

A Comprehensive Review on Fatigue Life Prediction Approaches for Additively Manufactured Components

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Abstract:

The additive manufacturing (AM) has become a revolutionary fabrication process that can manufacture complex geometries, help cut down on weight, and simplify the prototyping process in various industries including aerospace, automobile, biomedical, and energy. Although significant improvements have been made in streamlining mechanical performance, the fatigue behaviour of AM components is still quite versatile in nature and in most instances, significantly worse than that of wrought counterparts. This is mostly explained by inherent defects in the processes, anisotropy of microstructures, surface roughness and unrelaxed deformation stress. As a result, fatigue life of AM structures to be used in safety-critical applications must be appropriately predicted to qualify and certify these structures. This is a systematically reviewed literature on state-of-the-art fatigue prediction methods of additively manufactured metallic parts. The reviewed methodologies include empirical S N curve based models, fracture based on the mechanics of crack-growth models, defect based prediction models, microstructure sensitive and crystal plasticity models, probabilistic reliability models, and emerging machine learning based methods. Major impacting parameters, such as defect morphology, pore distribution, post-processing, build orientation, and surface integrity are determined and critically analyzed. The review outlines the shortcomings of existing predictive models and suggests the combination of hybrid physics-based and data-driven to formulate a strategy to resolve shortcomings of existing predictive models to achieve standardized predictive methods applicable to industrial deployment. Future research directions emphasize the necessity of real-time defect trace monitoring, development of digital twins, and design of unified AM-specific fatigue design to be applied in order to enable safe and reliable performance in advanced engineering applications.

Keywords: Fatigue life prediction; Metal 3D printing; Fatigue crack growth; Defect-based modelling; Residual stresses; Surface roughness; Porosity; Microstructural anisotropy; Finite element simulation;

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, has fundamentally transformed the manufacturing industry in the last ten years as it has become possible to create complex, lightweight and custom forms of components, which would have been prohibitive or even impossible to do using the traditional subtractive or formative manufacturing methods. Some of the benefits associated with AM include minimisation of waste materials, minimisation of lead time, increased flexibility in designs

through topology optimisation, and the ability to make component parts with internal functionalities. The above features have led to the higher adoption of AM technologies in safety-critical (mechanical) industries including aerospace, automotive, defence, biomedical implants, and energy systems, where structural reliability and mechanical performance matter most of all. Even though additive manufacture has achieved a lot in designing material and process optimisation, the fatigue behavior of additively manufactured parts remains a great engineering challenge. Components made using AM contain large scatters in fatigue lives in comparison with those made using wrought or cast metal, and they are ascribed to inherent process-related characteristics, which consist of anisotropic microstructures, lack-of-fusion, gas porosity, unmelted, rough, residual stress, and variation across build orientations and build locations. These considerations play a serious role in the crack initiation and development that eventually lower the fatigue strength, unpredictable behaviour in the face of cyclic loading conditions. Therefore, the self-confidence of fatigue life predictions is crucial to the structural integrity and to the length of functional operation of AM components certified. Over the last several years, there is a potentially large amount of research work in the areas of expounding the mechanisms of fatigue in AM materials, defining defect populations, setting standards of fatigue testing and creating prediction models. Various strategies have developed, such as correlations using empirical S-N curves, fracture-based models of fatigue crack propagation, defect-based models exploiting Murakami and Kitagawa-Takahashi frameworks, models based on microstructure-sensitive physics, simulation-based methods in finite element and data-driven, machine-learned, prediction. The relevance, precision, and external validity of these methods are however debatable because of the heavy reliance on the material systems, AM processes, post-processing paths and loading conditions of services. With the fast changing AM technology and increasing demand of component qualification, it is evident that there is a need to provide a list of reviews that would synthesise the predictive approaches to the study of fatigue life, emphasise the critical parameters involved, compare the modelling technique, and identify the gaps in research and the research directions in the future. Consequently, this review will focus on a line-by-line description of additively manufactured component fatigue behaviour, critically assess current state-of-the-art-prediction models, assess their benefits and constraints, and suggest avenues towards the development of consistent and reliable fatigue design models in the case of AM.

