3×10^7	450	[109]				
		/	Porosity = 0			500					
	TA15	LDED, Z	AN, 670°/5 h	Porosity < 0.05%	Tension, $R = 0.06$	1.6×10^5	221	[115]			
			DAN (670°/5 h, 920°/2 h)	/			191				
AN, 670°/5 h, HIP, 920°C/200 MPa/2 h			/	369							
DAN (950°/2 h FC, 600°/4 h AC)			$\sqrt{\text{area}} = 78\ \mu\text{m}$	720							
DAN (950°/2 h FC, 600°/4 h AC)			$\sqrt{\text{area}} = 8\ \mu\text{m}$	720							
DAN (950°/2 h FC, 600°/4 h AC)			$\sqrt{\text{area}} = 132\ \mu\text{m}$	760							
DAN (950°/2 h FC, 600°/4 h AC)			$\sqrt{\text{area}} = 22\ \mu\text{m}$	760							
DAN (950°/2 h FC, 600°/4 h AC)			$\sqrt{\text{area}} = 116\ \mu\text{m}$	800							
	DAN (950°/2 h FC, 600°/4 h AC)	$\sqrt{\text{area}} = 22\ \mu\text{m}$		5.4×10^5	800						

of Ti-6Al-4V alloy with bimodal microstructure. They used a thermos-mechanical deformation process to heat treat the Ti-6Al-4V alloy to change the rolled network structure into a bimodal microstructure. This change increased the fatigue strength of the sample from 500 to 550 MPa.

Xu et al. [111] annealed the SLM processed Ti-6Al-4V alloy sample at a low temperature to decompose the martensitic phase formed in manufacturing. They obtained very fine α Lath grains which improved both tensile strength and fatigue properties simultaneously. Wirth and his collaborators [126] carried out fatigue performance tests on powder metallurgy Ti-6Al-4V alloy under different heat-treating conditions and validated that $\alpha + \beta$ phase structure with fine lenticular grains had the best fatigue strength. Cao et al. [127] studied the effect of thermo-mechanical deformation on the fatigue properties of AM processed Ti-6Al-4V alloy through the hot-rolling treatment of $\alpha + \beta$ phase. It is validated that thermo-mechanical deformation treatment under β

phase transition temperature reduces the porosity, transforms the layered structure into elongated or lenticular grains along the rolling direction, and induces texture. Such treatment improves the fatigue strength of the structural part from 325 MPa at sintered state to 400–450 MPa (according to the degree of rolling and deformation). Both microstructure and porosity affect the fatigue performance of titanium alloy, but they show different effects under different stress levels, which will be described in Section 3.2.

The importance of microstructure regulation on fatigue properties of titanium alloys is obvious, especially for $\alpha + \beta$ phase and β phase titanium alloys which need microstructure optimization to obtain better fatigue strength [41]. Based on continuous exploration in post-AM treatment, a Laser Powder Bed Fusion (LPBF) process used for Ti-6Al-4V alloy is presented to stably obtain $\alpha + \beta$ phase microstructure. The steps of the DAN process are as follows: (1) 910° annealing (AN), (2) water quenching, (3) AN again at 750°, (4) air cooling (AC). Thus a

Table 4. Effect of surface roughness on HCF strength of AM processed titanium alloy.

Material	Progress	Post processing	Ra/ μm	Test status	Cycles	σ_e/MPa	Refs.
TC4	LENS, Z	AN, 600°/1 h	0.25	Tension, $R = 0.01$	10^6	482	[100]
	EPBF, Z	HIP, 920°C/103 MPa/2 h	20	Tension, $R = 0.1$	5×10^6	155	[101]
	LPBF, Z	AN, 730°/2 h	14			265	
	EBM, Z	/	32	Tension, $R = 0.1$	5×10^6	160	[119]
		HIP	32			180	
		HIP, M&P	1.6			800	
	LS, Z	AN, 650°/3 h	15			250	
		AN, 650°/3 h, HIP	15			320	
		AN, 650°/3 h, HIP, M&P	1.6			550	
	EBM, X/Y	/	27	Tension, $R = 0.1$	5×10^6	150	[116]
		HIP, 920°C/100 MPa/2 h	27			140	
		HIP, 920°C/100 MPa/2 h, M&P	1.6			650	
	LPBF, X/Y	AN, 710°/2 h	13			200	
		AN, 710°/2 h, HIP, 920°C/100 MPa/2 h	1.6			185	
		AN, 710°/2 h, HIP, 920°C/100 MPa/2 h, M&P	2			650	
	SLM, Z	/	/	Tension, $R = -1$	10^7	290	[103]
		HIP, 900°C/120 MPa/2 h	/			370	
		HIP, 900°C/120 MPa/2 h, SMAT	1.07±0.53			580	
	EBM, Z	/	32–42	Rotating bending, $R = -1$	10^7	140	[117]
		M&P	/			240–260	
		HIP, 920°C/100 MPa/2 h	30–41			195	
		HIP, 920°C/100 MPa/2 h, M&P	/			590	
	DMLS, Z	/	10–13			155	
		M&P	/			370	
		HIP, 920°C/100 MPa/2 h	12–13			195–220	
		HIP, 920°C/100 MPa/2 h, M&P	/			610	
	SLM, Z	/	39	Tension, $R = 0.2$	2×10^5	100	[104]
	SLM, X/Y	/	30			140	
	LPBF, 45°to Z	AN, 700°/1 h	8–24	Tension, $R = -1$	10^7	75–100	[105]
	SLM, 45°to Z	AN, 650°/3 h	13	Tension, $R = 0.1$	10^7	210	[118]
		AN, 650°/3 h, M&P	0.5			510	
	LAM, Z	AN, 650°/3 h	12	Tension, $R = 0.1$	10^7	210	[95]
		AN, 650°/3 h, M&P	/			490	
	LAM, 45°to Z	AN, 650°/3 h	12			200–210	
		AN, 650°/3 h, M&P	/			420–500	
	LPBF, Z	AN, 540°/4 h, HIP, 810°C/200 MPa/2 h	17.9±2	Tension, $R = 0.1$	3×10^7	300	[120]
		AN, 540°/4 h, HIP, 810°C/200 MPa/2 h, milled	0.3±0.1			600	
		AN, 540°/4 h, HIP, 810°C/200 MPa/2 h, blasted	10.1±0.2			500	
		AN, 540°/4 h, HIP, 810°C/200 MPa/2 h, vibratory ground	0.9±0.7			400	
		AN, 540°/4 h, HIP, 810°C/200 MPa/2 h, M&P	0.4±0.3			500	
	SLM, Z	AN, 670°/5 h	6.83	Tension, $R = -1$	3×10^7	221	[109]
		AN, 670°/5 h, electropolishing	0.54			242	
		DA (670°/5 h, 920°/2 h)	6.83			191	
		AN, 670°/5 h, HIP, 920°C/200 MPa/2 h	5.07			369	
	DMLS, X/Y	AN, 710°/2 h	13.0±0.7	Tension, $R = 0.1$	10^7	200	[121]
	EBM, X/Y	AN, 710°/2 h	27.1±0.91			150	
TC17	LDDED, X/Y	/	0.419	Tension, $R = 0.1$	2×10^5	365	[29]

Note: LS – laser sintering.

bimodal microstructure consisting of broken equiaxed primordial α grains within a lamellar secondary $\alpha + \beta$ matrix can be obtained [128–130]. Previous work validated that such bimodal microstructure can well balance the ductility and strength of titanium alloy, improve the near threshold fatigue crack growth resistance effectively, and in turn, improve the fatigue performance of the material. The HCF strength of AM manufactured titanium alloy influenced by different microstructures are summarized in Table 2.

3.2. AM defects

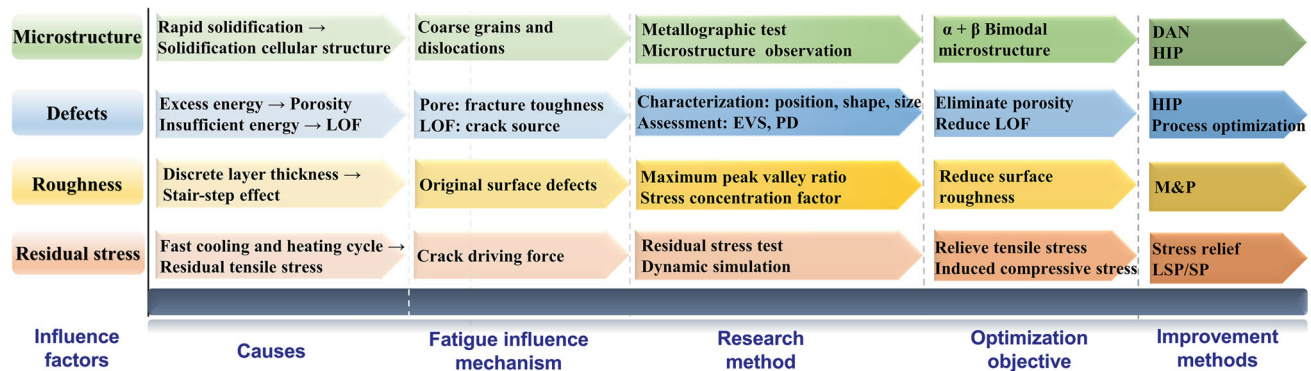
There is a difficult balance between laser energy input and metal powder melting during the LAM process, which

leads to inevitable manufacturing defects in AM processed structural parts. Excess input energy seriously affects the stability of the molten pool, resulting in the splashing or evaporation of molten metal droplets which cause pore defects. Spherical or ellipsoidal pores with diameters of about 1–100 μm usually present a random distribution in the material. On the other hand, insufficient input energy leads to LOF defects since metal powder could not be completely melted. The LOF defects are larger in size than pores, and usually show irregular wedges or bands with tips, as shown in Figure 6(a, b).

In the Standard E3166 [131] issued by ASTM, AM defects are described as pores (which may be isolated or located in clusters close to the surface or embedded in deep layers), LOF (which may be between layers

Table 5. Effect of residual stress on HCF strength of AM processed titanium alloy.

Material	Progress	Post processing	Residual stress/MPa	Test status	Cycles	σ_e /MPa	Refs.
TC4	LMD, X/Y	/	+180 to +250	Tension, $R = 0.1$	2×10^5	500	[99]
	SLM, Z	/	+75	Tension, $R = 0.2$	10^6	100	[104]
	SLM, X/Y	/	+60			140	
	SLM, Z	AN, 800°/2 h	/	Tension, $R = -1$	10^7	250	[106]
		HIP, 920°C/100 MPa/2 h	/			420	
	EBM, Z	/	+35			410	
	SLM, Z	AN, 670°/5 h	-100	Tension, $R = -1$	3×10^7	221	[109]
		AN, 670°/5 h, electropolishing	-420			242	
		DA (670°/5 h, 920°/2 h)	-100			191	
		AN, 670°/5 h, HIP, 920°C/200 MPa/2 h	-420			369	
	EBM, Z	/	+17	Tension, $R = 0.1$	10^7	200	[113]
		AN, 650°/5 h	+3			250	
TC17		HIP, 900°C/100 MPa/2 h	-16			540	
	LDED, X/Y	/	+150	Tension, $R = 0.1$	2×10^5	365	[29]

**Figure 5.** Influencing factors of AM on fatigue properties of titanium alloy.

Notes: LOF – Lack of fusion, EVS – Extreme Value Statistics, PD – Probabilistic distribution, DAN – Double Annealing.

or across layers), start and stop errors, inclusions, layering, under melting or over melting. A large number of studies have shown that under the action of cyclic load, AM defects usually become the starting points of crack initiation, as shown in Figure 6(c, d) which has a significant adverse effect on the fatigue performance of structural parts [98,106,115,132–135]. Present research mainly focused on the relationship between the size and location of defects as well as the resulting fatigue behavior [136]. Therefore, the first work to be done should be the effective observation and characterization of AM defects.

Computer tomography (CT) is an effective observation and testing method for AM defects in the industry. The core test parameter of CT technology is resolution, which is related to the size and number of detectors, the size of X-ray focus, and the size of the objects that affect the distance between the X-ray source, detection object, and detector. The typical commercial CT equipment used in the industry at present has a high resolution for pores with diameters more than 10 μm , while for defects whose sizes are less than this value, the judgment becomes inaccurate [137,138]. To further improve the resolution of CT equipment, the X-ray input energy has to be

increased and the scanning time greatly extended under the condition of maintaining the original field of view and signal-to-noise ratio. Thus the test cost is significantly increased [139]. As a global defect analysis method for AM processed parts, CT technology is difficult to accurately measure the shape, location, and characteristics of defects due to the limitation of resolution. However, conventional destructive testing methods such as Scanning Electron Microscope (SEM) could realize microscopic observation on the surface and sections of AM processed parts. SEM provides more refined local characteristics of defects, but it cannot carry out the global analysis. Therefore, the optimal solution is to combine the two methods to obtain the best analysis [140].

