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Development of a novel fatigue damage model with AM effects for life prediction of commonly-used alloys in aerospace

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Abstract: In the aerospace industry, more and more alloy parts with requirements of complex geometry and light weight are fabricated by additive manufacturing (AM) process, which has significant influence on their high-cycle fatigue properties. However, so far no work has been done to predict fatigue life of AM alloy parts through the damage mechanics based method. In this paper, a novel fatigue damage model with AM effects is proposed to address the issue, in which laser power, scan speed, hatch spacing and powder layer thickness are integrated in terms of the volumetric energy density, and the material parameters are calibrated with reported experimental data for the damage-coupled elastoplastic constitutive equations. After that, a good agreement is achieved numerically between the present theoretical model and published experimental results. Then the three most commonly-used alloy (SS316L, Ti6Al4V and AlSi10Mg) parts fabricated by AM process are studied in detail to investigate their several important characteristics, including the variation of fatigue life with the volumetric energy density, the variation of damage evolution rate with fatigue life subject to different volumetric energy densities, the relations between Young's modulus and fatigue life, and so on. Finally, several recommendations are presented for selection of the commonly-used AM alloy parts in aerospace, based on the engineering requirements and economy consideration.

Keywords: Additive manufacturing; Fatigue damage model; Aerospace alloy parts; Life prediction; Damage mechanics.

1. Introduction

Compared with traditional manufacturing techniques, additive manufacturing

(AM) can offer many benefits, such as the flexibility of design, effective use of resource, and reduction of energy consumption [1]. Recently, more and more aerospace industrial alloy parts are manufactured by AM technology [2-4] due to high requirements, such as complex geometry, light weight and lower cost and so on. In particular, the alloy parts manufactured by AM are subjected to fatigue loads, such that their fatigue damage and thus failure become common phenomena. Therefore, it is really important to develop a model for fatigue life prediction of alloy parts manufactured by AM for aerospace application.

A good literature review reveals that most studies on the fatigue of AM alloy parts were experimental-based work, and few of them by theoretical fatigue-life prediction. Since TiAl6V4, SS316L and AlSi10Mg are the most commonly-used alloy materials in aerospace industry, a lot of relevant studies were conducted. For example, the TiAl6V4 alloy parts produced by AM were studied for the influences of porosity, defects and processing parameters on fatigue properties [5-11]. Regarding AM SS316L alloy parts, analysis of the relationship between AM processing parameters and fatigue/fracture behaviors was carried out [12-14], with comparison of conventional materials [15]. In terms of AlSi10Mg alloy parts produced by AM, the effects of AM processing parameters were tested on mechanical properties and fatigue behavior [16-19].

Currently many methods are applied for fatigue life prediction of alloy parts. However, each of them has advantages and disadvantages. For example, the experimental-based statistical method needs a lot of data. On the basis of the fatigue characteristic curve of materials, the local stress-strain approach [20-21] is often used to compute the fatigue life of structures subject to simple fatigue loading conditions. The widely-used critical plane method [22-23] adopts a semi-empirical formula involving fatigue damage parameters, in which the meanings of damage parameters are not clear physically. Furthermore, some damage sensitive models are also developed. For example, the microdefect closure effect [24] is considered by the continuum damage mechanics (CDM) model, while the load history effect included

by the nonlinear damage model [25] on the basis of the S–N curve. The cumulative damage model [26] is proposed for low cycle fatigue life prediction of annealed low carbon steel, while a two-scale damage model [27] presented for high cycle fatigue. In terms of various material properties, different damage sensitive models are developed, for example, the ductile plastic damage model [28] for metal ductile fracture, the visco-plastic damage model [29] for the metal fatigue failure with the ratcheting effect, the creep damage model [30] for the parallel planar crack growth, and the anisotropic damage model [31] for the fatigue behavior of plain concrete.

In addition to the above damage sensitive models for fatigue analysis, the fracture mechanics approach [32-33] is also employed to analyze the fatigue crack propagation from an initial crack or defect, but it doesn't work well on the crack initiation life prediction. Furthermore, using damage variables to characterize the deterioration process of material properties, the continuum damage mechanics (CDM) theory based technique [34-36] is widely employed for fatigue life prediction in practical engineering application. Therefore, this approach is adopted here to analyze the fatigue damage and predict the fatigue life of alloy parts fabricated by AM process.

In this paper, a novel fatigue damage model with effects of AM process is developed to predict fatigue life of the commonly-used alloy materials in aerospace, in which the AM process parameters, including the laser power, the scan speed, the hatch spacing and the powder layer thickness, are integrated in terms of the volumetric energy density. The elastoplastic constitutive equations with damage are derived, and the novel fatigue damage model is formulated first with effects of AM process. The material parameters in the theoretical models are then calibrated, and the numerical algorithm is presented for fatigue life prediction of AM alloy parts. After that, the fatigue lives of alloy parts fabricated by AM process are predicted and the novel fatigue damage model is validated by the experimental results. Finally, three most commonly-used alloy (SS316L, Ti6Al4V and AlSi10Mg) parts fabricated by AM process in the aerospace industry are studied in detail to investigate several

important characteristics, and several recommendations are made for selection of the AM alloy parts based on the engineering requirements and economy consideration.

2. Theoretical models

In this section, two types of theoretical models are presented in order to apply the CDM-based method for fatigue life prediction of AM alloy parts.

