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A non-local approach based on the hypothesis of damage dissipation potential equivalence to the effect of stress gradient in fretting fatigue

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ABSTRACT

A non-local approach based on continuum damage mechanics is proposed to take into account the stress gradient effect on fatigue crack initiation in fretting fatigue. The concept of subRVE (sub Representative Volume Element) is introduced as a smaller constituent unit of RVE (Representative Volume Element) and with the dimension of material average grain size for the purpose of considering the heterogeneous damage in the RVE. The fatigue damage in the subRVE is regarded as uniform, while the stress of subRVE is not uniform due to the effect of stress gradient. The fatigue damage evolution of each subRVE is derived by the hypothesis of damage dissipation potential equivalence with consideration of stress heterogeneity in the subRVE. Fretting fatigue is analyzed using this approach due to a zone of high stress gradient exists in the contact area. The predicted result from the proposed non-local model is better than that from local model by comparing with the experimental data. The interaction between wear and effect of stress gradient is also investigated.

1. Introduction

Fretting fatigue is a process of damage accumulation which occurs when two bodies in contact experience small reciprocating motion and remote bulk fatigue stress. Due to the contact between the two bodies, fretting fatigue is characterized by severe stress gradient, which may be one order of magnitude larger than common notch fatigue configurations as reported by Fouvry et al. [1]. Significant effect of high stress gradient on the fretting fatigue life is observed in the experimental investigations [2,3].

The critical plane approaches were widely used to study the behavior of fretting fatigue [4–6]. In these approaches, the fretting fatigue life was predicted by using merely the local maximum value of fatigue damage parameter. Therefore, the effect of stress gradient was not considered. These approaches are also called local approaches. However, the existence of severe stress gradient in the contact zone can result in the failure of these local approaches. From the physical point of view, although the fatigue crack nucleates at the position with maximum stress firstly, the crack initiation involves a process of a crack growth to a small finite size, while the stress along the path is much less than the maximum stress under the presence of stress gradient. Therefore, the fatigue damage is not only controlled by the stress–strain response of the maximum stressed point, but also the whole stress field in the zone covering the path. There are two other explanations for the phenomenon. One is suggested by Neuber [7] who suggested that the stress calculated by using the homogenous and isotropic material is not the true stress in the vicinity of the stress concentrator. Another is proposed by Miller [8] who believed that the spatial distribution of the stress field affects the capability of a crack to propagate.

In order to take the effect of stress gradient into account, some non-local approaches were then developed by averaging the multiaxial fatigue damage parameters over a specific volume or area. The dimension of the volume or area is a critical parameter in the non-local approaches. Three critical plane based parameters are evaluated by Naboulsi and Mall [9] to investigate the crack initiation behavior with the utilization of the volume process method. The effect of size of process volume on the averaged value of parameters was also studied. It was reported in [2] that a critical averaging dimension with the order of material grain size appears to give realistic estimates of fatigue life. Fouvry et al. [10] proposed a non-local approach, through which the multiaxial fatigue criterion was modified by a weight function to describe the gap between the predicted fatigue strength and the tested one. Besides, a non-local approach with stress-gradient-dependent critical dimension was also developed by Fouvry et al. [1], in which the critical dimension was expressed as a function of the hydrostatic

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Nomenclature

$\mathbf{D}$	tensor damage variable	R_v	tri-axiality function
D	scalar damage variable	A_{II}	amplitude of the octahedral shear stress
S	section area of the RVE	$\sigma_{H,mean}$	mean value of the hydrostatic stress
S_D	total area of micro-cracks or micro-voids in the RVE	$\sigma_{eq,\max}$	maximum equivalent stress
S_R	effective area of resistance in the RVE	σ_{l0}	fatigue limit
$\tilde{\sigma}$	effective stress	σ_u	ultimate tensile stress
σ	stress with damage	a, M_0, β, b_1, b_2	parameters of stress-based damage model
ε	strain	q	shear traction
ε_{ij}^e	elastic strain	ds	increment of local relative slip
ε_{ij}^p	plastic strain	θ	wear coefficient
E	initial elastic modulus	σ_{axial}	axial fatigue stress
v	Poisson's ratio	F	normal force
α	backstress	Q	tangential force
σ_y	size of yield surface	R_s	axial stress ratio
$\dot{p}$	accumulated plastic strain rate	R_Q	tangential force ratio
$\dot{\lambda}$	plastic multiplier	r	pad radius
C_k, γ_k	parameters of constitutive model	b	half width of specimen
ϕ	damage dissipation potential	d	thickness of specimen
Y	strain energy density release rate	μ	coefficient of friction
σ_H	hydrostatic stress	σ_R	reaction stress

pressure gradient. Although these averaging methods are able to provide predicted results consistent with the experimental data, numbers of empirical fatigue damage parameters are employed while their link with the physical explanation is not obvious.