Pegues et al. [140] combined the above two methods to obtain 3D global (CT) and 2D local (SEM) results for AM defects of a tubular LPBF Ti-6Al-4V alloy sample. The 3D result is characterized by a high-resolution CT which made a global test on a 10 mm long sample. It showed the locations, shapes, sizes, and overall distribution of a large number of defects. The 2D result is characterized by a high-power digital microscope which collected images from the polished surface of the sample. It could provide precise observation on characteristic defects, and so

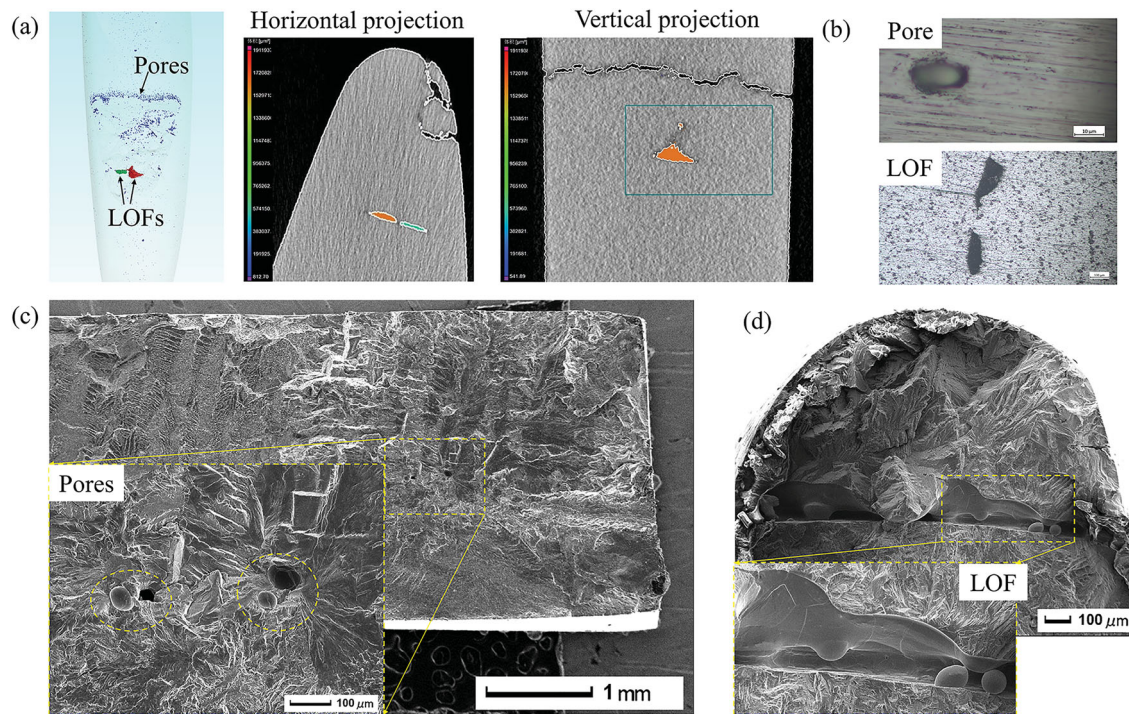


Figure 6. Defects on LAM processed TC17 samples. (a) and (b) Pores and LOFs observed by CT and OM; (c) Fatigue fracture of tensile specimen caused by pores; (d) Fatigue fracture of blade leading edge caused by LOF.

it is used to differentiate types of defects, and to analysis conditions on which defects generate.

Based on these observation conditions, the parametric characterization of AM defects is studied. Sanaei et al. [141] characterized four key features of AM defects, namely, Feret's diameter and area that reflect the size of defects, roundness, and aspect ratio that reflect the shape of defects. The parameters defined in 2D observation conditions are as follows: (1) the Feret's diameter of defect is the longest distance between any two points along the selection boundary; (2) the area of defect is the area of each defect within the external selected boundary; (3) the roundness of defect is a measure of irregularity of defect shape calculated by 4π (area/perimeter²) within a range of between 0 and 1; and (4) the aspect ratio of defect is a measure of elongation of each defect calculated by the ratio of a fitting ellipse to the longest diameter of defect, also within a range of between 0 and 1. A lower aspect ratio indicates a longer defect. The characterization method for the above parameters under 3D observation conditions is also proposed based on CT technology [142].

Molaei and his collaborators [94] researched the cyclic deformation and multiaxial fatigue behaviors (axial, torsional, and 90° axial torsion combined in-phase and out-of-phase) of PBF Ti-6Al-4V alloy thin-walled tubular specimens. The influence of parametric differences of AM equipment on the size and number of defects has

been investigated, as well as the resulting failure mechanisms and fatigue properties. It is found that the failure mechanism of AM samples was tensile failure after long-time operation, which showed that the fatigue behavior of the sample was mainly affected by manufacturing defects under HCF load. After HIP treatment, the fatigue life of the sample under the HCF condition was significantly improved, showing similar fatigue behavior to that of forged materials under different loads. This is because the HIP treatment made the defects close and shrink. However, the remaining LOF defects in the specimen are still the main source of crack initiation. In addition, the fatigue life of vertical and diagonal (45°) constructed specimens has been tested, and the latter showed a slightly longer fatigue life under torsional load and a shorter fatigue life under axial load. This could be attributed to the vertical relationship between the AM construction direction and the LOF defect growing direction.

A reasonable explanation has already been given for the fatigue initiation mechanism of metal materials. That is, local plastic deformation leads to the formation of low-energy subgrain dislocation under a saturated state, and eventually fatigue crack initiates when the dislocation develops into irreversible plastic deformation and results in cyclic damage [143,144]. As for AM processed metal materials, the stress concentration effect at the manufacturing defects promotes the generation of local plastic

deformation under HCF load, and then becomes the source of fatigue crack initiation regardless of the macro mechanical response of the part being elastic deformation or not [145,146]. The plastic deformation at the defect is mainly affected by the size (diameter and area) and shape (roundness and aspect ratio) of the defect, as well as nearby microstructure characteristics (phase composition, grain size, and crystal orientation). Manufacturing defects have little influence on the FCG of AM processed titanium alloy from the perspective of crack propagation. Leuders et al. [96] validated that local stress concentration caused by defects does not provide any additional driving for the FCG behavior of LPBF Ti-6Al-4V alloy. This conclusion is consistent with Poulin et al. [147] on the FCG behavior of LPBF Inconel 625 alloy. It is found that the Fatigue Crack Propagation Rate (FCGR) hardly changed but the fracture toughness was significantly affected in Inconel 625 alloy with different porosity levels (0.1%, 0.3% and 2.1%).

It is generally believed that larger defects are more likely to cause failure than smaller defects, and the largest defect directly affects the fatigue strength of the part [148]. AM processed titanium alloy usually contains a large number of small-size defects, which brings a huge workload to characterize each defect. In order to solve this problem, PD distribution models of various defects were developed. Günther and his collaborators [106] proposed a Weibull distribution diagram to evaluate the size of internal crack initiation defects in SLM and EBM materials. They determined the size of crack initiation discontinuity through Murakami's model [149] based on Weibull distribution, established the relationship between failure probability and average defect size in the defect size PD model, and characterized it by the maximum stress intensity factor (SIF $K_{I,max}$). The results show that pore defects have smaller $K_{I,max}$, while LOF defects have the largest $K_{I,max}$. The size of LOF defects is usually the same as the section spacing [97] and reaches the millimeter level, the average defect size is significantly larger than that of pore defects [106]. LOF defects often show very low roundness and aspect ratio [141,150], which is considered to be the main factor leading to fatigue failure of AM processed titanium alloy. Table 3 summarizes the HCF strength data of AM processed titanium alloys with defects of different sizes.

EVS method is a statistical method commonly used to predict the maximum defect size in AM processed parts. It was first applied in the iron and steel industry to predict the maximum inclusion size in large-volume pure steel through the observation of small-volume inclusions, because the maximum inclusions control the mechanical properties and fatigue behavior of steel [151,152]. Romano and his collaborators [153] proposed a method

to predict the distribution of defects in uniform volume AM processed parts without global scanning based on the EVS method. They perform X-ray CT on given volume materials with the same characteristics and then process CT test defects by peak value exceeding the threshold and EVS to determine the distribution of most harmful defects in the material. Finally, they predict the maximum defect in a larger volume through the Largest Extreme Value Distribution (LEVD). On this basis, they also predict the fatigue strength of the part according to the location of extreme defects combined with the Kitagawa-Takahashi diagram. A detailed description of the EVS method is given in Section 4.2.

Some physical models are developed in the prediction of AM defects for the shape of the molten pool and thermal properties of materials. The volumetric energy density (VED) model is one of the mainstream models to predict AM defects. Thijs et al. [154] gave its mathematical definition equation. Gong et al. [108,155] gave the relationship between the VED and the minimum defect size, which can provide process guidance for Ti-6Al-4V parts printed by PBF. Bertoli et al. [156] found the influence of VED change on the trajectory of a single molten pool, thus determining the appropriate numerical range. In addition, there are some less-used AM defect prediction models. Tang [157] superimposed multiple pool geometries obtained by the Rosenthal point source heat transfer model. It was found that these defects were caused by insufficient pool stacking in the transverse or vertical direction, and the density change of AM processed AlSi10Mg sample caused by LOF defects was effectively predicted. King et al. [158] deduced the melting criteria of 316L stainless steel under a moving Gaussian heat source and proposed a normalized enthalpy model, which can accurately predict the melting conditions under keyhole mode. The experimental results show that the melting conditions that meet the criterion display pinhole behavior, and the threshold transition point from conduction-controlled melting mode to pinhole-dominated melting mode can be clearly identified. Therefore, this method could be used to predict the generation and development of pore defects in the manufacturing process.

Sheridan et al. [159] compared the prediction effect of the above three models on the porosity of AM processed parts by tests within a relatively wide range of process parameters. The results show that the shape of the molten pool and the amount of VED absorbed are suitable for LOF prediction, but it is still far from real behavior. The normalized enthalpy model is suitable to predict the porosity of small hole mode in matrix and unit cell geometry, but the threshold must be modified according to different process characteristic parameters to ensure certain accuracy. A method of meshing and combining

multiple models is put forward to fully describe the whole process space to predict the size characteristics of porosity in LOF and keyhole modes. Using the least square method, three models of density, diameter, and roundness are constructed according to the tested average data. Each component is regarded as a separate training point, and variance analysis is performed on each model to approximately evaluate the error and its source. On this basis, the aperture regression model is applied for the life prediction framework and the given life prediction diagram shows a more accurate and conservative prediction result.

In summary, research results generally show that LOF defects generated in AM process are the most important factors affecting the fatigue performance of structural parts, so the observation, characterization, and evaluation of defects play an important role in the research of fatigue performance of AM processed parts. The prediction and evaluation of fatigue strength of AM processed parts based on AM defects will be especially described later.

3.3. Surface roughness

When the outer geometry profile of AM processed part has a certain angle with the construction plane or the growing direction, the layer-by-layer printing characteristics of AM process will make the inclined outer surface of the part uneven with the layer thickness as the step height. This phenomenon is called the stair step effect [160], which usually is inevitable for AM processed parts to face surface roughness problems at higher surfaces. Li et al. [161] pointed out that the oxidation and adhesion of partially melted particles on the surface of parts are the most important factors to determine surface quality. That means the optimal surface roughness could be obtained by DED, followed by SLM and EBM, because in the DED process the unused excess powder could be blown away. Li et al. [132] summarized three reasons for the high surface roughness of AM processed parts: (1) stair-step effect related to the increase of additive layers, (2) oxidation and adhesion of molten particles on the outer surface, and (3) surface pores and LOF defects. In any case, high surface roughness results in a serious adverse effect on the fatigue performance of AM processed parts [37].

Wycisk et al. [95] compared the fatigue limit of LAM processed Ti-6Al-4V alloy under AB state and M&P state. The sample at AB state doesn't experience surface treatment, and the average surface roughness is $R_a = 12\mu\text{m}$. The sample at M&P state has a significantly reduced surface roughness, $R_a = 0.16\mu\text{m}$ according to the standard of mirror polishing. The test results show that the fatigue limit ($\sigma_{\max}$) of the LAM net shaping Ti-6Al-4V specimen

at 10^7 cycles is 210 MPa, and the fatigue dispersion is low; the fatigue limit of the M&P sample is 500 MPa, and the fatigue dispersion is high. The results of fracture analysis showed that cracks initiated in many parts of the surface of the AB sample, and the higher surface roughness made the area with obvious concave convex more likely to become the source of fatigue cracks. The fatigue source of M&P specimens is mainly manufacturing defects, so it shows significant dispersion.