2.1 Formulation of elastoplastic constitutive model with damage

By the CDM [37-38] theory, the damage of material results from the formation and growth of micro holes or cracks, and the damage variable is often used to describe the degradation of material properties. In the engineering application, the representative volume element (RVE) is employed to represent the mechanics of a continuous media and the material properties are homogenized within RVE. For isotropic materials, the stiffness degradation of RVE represented by damage variable D is given by

$$D = \frac{E - E_D}{E} \quad (1)$$

in which E represents the Young's modulus of material without damage, and E_D the Young's modulus with damage.

For the small deformations, the total strain ε_{ij} is shown as

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p \quad (2)$$

where ε_{ij}^p is the plastic strain, and ε_{ij}^e is the elastic strain, namely

$$\varepsilon_{ij}^e = \frac{1+\nu}{E} \left(\frac{\sigma_{ij}}{1-D} \right) - \frac{\nu}{E} \left(\frac{\sigma_{kk} \delta_{ij}}{1-D} \right) \quad (3)$$

in which ν is Poisson's ratio and σ_{ij} represents stress component. The plastic strain rate is in the form of

$$\dot{\varepsilon}^p = \dot{\lambda} \frac{\partial f}{\partial \sigma_{ij}} \quad (4)$$

where $\dot{\lambda}$ is plastic multiplier and f von Mises yield function. The kinematic hardening behaviour of material is represented by Chaboche nonlinear model [39],

and the damage-coupled yield function is shown below

$$f = \sqrt{\frac{3}{2} \left(\frac{S_{ij}}{1-D} - \alpha_{ij} \right) \left(\frac{S_{ij}}{1-D} - \alpha_{ij} \right)} - Q \quad (5)$$

where S_{ij} is the deviatoric stress, and α_{ij} the deviatoric back stress expressed by

$\alpha_{ij} = \sum_{k=1}^M \alpha_{ij}^{(k)}$. Q represents the radius of yield surface, as defined by

$$\dot{Q} = \lambda b (Q_{\infty} - Q) \quad (6)$$

in which b and Q_{∞} are the material parameters. The plastic strain rate $\dot{\epsilon}^p$ [37], the accumulated plastic strain rate $\dot{p}$ and the rate of the deviatoric back stress $\dot{\alpha}_{ij}$ are obtained by

$$\dot{\epsilon}^p = \frac{3}{2} \frac{\dot{\lambda}}{1-D} \frac{S_{ij} / (1-D) - \alpha_{ij}}{(S_{ij} / (1-D) - \alpha_{ij})_{eq}} \quad (7)$$

$$\dot{p} = \sqrt{\frac{2}{3} \dot{\epsilon}_{ij}^p \dot{\epsilon}_{ij}^p} = \frac{\dot{\lambda}}{1-D} \quad (8)$$

$$\dot{\alpha}_{ij}^{(k)} = (1-D) \left(\frac{2}{3} C_k \dot{\epsilon}_{ij}^p - \gamma_k \alpha_{ij}^{(k)} \dot{p} \right) \quad (9)$$

in which C_k and γ_k are material parameters.

2.2 Formulation of novel fatigue damage model with effects of AM process

In the case of uniaxial cyclic loading, the fatigue damage evolution equation is given by [40]

$$\dot{D} = \frac{dD}{dN} = [1 - (1-D)^{\beta+1}]^{\alpha} \left[\frac{\sigma_a}{m(1-n\sigma_m)(1-D)} \right]^{\beta} \quad (10)$$

where N is the number of cycles and σ_a is stress amplitude during one loading cycle.

α, β and m are material parameters.

For most of the practical engineering applications, usually the multiaxial stress and strain states are common cases for structures and components. Therefore, the damage evolution equation under the multiaxial condition is presented below [41]

$$\dot{D} = \frac{dD}{dN} = [1 - (1-D)^{\beta+1}]^{\alpha} \left[\frac{A_{II}}{m(1-n\sigma_{H,m})(1-D)} \right]^{\beta} \quad (11)$$

in which A_{II} represents the amplitude of octahedral shear stress, given by

$$A_{II} = \frac{1}{2} \left[\frac{3}{2} (S_{ij,\max} - S_{ij,\min}) \cdot (S_{ij,\max} - S_{ij,\min}) \right]^{1/2} \quad (12)$$

where $\sigma_{H,m}$ represents the average hydrostatic stress by

$$\sigma_{H,m} = \frac{1}{6} (\sigma_{kk,\max} + \sigma_{kk,\min}) \quad (13)$$

In Eqs. (10) and (11) for the conventional uniaxial and multiaxial fatigue damage evolution through the fatigue damage computations of metal parts [40-41], no item is associated with the AM processing parameters, such that they are not suitable to predict the fatigue life of AM alloy parts. As well known, the AM processing is determined by several parameters including the laser power p , the scan speed v , the hatch spacing h , and the layer thickness t [6, 10, 13, 42-43], which have significant influence on the porosity, manufacturing defects and microstructures [5, 7-8], and thus on the fatigue behavior of AM alloy parts. In general, the fatigue life of AM parts may increase with the increase of the laser power p [12], while the fatigue properties may decrease as the scan speed v and the layer thickness t increases [13]. Furthermore, the manufacturing pores and defects during AM process may increase the stress concentration and thus decrease the fatigue life. Therefore, in order to include the influence of the AM processing parameters on the fatigue life of printed alloy parts, the volumetric energy density R_E due to AM processing is integrated into the fatigue damage evolution equations (10) and (11), and they are thus modified as Eqs. (14) and (15) below.

