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RRT Algorithm for Fatigue Life Prediction of SiC/AL Composites Considering Crack Path

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Keywords ： composite material, path planning, rapidly-exploring random tree, Fatigue life prediction, fatigue crack growth.

ABSTRACT

Fatigue life prediction of metal matrix composites (MMCs) remains a complex task due to their unique crack propagation behaviors, including deflection and branching, which are influenced by the reinforcement matrix. This study employs the Rapidly-exploring Random Tree (RRT) algorithm to simulate crack paths in MMCs and integrates the Maximum Circumferential Stress Criterion to guide path planning. A modified Paris model is proposed to incorporate the effects of crack deflection and branching, capturing the fatigue crack growth rate under cyclic loading. The model accounts for the random distribution of reinforcement particles and their influence on stress intensity factors. Crack propagation paths and fatigue life were simulated, comparison of experimental results indicates that the improved model achieves better performance in fatigue life prediction. This research provides a novel approach to integrating advanced path planning algorithms with fatigue crack growth theories, offering potential applications in structural integrity analysis of MMCs.

INTRODUCTION

Fatigue performance plays a critical role in structural design, but accurately predicting fatigue life remains challenging in engineering applications. Evaluating fatigue performance often involves time-consuming and labor-intensive processes. Under high-cycle fatigue (HCF) and very high-cycle fatigue (VHCF) conditions, traditional experimental methods require long cycles and high costs to obtain S-N curves and fatigue limits. Crack propagation analysis is widely applied in materials science and structural engineering to predict fracture behavior under various conditions. Common analysis methods include the equivalent strain method, energy method, critical plane method, and critical energy density method. Existing models are often limited to specific loading paths and materials, restricting their broader engineering applications. Machine learning (ML) algorithms enable the processing of large datasets, identification of patterns, and creation of predictive models for fatigue crack initiation and propagation. Deep learning models integrate multi-scale features, including material microstructures and stress distributions, improving prediction accuracy. Despite these advances, data-driven methods must address challenges like high data collection costs and time-intensive fatigue data acquisition processes. Traditional metal materials' fatigue life predictions rely on methods such as strength degradation models, damage accumulation models, energy methods, and S-N curves. Metal matrix composites (MMCs) generally offer superior fatigue performance compared to metal materials, the calculation of fatigue life for MMCs is more complex.

Real-time observation and characterization of 3D damage evolution are increasingly essential for ensuring the reliability of safety-critical components, particularly in aerospace, power, weapons, ship, and railway industries. Manufacturing defects, such as lack of fusion, and inclusions often initiate fatigue microcracks. Fatigue sensitivity varies with the location, size, and type of the largest defects. In composites, microstructural size effects, including grains, defects, and inclusions, significantly influence fatigue performance. Factors like load intensity, stress ratio, and loading sequences affect fatigue life. For over a century, structural material failure studies have predominantly used post-mortem analysis techniques, such as optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), electron backscatter diffraction (EBSD), and standard fatigue experiments. These semi-empirical models have limitations in fully leveraging computer tomography (CT) to capture fine defect morphology. Metal matrix composites show better fatigue performance, while alloys are more prone to fatigue

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and failure. Crack propagation rates are influenced by crack deflection and branching. Macroscopically, fatigue cracks propagate perpendicular to loading directions, while microscopically, crack deflection and branching hinder main crack growth. Interactions between cracks and microstructural barriers enhance the fatigue performance of metal matrix composites compared to alloys.

Cyclic loading causes damage accumulation, crack initiation, propagation, and eventual fracture in metals. Local plastic cyclic strain exceeding the material's limit triggers crack initiation, growth, and final fracture. Research by Ogawa and Sander et al. shows that VHCF crack growth is discontinuous, with rates (10^-11 to 10^-14 m/cycle) much lower than interatomic distances. Cracks do not propagate in every loading cycle but exhibit crack steps, contributing to discontinuous propagation.

Path planning algorithms identify collision-free paths with minimal distance and time. Obstacles in the environment influence planned paths. Algorithms are classified into graph-based, bionics-based, and sampling-based categories. Graph-based methods, such as Dijkstra and A*, build paths with high efficiency and optimal costs but struggle with high-dimensional spaces and complex environments. Bionics-based methods, like neural network and biomimetic algorithms, excel in nonlinear mapping, self-learning, and adaptive capabilities but face challenges like long training times and susceptibility to local minima. Sampling-based algorithms, including RRT (Rapidly-exploring Random Tree) and PRM (Probabilistic Roadmap), perform well in high-dimensional spaces and complex paths but often generate tortuous routes.

