International Journal of Fatigue 74 (2015) 173–182

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

The fatigue life prediction for structure with surface scratch considering cutting residual stress, initial plasticity damage and fatigue damage

Zhan Zhixin [a], Hu Weiping [a,*], Zhang Miao [b], Meng Qingchun [a]

[a] *Institute of Solid Mechanics, School of Aeronautics Science and Engineering, BeiHang University, Beijing 100191, China*
[b] *Institute of Manned Space System Engineering, China Academy of Space Technology, Beijing 100094, China*

ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 11 January 2015
Accepted 14 January 2015
Available online 22 January 2015

Keywords:
Damage mechanics
Residual stress
Scratch defect
Plasticity damage
Fatigue

ABSTRACT

In this paper, a continuum damage mechanics based fatigue model is used to evaluate the effect of surface scratches resulting from accidental scrapes on the fatigue life of structures. First, a dynamic analysis is conducted to simulate scratch generation. Second, the initial damage field caused by plastic deformation in the scraping process is calculated. Third, for structures with scratches under fatigue loading, Chaudonneret's damage model for multiaxial fatigue is applied and the finite element implementation is presented. At last, this method is applied to life calculation for scratched specimens and for a scratched fixed plate. The theoretical calculation tallies with the experimental results.

1. Introduction

In the field of mechanical engineering, fatigue failure [1] is a common phenomenon. It has already become an important factor in determining the economy and security of structures in many engineering fields. Therefore, it is important to examine the optimal approach to life calculation for structures.

Numerous methods have been adopted to predict the fatigue life of the components, such as the methods of stress equivalents [2] and stress invariants [3], in which the S-N curves and stress field are the basis for life prediction. The local stress strain method [4,5] is another method to predict fatigue life. It is based on the stress strain course at the notch root and combined with the material fatigue characteristic curve. Many researchers have attempted to determine the fatigue damage parameter for S-N curves in order to predict fatigue life. For example, the critical plane approach was proposed by Stanfield [6] in 1935 and developed by Stulen and Cummings [7] and searches for the maximum fatigue damage parameter over a number of different planes. However, there is not enough information on the influence of mean stress and strain on the critical plane orientation [8], and this method is lack of description to the process of fatigue damage evolution. An approach based on continuum damage mechanics can describe the evolution of fatigue damage continuously by introducing damage variables to represent the damage state of materials and constructing a damage evolution equation to reflect the developing law of damage, which has been applied in practical engineering applications [9–12].

However, there is another type of fatigue problem that is different from plain fatigue problems and needs to be addressed in practical applications. This is the fatigue problem of a structure with defects, such as pits or scratches, which have been introduced unintentionally into components by impact or a scrape. Cracks can originate and grow from these pre-existing macroscopic defects. The methods applied to plain fatigue problems cannot be used directly for failure analyses of structures with defects due to the complex effects of a defect. The influence of surface defects on the structural fatigue life is threefold. First, the residual stress [13,14] field and plastic strain field formed around the defect. The second is the plasticity damage in the local region of defect. The last aspect is local stress concentration caused by the geometric shape of defect [15,16].

In this paper, assuming that the process of scratch generation is similar to the process of metal cutting, a dynamic analysis is conducted to simulate the process of scratch generation and furthermore to calculate the plastic strain field and residual stress field. Then the initial damage field caused by plastic deformation of the scraping process is evaluated with Lemaitre's damage model. For the case of structures with scratches under fatigue loading, the Chaudonneret's damage model for multiaxial fatigue is applied,

* Corresponding author at: Room D604, New Main Building, 37th Xueyuan Road, Beihang University, Beijing 100191, China. Tel.: +86 01082338489.
E-mail address: huweiping@buaa.edu.cn (W. Hu).

http://dx.doi.org/10.1016/j.ijfatigue.2015.01.011
0142-1123/

and the finite element implementation is presented for the life prediction. Finally, the above method is applied to calculate the fatigue life of a scratched specimen and a scratched fixed plate. The results show a good agreement with the experimental data.

2. Model

2.1. Residual stress analysis model

The residual stress analysis model needs to take into account metal cutting deformation theory, plastic theory and finite element theory [17,18]. During a simulation of cutting, the cutting tool is much harder than the structure, so the cutting tool is regarded as a rigid body while the structure is regarded as the elastic–plastic body. The constitutive relationship of structure material is described by a piecewise linear plastic model, which is a common used model. The stress–strain curve of 7075 aluminum alloy is shown in Fig. 1 and the mechanical properties of 7075 aluminum alloy are presented in Table 3 in Section 3.1.1.

The relation between strain rate and yield stress in this model is:

$$\sigma_y(\varepsilon^p_{eff}, \dot{\varepsilon}^p_{eff}) = \sigma_y(\varepsilon^p_{eff})\left[1 + \left(\frac{\dot{\varepsilon}^p_{eff}}{C}\right)^{\frac{1}{P}}\right] \tag{1}$$

where ε^p_{eff} is effective strain and $\dot{\varepsilon}^p_{eff}$ is effective strain rate, C and P are constants calibrated by experimental data, $\sigma_y(\varepsilon^p_{eff})$ is the yield stress without considering the strain rate, and can be represented by yield stress and tangent modulus.