For the condition of uniaxial fatigue,

$$\dot{D} = \frac{dD}{dN} = [1 - (1 - D)^{\beta+1}]^{\alpha} \left\{ \frac{\sigma_a [1 + \Delta(E_d, E_{d0})]}{m(1 - n\sigma_m)(1 - D)} \right\}^{\beta} \quad (14)$$

For the condition of multiaxial fatigue,

$$\dot{D} = \frac{dD}{dN} = [1 - (1 - D)^{\beta+1}]^{\alpha} \cdot \left\{ \frac{A_{II} [1 + \Delta(E_d, E_{d0})]}{m(1 - n\sigma_{H,m})(1 - D)} \right\}^{\beta} \quad (15)$$

where $E_d = p / (vht)$ is the volumetric energy density, p the laser power, v the scan speed, h the hatch spacing, and t the layer thickness. E_{d0} presents a reference

volumetric energy density for the AM parts with the minimum porosity [13, 42]. The term $\Delta(E_d, E_{d0}) = |1 - R_E|^{3R_E}$ is proposed for AM effect, in which $R_E = E_d / E_{d0}$ is called the ratio of volumetric energy density. This new term not only ensures the dimensionless consistency, but also physically reflects the relationships between the fatigue behavior and the AM processing parameters. For example, the increasing rate of damage of AM parts with the minimum porosity is the slowest subject to fatigue loading, if the volumetric energy density R_E is equal to the reference volumetric energy density E_{d0} . However, the increasing rate of damage becomes faster and the fatigue life of AM parts shorter, when the volumetric energy density R_E is much smaller than the reference volumetric energy density.

For the condition of constant stress, the fatigue life or the number of cycles is computed by integrating Eqs. (14) and (15) from $D=0$ to $D=1$.

For the condition of uniaxial fatigue,

$$N_f = \frac{m^\beta}{(1-\alpha)(1+\beta)} \left\{ \frac{\sigma_a [1 + \Delta(E_d, E_{d0})]}{(1 - n\sigma_m)} \right\}^{-\beta} \quad (16)$$

For the condition of multiaxial fatigue,

$$N_f = \frac{m^\beta}{(1-\alpha)(1+\beta)} \left\{ \frac{A_H [1 + \Delta(E_d, E_{d0})]}{(1 - n\sigma_{H,m})} \right\}^{-\beta} \quad (17)$$

3. Validation of novel fatigue damage model

Recently many experimental investigations were conducted on the fatigue behaviour of the three most commonly-used alloy (SS316L, Ti6Al4V and AlSi10Mg) parts fabricated by AM process in the aerospace industry. In this section, the novel fatigue damage model is validated by experimental results of alloy parts fabricated by AM process.

3.1 Calibration of material parameters

In this sub-section, the material parameters are calibrated for the theoretical model. The material parameters in elastoplastic constitutive equations are calibrated on the basis of uniaxial tensile experimental data. In the present work, the isotropic hardening isn't considered. However, the nonlinear kinematic hardening behaviour of

material is represented by three components of back stress, as expressed below

$$\sigma = \sigma_y + \sum_{k=1}^3 \frac{C_k}{\gamma_k} (1 - e^{-\gamma_k \epsilon_p}) \quad (18)$$

where σ_y is the initial yield stress. Material parameters C_k and γ_k are determined by the least squares approach, and the calibrated results for the three different materials are listed in Table 1.

In terms of the material parameters (α, β, m, n) in the novel fatigue damage model, the two parameters β and n , and the integral item of $m^\beta / [(1-\alpha)(1+\beta)]$ in Eqs. (16) and (17) are calibrated, according to the fatigue test data of smooth parts by the least squares approach. After that, the two parameters α and m are numerically determined based on the CDM–finite element scheme [44-45]. For the given material, constant α , β and n are assumed, while m varies with the AM process parameters. Based on the published experimental results, the calibrated parameters are listed in Table 1 for SS316L [12], Ti6Al4V [10], and AlSi10Mg materials [46].

Table 1 Calibrated parameters for SS316L, Ti6Al4V, and AlSi10Mg.

Material	C_1	C_2	C_3	γ_1	γ_2	γ_3	α	β	m	n
SS316L	119280	14504	1955	2840	259	23	0.98	2.935	9685	0.00124
Ti6Al4V	143706	13908	3051	1671	183	25	0.92	1.932	26216	0.00182
AlSi10Mg	16910	4218	1665	178	74	15	0.88	3.82	1684	0.00053

3.2 Computational flowchart

In this sub-section, the computational flowchart is presented in order to predict fatigue life of AM alloy parts. The numerical simulation of elastoplastic constitutive model with damage and novel fatigue damage model subject to the effects of AM process are involved in the computational flowchart. The two theoretical models are implemented through the user-defined material subroutine UMAT on the ABAQUS platform. The computational flowchart is illustrated in Fig. 1 and detailed below.

Fig. 1 The computational flowchart for fatigue life computation of the AM alloy parts.