Greitemeier and his collaborators [121] studied the fatigue properties of Ti-6Al-4V alloy samples manufactured by DMLS and EBM and concluded that the HCF performance mainly depends on the surface roughness. The surface roughness of the DMLS sample is $R_a = 13\mu\text{m}$, $R_t = 110\mu\text{m}$; while the EBM sample is $R_a = 27\mu\text{m}$, $R_t = 214\mu\text{m}$. The fatigue limit of DMLS and EBM specimens at 10^7 cycles is 200 and 150 MPa respectively. They counted the fatigue test data of DMLS Ti-6Al-4V samples with different surface roughness obtained by Wycisk et al. [95,162] and Vlcek et al. [163] on different additive manufacturing equipment, and drew S-N curves of different surface roughness. The law between fatigue limit and surface roughness can be judged from the curve, the higher the roughness, the lower the fatigue limit.

When considering the influence of surface roughness on fatigue performance of AM processed parts, researchers usually use some equivalent methods to obtain the key influencing parameters of surface roughness, such as maximum peak valley ratio equivalent [121], stress concentration factor equivalent [164], etc. Greitemeier et al. [121] used the equivalent initial defect size (EIFS) method, combined with Murakami et al. [165]'s work on the correlation between characteristic surface roughness and EIFS, to achieve the equivalent EIFS value to describe the effect of surface roughness based on fracture mechanics method. They deduced EIFS from the S-N curve data of AM processed part, then correlated it with surface roughness obtained from the test, and described the equivalent initial defect geometry by semi-elliptical surface cracks. Furthermore, they successfully predicted the fatigue data of AM processed Ti-6Al-4V alloy based on the linear relationship between EIFS and surface roughness values.

In order to solve the adverse effect of surface roughness on fatigue performance of AM parts, relevant research has been carried out and found that improving surface roughness can significantly improve the HCF strength of titanium alloy [107,108,117]. Bagehorn et al. [120] used four commonly used surface roughness improvement methods to treat LPBF Ti-6Al-4V alloy samples, namely, milling, SP, vibration grinding,

and micromachining. The results show that the surface roughness of the sample reduces from $R_a = 17.9 \mu\text{m}$ to $R_a = 0.3 \mu\text{m}$ after milling; the 3×10^7 cycle fatigue strength of the AB sample increased from 300 to 775 MPa after treatment, showing the best effect. The improving effect of SP on surface roughness is limited ($R_a = 10.1 \mu\text{m}$), and the 3×10^7 cycle fatigue strength increased to 525 MPa. It is mainly because the residual compressive stress field introduced into the surface layer of the specimen improved the fatigue performance. Kumar et al. [98] also validated this conclusion by their fatigue life test on LPBF Ti-6Al-4V alloy after SP. It is worth noting that although HIP is often used as post-treatment for AM parts to eliminate internal defects like pores and could effectively improve the fatigue performance of parts, it could not reduce the surface roughness of parts, so it should be combined with a variety of processes to obtain the best effect. Table 4 shows the HCF strength data of AM processed titanium alloys with different surface roughness after various post-treatments.

3.4. Residual stress

The repeated rapid heating and cooling process on the deposited layer during metal additive manufacturing makes the solidified alloy experience an extremely complex thermal cycle, which not only leads to the unique properties of AB material in microstructure, but also has a significant impact on residual stress. During AM process, expansion wave was generated when the local region was rapidly heated by a high-energy beam (laser/electron beam), but then it was restrained by surrounding materials, resulting in local compressive plastic strain. In the subsequent rapid cooling process, the alloy shrunk, resulting in high tensile stress [166]. Sikan et al. [7] examined the residual stress field of titanium alloy compressor blades whose blade tips were repaired using electron beam wire-feed AM technology. The results showed that the intensity of the compressive residual stress near the interface and HAZ on both the basin and back sides was significantly reduced compared with before repair, and a tensile residual stress area could be observed. This is attributed to the formation and solidification of new stress-free β grains [167]. However, the stress relief is not apparent at the center and root section of the blade far from the repair region.

Under HCF load, the high and uneven residual tensile stress acts as an additional crack driving force, causing the initial stress state to move to a higher stress ratio, which can be understood as the overall translation of the applied load spectrum to the high stress direction. Thus the fatigue life of the structural part is reduced obviously, showing poor fatigue performance [96,104,168].

In order to clarify the rule and mechanism of the influence of residual stress field caused by AM process on the fatigue performance of structural parts, a large number of comparative fatigue tests and near threshold FCG studies have been carried out to describe the principle of the influence of residual stress on the fatigue crack initiation mechanism. Rangaswamy et al. [169] used neutron diffraction and contour method to test the residual stress distribution in LENS AISI 316 stainless steel and Inconel 718 nickel base alloy samples. The results show that the residual stresses in AM processed parts are approximately uniaxial, with high stresses in the growth (z) direction, and very low residual stresses in the (x/y) plane perpendicular to the growth direction. The residual stress in the Z direction measured in the test is compressive stress, with a value close to 400 MPa. Compressive stress is beneficial in resisting fatigue cracks. However, the residual stress in the Z direction near the surface of the specimen is tensile stress, with a value of up to 200 MPa. This means that although the residual compressive stress in the center of Z direction of the AM processed part can reduce the applied tensile load, the residual tensile stress near the surface raises the applied tensile load, resulting in a larger load borne by the surface, and the fatigue crack is more prone to sprout.

The influence of residual stress on the FCG stage is more significant. The research of Leuders et al. [96] shows that the material behavior is particularly affected by the internal stress in the subsequent stage of crack propagation. The fatigue life of SLM Ti-6Al-4V alloy was tested under the condition of stress ratio $R = -1$ and the maximum stress $\sigma_{\max} = 600$ MPa. It was found that the fatigue life of the AB sample was 27,000 cycles, and it increases to 93,000 cycles after 800° heat treatment and even increases to 290,000 cycles (more than 10 times increase) after 1050° heat treatment. The microstructure of the material after 800° heat treatment has little difference from that of the AB sample, with almost no change in grain size and grain morphology, but the residual tensile stress in all directions introduced by AM process is significantly eliminated. Therefore, even if the SR heat treatment is carried out at a lower temperature without changing the microstructure, it leads to FCG behavior similar to that of a forged Ti-6Al-4V specimen and effectively restores the fatigue performance of the part. However, HIP samples withstood 2×10^6 cycles without failure, indicating that the elimination of internal pores has a greater impact on the fatigue performance of AM processed parts than residual stress and microstructure control.

Cain et al. [170] validated the correlation between FCGR and residual stress level of SLM Ti-6Al-4V alloy. They compared the effect of residual stress anisotropy

on the FCGR resistance of samples by combining the FCG test results in three growth directions. In simple words, a faster FCGR can be observed at a higher residual stress level. Further, Becker and his collaborators [168] described the influence of residual stress on the near threshold FCGR of LPBF Ti-6Al-4V alloy. They found that the change of near threshold FCGR was mainly due to the crack opening and closing effect caused by residual stress. The experimental data show that there is a negative correlation between the effective near critical fatigue crack growth rate $\Delta K_{\text{eff},0}$ and the effective stress ratio R_{eff} . Under the action of residual tensile stress, the R_{eff} increases, but FCGR remains unchanged. Therefore, the residual stress shows different effects on the near threshold FCG under different stress ratios. At a low stress ratio, the residual stress significantly affects the near threshold FCG behavior; while at a high stress ratio, the effect of residual stress is smaller because the maximum SIF K_{max} applied is high. In addition, the residual stress field caused by the LPBF process is uneven. Relevant reports pointed out that there is local fluctuation in residual stress inside AM processed structural parts [171], which affects the tip crack driving force. In general, the residual stress only affects the FCGR of AM processed part in the range of low stress ratio, and has no significant effect on the fracture toughness of the material, which is quite different from the effect of pore defects on the fatigue performance of AM part.

However, the residual stress field introduced by AM process has less influence on the fatigue performance of AM parts as compared with the AM defects (especially porosity / LOF). The test result shows that even if the SR annealing treatment is applied to AM processed parts, there is no significant improvement in HCF behavior [95,118]. This result confirms our conclusion that residual stress plays a less important role in the HCF strength of AM parts than additive manufacturing defects. Table 5 presents the HCF strength data of AM titanium alloy samples with different residual stresses.

The above researches analyze the influence of different AM characteristics on the HCF behavior of AM processed parts from many aspects. However, the evolution rules of microstructure characteristics and residual stress field in AM area under service load are ignored, as well as the influence of different load characteristics (such as fatigue load stress ratio, stress amplitude, and cycle numbers) on FCG characteristics. For example, Sun et al. [172] conducted an experimental characterization study on the micro process of ultra-high cycle fatigue crack initiation and evolution of TC17 titanium alloy and found that nanocrystals were generated on the crack propagation path under ultra-high cycle load when cycle numbers exceeded 10^8 , which was an important factor in the

initiation and evolution of ultra-high cycle fatigue cracks. But for AM processed titanium alloy such research has not been conducted yet. The anisotropic characteristics and residual stress fields resulting from the complex thermal history experienced during actual implementation can lead to multiaxial stress at fatigue critical positions of the AM components. Multiaxial fatigue is a problem that must be addressed before AM repaired titanium alloy blades can be put into industrial use. More importantly, the fatigue data obtained in current studies are usually generated under constant amplitude loading, while the service load history is usually of variable amplitude nature. Therefore, research on fatigue performance of AM repaired blades considering the working environment of compressors will be more engineering oriented. This point is a major challenge that the future AM repair field must face, which is briefly summarized in Section 4.3, but there is a serious lack of related research. All these issues will pose challenges to the research on AM repair in the future. The prediction and evaluation on fatigue performance of AM processed parts are extremely complex since the AM defects and microstructure characteristics are very different in sensitivity to fatigue behavior. That is to say, current research on the evolution mechanism of fatigue damage of AM repaired titanium alloy blade is insufficient to fully support the fatigue performance prediction and evaluation of AM repaired titanium alloy blades, and in turn, cannot provide technical support for rapid field maintenance and repair of the aero-engine blade.

4. Evaluation on fatigue properties of AM titanium alloy blade

The estimation of fatigue strength (especially the quality control of parts containing defects and uneven components) is a very important issue. After decades of theoretical and technological development, it was not solved until a complete solution to this problem was established in the mid-1980s [173], through which the fatigue life ranges of clean steel, welded parts, and other uneven materials could be preliminarily mastered, and guidance for engineering application was provided. The AM repair of aero-engine blades poses new challenges to traditional fatigue evaluation methods. On the one hand, AM processed parts have unique microstructure, manufacturing defects, surface roughness, and residual stress characteristics, which bring great changes to the fatigue performance of the parts. The fatigue prediction model used before is established based on welded structural parts. Its adaptability to AM processed parts needs to be reviewed and verified again. Similarly, traditional fatigue

evaluation criteria need to be reconsidered with diversified influencing factors. On the other hand, the military aero-engine blades operate in a battlefield environment that is treacherous and changeable, and rapid field repair for war damage is a hard demand to be faced in field maintenance. Present post-processing methods such as SR annealing [174], HIP [175], M&P [176], and so on are difficult to implement quickly, and the influences of pores and residual stresses cannot be eliminated. Therefore, the fatigue prediction based solely on stress concentration equivalence and linear elastic fracture mechanics (LEFM) cannot meet the needs of assessment on reliability and structural integrity of AM repaired aero-engine blades. Traditional mechanical models need to be further developed to address the fatigue evaluation of AM components considering complex defect structures and various influencing factors.

In recent years, data science methods such as big data and machine learning (ML) developed rapidly with the support of computing technology and became popular tools to solve engineering problems in the new era [177]. Such methods developed data-driven research mode and data fusion theory by exploring the correlation between physical quantities and engineering variables. Fatigue strength based on data fusion has achieved success in fault diagnosis and life prediction of complex structures and could be used to ensure full life safety and high reliability of mechanical structures. It has become a cutting-edge technical means used to solve this kind of problem [178]. However, these methods also have some disadvantages such as huge demand for fatigue samples of the same materials under the same status and lack of engineering universality. The application of these methods in the field of fatigue evaluation of AM processed parts still needs to be further verified.

4.1. Fracture mechanics model for fatigue evaluation

The high cycle fatigue fracture behavior of metals can generally be divided into the following stages [179]: crack nucleation stage, short crack growth stage (state I), long crack growth stage (state II), and final fracture stage (state III), as shown in Figure 7. At the crack nucleation stage, dislocation accumulation of titanium alloy under HCF load will cause local high stress state which induces twinning, slip or microcracks. The interaction between dislocations will form dislocation cells or dislocation walls, and further result in slip bands [172,180]. Microcracks will grow along or across the grain boundary, then develop into short crack propagation [181,182]. The short crack growth stage can be further divided into microscopic short crack stage and physical short crack

stage according to the crack length. During the short crack growth stage, fine fatigue striations can be observed on the crack propagation path, indicating lower FCGR at the initial stage of crack growth. During the long crack growth stage, the distances between fatigue striations will become larger, demonstrating the gradual increase of FCGR with crack growth. Fatigue fractures in this stage always show river patterns, ridge patterns, or tearing ridges, which indicate plastic deformation during crack propagation. LEFM methods are usually used to study the FCG behavior during the long crack growth stage. Finally, the test sample breaks instantaneously under a fatigue load. A large number of dimples can be observed as ductile fracture characteristics, with shear lips appearing on the edge of the fracture. Cracks tend to nucleate from defects (if there are any), and then propagate around. The propagation direction of cracks changes due to the forms of fatigue loads applied to the test sample.