The Maximum Circumferential Stress Criterion predicts material failure under multiaxial stress states and models fatigue damage in composites. It accounts for stress concentration and crack propagation under complex stress conditions, improving predictions of fatigue life and failure modes. Applying this criterion in the RRT algorithm increases the likelihood of crack path prediction aligning with actual propagation, reducing deviations.

The prediction of the fatigue life of parts is of great significance for product design and production safety. Composite materials possess superior performance compared to traditional materials and are therefore widely used in certain fields. The current prediction models are used to obtain the fatigue life of composite material parts within a limited range. To more accurately predict the life of composite parts, it is urgently necessary to study the following issues:

(1) As a new type of material, the research maturity of composites is far lower than that of traditional materials, and their test data is not as rich as that of common metals. Compared to alloys, it is more difficult to collect the parameters of composites. Numerous factors affect the performance of composites, including the volume of the reinforcement matrix, the properties of the metal matrix alloy, and the material manufacturing process. In summary, reproducing experimental data for composites is a challenge.

(2) Due to the material characteristics of composites, their fatigue behavior is quite different from that of normal alloys. Because of the presence of the reinforcement matrix, fatigue cracks in composites are prone to crack deflection and branching, which significantly affect the fatigue life of parts made from composites.

In conclusion, this paper explored key topics in fatigue life prediction, crack propagation analysis, and path planning techniques. The RRT algorithm's generation of tortuous paths effectively simulates the phenomenon of crack steps. By introducing the Maximum Circumferential Stress Criterion as a probability function in the RRT algorithm, it increases the likelihood of the search tree extending in the actual crack propagation direction, thereby reducing the deviation between the predicted crack path and the actual path.

CRACK PROPAGATION PATH MODEL

Crack propagation direction

To correctly calculate the crack propagation path, it is necessary to determine the direction of crack propagation. The Maximum Circumferential Tensile Stress theory, proposed by Erdogan and Sih, states that the crack propagation direction is determined by the direction of the maximum circumferential tensile stress. Therefore, the following conditions must be met:

$$\frac{\partial \sigma_{\theta\theta}}{\partial \theta} = 0, \frac{\partial^2 \sigma_{\theta\theta}}{\partial \theta^2} < 0 \tag{1}$$

where $\sigma_{\theta\theta}$ is the circumferential stress, and θ is the angle between the crack propagation direction and the original crack. The definition of $\sigma_{\theta\theta}$ is as follows:

$$\sigma_{\theta\theta} = \frac{1}{2\sqrt{2\pi r}} cos\frac{\theta}{2}[K_I(1 + cos\,\theta) - 3K_{II}\,sin\,\theta] \tag{2}$$

where K_I and K_{II} are the stress intensity factors for mode I and mode II cracks, respectively. Therefore, the crack propagation direction θ_0 can be obtained from the equation:

$$\theta_0 = cos^{-1}\left(\frac{3K_{II}^2 + K_I\sqrt{K_I^2 + 8K_{II}^2}}{K_I^2 + 9K_{II}^2}\right) \tag{3}$$

In numerical analysis, there are several methods for determining stress intensity factors (SIFs), among which the Integral Interaction Method is usually the most accurate. This method can estimate K_I and K_{II} separately. It is numerically easier to implement, more accurate, and requires fewer meshes. This method relies on the domain integral method. To compensate for the inability of the domain integral to separateK_I and K_{II}, an auxiliary field is introduced. The energy release rate is expressed in terms of mixedmode stress intensity factors K_I, K_{II} and K_{III} as follows:

$$J(s) = \frac{K_I^2 + K_{II}^2}{E^*} + \frac{1+v}{E} K_{III}^2 \tag{4}$$

where:

$$E^* = \begin{cases} \frac{E}{(1-v^2)}, & Plane\ strain \\ E, & Plane\ stress \end{cases} \tag{5}$$

$$J^s(s) = \frac{1}{E^*}[(K_I + K_I^{aux})^2 + (K_{II} + K_{II}^{aux})^2] + \frac{1+v}{E}(K_{III} + K_{III}^{aux})^2$$
$$= J(s) + J^{aux}(s) + I(s) \tag{6}$$

$$I(s) = \frac{1}{E^*}(2K_I K_I^{aux} + 2K_{II} K_{II}^{aux}) + \frac{1+v}{E}(2K_{III} K_{III}^{aux}) \tag{7}$$

where $J^s(s)$ denotes the superimposed state, $J(s)$ is the actual state domain integral, $J^{aux}(s)$ is the auxiliary state domain integral, and $I(s)$ is integral with interacting auxiliary and actual terms.