- (1) All the parameters are initialized and the initial damage of each element is set to 0.
- (2) The elastoplastic constitutive equations with damage are solved to obtain the stress field and strain field. In the following numerical simulation, the jump-in-cycles procedure [47] is used to save computation time. The damage increment with regard to the ΔN loading cycles is then computed,

$$\Delta D^{(i+1)} = [1 - (1 - D)^{\beta+1}]^{\alpha} \cdot \left\{ \frac{A_{II} [1 + \Delta(E_d, E_{d0})]}{m(1 - n\sigma_{H,m})(1 - D)} \right\}^{\beta} \cdot \Delta N \quad (19)$$

After that, the accumulated damage for each element is obtained by

$$D^{(i+1)} = D^{(i)} + \Delta D^{(i+1)} \quad (20)$$

- (3) In the case of the accumulated damage of any element reaching 1.0, the fatigue failure occurs, and the number of loading cycles at this stage is the corresponding fatigue life N_f . Otherwise, the material properties of all the elements are computed according to the accumulated damage, namely

$$\begin{cases} E^{(i+1)} = E^{(i)} (1 - D^{(i+1)}) \\ C_k^{(i+1)} = C_k^{(i)} (1 - D^{(i+1)}) \\ \gamma_k^{(i+1)} = \gamma_k^{(i)} (1 - D^{(i+1)}) \end{cases} \quad (21)$$

Correspondingly, the stress, strain and damage fields of structure are reanalysed until the accumulated damage reaches 1.0.

3.3 Comparisons for alloy parts fabricated by AM

3.3.1 SS316L alloy parts

In this sub-section, the fatigue lives of SS316L alloy parts subject to different maximum stresses are predicted numerically via the present novel theoretical model. The published experimental results reveal that the volumetric energy density $E_d=104.52 \text{ J/mm}^3$ produces the minimum porosity of 0.38% within the SS316L parts [42]. Therefore, this volumetric energy density E_d is used as the reference volumetric energy density E_{d0} in following numerical simulation.

The predicted results versus the experimental data are plotted in Fig. 2, in which the individual predicted results corresponding to the different ratios of volumetric energy density R_E are shown in Fig. 3 at $R_E = 0.25\sim 0.593$ and Fig. 4 at $R_E = 0.7\sim 1.5$, with the input given by the published experimental maximum stresses ranged from 200 MPa to 660 MPa and the ratios of volumetric energy density R_E from 0.25 to 1.5 [11-13, 45] for the fatigue tests of SS316L alloy parts conducted by a MTS testing system at ambient conditions with the stress ratio of 0.1. Fig. 2 demonstrates 122 sets of theoretically predicted data, where most of the predicted fatigue lives are obviously in consistent with the experimental results. However, the present fatigue damage model doesn't work well for the life prediction when the ratio of volumetric energy density R_E is lower than 0.5, as shown in Fig. 3(a-c), meaning that higher porosities or defects exist in the SS316L alloy parts fabricated by AM. In particular, it is observed that there are 13 sets of predicted data beyond the three-error bands. Probably there are three reasons for the 13 sets of predicted fatigue data lying out of the three-error bands. First, the dispersion of fatigue data exists, and it becomes more obvious when the ratio of volumetric energy density R_E is lower than 0.5. Second, the AM induced manufacturing defects inside the experimental specimens have negative effects on the fatigue life, and the multiple sources of cracks may occur at these defects. Third, the porosity of AM materials becomes higher, if the ratio of volumetric energy density R_E

lowers further. Therefore, the corresponding experimental fatigue lives become shorter than the predicted results, and thus they lay out of the three-error bands.

Fig. 2 The predicted life versus experimental life for SS316L alloy parts.

Fig. 3 Variation of the predicted life against experimental life subject to different ratios R_E : (a) $R_E=0.25$, (b) $R_E=0.333$, (c) $R_E=0.5$, (d) $R_E=0.593$.

Fig. 4 Variation of the predicted life against experimental life subject to different ratios R_E : (a) $R_E=0.7$, (b) $R_E=1$, (c) $R_E=1.3$, (d) $R_E=1.5$.

As well known, the AM process not only affects the fatigue life of AM alloy parts, but also the microstructure. A typical initial microstructure for the AM SS316L is shown in Fig. 5(a) [12], and the orientation of preparing test specimens by EDM wire cutting is shown in Fig. 5(b) [12], and it is along the same orientation of printing sample blocks on the build platform. In this experimental work [12], no post-processing heat treatment was conducted on the AM alloy parts, since the effect of post-processing heat treatment on fatigue properties may be negligible [12, 48-49], and the fatigue properties of SS316L are generally insensitive to the residual stress.

Fig. 5 (a) Microstructure of AM SS316L, (b) the orientation of sample blocks on the build platform and preparation of test specimens by EDM wire cutting [12].