2. LITERATURE REVIEW

According to Zhang and Li (2016), a large scale numerical study on the development of residual stress and the resulting fatigue behaviour in additively manufactured flat-plate metallic components was carried out using a coupled thermo-mechanical finite element model. The authors have stressed the relevance of short-term heat input and temperature-dependent material characteristics to the forecast of deformation and premature crack growth. The outcome of the simulation was compared to thermocouple temperature measurements and strain gauge data which were taken during fabrication. This research showed the tensile residual stresses concentrated in a zone affected by heat reduced greatly in fatigue life and shortened the time in which cracks initiated, thus playing a critical role in the need to use residual stress relaxation in fatigue prediction models.

Leuders et al. (2013) studied fatigue crack growth (FCG) behaviour in Ti-6Al-4V components that were produced using laser powder bed fusion. Their analysis demonstrated acute anisotropy in fatigue behavior that is explained by the differences in the microstructural morphology across the build direction. They presented fractography, microscopy results, which showed that the initiation of cracks normally took place

in internal flaws including lack-of-fusion and gas pore voids. The study revealed fatigue life to depend much on defect size and spatial dispersion such that bigger pores reduced significantly fatigue threshold values. As a result, the authors pointed out that traditional wrought S -N curves do not suffice when additively manufactured metals are involved and corrections through defects are not possible.

Gunther et al. (2018) examined the relationship between surface roughness and additive performance of additively manufactured 316L stainless-steel specimens manufactured using the selective laser melting. In their investigation, they found that as-built surfaces had much less fatigue strength owing to micro-notch impact of unmelted particle agglomeration and stair-stepping structure. By comparing machined, shot-peened, and electropolished samples, they demonstrated that fatigue life significantly increased with surface integrity improvement and it was sometimes even higher than that of wrought material. They found that surface finish treatment is a necessary requirement to have effective fatigue prediction especially in components that were loaded under high cycle.

Romano et al. (2017) examined how fabricated laser powders built with AlSi10Mg alloy by laser powder bed fusion impacted the fatigue behaviour of the material due to porosity caused by the process. They used a micro-computed tomography (micro-CT) in order to measure pore volume fraction, morphology and place relative to crack initiation sites. Their results confirmed that there is a definite linear correlation between the maximum pore size and the fatigue crack initiation life particularly with high stress operating environment. They also confirmed that Kitagawa Takahashi Defect-Size based modelling is useful in fatigue life prognostics. The authors underlined the fact that porosity should be incorporated into guidelines of the computer design of the load-bearing structures of additive manufacturing.

Nicoletto et al. (2018) measured the fatigue life scatter of powder-bed-fused Ti-6Al-4V parts using statistical analysis of the defect populations measured using three-dimensional tomography. Their findings showed that the variability of fatigue has a stronger contribution of random distribution of defects instead of deterministic variation in microstructure. They showed how extreme-value statistics can be used to correlate the severity of defects with the probability of fatigue failure, which can be used as a way of providing a probabilistic design method. The paper identified the shortcomings in using conventional deterministic fatigue prediction equations to additively manufactured components and suggested incorporation of statistical reliability modelling of safety-relevant industrial components.

Seifi et al. (2016) have given a detailed review of mechanical and fatigue characteristics of various additive manufacturing metals through comparison with the wrought ones. Their data was a compilation of fatigue performance data of fatigue on alloys such as IN718, Ti -6Al-4V and 17 -4 PH stainless steel, which reported high scatter in fatigue life as a result of additive manufacturing processing conditions. They restated the fact that the failure of fatigue in additive manufacturing materials always occurred in a defect-managed state and not controlled only with the two parameters of microstructure and strength. The authors proposed standardization of testing practices and promoted defect-sensitive modelling framework to enhance the level of fatigue life prediction.