By setting K_I^{aux}=1 and $K_{II}^{aux} = K_{III}^{aux} = 0$,we get:

$$K_I = \frac{E^*}{2} I(s) \tag{8}$$

By setting K_{II}^{aux}=1and $K_I^{aux} = K_{III}^{aux} = 0$, we get:

$$K_{II} = \frac{E^*}{2} I(s) \tag{9}$$

$$K_{III} = \mu I(s) \tag{10}$$

Construction of the obstacle environment in MMCs

Metal matrix composites are typically composed of two or more different types of materials, where the metal acts as the matrix and the other material, usually reinforcement, is uniformly dispersed within the metal matrix. The particles are randomly distributed within a certain range on a microscopic scale, and their shapes are mostly irregular polygons. In the simulation of this paper, for simplicity, it is assumed that the shape of the reinforcement is a rectangular prism within a certain volume range. Based on these characteristics, a distribution model for the reinforcement in metal matrix composites is constructed. To efficiently store the built three-dimensional obstacle environment, the location information of the obstacles is stored in the form of obstacle nodes. The number of seeds determines the density of the reinforcement in the material, while the size range determines the volume of the reinforcement. The mechanical properties of the composite material are affected by factors such as the density and size of the reinforcement, thus the model can be modified according to the actual characteristics of the material during the simulation process.

In the domain of path planning, the efficient storage and processing of data are essential for enhancing the speed of complex analyses. VTKPolyData is utilized as one of the primary data structures for describing geometric shapes and topological structures. It enables the representation of points, lines, polygons, and more intricate three-dimensional mesh structures, and is widely applied in data analysis, model rendering, and visualization across various fields. This method is primarily composed of point sets, cell sets, and attribute data. Polygons are represented as closed geometric units composed of three or more vertices, encompassing their geometric shapes and topological relationships within three-dimensional space. The geometric shapes of fatigue test specimens were constructed, with spherical elements employed as reinforcement bases, as illustrated in Figure 1:

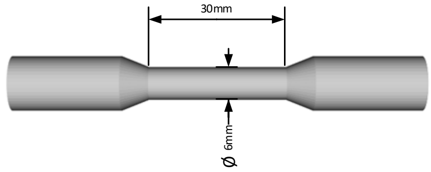


Fig. 1 Modeling of Fatigue Test Specimens for MMCs

Crack path selection

The Rapidly-exploring Random Tree (RRT) algorithm is an efficient path planning algorithm commonly used in robot path planning and other fields. It has gained wide attention for its excellent path planning capabilities in high-dimensional spaces and complex constraint conditions.

The RRT algorithm is based on an incremental search method, exploring the space by randomly sampling points and gradually constructing a search tree. The basic idea is to randomly select nodes in the space, and then extend a path from the nearest existing node in the tree to the new node. This strategy allows the algorithm to effectively handle high-dimensional spaces and complex constraints. The basic steps of the RRT algorithm are as follows:

(1) Set the initial node as the root of the tree and add it to the tree. In this paper, the tip of the initial crack is set as the initial node.

(2) Randomly generate a node in the search space, referred to as a random node.

(3) Find the node in the tree that is closest to the random node, referred to as the nearest neighbor node.

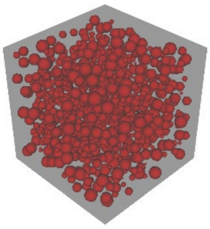
(4) Extend a certain distance from the nearest neighbor node towards the random node to create a new node. The position of this new node needs to meet the step length limit and must not intersect with obstacles.

(5) If the new node is valid, add it to the tree and update the parent-child relationship.