As mentioned above, the AM process has significant influence on the microstructure of SS316L materials [50-53], including the porosity, inclusion, dislocation, grain boundary and other defects, and thus it greatly influences the mechanical behaviour and fatigue life of alloy parts. For example, the microstructure is homogeneous if the AM building direction is 0° , while the microstructure becomes inhomogeneous with larger dendritic grains when the AM building direction is 90° . As such, the mechanical properties at the AM building direction of 0° are better than those at the AM building direction of 90° [54]. Furthermore, the increase of laser power p is favourable to the increases of texture degree, grain shape aspect ratio and low-angle boundary fraction, and to making the crystal growth direction in accordance with the AM building direction [55]. In addition, the partially molten powder particles within the microstructure result in the lower tensile strength the premature failure of alloy parts [56], and the lower fatigue life of AM alloy parts, which is also illustrated theoretically in Fig. 2. In fact, there are many experimental approaches to capture the potential effects of microstructures on the fatigue behaviour, such as the electron backscatter diffraction (EBD) testing on the initial microstructure, the scanning electron microscope (SEM) testing on the fracture surfaces, the fatigue testing on the metal samples.

3.3.2 Ti6Al4V alloy parts

Ti6Al4V is a widely-used titanium alloy in aeronautics and astronautics

engineering, and their fatigue behaviour due to AM process were studied experimentally, but no work is carried out through the fatigue damage model. Here the presently proposed novel fatigue damage evolution equation is employed for numerical prediction of the fatigue lives and then compared with the published experimental results. The reference volumetric energy density E_{d0} for Ti6Al4V is taken as 62.17 J/mm^3 [10, 57-62] for the following numerical prediction.

The predicted results versus the experimental data are plotted in Fig. 6, in which the input is given by the published experimental maximum stresses ranged from 100 MPa to 600 MPa, and the ratios of volumetric energy density R_E from 0.64 to 1.78 through the fatigue tests of Ti6Al4V alloy parts by a MTS testing system [4, 10, 58-59, 63-64]. It is observed from Fig. 6 that most of the predicted fatigue lives coincide with the experimental results, and only 12 sets of data are located outside the three error band. Here, there are two possible reasons making the some experimental fatigue data beyond the three-error bands. One is directly due to the dispersion of fatigue data, as shown in Fig. 6, and the other the higher density of AM materials when the ratio of volumetric energy density R_E becomes larger. Therefore, the 12 sets of presently predicted fatigue lives are shorter than the experimental those, which lay out of the three-error bands.

Fig. 6 The predicted life versus experimental life for Ti6Al4V alloy parts.

Fig. 7 Microstructure of AM Ti6Al4V (a) AM as-built, (b) AM annealed at 700°C for 1 hour [57].

The above discussion on the fatigue life of printed alloy parts greatly influenced by the AM process in fact results from the microstructure of the parts directly by the AM process. A typical initial microstructure of Ti6Al4V is shown in Fig. 7 [57], and the AM alloy parts was fabricated in vertical orientation through the laser-based PBF machine [57] with a post-processing, in which the parts were preheated at 700°C first for one hour and then underwent free convection air-cooling at room temperature to relieve the residual stress. In general, the fatigue strength of the bimodal microstructure is higher than that of the lamellar and equiaxed microstructure [65-66],

and their fatigue strength may be dependent on the microstructural parameters of AM Ti6Al4V material [67-69]. For example, the fatigue strength for the bimodal microstructure increases first, and then declines with the increase of the volume fraction α_p . For the equiaxed and lamellar microstructure however, the fatigue strength decreases with the increase of α grain size or α lamellar width. Furthermore, the microstructures such as pores and defects [6] significantly influence the fatigue life of AM alloy parts. For example, the higher laser power p may result in the lower pores and defects, which is favourable for the improvement of fatigue life, as illustrated theoretically in Fig. 6. Apart from that, the post-processing heat treatment also has obvious influence on the fatigue behaviour of AM alloy parts, because it directly affects the microstructure of the AM Ti6Al4V such as grain size and dominant phase fraction [70-72], where usually a suitable heat treatment may greatly improve the mechanical properties and fatigue life of the AM Ti6Al4V [64]. This is also understood at macro-scale level that the heat treatment may relieve residual stress, and thus have adverse influence on the fatigue crack growth rate and threshold values [6]. Experimental techniques are generally required to obtain the results of microstructures and heat treatment for Ti6Al4V alloy, such as the microstructural characterization by the electron-optical microscopy, uniaxial tension, fatigue crack initiation and growth.

3.3.3 AlSi10Mg alloy parts

As another widely-employed material in the aerospace and automotive industries, AlSi10Mg alloy has obvious advantages such as light weight and high mechanical properties [17, 19]. Although many experimental studies were conducted for the mechanical properties and fatigue behaviour of AM AlSi10Mg alloy parts, no work is carried out for the fatigue-life prediction by the fatigue damage model. In this sub-section, the proposed novel fatigue damage model is applied to predict the fatigue life of AlSi10Mg alloy parts and the predicted results are compared with the reported experimental data. Here, the reference volumetric energy density of $E_d=60 \text{ J/mm}^3$ is

used in the following numerical prediction [17, 73].

The predicted results versus the experimental data are plotted in Fig. 8, with the input given by the published experimental maximum stresses ranged from 80 MPa to 280 MPa, and the ratios of volumetric energy density R_E from 0.36 to 1.11 [16, 46, 74-75], through the force-controlled fatigue tests of AlSi10Mg alloy parts. It is found from Fig. 8 that most of the predicted fatigue lives are consistent with the experimental results. However, there are 9 sets of data outside the three-error bands, 4 of them at $R_E = 0.36$ and the other at $R_E = 1.11$. Obviously the fatigue data disperse at $R_E = 0.36$ and 1.11, as shown in Fig. 8. As well known, the lower ratio of volumetric energy density, such as $R_E = 0.36$, leads to the higher porosity of AM alloy parts, resulting in the much shorter experimental fatigue lives compared with the predicted ones. However, if the ratio of volumetric energy density R_E increases highly, such as $R_E = 1.11$, the AM alloy parts become much lower porous.