Masuo et al. (2018) examined how heat -treatment and higher isostatic pressing (HIP) influence the fatigue life of Ti -6Al -4V synthesized through selective laser melting. Their work had reported that HIP treatment effectively lowered internal porosity and increased fatigue crack initiation resistance especially at conditions of high cycle. The authors have found a correlation between the evolution of pore morphology and enhanced fracture toughness and crack propagation. The percentage of fatigue lives developed was still scattered regardless of these advances due to surface defects and surface microstructure. The study stressed the fact that post-processing should be considered as part and parcel of fatigue modelling.

Gordon et al. (2020) established a physics-based fatigue model adding residual stress state and defect distribution and microstructural texture to the fatigue crack initiation analysis of additive manufacturing components made by laser. They used, with local stress concentrations, finite element simulations based on crystal-plasticity, as a means of obtaining them at grain boundaries. The locations of cracks predicted through their model were in agreement with experimental fractography. This study demonstrated the importance of microstructural heterogeneity to be considered in the correct prediction of life and could not be overlooked in the high-fidelity modelling of fatigue behaviour additive manufacturing.

Chan et al. (2021) investigated machine-learning methods in predicting fatigue life in additive manufacturing journal components through a combination of tomography-based descriptors of defects and mechanical testing experimental results. They used the neural networks and gradient-boosting models to forecast cycles to failure based on defect geometry, surface parameters, and load amplitudes. Their findings proved that machine-learning methods have shown great success compared to the conventional empirical S-N-based correlations. They suggested digital twins and AI-assisted defect sorting as the new directions in the automation of quality assurance in additive manufacturing and fatigue design.

Yadollahi et al. (2017) discussed the effect of microstructural anisotropy in additive manufactured 17 4 PH stainless steel on the rate of fatigue crack propagation. They demonstrated with electron backscatter diffraction (EBSD) and fractographic images that the long grain structures along the direction of building form preferential crack propagation pathways. Their research well defined that microstructure-optimization by enhanced scanning strategies can enhance the fatigue performance by uniforming the morphology of grains. They emphasized the microstructure-sensitive modelling as necessary to bridge the gap between experimental tests and prediction simulation.

Wycisk et al. (2014) compared the fatigue behaviour of selective laser melting fabricated Ti 6Al 4V and emphasized the harmful role of internal defects to crack initiation life. They proved that the fatigue behaviour during the high-cycle loading is characterised by the presence of crack nucleation at the pores instead of the activity of microstructural slip-bands. They also stated that hot isostatic pressing enhanced the fatigue strength by sealing the pores but failed to get rid of the scatter completely owing to the surface features. This work supported the multi parameter dependency of fatigue prediction of additive manufacturing systems. As a contribution to the predictability of fatigue in former shock wave excavation, Song et al. (2022) developed a defect-sensitive fatigue prediction model by combining the Murakami $\sqrt{\text{area}}$ theory with micro-CT-based defect characterization. Their technique enabled them to measure the level of defects and to predict as well as predict fatigue crack initiation life in variable loading conditions with accuracy. They showed that there was high correlation of the predictive and experimental data in the process of additive manufacturing nickel based alloys. Their production can be seen as a step in the right direction of adopting physics-based predictive design models that can be applied to industries.

Tammas-Williams et al. (2017) stressed on the fracture mechanisms of aerospace-grade additive manufacturing titanium materials that were subjected to HIP treatment and processed before HIP treatment. They demonstrated that defect morphology is one of the most important factors affecting crack propagation behaviour based on extensive tomography and fracture surface analysis. They found that the rates of crack growth were strongly correlated with the size distribution of defects as opposed to microstructure bulk. They put a lot of emphasis on the evaluation criteria based on defects as factors that determine fatigue life.