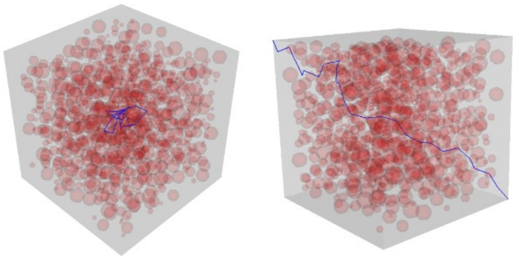
(6) Check whether the new node meets the target condition.

Repeat steps 2-6 until the target condition is met.

As shown in the Fig.2, since the crack needs to "bypass" the reinforcement matrix, the crack will deflect, resulting in an increase in the total crack length. This increase corresponds to the fatigue life of the composite material and the same metal. The path planning model can select the shortest path that bypasses obstacles.



(a) obstacle environment in MMCs



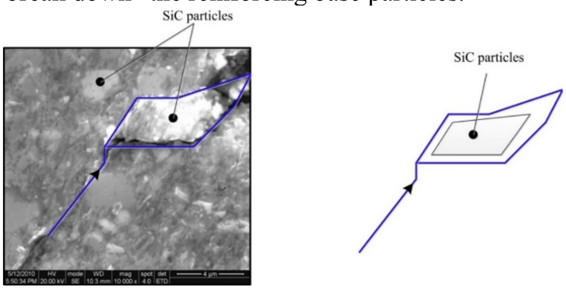
(b) crack path prediction

Fig. 2 Localized Crack Propagation Path in MMCs

Additionally, in the original RRT algorithm, random nodes are selected in step 2. In the process of calculating the crack path, the magnitude of stress can be introduced as a probability by combining the RRT algorithm with the Maximum Circumferential Stress Criterion to guide the process. This process making the crack extend in the direction of the stress, thereby increasing accuracy.

Crack branching

In addition to crack deflection, crack branching also occurs during the crack propagation in composites. The Paris equation explains crack propagation as driven by the stress intensity factor at the fatigue crack tip. When the stress intensity factor at the crack tip remains constant and the crack branches, the stress intensity must drive two or more cracks, as shown in Fig.3. At this time, the extension rate of the main crack will be affected. Observed by electron microscope, fatigue cracks are blocked by randomly distributed reinforcement bases during the crack propagation. The cracks will bypass the reinforcement bases and continue to grow. In a few cases, the cracks will pass through non-metallic particles. It can be understood that the stress intensity at the crack tip is sufficient to "break down" the reinforcing base particles.



(a) Crack bifurcation in MMCs (b) Crack simulation

Fig. 3 Crack propagation in the MMCs

Once the conditions for crack deflection are identified, the steps to determine crack branching are as follows:

(1) First, use the RRT algorithm in conjunction with the magnitude of stress to determine the direction of crack propagation.

(2) For branches that may produce branching, use them as starting points, and reapply the path planning algorithm to calculate the fatigue life of the branched cracks.

(3) Repeat steps 2 and 3 to complete the analysis of branched cracks.

(4) Select the shortest crack as the critical crack and calculate its fatigue life.

FATIGUE LIFE MODEL

Damage quantification

The purpose of crack propagation analysis is to estimate the crack propagation life in detail, i.e., the number of load cycles/time required for a crack to extend from its initial length to the allowable terminal length under fatigue load. In material fatigue analysis, using the Paris formula and related crack growth models for damage quantification is an effective method. The Paris formula is a classical formula used to describe the crack growth rate in materials and is widely applied in the field of fracture mechanics. It particularly focuses on the crack growth behavior of materials under fatigue load.

The calculated crack length can be used to define the damage degree of the material. According to Miner's rule, the definition of the damage degree involves the contribution of each cycle to the material's life. By accumulating the damage degree of each cycle, we can assess the overall fatigue damage of the material under a given complex load history. If the accumulated damage degree equals 1, the material will be in a critical state of fatigue fracture. In terms of damage quantification based on fatigue crack length, the damage degree D can be defined as the ratio of the current crack length a to the predicted crack length L_{pred}, i.e.:

$$Dam(a) = \frac{a}{L_{pred}} \tag{11}$$

The damage degree Dam defined in this way is a value between 0 and 1. When the crack length reaches or exceeds L_{pred}, the damage degree reaches 1, indicating potential structural failure. By dynamically monitoring the development of cracks and applying the Paris formula, not only can the current damage level be assessed, but also the future development of cracks under specific stress conditions can be predicted.