In terms of traditional mechanical evaluation models, scholars have developed many fatigue-prediction models (as shown in Figure 8) based on the theory of fracture mechanics, the generalization of Paris' law, the AM defect analysis of EVS with different PD functions, and the El Haddad and Topper correction of K-T diagram, which give great guidance on fatigue performance evaluation of parts with AM defects.

Paris et al. [185] believe that the SIF at the crack tip is the driving force for fatigue crack growth during crack growth stages, so they proposed a formula to describe the law between FCGR and SIF variation range, which is called Paris' law, and the formula is described as follows.

$$\frac{da}{dN} = C(\Delta K)^m \quad \Delta K_{th} < \Delta K < K_{Ic} \quad (1)$$

where a is the crack length, N is the number of stress cycles, C and m are Paris constants, and $\Delta K = K_{max} - K_{min}$ is the SIF variation range. In LEFM, ΔK_{th} is introduced as the threshold value of crack propagation for the case of infinite life of materials, and K_{Ic} is introduced as the fracture toughness for the static failure of materials.

The above Paris equation establishes the relationship between fracture mechanics and fatigue fracture, and firstly gives the method to estimate the fatigue life of structural parts from the perspective of crack propagation. Many research works have been carried out on the application of this equation in different stages and different fields. Both Foreman et al. [186] and Laird [187] studied the modification of the Paris equation in terms of fatigue limit and crack growth threshold. Elber [188] studied the modification of the Paris equation in terms of crack closure. The application of the Paris equation in the short crack growth stage is quite extensive. Pearson [189] studied the use of the Paris equation to predict

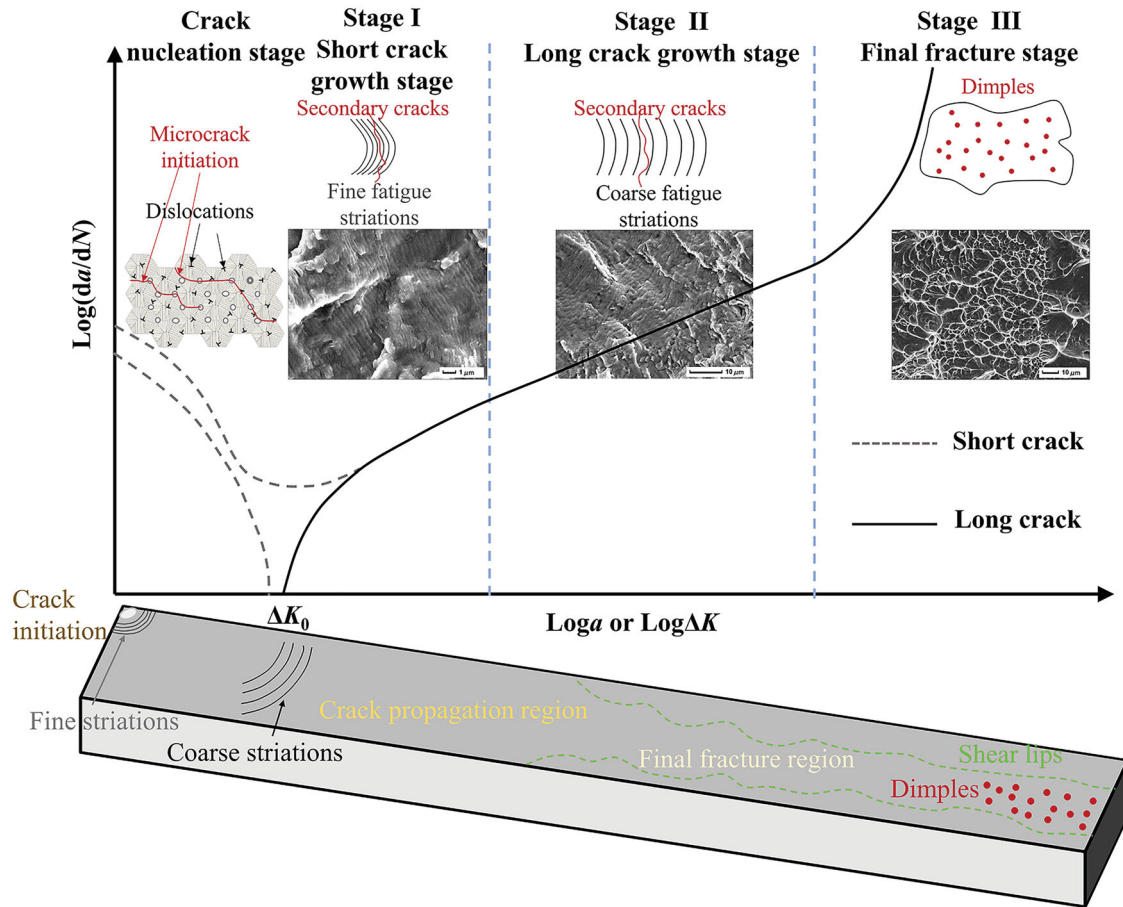


Figure 7. HCF fracture behavior of titanium alloy.

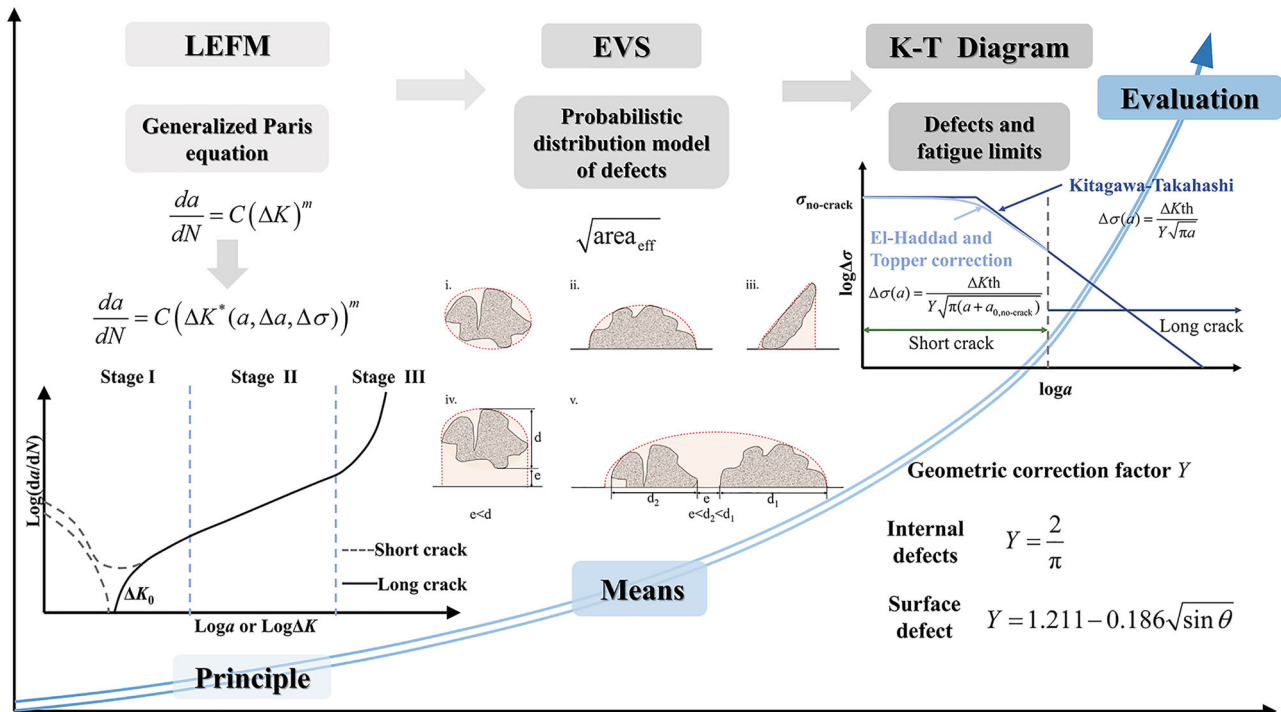


Figure 8. Development of mechanical models for fatigue properties evaluation of AM processed titanium alloy [95,117,149,183,184].

the growth of cracks from 0.00025 to 0.02 in. El Haddad et al. [190,191] predicted crack length at different cyclic numbers based on the Paris equation and strain intensity factor. Kitagawa and Takahashi [192] discussed the application of fracture mechanics to small cracks in the initial stage. Ritchie and Lankford [193,194] extended the Paris equation to the life prediction analysis of small fatigue crack problems, supporting alloy design. Pugno et al. [183] proposed to combine the S-N curve with the Paris equation when studying the specimen with an initial crack size of a_i , and established the generalized Paris Law [195].

The S-N curve (Wöhler curve) describes the fatigue crack behavior of the specimen in the LCF state and HCF state as follows:

$$N_0 \Delta \sigma_R^k = N_\infty \Delta \sigma_0^k = N_f \Delta \sigma^k = \bar{C} \quad N_0 < N_f < N_\infty \quad (2)$$

where k is the Wöhler parameter, $\Delta \sigma_R$ is the stress range when the specimen encounters a static failure, $\Delta \sigma_0$ is the fatigue limit of the specimen, $\Delta \sigma$ is the stress range at specimen life of N_f , N_0 , N_∞ and N_f are the corresponding cycle number of $\Delta \sigma_R$, $\Delta \sigma_0$ and $\Delta \sigma$, respectively. For titanium alloy, the values are normally given as $N_0 = 10^3$, $N_\infty = 3 \times 10^7$ (or 10^7).

The equation for the specimen with an initial crack size of a_i can be established as:

$$a_i^{(2-m/2)} = \left(\frac{m-2}{2} \right) C \pi^{m/2} \Delta \sigma^m N_f \quad (3)$$

Under this condition, the Wöhler parameter in the S-N curve is different from the material constant k in the conventional S-N curve but equivalent to the Paris index m . Therefore, the S-N curve depends on the initial crack size a_i , and the fatigue limit obtained from the above formula also depends on a_i , being inconsistent with the value directly calculated from the crack growth threshold.

For a given material crack growth threshold ΔK_{th} and fatigue limit $\Delta \sigma_0$, the threshold size of the sample under infinite life conditions (called the El Haddad parameter [190]) could be calculated as:

$$a_0 = \frac{1}{\pi} \left(\frac{\Delta K_{th}}{\Delta \sigma_0} \right)^2 \quad (4)$$

Similarly, the threshold size at static failure status could be calculated through the fracture toughness K_{Ic} and the tensile strength σ_R :

$$a_0^S = \frac{1}{\pi} \left(\frac{K_{Ic}}{\sigma_R} \right)^2 \quad (5)$$

The Paris equation is extended [183,196], and the relationship between SIF and remote stress σ as well as the

relationship between crack length a and fracture quantum Δa is established.

$$K^* = \sigma \sqrt{\pi(a + \Delta a/2)} \quad (6)$$

where Δa is a material parameter related to $\Delta \sigma$. It is correlated with a_0 for infinite life cases and a_0^S for static failure cases. To consider the influence of this additional crack size, Pugno established the generalized Paris Law as follows:

$$\frac{da}{dN} = C(\Delta K^*(a, \Delta a, \Delta \sigma))^m \quad (7)$$

The generalized Paris Law realizes the formal matching of the Basquin equation and Paris equation, and fully considers the influence of initial crack size on the FCG behavior of samples. For AM processed titanium alloy, defects introduced in the manufacturing process can be regarded as initial cracks, which must be considered for the AM process. Therefore, it is scientific to evaluate the fatigue performance of AM processed titanium alloy parts based on the generalized Paris Law. In this method, it is a prerequisite to accurately evaluate the defects and use the evaluation results for fatigue prediction.

Usually, the maximum predicted defect size is used for approximate evaluation to avoid characterizing all defects and achieve the equivalence of AM defects and initial cracks. Various PD functions have been used to predict the defect distribution and maximum defect size, including Gumbel distribution based on EVS [197], generalized Pareto distribution [152], Weibull distribution [106], and so on. These methods and models have become essential tools to link the theory of fracture mechanics with the fatigue evaluation model for AM processed parts.

Murakami et al. [198] are the first to propose an EVS method for the prediction of the fatigue limit of metals containing impurities. They defined the square root of the projected area of inclusions in pure steel ($\sqrt{\text{area}}$) as the inclusion size at the crack initiation position and carried out fatigue tests to verify the correlation between the square root and the fatigue limit of pure steel. They used the EVS data of defects observed/sampled from pure steel to predict the maximum defect size in samples and believed that this size determined the fatigue performance of samples. Subsequently, they used the Gumbel Distribution based on EVS to evaluate the inclusion size of the ultra-clean bearing steel manufactured by electron beam remelting and found that the inclusion size was significantly reduced compared with the conventionally manufactured ultra-clean bearing steel [197].