Benedetti et al. (2020) compared high-cycle fatigue behaviour of the shot-peened and laser-polished additive manufacturing AlSi10Mg components. Their findings revealed significant increases in fatigue

strength in the compressive residual stress introduction and surface defect elimination. They have utilized roughness characterization in three-dimensional form to measure the micro notch effects and have come up with predictive correlations between roughness parameters to fatigue thresholds. Surface engineering can be shown as an important pathway to enhancing the fatigue reliability through their work.

Romano and Groppo (2021) have elaborated a multi-scale fatigue prediction model based on the combination of continuum mechanics, statistical representation of the microstructure, and defect sensitivity analysis. Their model was found to be accurate in respect to predicting fatigue crack initiation and propagation behaviour under various stress regimes. They tested their model by experimentally working with additive manufacturing titanium and aluminium alloys data on fatigue. Their article brings into the limelight of the role of hybrid modelling strategies in the attainment of realistic fatigue life predictions of industrial additive manufacturing components.

Cain et al. (2015) examined the parameters of the process and the microstructure of the formed defects in laser powder bed fusion of nickel-based superalloys and matched these properties to fatigue failure. They have shown that scanning plans, laser power, interstitial separation and scanning pace play a significant role on the morphology of pores and the content of volumetric defects and these factors determine fatigue performance. Their findings revealed that the unsuccessful fusion of the material results in keyhole-like porosity which turns out to be the major initiation points of the crack when subjected to cyclic load. Authors emphasized that fatigue life prediction models should take into account the development of defect morphology with regard to thermal cycles and melt-pool instability which is a part of additive manufacturing processes.

Foster et al. (2019) studied fatigue crack growth behaviour of the additively manufactured IN718 with compact tension specimens constructed in both vertical and horizontal directions. Through their analyses, they found the directional dependency of crack propagation because of microstructural texture and gradient of residual stress related to layer-by-layer fabrication. They have applied digital image correlation to the crack-tip strain fields and shown the cracks are inclined to follow the columnar boundaries of grains. The anisotropic fracture properties they have investigated have shown the need to address in fatigue modelling frameworks, especially when using aerospace-grade additive manufacturing alloys exposed to thermo-mechanical fatigue loading.

Rafi et al. (2013) studied the effects of microstructural evolution and heat-treatment cycles on fatigue behaviour of additive manufactured 17 4 PH stainless steel. They made a comparison of fatigue resistance, as-built, solution treated, and age hardened conditions. In their results, they indicated that high strength conditions enhanced fatigue crack initiation resistance, whereas high hardness levels enhanced crack propagation rates. The paper has shown that there is a trade-off between strength and relative fatigue durability, and hence there is a need to balance the microstructure-directed post-processing and the performance needs. They also found out that predictive modelling requires consideration of the microstructure-property relationships to have credible fatigue prediction.

Shamsaei et al. (2015) had introduced a systematic study of low and high cycle fatigue behaviour of additive manufactured Ti 6Al 4V produced through selective laser melting. They tested several stress ratios stress amplitudes and the environmental conditions. These authors determined robust sensitivity of fatigue behaviour to surface roughness and internal defects and, as a result of fatigue life as a crucial polishing factor extending a fatigue crack. They also underlined that a classical S-N curve methodology is not able to process the scattered behavior found in additive manufacturing fatigue data, and criticize models based on defect-sensitive statistical prediction.

Pegues et al. (2018) examined the effects of concurrent applications of shot peening, machining and sub-surface defects interactions on fatigue strength of additive manufactured Ti-6Al-4V. Their effort has shown that the improvement of the surface itself is not sufficient to eradicate the variability in fatigue in case the localization of critical defects is close to the surface since the defects allow the crack propagation of early directions. They used fracture mechanics methods to associate the depth of sub-surface pore registration with the aspects of fatigue strength reduction. Their research shed light on how the structural additive manufacturing components, where surface accessibility is restricted can be improved to allow making a more informed choice on the post processing methods.