Fatigue life calculation

In materials science, the Paris formula is a key empirical model used to predict and analyze the crack growth behavior of materials under fatigue loads. The Paris formula focuses on the crack growth rate, i.e., the rate at which the crack length changes with the number of loading cycles. Its expression is:

$$\frac{da}{dn} = C(\Delta K)^m \tag{12}$$

where $\frac{da}{dn}$ is the crack growth rate, which is the ratio of the change in crack length to the number of loading cycles. C and m are material-dependent constants that need to be determined through experiments. ΔK is the range of the stress intensity factor, used to describe the stress state at the crack tip. Generally, for mode I cracks, ΔK can be calculated using the following formula:

$$\Delta K = \Delta\sigma\sqrt{\pi a}Y \tag{13}$$

where $\Delta\sigma$ is the stress range, which is the difference between the maximum stress and the minimum stress; a is the crack length; and Y is the geometric shape factor, which depends on the shape and position of the crack and the geometry of the specimen.

When crack branching occurs, assuming that the only driving force for crack propagation is the stress intensity factor at the crack tip as described earlier, the stress intensity factor at the crack tip is dispersed when the crack branches. The calculation of the new stress intensity factor is obtained by Equation (6). The formula for the crack propagation rate after branching is as follows:

$$\frac{da_x}{dn_x} = C(\Delta K_x)^m \tag{14}$$

where a_x is the length of the branched crack, n_x is the life length corresponding to the branched crack, and ΔK_x is the range of the stress intensity factors of the branched crack. If there are n cracks in the vertical plane of the crack, then:

$$\Delta K = \sum_{x=1}^{n} \Delta K_x \tag{15}$$

Since the magnitude of ΔK depends on the stress range and the existing crack length, it increases with the increase in crack length. Therefore, it cannot be directly calculated from the crack length and crack growth rate. However, in the calculations, it can be assumed that between every two passage points, the crack length is considered a constant value, and the fatigue life corresponding to the current micro-crack is calculated. The total life of the material is the sum of the segmented crack lives:

$$N = \sum_{i=1}^{n} \frac{a_i}{C(\Delta K_i)^m} \tag{16}$$

The total crack propagation life can be expressed as:

$$N_c = \sum_{i=1}^{n} \frac{a_i}{C(\Delta K_i)^m} + \sum_{j=1}^{z} \frac{a_j}{C(\Delta K_x)^m} \tag{17}$$

where:

$$\sum_{j=1}^{z} \frac{a_j}{C(\Delta K_x)^m} = min\begin{bmatrix} \sum_{j=1}^{z_1} \frac{a_j}{C(\Delta K_x)^m} \\ \sum_{j=1}^{z_2} \frac{a_j}{C(\Delta K_x)^m} \end{bmatrix} \tag{18}$$

The theoretical life value of the simulated metal material can be rewritten as:

$$N_A = \frac{1}{C(F\Delta\sigma\sqrt{\pi})^m}\left[\frac{a_c^{1-\frac{m}{2}} - a_0^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right] \tag{19}$$

The calculation formula for the life correction factor D is as follows:

$$D = \frac{N_c}{N_A} \tag{20}$$

Therefore, the fatigue life of the composite material is expressed as:

$$\begin{aligned} N_{cp} &= D \times N_{ap} \\ &= \frac{D}{C(F\Delta\sigma\sqrt{\pi})^m}\left[\frac{a_c^{1-\frac{m}{2}} - a_0^{1-\frac{m}{2}}}{1-\frac{m}{2}}\right] \end{aligned} \tag{21}$$

Simulation analyses

This paper proposes a life prediction model for metal matrix particle reinforced composites. In order to verify the accuracy of the model, the test data(Tables 1 and 2) in the literature is used for verification.