The $\sqrt{\text{area}}$ parametric model can be effectively applied to the fatigue limit assessment of ultra-clean bearing steel with inclusions or minor defects as the fracture initiation point. Murakami et al. [197] analyzed the influences

of Vickers hardness, surface defect geometry, and size on fatigue limit based on the fatigue limit test results of more than 15 kinds of materials under rotating bending and tension compression, and established the prediction model among defect size, matrix Vickers hardness and fatigue limit of ultra-clean bearing steel.

$$\sigma_w = \frac{C(HV + 120)}{(\sqrt{\text{area}})^{1/6}[(1 - R)/2]^\alpha} \quad (9)$$

where C is the material parameter related to defect location, $C = 1.43$ when the defect exists on the surface, $C = 1.41$ when the defect exists inside but contacts the surface, and $C = 1.56$ when the defect exists inside the material. σ_w is the fatigue limit prediction value of the sample, which is an area parameter of the defect. HV is the Vickers hardness, R is the stress ratio, and $\alpha = 0.226 + HV \times 10^{-4}$ is an empirical parameter.

The above formula expresses Murakami et al.'s cognition about defects in structures. As long as the fatigue limit problem is involved, defects occupying three-dimensional space can be treated as cracks. On this basis, Murakami et al. [148] listed both test and analysis results of equivalent area parameters corresponding to different defect shapes, Vickers hardness of defect area, fatigue limit test values, and fatigue limit prediction values, which validated the effectiveness of their prediction model. Subsequently, the research work of Shojima et al. [199] and Matsunaga et al. [200] confirmed that this parameter method applied to Ti-6Al-4V alloy.

After that, researchers applied this method to AM processed parts. Masuo and his collaborators [117] also used the EVS-based parameter method to define the

maximum expected defect size in AM processed parts of EBM and DMLS Ti-6Al-4V specimens. They classified the defects in AM processed titanium alloy into five categories:

- (i) Internal defects with irregular shapes;
- (ii) Surface defects with irregular shapes;
- (iii) Inclined defects in contact with the surface;
- (iv) Irregular shaped internal defects interacting with the surface;
- (v) Two adjacent defects interacting with each other.

The estimation method which could effectively predict defect area has been given for these five types of defects, as shown in Figure 9. When multiple defects are close to each other, the fatigue crack caused by one defect may be connected with another nearby defect(s). When the distance between defects is less than the maximum size of smaller defects (see Figure 9(v)), it must be considered to calculate the effective defect area. For the case where multiple small internal defects are close to each other, the minimum circumscribed ellipse should be used to define the effective defect area $\sqrt{\text{area}_{\text{eff}}}$.

On this basis, Masuo et al. [117] introduced the effective defect area into the prediction model (Equation (9)) proposed by Murakami et al. [198] and obtained Equation (10). They used the smooth contour area of constrained irregular shape defects as the effective defect area, and calculated the maximum SIF at the internal or surface cracks along the irregular shape defects by this parameter. They believe that SIF at irregular shape defects drives the cracks into regular circular cracks in the process of crack growth. The work of Wu et al. [201] confirms

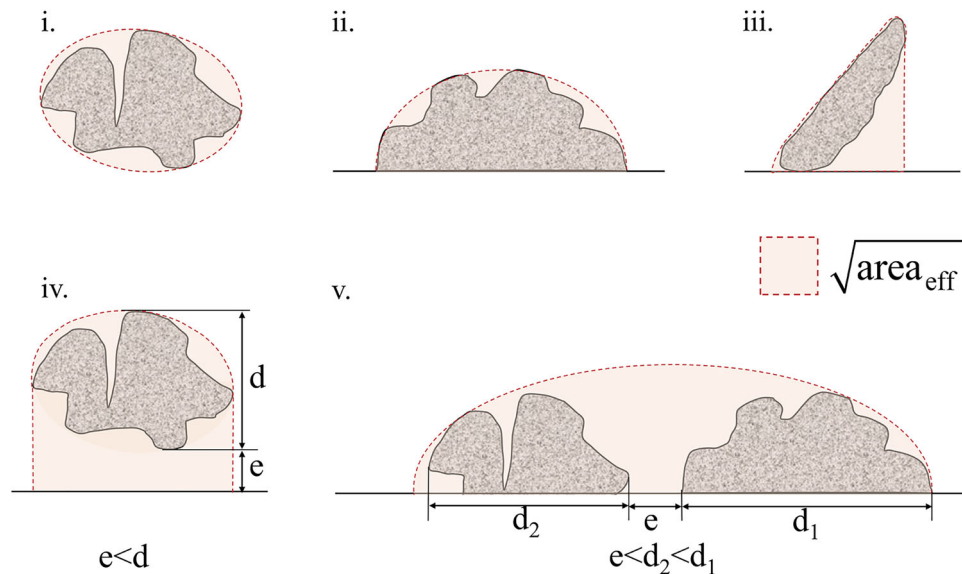


Figure 9. Estimation method of effective area of irregular defects and surface defects. Reprinted with permission from Masuo et al. [117] (Copyright (2018) Elsevier).

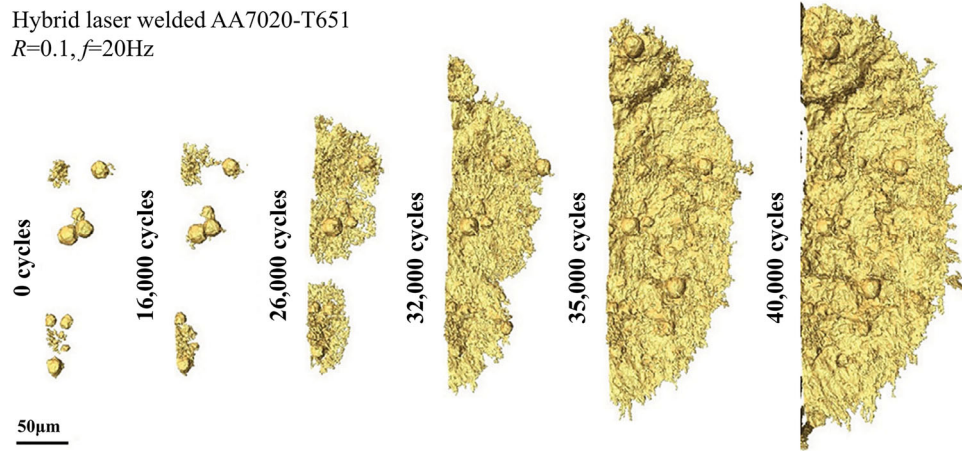


Figure 10. Interaction of AM defects under fatigue loading. Reprinted with permission from Wu et al. [201] (Copyright (2017) Elsevier).

this assertion, as shown in Figure 10.

$$\sigma_w = \frac{1.43(HV + 120)}{(\sqrt{\text{area}_{\text{eff}}})^{1/6}} \quad (10)$$

The EVS method is also used to evaluate AM defects and quantify defect size through parameters. Günther et al. [106] used the Weibull distribution function to evaluate the fatigue life of SLM and EBM Ti-6Al-4V materials under ultra-high cycle load. They used Weibull probability plots to evaluate the internal crack initiation size in AM processed specimens for defects including LOF, porosity, and α phase cluster. It was found that the porosity and α phase cluster show similar average defect size, while the LOF defect has an obviously larger average size. The effect of defect size on fatigue life was evaluated for specimens that failed due to the three types of internal defects. Sandell et al. [202] used a combined method of X-ray CT test, EVS, and fracture mechanics to predict the fatigue life of the EBM Ti-6Al-4V specimen. The results show that the predicted fatigue life obtained by deterministic FCG calculation with the worst defect observed by X-ray CT test is conservative and accurate, the error lies within the double dispersion band, and no specimen (including those with initial LOF defects) fractured outside the prediction boundary. The only problem is that this model uses very little defect information. After summarizing such methods, Molaei and his collaborators [94,140,142,203] also used EVS to predict the defect distribution in the LPBF Ti-6Al-4V sample. They defined the effective defect size and calculated the most dangerous defect by parameter method; Fatigue was predicted with high accuracy considering various loading statuses such as uniaxial, multiaxial, torsional, etc.

These works show that a series of evaluation models can be used to predict the fatigue performance of AM processed parts regardless of their fatigue life or

strength in case the manufacturing defects could be accurately identified and the distribution of the most dangerous defects be predicted. Based on fracture mechanics theory and defect equivalence method, different fatigue evaluation methods have been developed for AM components, such as the local method based on SIF, El Haddad and Topper correction method of K-T diagram, critical distance theory, etc.

Aiming at the fatigue evaluation of welded joints, Atzori et al. [204] collected the stress and strain near the weld toe employing numerical simulation and strain test, predicted the fatigue behavior of welded joints by local method, semi-local method, and structural method based on notched SIF, and compared the advantages and disadvantages of each method. The parameters that affect the fatigue strength prediction are mainly three types: the size of welded joints, the geometry of welded joints, and the application range of nominal stress. The results show that the fatigue design dispersion band based on NSIF local method is applicable to predict the fatigue strength of structural steel weld toes within 6–100 mm thickness. But for AM processed structural parts, it is validated in various studies that AM defects are the most significant factors affecting fatigue performance, and the local stress concentration caused by AM defects affects the hot spot stress of the part, so the evaluation of fatigue strength of AM part by (semi) local method cannot achieve the desired effect.

The K-T diagram is a double logarithmic curve describing the crack length and fatigue failure stress. Kitagawa and Takahashi [192] believe that the crack growth rate is slow at the short crack growth stage. He defines the failure stress at this stage as the fatigue limit of crack-free materials, as shown in Equation (11). At the long crack growth stage, the failure stress decreases significantly with the growth of the crack length, so the failure stress can be described as a function of the crack

length (Equation (12)).

$$\Delta\sigma = \Delta\sigma_{\text{fat}} \quad (11)$$

$$\Delta\sigma(a) = \frac{\Delta K_{\text{th}}}{Y\sqrt{\pi a}} \quad (12)$$

where $\Delta\sigma_{\text{fat}}$ is the fatigue limit of crack-free materials, ΔK_{th} is the threshold value of crack growth, a is the crack length, and Y is the geometric correction coefficient (related to crack location).

The two equations for short and long crack stages appear to be two straight lines in the K-T diagram as shown in Figure 11(a). It is inappropriate to describe the short crack growth stage by a constant model, although its FCGR is low and its failure stress changes little with the crack length before entering the long crack growth

stage. Therefore, El Haddad and Topper modified the K-T diagram to solve this problem and obtained a more conservative equation (Equation (14)) using the threshold size $a_{0,\text{fat}}$ (Equation (13)) of crack-free material as the material constant.

$$a_{0,\text{fat}} = \frac{1}{\pi} \left(\frac{\Delta K_{\text{th}}}{\Delta\sigma_{\text{fat}}} \right)^2 \quad (13)$$

$$\Delta\sigma(a) = \frac{\Delta K_{\text{th}}}{Y\sqrt{\pi(a + a_{0,\text{fat}})}} \quad (14)$$

It could be obtained as the following from these two formulae:

$$\Delta\sigma(a) = \Delta\sigma_{\text{fat}} \sqrt{\frac{a_0}{a + a_0}} \quad (15)$$