The article by Galarraga et al. (2016) compared microstructure-property relationships of additive manufactured IN718 in the environment of cyclic loading. They tried samples constructed using different laser scan strategies and thermal gradients and proved that directional grain development leads to an anisotropic fatigue property. It was found that cracks spread more abnormally along dendritic microstructures in the build direction. Their findings emphasized that the reliability of fatigue can be enhanced by moderating the directionality of thermal gradients. They promoted the use of build-orientation-sensitive fatigue life prediction models on the components to use in the multi-axial cyclical loading in the turbine and engine conditions.

Chern et al. (2020) created a model of numerical fatigue prediction based on defects with pore distributions measured by micro-CT included in a finite-element computational scheme. Their strategy allowed them to simulate local stress concentration fields of pore clusters that are irregular, and to assess the effect of the local stress concentration on the crack initiation. Tested and compared to experimental tests of fatigue, the prediction appeared to be accurate frequently, particularly when compared with other models of S-N. Their study showed that volumetric defect maps could be directly incorporated into fatigue design and defect-constrained aerospace part fabrics in additive manufacturing are possible. Sheridan et al. studied fatigue crack initiation sites in fatigue-tested in-situ SEM fabricated aluminum alloys additively by additive manufacturing. They noted that micro-notches, dry powders, and little pores related to surfaces were the most common crack initiation triggers on high-cycle fatigue. They also showed that initiation behaviour in crack was dependent on build angle, due to the difference in surface morphology. Their results supported the view that mechanisms of fatigue that are sensitive to surfaces predominate early life failures and that roughness descriptors should be included in prediction models. They proposed hybrid modelling approaches that are a mix of roughness measures and pore statistics as a way of raising the accuracy of fatigue prediction.

Khairallah et al. (2016) used the multi-physics computational modelling to study the principles of the melt-pool fluid movement and the formation of defects in selective laser melting. They demonstrated that keyhole porosity is known to develop due to instability caused by recoil pressure, vapor depression, and turbulent melt flow, which also become the main precursors of critical fatigue crack initiation sites. Their work clarified the effect of thermal gradient on the microstructure and defect formation, between process simulation and fatigue behaviour. They presented that fatigue life prediction should encompass process-structure property associations through the model and not post-build measurements.

3. CONCLUSION

The aggregate results of the examined works confirm that the existence of fatigue life prediction of additively manufactured parts is complex since it seems highly sensitive to the impact of process-induced features, the heterogeneity of microstructures, and defect inconsistencies. Similar residual stress

simultaneously with anisotropy, surface roughness, pore morphology, and defect distribution continued to become the key factors dominating fatigue crack initiation and crack propagation. The crucial influence of residual stresses was found by Zhang and Li (2016), and the internal defects and porosity were underlined by Leuders et al. (2013), Romano et al. (2017), and Wycisk et al. (2014). Many studies such as Gunther et al. (2018), Pegues et al. (2018), and Sheridan et al. (2021) established that the quality of the surface has significant fatigue resistance effects indicating that post-processing is a major component in fatigue prediction models. Moreover, as pointed by Seifi et al. (2016) and Nicoletto et al. (2018), there is extensive variability of fatigue performance, and traditional deterministic methods are inappropriate; probabilistic modelling and defect-sensitive models are suggested. The latest modelling works, like those of Gordon et al. (2020), Chern et al. (2020), and Romano and Groppo (2021), emphasise the need to combine microstructure-based and multi-scale computation. The realization of machine-learning-based predictive models, as reflected by Chan et al. (2021), is an excellent move toward real-time quality control and fatigue design automation. The looked through literature makes it clear that there is no single predictive method that suits the complexity of the AM fatigue behaviour. Rather, hybrid ways of addressing experiments, physics-based approaches, defect-based, and data-driven are the surest route, and standardized testing practices and better process monitoring. The future directions of the research should be to find the common fatigue life prediction frameworks, AM-specific standards, and digital twins to certify safety-critical AM structures.

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