Recently, the continuum damage mechanics (CDM) approach has been developed rapidly and has been introduced to the plain fatigue problems [11]. Generally, the fatigue life is predicted by using the local maximum stress in the dangerous RVE under the assumption that fatigue damage field in the RVE is uniform. However, significant discrepancies are observed between the results obtained by the local CDM approach and the experimental data for the case of high stress gradient. The non-local CDM method is then proposed. Marmi et al. [12] applied the Lemaitre–Chaboche fatigue mode [13] to predict the fatigue life of tensile samples with notches, in which the local approach and the non-local approach are compared. The generalized Papadopoulos formula [14] was applied to the equivalent stress used in the Lemaitre–Chaboche fatigue model and the critical distance was determined according to the distribution of the mean tri-axiality factor. Comparing to the experimental data, the non-local method gives reasonable estimate of the fatigue lives while the results predicted by the local approach are conservative.

CDM approaches have also been used to the fretting fatigue problem, including uncoupled CDM approach [15–17], coupled CDM approach [18,19], and coupled CDM approach in conjunction with the microstructure method [20]. For capturing the stress gradient effect, the similar strategy suggested in the literature [2] is also adopted in the uncoupled CDM approach. Stress-related variables in the damage evolution equation are averaged in the process zone having a dimension equal to the critical distance [15–17]. However, few non-local methods are investigated in the coupled CDM approach. The main reason may be that the fatigue damage is coupled in the constitutive model of material and therefore the stress redistribution is considered [18], which reduces the gap between the calculated stress and the real stress. Even though, the local method in the coupled CDM approach cannot give reasonable prediction of fretting fatigue life for some cases with high stress gradient.

Other aspect of the fretting fatigue is the phenomenon of wear. The effects of wear on the contact geometry, contact stress, subsurface stress and critical plane parameters are widely studied by McColl et al. [21], Madge et al. [22,23] and Zhang et al. [24]. The results indict that the predicted fretting fatigue life with considering the effect of wear is more reasonable, especially for the case of gross sliding. In the case of partial slip, the wear scar on the contact surface of the specimen is also observed in the fretting fatigue experiments [25]. From the investigation of the effect of wear conducted by Shen et al. [19,26], the wear is needed to take into account for the case of partial slip. Hence, the investigation of the interaction between wear and effect of stress gradient during the fretting damage becomes valuable.

In this study, a non-local method in the coupled CDM approach is proposed to investigate the fretting fatigue behavior under the partial slip condition. As we know, RVE is a basic concept of CDM, in which the damage is assumed to be uniform. However, this assumption is unreasonable when obvious stress gradient exists in material. For the purpose of considering the heterogeneous damage caused by the stress gradient effect, the concept of subRVE is introduced as a smaller constituent unit of RVE and with the dimension of material average grain size. The fatigue damage in the subRVE is regarded as uniform, while the stress of subRVE is not uniform due to the effect of stress gradient. The damage evolution of each subRVE is derived based on the hypothesis of damage dissipation potential equivalence. The damage coupled Chaboche plasticity model is used to calculate the stress–strain response of the fretting contact and the effect of wear is also considered. The predicted results by the non-local approach are compared to the experimental data and the results by the local approach, and the interaction between wear and effect of stress gradient is also investigated.

2. Models

In this section, the damage variable is defined in the framework of CDM firstly, in which isotropic damage is assumed and the damage variable is a scalar D. Then, the damage coupled Chaboche plasticity model is introduced to calculate the stress–strain response under fretting fatigue loadings. A non-local fatigue damage model based on the hypothesis of damage dissipation potential equivalence (DDPE) is proposed to accumulate the fatigue damage of subRVEs. In order to take the effect of wear into account, the