International Journal of Mechanical Sciences 85 (2014) 30–37

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Fretting fatigue simulation for aluminium alloy using cohesive zone law approach

Kyungmok Kim [a,*], Myung-Jin Yoon [b]

[a] School of Aerospace and Mechanical Engineering, Korea Aerospace University, 76 Hanggongdaehang-ro, Deogyang-gu, Goyang, Gyeonggi-do 412-791, Republic of Korea
[b] Faculty of Mechanical and Automotive Engineering, Kyungil University, Gyeongsan, Gyeongsangbuk-do 721-701, Republic of Korea

ARTICLE INFO

Article history:
Received 20 January 2013
Received in revised form
8 March 2014
Accepted 2 May 2014
Available online 10 May 2014

Keywords:
Fretting fatigue
Cohesive zone law
Finite element analysis
Fracture

ABSTRACT

This paper describes high-cycle fretting fatigue modelling for 7050-T7451 aluminium alloy using a cohesive zone law. For the sake of crack generation arising from cyclic bending, a bilinear, cycle-dependent cohesive zone law is used including stiffness degradation and reduction of fracture energy with respect to fatigue cycles. The reduction rate of fracture energy is determined with experimental data. Implicit analysis is employed with commercial finite element software. Additionally, bending fretting experiments are performed with unnotched specimens and flat-and-rounded pads. Imposed stress amplitude (*S*)–number of cycles to failure (*N*) curves are determined after fretting fatigue tests. Direct comparison between simulation and experimental *S*–*N* curves is performed; maximum error is found to be 20% at the 5×10^4th cycle. It is demonstrated that a proposed method allows simulating fretting fatigue and predicting fretting life of aluminium alloys.

1. Introduction

Fretting fatigue is observed in various aerospace components including landing gears, fuselage frames, bulkheads, wing skins, and dovetail joints. Particularly, in riveted joints, fretting fatigue is considerable contact damage, since cracks are generated near contact edges [1]. Aluminium alloys are superior to other alloys in terms of manufacturing costs, replacing risk, and production infrastructure [2]. Moreover, the alloys have high strength, high fracture toughness, and good corrosion resistance.

For the practical use of aluminium alloy, numerous studies on fatigue behaviour were performed [3–6]. Fatigue tests with notched and unnotched Al7050-T7451 plates were conducted for determining stress amplitude (*S*)–number of cycles to failure (*N*) data [3,4]. Crack initiation during cyclic loading was observed with a scanning electron microscope [5]. The evolution of cracking was monitored in a notch under moderately high fatigue loads. Crack growth rate as well as fatigue life was evaluated by conducting a spectrum crack growth experiment [6]. The influence of sample orientation on fatigue life was investigated. In order to evaluate fatigue damage and determine fatigue life, measured *S*–*N* scatters were analysed [7]. The relation between stress amplitude and number of cycles to failure was obtained by expressing *S*–*N* scatter as an approximate mathematical function. In the literature, various curve fitting forms were proposed for low-and high-cycle fatigue regimes.

Meanwhile, some studies on fretting fatigue of aluminium alloys were reported. Fretting fatigue tests of Al7050-T6 were conducted and fretting damage zones were characterised [8]. It was identified that fretting degradation depends on the microstructure of Al7050-T6. The effects of microstructural characteristics were studied on the fretting response in 2XXX series aerospace aluminium alloys [9]. Fretting fatigue tests were performed for identifying the influences of slip character, alloy purity, grain structure and yield strength on crack nucleation and growth. Fretting fatigue *S*–*N* data of 2014A were measured at a pad pressure of 103.5 MPa and at zero stress ratio [10]. In addition, influence of bridge pad span was studied on fretting fatigue life. Fretting fatigue behaviour of Al7075-T6 was investigated at room temperature and sub-zero temperature [11]. Fretting fatigue tests at -25 and $-50\,^{\circ}C$ were conducted using flat-and-rounded contact configuration. It was observed that fretting fatigue life at sub-zero temperatures rises significantly up to around 220% for low working stresses and reduces to about 50% for higher working stresses. It is known that surface treatments such as shot peening or laser peening have an influence on fretting fatigue life. The effects of shot and laser peening on fretting fatigue were investigated [12]. Fretting fatigue tests were employed with shot peened

* Corresponding author. Tel.: +82 2 300 0288; fax: +82 2 3158 2191.
E-mail address: kkim@kau.ac.kr (K. Kim).

http://dx.doi.org/10.1016/j.ijmecsci.2014.05.001
0020-7403/

Nomenclature

a	half length of crack length
D	damage variable
E	modulus of elasticity
G_1^c	fracture energy after the first cycle
G_N^c	fracture energy after N cycles
K_{IC}	mode 1 fracture toughness
N_f	number of cycles to failure
T_L	normal stress after N cycles
T_S	shear stress after N cycles
T_N^{max}	max. nominal stress after N cycles
T_L^{max}	max. nominal normal stress after N cycles
T_S^{max}	max. nominal shear stress after N cycles
σ_1	ultimate tensile strength
σ_N	applied stress amplitude at the stress ratio of -1
δ_N^o	effective displacement at damage initiation after N cycles
δ^f	total displacement to complete failure
δ_N^{max}	max. value of a displacement after N cycles
δ_L^{max}	max. value of normal displacement during the loading history after N cycles
δ_S^{max}	max. value of shear displacement during the loading history after N cycles

and laser peened Al7075-T651 alloys. Both surface treatments were found to increase fretting fatigue lives.