The strain rate and cutting heat are closely related with the cutting velocity [17,19] in the process of metal cutting. If the cutting velocity is slow, then the high strain rate and cutting heat can be ignored. In the simulation of cutting process, the velocity of cutting in this paper is rather low and the value is 1.24 mm/s, thus the high strain rate and cutting heat were not taken into account in the numerical simulation. As the scratch is generated, the separation criterion adopted in finite element simulation is a physical criterion [20], which is defined by the physical quantities of the element node on the cutting tool. The physical quantity used in this paper is the strain of the element node. When the value of the strain exceeds the corresponding physical condition of a given material, the element nodes are separated. This type of criterion is closer to the actual situation in the finite element simulation for a metal cutting process [21].

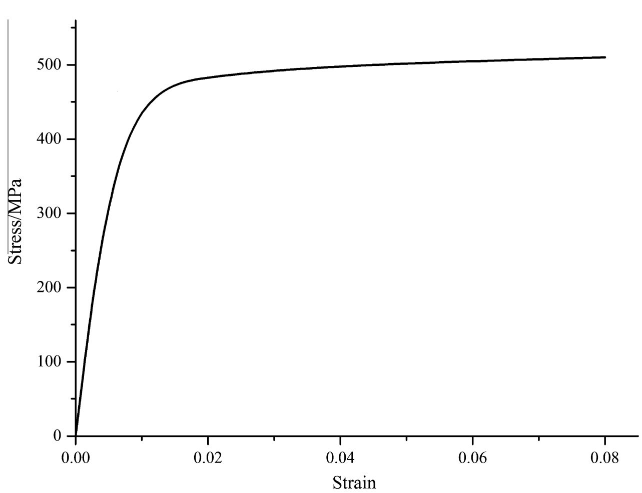

Fig. 1. Stress–strain curve of 7075 aluminum alloy.

As the cutting tool advances, there is considerable strain at the tip of tool, and then the strain begins to diffuse along the shear angle and the contact surface. As this action continues, chips are formed. Once the cutting is complete, residual stresses exist in the zone near the scratch.

2.2. Initial plastic damage analysis model

Lemaitre and Chaboche [22] have presented fundamental concepts in damage mechanics. For isotropic materials, the damage variable D is used to represent the stiffness deterioration under the fatigue load, which is expressed by

$$D = \frac{E - E_D}{E} \tag{2}$$

where E is Young's Modulus without damage and E_D is Young's Modulus with damage. As E_D ranges from E to 0, D varies between 0 and 1.

Based on elastic theory, the constitutive relation for isotropic materials with damage can be derived as

$$\sigma_{ij} = (1 - D)\delta_{ij}\lambda\delta_{kl}\varepsilon_{kl} + 2(1 - D)\mu\varepsilon_{ij} \tag{3}$$

where σ_{ij} and ε_{ij} stand for stress components and strain components, respectively. λ and μ are the Lamé constants.

After the completion of the residual stress analysis, the initial damage induced by the plastic deformation can be calculated according to Lemaitre's plasticity damage model [23]

$$\dot{D} = \left(\frac{\sigma^2_{eq}R_v}{2ES(1 - D)^2}\right)^s \dot{p} \tag{4}$$

where σ_{eq} is the von Mises equivalent stress and $\dot{p}$ is the rate of accumulated plastic strain, which is defined in accordance with the von Mises criterion: $\dot{p} = \sqrt{\frac{2}{3}\dot{\varepsilon}^p_{ij}\dot{\varepsilon}^p_{ij}}$. $\dot{\varepsilon}^p_{ij}$ stand for the components of plastic strain rate. S and s are material parameters. R_v is the triaxiality function: $R_v = \frac{2}{3}(1 + \mu) + 3(1 - 2\mu)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2$, σ_H is the hydrostatic stress.

This formula can be integrated over one cycle to calculate the initial damage induced by the plasticity as follows:

$$D_0 = \left(\frac{\sigma^2_{eq\max}R_v}{2ES}\right)^s \Delta p \tag{5}$$

where $\sigma_{eq\max}$ is the maximum equivalent stress which is calculated by maximizing the von Mise stress over a loading cycle. Δp is the accumulated plastic strain over one cycle.

The two parameters, S and s, in the plasticity damage model need to be identified from experimental data. Details about this method are presented in Section 3.2.

2.3. Fatigue damage model

2.3.1. Uniaxial fatigue damage model

In uniaxial cyclic loading, the cumulative fatigue damage model can be illustrated as follows [24]:

$$\dot{D} = \frac{dD}{dN} = \left[1 - (1 - D)^{\beta+1}\right]^{\alpha(\sigma_{\max},\sigma_m)} \cdot \left[\frac{\sigma_{\max} - \sigma_m}{M(\sigma_m)(1 - D)}\right]^\beta \tag{6}$$

where D is the damage scalar variable and N is the number of cycles. $\sigma_{\max}$ and σ_m are the maximum and mean applied stress, respectively. β is a material parameter. The expression of $\alpha(\sigma_{\max}, \sigma_m)$ is defined as

$$\alpha(\sigma_{\max}, \sigma_m) = 1 - a\left\langle\frac{\sigma_{\max} - \sigma_f(\sigma_m)}{\sigma_u - \sigma_{\max}}\right\rangle \tag{7}$$