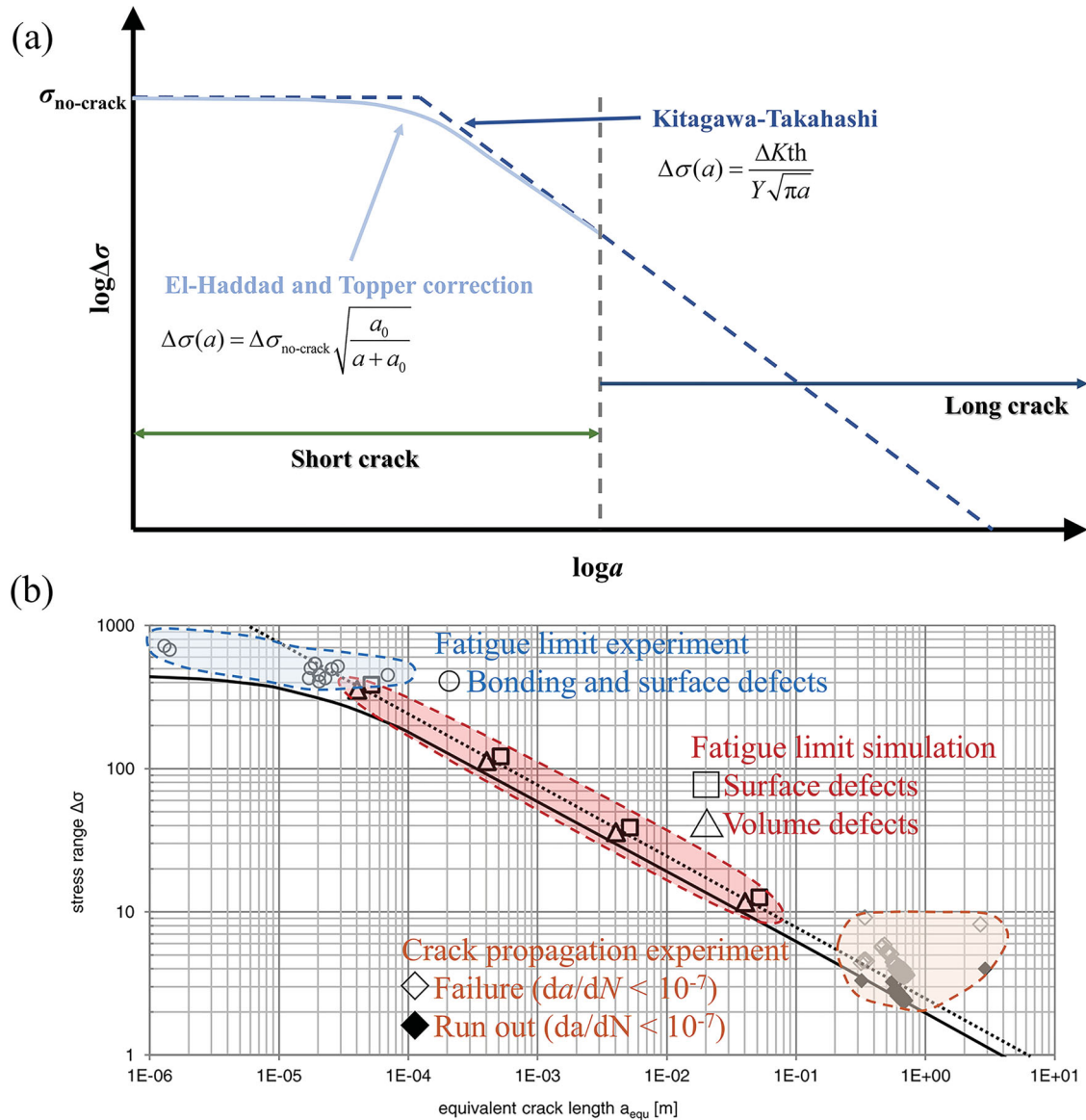


Figure 11. K-T diagram with El Haddad and Topper corrections (a) Schematic diagram; (b) Experimental data and simulation results. Reprinted with permission from Wycisk et al. [95]. (Copyright (2014) Elsevier).

This correction correlates the failure stress with the initial crack length during the whole crack growth stage, as shown in Figure 11(a), and leads to a more accurate fatigue limit prediction for cracked specimens in the short crack growth stage. But the prediction result in the long crack growth stage is relatively conservative. The test and simulation results in Wycisk et al.'s work [95] confirm this. They tested the fatigue limit and crack growth behavior of LAM Ti-6Al-4V alloy specimens with surface cracks and volume defects, and simulated and predicted the fatigue limit of the specimens based on the LEFM method. The test and simulation results can be seen in Figure 11(b). All the fatigue prediction results are conservative for samples with long defects (cracks) in the CT test.

For specimens with AM defects, the accuracy of fatigue prediction by the above models depends largely on the selection of geometric correction factors. In this regard, researchers have given a perfect solution, that is, using Equation (16) to take the geometric correction factor for internal defects [149], and using Equation (17) to take the geometric correction factor for surface defects under HCF condition [184]:

$$Y = \frac{2}{\pi} \quad (16)$$

$$Y = 1.211 - 0.186\sqrt{\sin \theta} \quad (17)$$

where θ is the angle between the crack front and the sample surface.

Most observations on the fatigue failure initiation position show that fatigue failure often originates from surface failure [205–207]. This can be attributed to the fact that the post-treatment eliminates defects such as pores inside the part, which is also affected by the large stress concentration effect at surface defects. Therefore, surface defects have a greater effect on fatigue failure than internal defects, which is also validated by Murakami [149]. Through fatigue tests on specimens containing inclusions under uniaxial load, it is found that the maximum SIF of an internal defect was about $K_{\max} = 0.5\sigma\sqrt{\pi\sqrt{\text{area}}}$, while that of the surface defect could reach $K_{\max} = 0.65\sigma\sqrt{\pi\sqrt{\text{area}}}$. This means surface defects are more harmful to fatigue performance than internal defects in case the two defects have similar sizes and shapes. The work of Sanaei and Fatemi [208] also confirms that when dealing with the shear failure mode, defect equivalence can be achieved by projecting the defect area on the maximum shear plane. Therefore, the characterization of the maximum effective defect area of AM processed parts should first focus on surface defects and initial defect size equivalent to surface roughness.

Romano et al. [209] proposed a fatigue crack growth model based on the maximum defect size, which can predict fatigue life and data dispersion within elastic regions. The model is used to predict the uniaxial high cycle fatigue life and fatigue strength of SLM AlSi10Mg specimens and gives highly accurate predicting results. Based on the evaluation of SIF, the most dangerous defect in the CT test sample can be defined, then the maximum defect in the measured volume of the sample can be predicted and calculated by parameters. For a given percentage threshold, the lower limit S-N curve is obtained to evaluate material safety through the manually calculated defined maximum defect size. For the fatigue strength of AM processed part under the short crack growth model considering defects, the influence of defects is introduced into the K-T diagram, and then the K-T diagram is modified to predict fatigue strength. The fatigue life is also estimated by the model based on defect distribution law, and the dispersion band of prediction results is given.

On this basis, with the improvement of computing power, some complex crack growth equations can be solved by numerical methods. For example, the NAS-GRO equation [210], which accounts for the stress ratio R , crack closure, and tails at the upper and lower ends of the growth rate curve and is described as follows:

$$\frac{da}{dN} = D \left[\left(\frac{1-f}{1-R} \right) \Delta K \right]^n \frac{\left(1 - \frac{\Delta K_{th}}{\Delta K} \right)^p}{\left(1 - \frac{\Delta K_{max}}{\Delta K_c} \right)^q} \quad (18)$$

where D and n are material parameters, p and q are empirical coefficients that determine the curvature of the growth rate curve in the tail regions selected to fit the experimental data, and f is the Newman crack closure function [210].

Romano et al. [211] simulated the fatigue crack growth of SLM AlSi10Mg alloy by NASGRO 4.0 software and estimated the fatigue strength and fatigue life based on numerical simulation results. They calculated SIF by the standard solution of surface crack propagation of cylindrical specimens, described the crack size by crack depth a , and approximated the defect shape by a semi-circular crack. The initial crack depth a_i was determined by the defect area parameter, the ΔK - da/dN relationship was described by an equation built in NASGRO solver, and the parameters were obtained from the FCG test on CT samples. They calculated three different conditions by the Newman model, and the results showed that the parameter model with plastic correction had the highest prediction accuracy, highlighting the importance of elastic-plastic conditions for correctly analyzing the fatigue performance of structural parts with AM defects.

In addition to NASGRO, there are also commercial crack growth numerical software such as AFGROW and FASTRAN, which use control equations that consider different crack growth and closure mechanisms. Wycisk et al. [95] used AFGROW to predict the HCF fatigue of the LAM Ti-6Al-4V cylindrical specimen, with a stress ratio of 0.1. The finite element software simulation accurately predicted the fatigue life of AM samples with large initial defects, but overestimated the fatigue life of samples with small initial defects, making the later prediction result more dangerous. Fortunately, the El Haddad and Topper corrections gave a conservative assessment of the fatigue limit of smaller initial defects as mentioned above. The combination of these two methods can effectively predict the fatigue limit of AM processed Ti-6Al-4V alloy considering the effect of defects. In recent research, Molaei et al. [212,213] conducted fatigue assessments of notched components using FASTRAN software. Test specimens were assumed to follow the mode I crack initiation and growth with equivalent axial stress to be evaluated starting from the local equivalent von Mises stress using the appropriate stress. It is worth mentioning that, good agreement was found between the prediction and experimental sequences of LAM Ti-6Al-4V specimens in both the AB and machined conditions.

Other theoretical systems such as the critical plane method [214], Von Mises and maximum principal stress criteria [203,215] are the explorative use of traditional methods in this field. However, these methods also have some disadvantages such as insufficient applicability to AM components with different process parameters and failure to consider multiaxial stress states. The application of these methods in the fatigue evaluation of AM processed parts still needs to be further verified.

In summary, further research can be conducted in several specific areas. Firstly, data-driven methods can help link the AM process parameters to fatigue performance, clarifying the role of factors such as grain structure, texture, second phases, residual stresses, etc. in fatigue prediction and guiding the optimization of AM repair processes with numerical simulation methods. Secondly, real-time detection data on defect formation during the AM process [216–218] can serve as an important input parameter for fatigue evaluation, which contributes to a deeper understanding of the fatigue failure mechanism of AM components. Finally, the difficulty in evaluating fatigue of AM components lies in the complex microstructures, defects, and residual stresses. Therefore, developing high-precision in-situ characterization methods [219,220] is an important research direction for the future.

4.2. ML strategy for fatigue evaluation

Many complex factors affect the fatigue properties of AM materials, such as microstructure, residual stress, surface roughness, defects, post-processing, etc. Traditional mechanical models need to combine these factors to improve prediction accuracy, resulting in low efficiency and high cost. Through learning a large amount of testing and simulation data, the ML method can incorporate various AM processes, post-processing, and characterization parameters into the model for fatigue life prediction, fatigue crack behavior, fatigue damage diagnosis, and fatigue strength prediction, as shown in Figure 12. ML strategy possesses advantages in terms of computation efficiency and prediction accuracy [221]. Nonetheless, the application of ML in predicting fatigue properties of AM materials is still limited, let alone in AM repaired titanium alloy blades.

Zhan et al. [223] used the continuum damage mechanics (CDM) and two typical ML models (ANN and RF) to predict the fatigue life of AM Ti-6Al-4V and other aerospace alloys. The input parameters of the ML model include 4 AM processing parameters (laser power P , scanning speed v , hatch space h , powder layer thickness t) and 2 fatigue loads parameters (maximum stress $\sigma_{\max}$, stress ratio R), and the output is the fatigue life N_f of AM specimens. The CDM-based computational approach is employed to acquire fatigue data to train ML models. The ML computational flowchart is shown in Figure 13(a). The prediction results show that five fatigue lives predicted by the ANN model locate outside the three-error bands, while all data by the RF model locate within the error band, as shown in Figure 13(b). This indicates that the ML method can effectively predict the fatigue life of AM alloy.

In addition, Zhan and his collaborators [224] also used the CDM-RF model to carry out the data-driven prediction of the fatigue life of LMD TA2-TA15 and TC4-TC11 titanium alloys. The input variables of the model are material types and load conditions ($\sigma_{\max}$, K_t and R), and the output variable is fatigue life N_f . The model strategy is to use the fatigue life under different fatigue loads computed by numerical simulations based on the CDM method and fatigue experiments for training. The trained RF model can be used to predict the fatigue life of AM titanium alloy. Figure 14(a) is the CDM-RF model strategy. The prediction results show that the fatigue life prediction performance of the CDM-RF method is better than that of the CDM method for AM titanium alloys, as shown in Figure 14(d,e). For the AM TA2-TA15, the predicted results by the CDM-RF have higher accuracy, especially for the notched specimen (Figure 14(c)).

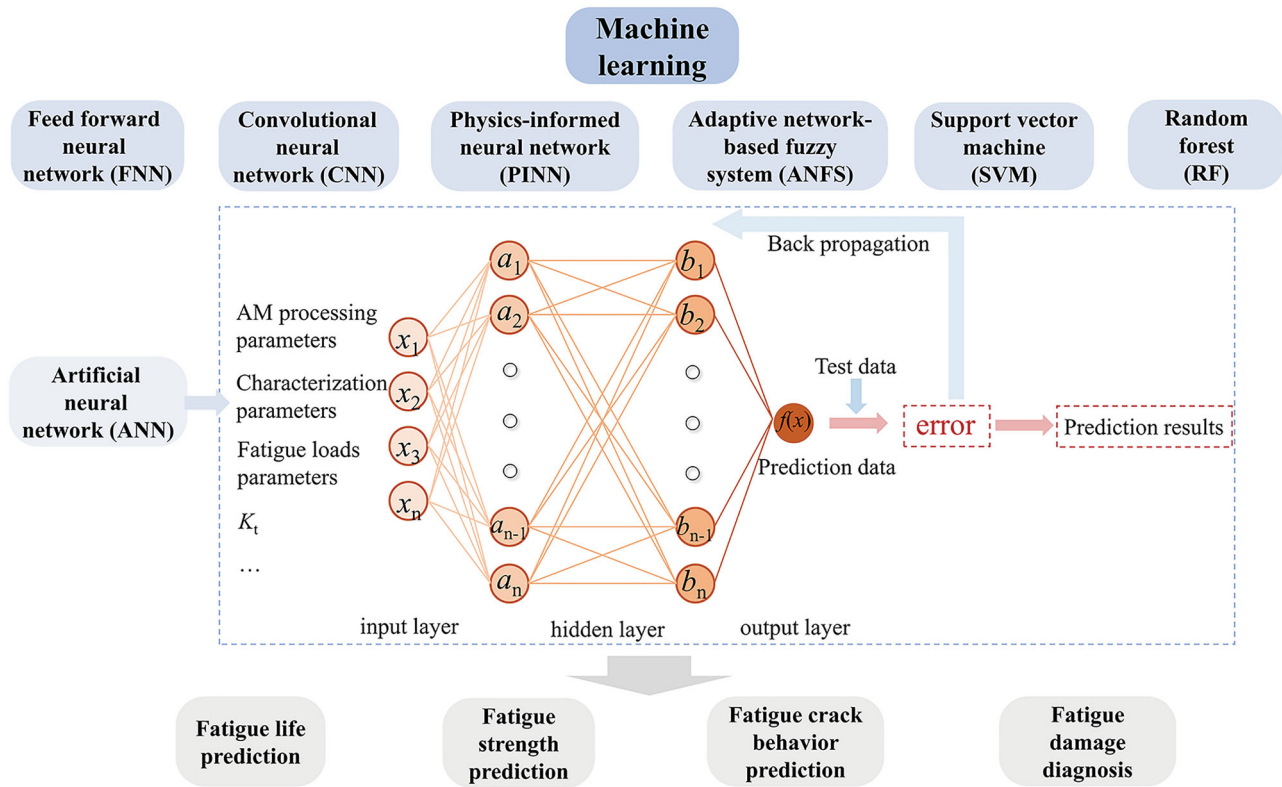


Figure 12. Summary of the application of applying ML strategy in predicting the fatigue properties of AM materials (Artificial neural network as an example) [222].