Table 1 Composition of the Aluminum alloy (mass: %)

Material	Si	Mg	Cu	Mg	Mn	Al
Al alloy	20	0.3	0.116	0.3	0.116	remain

Table 2 Material properties of SiC/AL

Material	E(GPa)	δ_b(MPa)	$\delta_{0.2}$(MPa)	ψ (%)	P(C^{-1})
Al-20Si	89.1	361	309	10	24.2
SiC	450	-	-	-	3.4

In the reference, by preparing a new type of aluminum alloy, and using this aluminum alloy as a matrix which reinforced by SiC particles, a SiC / AL composite material was prepared. Table 2 shows the basic properties of the metal matrix. Material parameters C and m are equal to 8.8×10^{-6} and 0.05 respectively.

Fig.3 shows the relationship between the calculated life curve of the composite material and the test results. The curve can predict the life trend of experimental materials well. The tensile strength, elongation and other parameters of the metal matrix will change to varying degrees after adding the reinforcing base. Different from the regular fatigue life prediction method, crack deflection and residual stress are considered, and the change in material properties caused by the strengthening base is ignored. For comparison, the prediction results obtained using the Dijkstra algorithm have been added. It can be seen from Figure 4 that the Dijkstra algorithm exhibits significant deviations in the predicted fatigue life. While this model can predict the life of composite materials more accurately.

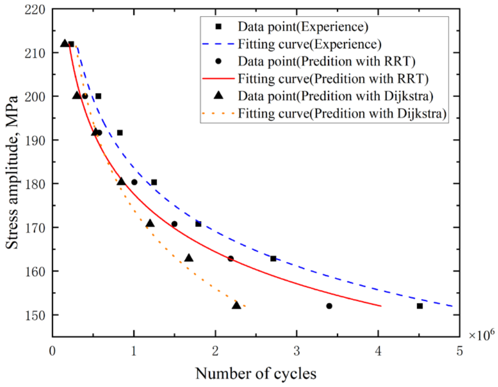


Fig. 4 Comparison of prediction and test data for SiC/AL composites

CONCLUSIONS

In this study, a random and distribution of reinforcement particles is established. The crack propagation model is built based on the Rapidly-exploring Random Tree (RRT) algorithm. Considering the crack bifurcation in MMCs materials, the existing crack propagation model is modified. The following conclusions could be drawn by calculation and analysis:

(1) Due to crack deflection caused by the addition of non-metallic particles, the cracks in MMCs materials have longer paths. It can be concluded that the addition of non-metallic particles increases the fatigue life of the base metal.

(2) Based on the behavior of crack propagation, the Rapidly-exploring Random Tree (RRT) algorithm is used to simulate the behavior of crack propagation, and the direction of crack propagation is selected through the influence of the stress intensity factor. Experimental data have validated the effectiveness of the model.

(3) The test and prediction data demonstrate the model's feasibility, though some discrepancies exist. These errors may arise from differences between the randomly constructed obstacle environment and real conditions, particularly when cracks cross obstacles instead of bypassing them, resulting in lower-than-expected predictions.

Results of analysis suggest that under cyclic loading, the calculation model could simulate the microscopic failure mechanism of MMCs materials. Under more sufficient test conditions and data, it is possible that this model could provide a certain reference for improving the life prediction of composite materials.

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NOMENCLATURE

Parameter names	Parameter Description	Unit
$\sigma_{\theta\theta}$	circumferential stress	MPa
θ	angle between the crack propagation direction and the original crack	degree
K_I	stress intensity factors for mode I	MPa$\cdot\sqrt{m}$
K_{II}	stress intensity factors for mode II	MPa$\cdot\sqrt{m}$
K_{III}	stress intensity factors for mode III	MPa$\cdot\sqrt{m}$
θ_0	crack propagation direction	degree
$J(s)$	actual state domain integral	
E	Elastic modulus	MPa
E^*	Modified elastic modulus	MPa
v	Poisson's ratio	
$J^s(s)$	superimposed state	
$J^{aux}(s)$	auxiliary state domain integral	
$I(s)$	integral with interacting auxiliary and actual terms	
μ	shear modulus	MPa
θ_1	minimum deflection angle	degree
θ_1	maximum deflection angle	degree
ΔK	stress intensity factor range	MPa$\cdot\sqrt{m}$
C, m	material parameters of Paris formula	
a	crack size	
a_x	sub-crack length	
Dam	Damage degree	
N	the total life of the material	cycles
N_A	theoretical life of alloy	cycles
N_C	theoretical life of composite	cycles
N_{cp}	fatigue life of the composite	cycles
N_{an}	fatigue life of the alloy	cycles