Fig. 8 The predicted life versus experimental life for AlSi10Mg alloy parts.

The above analysis of the fatigue life of printed AlSi10Mg alloy parts significantly affected by the AM process in fact arises from the microstructure of the

parts directly by the AM process. A typical initial microstructure of AlSi10Mg is shown in Fig. 9 [75], where the AM alloy parts were fabricated by the selective laser melting system with a post-processing, in which the parts were heated at 300°C for two hours and then underwent air-cooling at room temperature to relieve the residual stresses [75].

Fig. 9 Microstructure of AM AlSi10Mg (a) horizontally built, (b) vertically built [75].

As mentioned above, both the microstructure and heat treatments have significant effects on the mechanical properties and the fatigue behaviour of AM AlSi10Mg alloy. In general, increasing the powder layer thickness t promotes defects within the microstructures, such as the discontinuities, irregularities, and balling [76], leading to the poor fatigue properties and low fatigue life of AM alloy parts, as illustrated theoretically in Fig. 8. Moreover, it is noted that the double unidirectional scan strategy with different laser powers at the same speed is useful to reduce the pores [77], and the AM process parameters may be designed to increase the density and reduce the imperfections and porosity [78] for the purpose of the improvement of fatigue life. Literature review also shows that the size, shape and arrangement of the α -Al matrix and the eutectic Si-particles in the microstructure are associated with the AM process and the post heat treatment [46], while the microstructural changes resulting from the post treatment have significant effects on the tensile properties, fracture toughness and fatigue resistance [74]. For example, the post heat treatment at 300°C peak-hardening is favourable for improvement of the fatigue resistance and static tensile strength [46]. The heat treatment is also able to modify and homogenise the microstructure of AM AlSi10Mg to obtain a supersaturated solid solution and

make Si diffuse to form spheroidal particles [79-80], which is favourable to improve the mechanical properties and increases the fatigue life [81]. In addition, Si atoms after solution heat treatment precipitate from the supersaturated Al matrix to form small Si particles, and the size of the Si particles increases with the increase of the solution temperature [19]. In general, the improvement of the fatigue behaviour by the heat treatment is due to the induced ductility, microstructure transformation, and the residual stress reduction. For better understanding of the effects of the microstructure and heat treatment on the fatigue properties of the AM AlSi10Mg, the comprehensive experimental work is required, including the scanning electron microscope (SEM), the energy dispersive X-ray, nano-indentation, uniaxial tension, and fatigue tests.

4. Fatigue life predictions for AM alloy parts by the present novel model

In this section, fatigue lives are predicted in detail for AM alloy parts by novel fatigue damage model, and several important characteristics are investigated. They include (a) the variation of fatigue life N_f with the volumetric energy density subject to different maximum stresses and stress ratios; (b) the variation of damage extent D with the number of loading cycles N subject to different volumetric energy densities; (c) the variation of the damage evolution rate dD/dN with the number of loading cycles N ; (d) the variation of Young's modulus E with the number of loading cycles N ; e) and the variation of von Mises stress with the number of loading cycles N .

4.1 SS316L alloy parts

For AM SS316L alloy parts, Fig. 10 is plotted for the variations of fatigue life N_f with the ratio of volumetric energy density R_E subject to different maximum stresses and stress ratios. It is found that the fatigue life N_f increases fast as the ratio of volumetric energy density R_E increases, when the ratio R_E is smaller than 1.0. However, if the ratio R_E approaches to 1.0, the fatigue life N_f reaches the maximum value, meaning that the AM parts may have the minimum porosity. Furthermore, when the ratio R_E is larger than 1.0, there is no obvious change of fatigue life.

For further understanding of damage evolution with the given maximum stress of

600 MPa and the stress ratio of 0.1, Fig. 11 is plotted for the evolution curve of damage extent D under different ratios of volumetric energy density R_E , and Fig. 12 for the variation of the damage evolution rate dD/dN against the number of cycles N . As illustrated in Fig. 11, the increasing rate of damage extent D with the number of loading cycles N becomes faster and faster for a certain ratio of volumetric energy density R_E , if the ratio R_E is larger than 1.0, while the damage evolutionary rate dD/dN decreases with the increase of the ratio R_E , when the ratio R_E is smaller than 1.0, as shown in Fig. 12.

The Young's modulus E of material versus the number of cycles N is plotted in Fig. 13. As the damage extent D increases with the increase of the number of loading cycles N , the Young's modulus E decreases gradually. However, the Young's modulus E decreases drastically if the damage extent D exceeds 0.1, resulting in the rapid decrease of von Mises stress. Fig. 14 is plotted for the evolution curve of von Mises stress with the number of loading cycles N under fatigue loads. It is also shown that the von Mises stress decreases with the increase of the number of loading cycles N , as a result of the accumulated fatigue damage. Moreover, it is noted that the Young's modulus E and the von Mises stress decrease drastically almost at the same time, when the number of loading cycles N reaches to 90% of the fatigue life N_f .