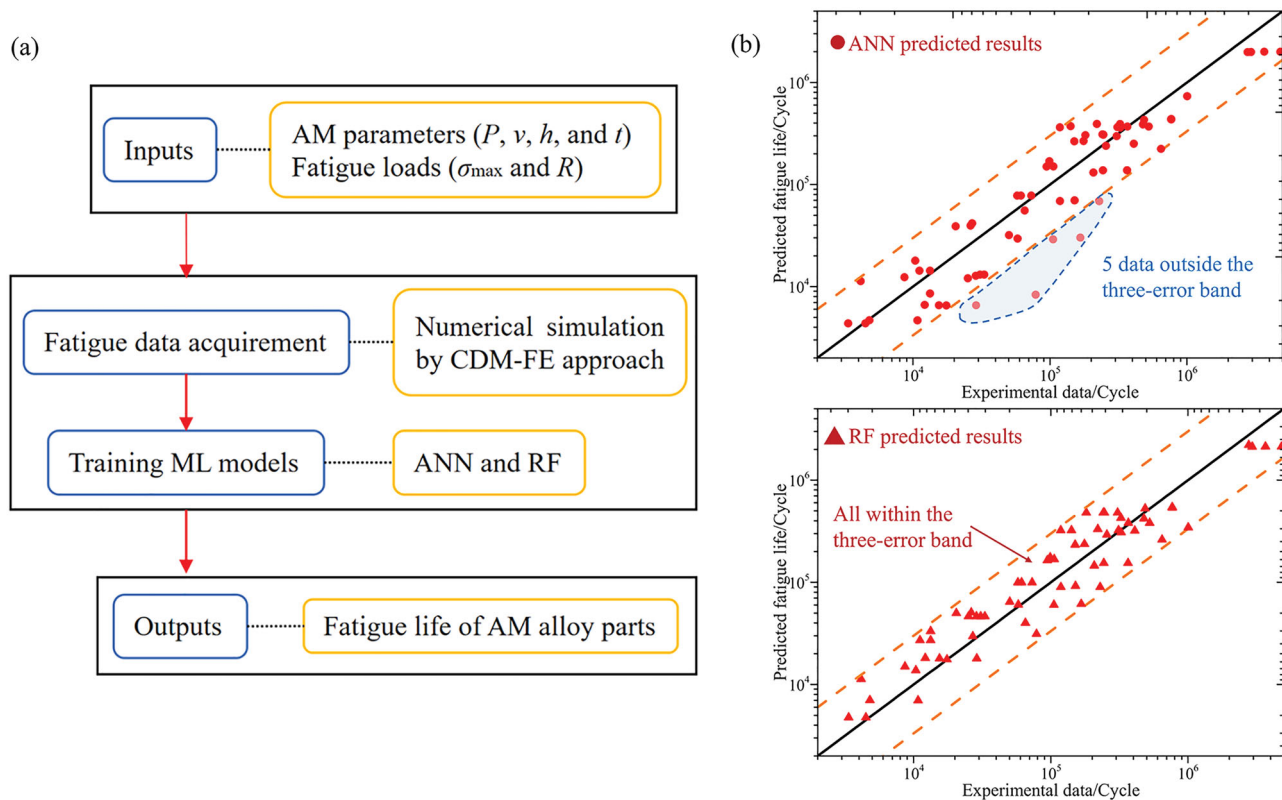


Figure 13. The fatigue life prediction of AM Ti-6Al-4V alloys with the CDM-ANN/RF method. (a) Computational flowchart; (b) Variation of the predicted fatigue life against experimental data by ML. Reprinted with permission from Zhan et al. [223] (Copyright (2021) Elsevier).

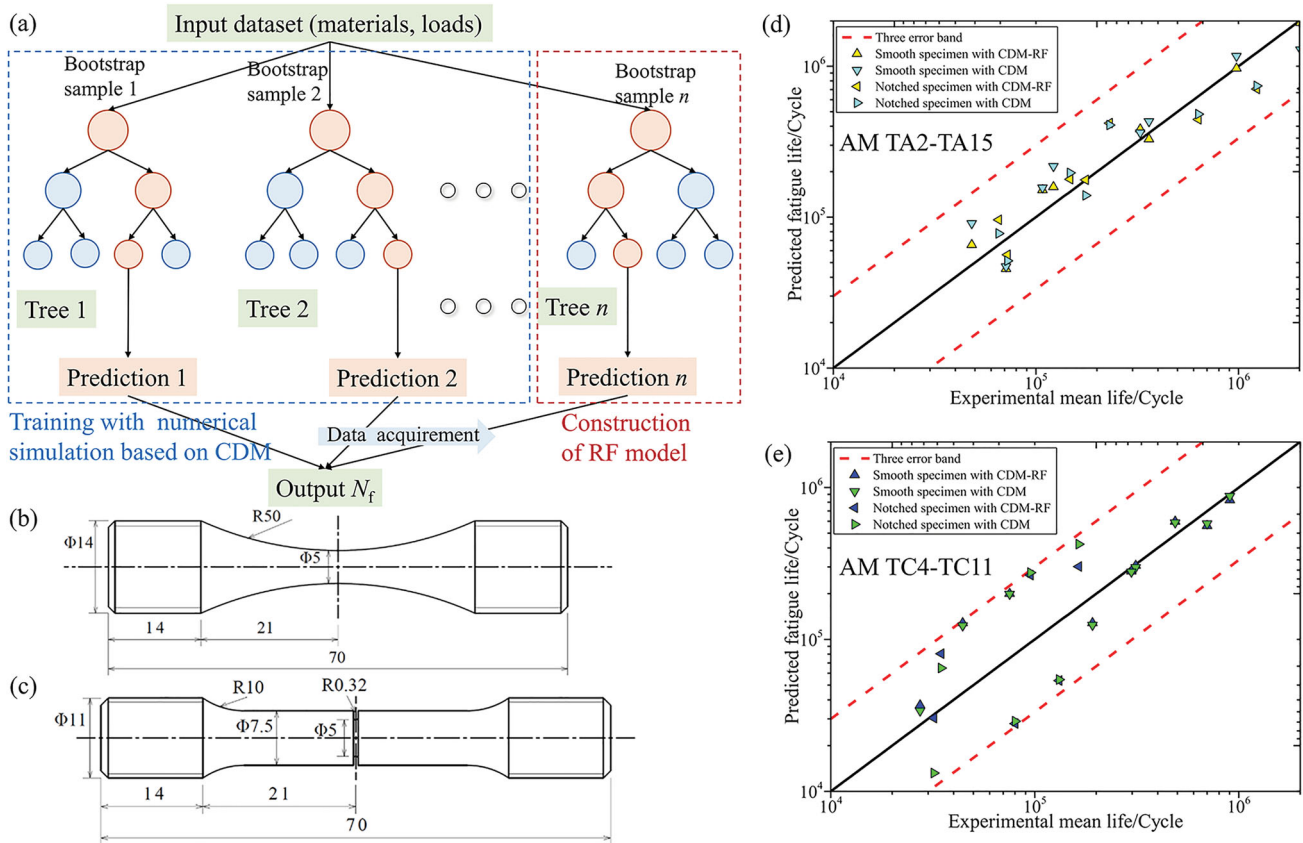


Figure 14. The fatigue life prediction of LMD TA2-TA15 and TC4-TC11 titanium alloys with the CDM-RF method. (a) CDM-RF strategy; (b) Smooth specimen; (c) Notched specimen; (d) Prediction results for AM TA2-TA15; (e) Prediction results for AM TC4-TC11. Reprinted with permission from Zhan et al. [224] (Copyright (2021) Elsevier).

Finally, it is necessary to take the influence of internal defects into account in the ML model.

Snow et al. [225] trained a CNN model to research the correlation between the process monitoring data (including layerwise imagery, multi-spectral emissions, and laser scanning vector data), part manufacturing defects, and fatigue performance of LPBF Ti-6Al-4V. Defect data was collected through X-ray CT scanning and automated defect recognition software. The CNN classifiers were trained with defect data as input. The model architecture is shown in Figure 15(a). The training results show that fatigue critical LOF defects can be detected via ML of in situ sensor data. Figure 15(b) shows the application of the trained CNN to the case of 200 layers, and the defects and fatigue life of the four selected fatigue parts gauge regions have been accurately predicted. The larger the defect density, the lower the fatigue life.

Chen et al. [226] proposed a probabilistic physics-guided neural network (PPgNN) method for modeling. AM processing parameters (scanning speed v , laser power P , hatch space H , layer thickness t , heat temperature HT , heat time Ht) can be trained to learn both

mean and variance of the fatigue life of SLM Ti-6Al-4V in AB and annealed conditions with this developed model. The architecture used for all data is shown in Figure 16(a) with the selective neurons for missing data. Figure 16(b) shows the contrast in predictive performance between models trained with all data (with missing data) and models trained with complete data (without missing data) by the logarithmic scoring rule. The results showed that the model is more likely to produce good predictions by considering the incomplete data set for training. They also compared the sensitivity of process parameters, as shown in Figure 16(c), and studied the influence of process parameters on the mean and variance of the fatigue life. It is interesting to find that the fatigue life is highly sensitive to post-process parameters (heat temperature HT and heat time Ht) compared to in-process parameters (speed v , power P , hatch space H , and layer thickness t).

For predicting the fatigue life of LDED Ti6.5Al2ZrMoV titanium considering the influence of AM microstructures and defects, Dang et al. [227] utilized a support vector regression (SVR) algorithm by post-mortem fractography analysis. The pores can be divided into four types