One of successful methods for reproducing fracture of material is cohesive zone modelling. In a cohesive zone model, it is possible to simulate interfacial fracture between physical parts and characterise post-yield softening with various forms (e.g. bilinear, exponential, power-law, polynomial, or trapezoidal form). In addition, traction and separation response in a cohesive zone law includes stiffness degradation under repeated loading. Various cohesive zone models have been developed for materials including composites, polymers, ceramics, metals, etc. A cohesive zone model was proposed for describing interfacial fracture in concrete and cementitious composites [13,14]. A cohesive fatigue model was proposed for crack propagation of a polymer [15]. A typical bilinear cohesive law was combined with an evolution law relating cohesive stiffness, the rate of crack opening displacement and the number of cycles. A finite element model using a bilinear cohesive zone law was developed for pure alumina at the microscopic scale [16]. A cohesive zone was inserted between grains. A cyclic simulation was then conducted during a few dozen cycles. Grain separation due to external loading was simulated. A cohesive zone model was developed for predicting crack growth in single crystal [17]. Crack growth modelling was employed within pure fatigue regime and creep-fatigue regime. Exponential cohesive zone behaviour was used for energy dissipation. An irreversible cohesive zone model was proposed for fatigue crack growth along an interface in a double-cantilever beam [18]. The actual process of material separation during fatigue crack growth was described by using an irreversible constitutive equation. Recently, a cohesive model was developed with a stress-state dependent traction–separation law [19]. Typical stress-life response was reproduced by the model based on damage evolution with two cohesive fatigue parameters.

Cohesive zone laws are implemented in finite element framework. Particularly, in implicit finite element analysis, computation time is greatly dependent on the total number of elements and the total number of loading steps. For this reason, a conventional cohesive zone law is sometimes ineffective for simulating high-cycle fatigue (e.g. 10^7 fatigue cycles). A few strategies have been taken into account for a high-cycle fatigue modelling [20,21]. For a degradation process involving high-cycle fatigue, a cycle jump strategy was considered. In a strategy, fatigue damage variables were calculated after certain number of cycles with a quasi-static constitutive equation [20]. The extraction strategy of strain energy release rate from a cohesive zone was used for describing crack propagation under cyclic loading [21]. In explicit finite element analysis, a fatigue damage model was developed using Paris type crack growth law. In the model, strain energy of a cohesive zone was released during cyclic loading without stiffness degradation. For strain energy release, total displacement at failure after crack initiation was reduced in a bilinear cohesive zone law. A high-cycle fatigue simulation using a bilinear cohesive zone law was developed for Al7050-T7451 [22]. A bilinear, time-dependent cohesive zone law was implemented in a three-dimensional finite element model. For reproducing high-cycle fatigue of 7050-T7451 aluminium alloys, stiffness degradation and reduction of fracture energy were applied to a model. Bending fatigue tests with Al7050-T7451 plates were performed for determining S–N curves. It was demonstrated that it is possible to simulate high-cycle fatigue with a cohesive zone law. However, fretting fatigue life of Al7050-T7451 has not been predicted despite of its importance. Fretting fatigue life of aluminium alloy is typically shorter than pure fatigue lifetime, since fretting gives rise to contact degradation between two components. Nevertheless, little is reported on methods to predict fretting fatigue life of aluminium alloy.

In this study, a three-dimensional finite element model using flat-and-rounded contact configuration was generated for simulating fretting fatigue of Al7050-T7451. A bilinear, cycle-dependent cohesive zone law was described using the property of experimental S–N curves. For validation, fretting bending fretting fatigue tests were conducted at dry and room temperature condition. Direction comparison between simulation and experimental S–N curves was then performed.

2. High-cycle fatigue model using cycle jumping strategy

A conventional cohesive law enables specification of mechanical properties and characterisation of progressive degradation of material stiffness [23]. However, for high-cycle fatigue modelling, a cycle-by-cycle analysis is sometimes inefficient in terms of computation time and output file size. Thus, certain number of cycles is skipped by reducing stiffness and fracture energy according to the number of cycles (cycle jump strategy).

Fig. 1 illustrates a bilinear, cycle-dependent cohesive zone law with cycle jump strategy. In the proposed law, it was assumed that stiffness and fracture energy (i.e. critical strain energy release rate, G^c) of a cohesive element are reduced with respect to number of cycles. The reductions of fracture energy and of stiffness were achieved by reducing the maximum nominal stress along the linear softening. Meanwhile, the maximum value of a displacement (δ_N^{max}) after the Nth cycle was determined with maximum values of normal and shear displacements (δ_L^{max} and δ_S^{max}) attained during the loading history. The effective displacement at crack initiation (δ_N^o) was changed as T_N^{max} and was reduced along the linear softening. Here, it was assumed that the total displacement to failure was maintained as constant. Thus, the effective displacement at failure relative to the displacement at crack initiation (i.e. $\delta^f-\delta_N^o$) was reduced with respect to number of cycles.