Based on the above analysis, several items are summarized for the fatigue damage characteristics of the AM SS316L alloy parts. First, the ratio of the volumetric energy density R_E dominates the fatigue life and fatigue damage evolution rate of SS316L alloy parts. Second, the smaller the ratio R_E is, the faster the damage evolution rate dD/dN is, which induces the rapid decrease of the Young's modulus E , and thus the load capacity of alloy parts and the von Mises stress decreases fast. Third, the design value of the ratio R_E for the AM SS316L alloy parts should be between 0.8 and 1.2 in order to better meet the requirement of fatigue life in the engineering application.

Fig. 10 Variation of the fatigue life with the volumetric energy density subject to: (a) different maximum stresses, (b) different stress ratios.

Fig. 11 Variation of the damage extent D with the number of cycles N .

Fig. 12 Variation of the damage evolution rate dD/dN with the number of cycles N .

Fig. 13 Variation of the Young's modulus E with the number of cycles N .

Fig. 14 Variation of the von Mises stress with the number of cycles N under different ratios R_E : (a) $R_E=0.25$, (b) $R_E=0.333$, (c) $R_E=0.5$, (d) $R_E=0.593$, (e) $R_E=0.7$, (f) $R_E=1$, (g) $R_E=1.3$, (h) $R_E=1.5$.

4.2 Ti6Al4V alloy parts

Fig. 15 demonstrates the variations of fatigue life N_f with the ratio of volumetric energy density R_E for AM Ti6Al4V alloy parts if subjected to different maximum stresses and stress ratios. It is observed that the fatigue life increases fast as the ratio of volumetric energy density R_E increases, when the ratio R_E is smaller than 1.0. However, if the ratio R_E approaches to 1.0, the fatigue life reaches the maximum value, meaning that the AM alloy parts may have the minimum porosity. Moreover, if the ratio R_E exceeds 1.0, the fatigue life changes little.

Fig. 16 is plotted for the evolution curve of damage extent D under different ratio of volumetric energy densities R_E and Fig. 17 plotted for the damage evolution rate dD/dN versus the number of loading cycles N with the given maximum stress of 500 MPa and the stress ratio of 0.1. It is found that the increasing rate of damage extent D with the number of cycles N becomes faster and faster for a certain ratio of volumetric energy density R_E . Furthermore, the damage evolutionary rate dD/dN decreases with the increase of the ratio R_E when it is smaller than 1.0, while the trend of the change is opposite if it is larger than 1.0.

The Young's modulus E of material versus the number of cycle N_f is shown in Fig. 18. It is known that the Young's modulus E decreases with the increase of the number of cycles N , resulting from the fatigue damage accumulation. Fig. 19 is plotted for the von Mises stress versus the number of loading cycles N . It is seen that the von Mises stress decreases as the number of loading cycles N increases, and results from the accumulated fatigue damage. It is also noted that the Young's modulus E and the von Mises stress decrease drastically when the number of loading cycles N reaches to 80% of the fatigue life N_f .

Based on the above discussion, it is concluded that the ratio of the volumetric energy density R_E has an important effect on the fatigue damage characteristics of the AM Ti6Al4V alloy parts. When the ratio R_E exceeds 1.39, the damage evolution rate dD/dN increases rapidly, leading to the fast decrease of the Young's modulus E and the von Mises stress, and thus the fatigue life N_f becomes much shorter. In addition, the fatigue resistance of the AM Ti6Al4V alloy parts is very promising if the designed

value of the ratio R_E ranges between 0.9 and 1.1.

Fig. 15 Variation of the fatigue life with the volumetric energy density subject to: (a) different maximum stresses, (b) different stress ratios.

Fig. 16 Variation of the damage extent D with the number of cycles N .

Fig. 17 Variation of the damage evolution rate dD/dN with the number of cycles N .

Fig. 18 Variation of the Young's modulus E with the number of cycles N .

Fig. 19 Variation of the von Mises stress with the number of cycles N under different ratios R_E : (a) $R_E=0.64$, (b) $R_E=0.73$, (c) $R_E=1$, (d) $R_E=1.39$.

4.3 AlSi10Mg alloy parts

Fig. 20 is plotted for the variations of fatigue life N_f with the ratio of volumetric energy density R_E for AM AlSi10Mg alloy parts subject to different maximum stresses and stress ratios. Here the fatigue life N_f increases fast as the ratio of volumetric energy density R_E increases, when the ratio R_E is smaller than 1.0. If the ratio R_E is over 1.0, the change of fatigue life N_f is very small.

For further understanding of fatigue damage evolution with the given maximum stress of 180 MPa and the stress ratio of 0.1, Fig. 21 is plotted for evolution curve of damage extent D under different ratios of volumetric energy density R_E , where the increasing rate of damage extent D with the number of loading cycles N becomes faster and faster for a certain ratio of volumetric energy density R_E if the ratio R_E is larger than 1.0. Fig. 22 is plotted for the damage evolution rate dD/dN versus the number of loading cycles N , where the damage evolutionary rate dD/dN decreases with the increase of the ratio R_E when it is smaller than 1.0.