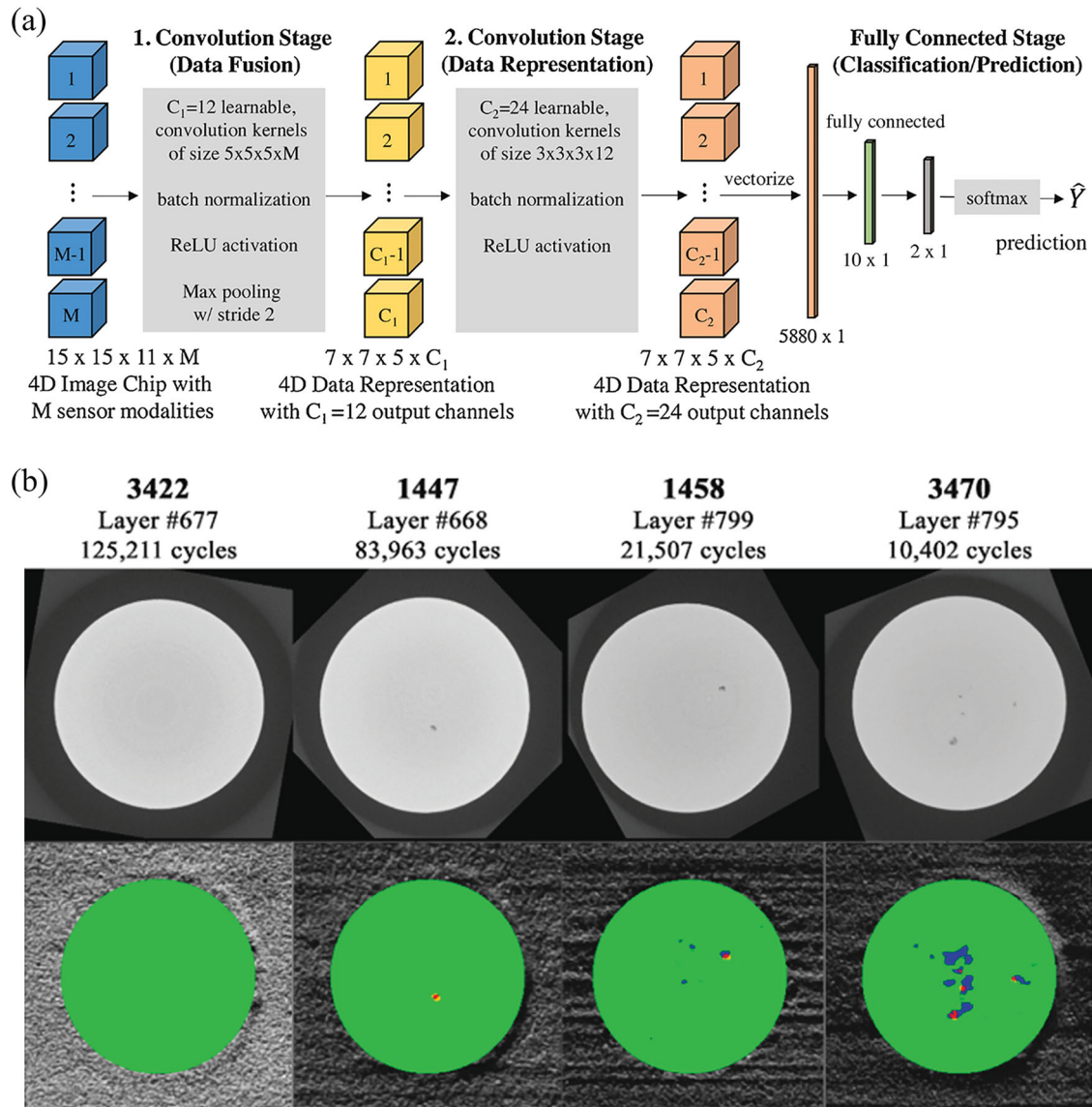


Figure 15. The internal defects and fatigue life prediction of LPBF Ti-6Al-4V alloys with the CNN method. (a) Architecture for defect classification; (b) Fatigue life and XCT results for four fatigue parts from the training and testing data sets. Reprinted with permission from Snow et al. [225] (Copyright (2021) Elsevier).

according to the crack initiation modes, namely small pores ($d_1 < \text{small-size } \alpha \text{ phase}, < 20 \mu\text{m}$), medium pores (small-size α phase $< d_2 < \text{micro-columnar grain}, 20\text{--}60 \mu\text{m}$), big pores (micro-columnar grain $< d_3$, with easily observed facets, $> 60 \mu\text{m}$) and large pores (micro-columnar grain $< d_3$, with less identifiable facets, $> 120 \mu\text{m}$). ΔK , Pore types, $\sigma_{\max}$, r_d (ratio of distance to the free surface and equivalent diameter of pore), and area (projected area along load direction of pore) were introduced as input variables for different SVR models to compare and analyze the fatigue life prediction results. Results showed that the stress intensity factor range obtained by Murakami's approach and the pore types determined by the relationship between pore size,

microstructure size, and facet were verified to be reasonable input variables for the SVR fatigue life prediction model. The SVR algorithm is an effective approach to obtain the relationship between pore parameters and the fatigue life of the LDED Ti-6.5Al-2Zr-Mo-V titanium alloy.

In summary, it is meaningful to collect a large number of numerical and experimental data to train ML models to predict the fatigue performance of AM components. Nonetheless, the application of ML in predicting the fatigue properties of AM alloys is still rare, especially for the fatigue limit prediction of aero-engine titanium alloy blades. This is due to the lack of fatigue limit experimental data in the published literature and the high

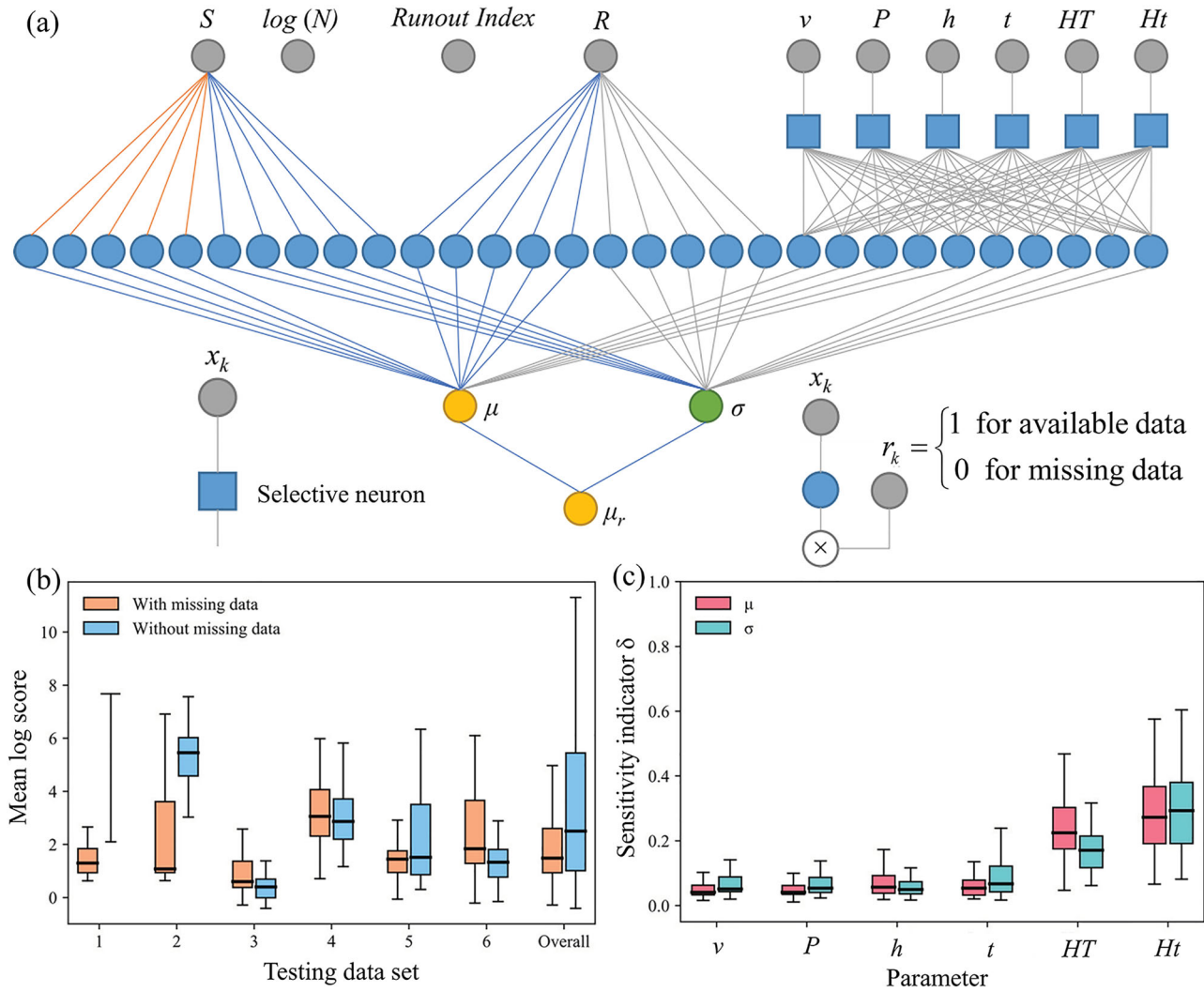


Figure 16. The fatigue life prediction of SLM Ti-6Al-4V alloys with the PPgNN method. (a) Architecture for fatigue analysis considering missing data; (b) Prediction comparison between model trained with missing data and model trained with complete data; (c) Sensitivity indicators for process parameters. Reprinted with permission from Chen et al. [226] (Copyright (2021) Elsevier).

time-consuming and high cost of the test process. If the challenges such as data volume, defect identification, blade structure, and load characteristics can be solved, ML is expected to become a powerful tool for the efficient and accurate prediction of fatigue properties of AM repaired aero-engine blades.

4.3. Fatigue evaluation considering the operational environment of compressor blades

The complex operational environment of compressor blades poses a huge challenge to the prediction of fatigue properties. Byrne et al. [228] identified two states of crack propagation in compressors. The first type is the LCF mode dominated by centrifugal force, where the influence of HCF related cycles on crack propagation is minimal, and the crack propagation speed can be ignored.

The second is that LCF driven cracks propagate to a certain extent, causing the SIF under resonance conditions to be greater than the threshold, and HCF driven cracks continue to propagate.

The complex operational environment of the compressor makes it impossible to monitor the crack initiation and propagation of the blade during service. Numerical simulation is an important means of fatigue prediction and evaluation [229] but with low accuracy. Zhu et al. [230] adopted the Chaboche plastic model and the Fatemi-society criterion to establish a method for fatigue life prediction and reliability assessment of 950X steel turbine disks, based on the probabilistic framework for multi-axis LCF evaluation of notch components and the combination of finite element simulation with engine load spectrum. Wang et al. [231] studied the crack growth behavior of the FV520B-I blade under centrifugal and

aerodynamic loads, as well as the stress distribution and fatigue life at the critical position, and established the fatigue life evaluation model of the blade. However, there are too many simplifications in the process of numerical calculation, resulting in a large difference between the simulation loads and the in-service condition.

In fact, fatigue evaluation of AM compressor blades considering in-service loads is very rare. Qu et al. [232] predicted the fatigue crack growth life of the SLM Ti-6Al-4V compressor impeller considering the comprehensive influence of AM residual stress and external load. However, they only studied the fatigue crack growth life at the start-up and stop stages, which is a relatively harsh load condition. Although the randomness of the simulation under such conditions is very small, it only covers a small part of the aero-engine operating conditions.

At present, deterministic life prediction methods for complex operating conditions [233] and specific load spectra [234] have been developed, which have been applied to predict the fatigue failure of compressor impellers. The microstructure, residual stress, and manufacturing defects of AM process make it difficult to predict the fatigue crack initiation and propagation of AM repaired compressor blades. Therefore, the fatigue evaluation method of AM aero-engine blades considering in-service operating conditions and AM characteristics still needs to carry out a lot of research and verification work to ensure the safety of use.

5. Summary and outlooks

In summary, we have introduced the application of AM in the repair of aero-engine blades and presented a comprehensive overview on the latest progress of the influencing factors on fatigue behavior of AM parts and predicting fatigue properties of AM repaired blades by various methods.

(1) The repair technology used for aero-engine blades has gradually changed from grinding repair to AM repair. Grinding can deal with small-scale damage, and reduce the stress concentration in damaged areas, but the grinding gap remains as the source of fatigue cracks. In addition, grinding cannot restore blade shape, which certainly affects the aerodynamic performance of the compressor. AM repair can cover the shortage of grinding and restore the blade shape, but it introduces a residual stress field during hot processing and causes differences in the structure of the repaired area and the matrix, affecting the mechanical properties and fatigue performance of the blade. Many cases of AM repaired

blades showed that AM process still has to go a long way before it could replace grinding in repairing aero-engine blades, and there are some key problems to be solved including the control of material structure, AM defects, and residual stress.

- (2) The inherent properties of AM process such as microstructure, manufacturing defects, surface roughness, residual stress as well as their complex interactions make the fatigue crack initiation and propagation behavior of AM processed parts very complicated. Among them, LOF and porosity defects have the greatest impact on the fatigue performance of AM parts, while the effect of residual stress is not significant. Some post-treatments could effectively weaken the influence of AM defects. For example, HIP can close pores, M&P can improve surface roughness, and annealing can eliminate residual stress and regulate microstructure. But it should be noted that some post-treatments are not applicable engineeringly. The evolution characteristics and interactions of inherent properties of AM processed blades still show significant impacts on the fatigue performance under service conditions although considerable efforts have been made in the research of FCG behavior and fatigue properties of AM processed parts in recent years. This should be the focus to be studied to promote the application of AM repair in engineering. Conversely, the study can also provide help for the damage tolerance design of AM processed blades.
- (3) The evaluation of fatigue strength of AM processed blades started from fracture mechanics and focused on the size, shape, and location of AM defects. The breakthrough in the characterization and evaluation technology of AM defects supported the development of fatigue evaluation. However, current fatigue prediction models (regardless of prediction for fatigue limit or fatigue life) are limited to fitting or dimensional image correlation with fatigue test results, generally based on phenomena and laws among physical parameters, lacking in-depth research on the physical mechanism of fatigue damage of AM parts. It can be foreseen that further study on AM defects evolution and interaction under in-service loads will improve the accuracy of fatigue evaluation for AM processed blades. With the development of computing technology, big data, and machine learning methods will have more applications in the field of fatigue evaluation for AM processed blades, and gradually become important means to ensure the structural strength and reliability of AM parts.

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Disclosure statement

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Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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