The Young's modulus E of AM AlSi10Mg alloy versus the number of loading cycles N is plotted in Fig. 23. The Young's modulus E decreases as the fatigue damage increases due to the increase of the number of loading cycles N . The evolution curve of von Mises stress with the number of loading cycles N under fatigue loads is shown in Fig. 24, where the von Mises stress decreases as the number of loading cycles N increases, resulting from the accumulated fatigue damage. Furthermore, it is found that the Young's modulus E and the von Mises stress decrease drastically when the number of loading cycles N reaches to 85% of the fatigue life N_f .

In summary, several conclusions are drawn for better understanding of the fatigue damage characteristics of the AM AlSi10Mg alloy parts. First, the fatigue life N_f and fatigue damage evolution rate dD/dN are closely related to the ratio of volumetric energy density R_E . Second, when the ratio R_E is smaller than 0.83, the Young's modulus E drops quickly with the increase of the number of loading cycles N , and the load capacity and the von Mises stress also drop very fast. Third, it is important to make the value of the ratio of volumetric energy density R_E located between 0.85 and 1.2 in order to achieve a longer fatigue life of the AM AlSi10Mg alloy parts.

Fig. 20 Variation of the fatigue life with the volumetric energy density subject to: (a) different maximum stresses, (b) different stress ratios.

Fig. 21 Variation of the damage extent D with the number of cycles N .

Fig. 22 Variation of the damage evolution rate dD/dN with the number of cycles N .

Fig. 23 Variation of the Young's modulus E with the number of cycles N .

Fig. 24 Variation of the von Mises stress with the number of cycles N under different ratios R_E : (a) $R_E = 0.56$, (b) $R_E = 0.72$, (c) $R_E = 1$, (d) $R_E = 1.25$.

4.4 Recommendations for selection of the commonly-used AM alloy parts in

aerospace engineering

In this sub-section, several recommendations are made on how to optimally select the AM alloy parts, based on the engineering requirements and economy consideration.

- (1) As well known, the Young's moduli of SS316L, Ti6Al4V and AlSi10Mg are given about 200, 110 and 70 GPa respectively, and their yield stresses given about 600, 850 and 180 MPa respectively. On the basis of the above computed results, SS316L or Ti6Al4V alloy materials are recommended for requirement of fatigue life, if the same structural geometric sizes are designed for the AM alloy parts, since both materials have a stronger ability to resist deformation and destruction compared with the AlSi10Mg alloy part.
- (2) In the design of aircraft, light weight is considered as a critically important factor. It is also known that the densities of SS316L, Ti6Al4V and AlSi10Mg alloy materials are approximately 7.98g/cm^3 , 4.43g/cm^3 and 2.67g/cm^3 , respectively. Based on the above numerically predicted results, the AlSi10Mg alloy part as the lightest weight material is recommended for requirement of fatigue life, if the same structural geometric sizes are given for the AM alloy parts, since the weight of the recommended AlSi10Mg alloy is only about 33% of the SS316L alloy and 60% of the Ti6Al4V alloy.
- (3) By a simple survey of the current market, it is understood that the SS316L, Ti6Al4V and AlSi10Mg materials are priced at about \$10/kg, \$150/kg and \$85/kg, respectively. According to the above numerical analysis, the SS316L alloy is recommended for the requirement of fatigue life of 10^5 with the given maximum stress of 180 MPa, if the same structural geometric sizes are required for the AM alloy parts, since the price of the recommended SS316L is only about 12% of the Ti6Al4V alloy and 35% of the AlSi10Mg alloy. However, if the economy is considered as a relatively minor factor, the SS316L or Ti6Al4V alloy materials are recommended, for the requirement of fatigue life of 10^5 with the given maximum stress exceeding than 180 MPa.

5. Conclusions

In this paper, a novel fatigue damage model is developed with consideration of AM effects to predict the fatigue life of commonly-used alloy materials in aerospace engineering, and then verified by comparing the theoretically predicted fatigue lives of AM alloy parts with the experimental data published in open literature. Furthermore, the fatigue lives of SS316L, Ti6Al4V and AlSi10Mg alloy parts are numerically predicted by the present fatigue damage model in detail to investigate their several important characteristics. Finally, several recommendations are presented for selection of the AM alloy parts, based on the engineering requirements and economy consideration. The main conclusions are thus summarized as follows.

- (1) The ratio of the volumetric energy density R_E dominates the fatigue life and fatigue damage evolution characteristics of AM alloy parts. The fatigue life N_f increases fast as the ratio of volumetric energy density R_E increases, when the ratio R_E is smaller than 1.0. Furthermore, the smaller the ratio R_E is, the faster the damage evolution rate dD/dN is, meaning that the Young's modulus E decreases rapidly, and thus the load capacity of alloy parts and the von Mises stress decrease.
- (2) In order to better meet the requirement of fatigue life for practical aerospace engineering, the designed value of the ratio R_E ranging from 0.9 to 1.1 is recommended for the three different AM alloy parts.
- (3) For the same geometric size or volume of AM alloy parts meeting the requirement of fatigue life, the most economical candidate is the SS316L. Considering light weight in the design of aircraft, the AlSi10Mg alloy part is the ideal candidate. Furthermore, in view of the stiffness and strength of alloy parts, it's better to choose SS316L or Ti6Al4V, which are stronger to resist destruction.

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Graphic abstract

The predicted life versus experimental life for SS316L alloy parts.

Variation of the fatigue life with the volumetric energy density subject to:
(a) different maximum stresses, (b) different stress ratios.

Variation of the damage evolution rate with the number of loading cycles.