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About the effect of plastic dissipation in heat at the crack tip on the stress intensity factor under cyclic loading

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ABSTRACT

Because of the reverse cyclic plastic zone at the crack tip, there is plastic dissipation in heat at the crack tip under cyclic loading. That creates a heterogeneous temperature field around the crack tip. A thermo-mechanical model is proposed in this paper for evaluating the consequence of this temperature field on the Mode I stress intensity factor. Two cases are studied: (i) the theoretical problem of an infinite plate with a semi-infinite through crack under Mode I cyclic loading, and (ii) a finite specimen with a central through crack. In the first case, the main hypothesis and results are presented from the literature but no heat loss is taken into account. In second case, heat loss by convection is taken into account with a finite element analysis, while an analytical solution exists in the literature for the first case. In both cases, it is assumed that the heat source is located in the reverse cyclic plastic zone. The heat source within the reverse cyclic plastic zone is quantified by experiments on a mild steel under $R = 0.1$. It is shown that the crack tip is under compression due to thermal stresses coming from the heterogeneous temperature field around the crack tip. The effect of this stress field on the stress intensity factor (its maximum, minimum and its range) is calculated. This paper shows that experiments have to be carried out to determine the heat source within the reverse cyclic plastic zone. This is the key parameter to quantify the effect of dissipation at the crack tip on the stress intensity factor.

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1. Introduction

It is known in the literature [1,2] that during plastic strain a significant part of the plastic energy (around 90% for metals) is converted in heat. During a cyclic loading of a cracked structure, the plasticity is located in the reverse cyclic plastic zone near the crack tip. This phenomenon was first explained by Paris in 1964 [3] and studied later by Rice in 1967 [4]. This effect is now well-known and participates for instance in the explanation of the crack closure phenomenon which was first identified by Elber in 1970 [5]. As was noticed by the authors in 2011 [6], the dissipated energy in the reverse cyclic plastic zone also generates a heterogeneous temperature field which depends on the intensity of the heat source associated with the plasticity and the thermal boundary conditions of the cracked structure. Due to the thermal expansion of the material, the temperature gradient near the crack tip creates thermal stresses which contribute to the stress field in this region.

The main aim of this work is to quantify the effect of the heterogeneous temperature field on the stress intensity factor. The previous paper by the authors [6] was devoted to the theoretical problem of an infinite plate with a semi-infinite through crack without any heat loss. Indeed, there are two significant problems to solve when estimating the thermal stresses: the first one is the quantification of the heat source associated with the plasticity near the crack tip; the second one is to make a good estimation of the boundary conditions of the thermal problem (convection from the surface of the cracked structure, for example). The heat source has to be deduced from experimental temperature field measurement with an inverse numerical method (using finite element analysis). The geometry of a real specimen has to be taken into account together with the convection boundary conditions over all the specimen surfaces.

The present paper is first focused on the theoretical problem of an infinite plate with a semi-infinite through crack under fatigue loading in Mode I (Fig. 1). The hypothesis and the main results associated to this problem, solved by the authors in 2011 [6], are recalled to understand the most significant phenomena. Then,

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Nomenclature

a	thermal diffusivity	K_{th}	threshold stress intensity factor in Mode I
c	crack length	Pe	Péclet number
q	heat source per unit length of the crack front	α	linear coefficient of thermal expansion
r	radius	ε_r, ε_θ, ε_z	radial, circumferential and out of plane strains, respectively
r_R	radius of the reverse cyclic plastic zone	λ	heat conductivity
t	time	ρ	density
u_r, u_θ, u_z	radial, circumferential and out of plane displacement, respectively	σ_r, σ_θ, σ_z	radial, circumferential and out of plane normal stresses, respectively
C	heat capacity	σ_y	yield stress
E	Young modulus	ν	Poisson ratio
$K_{I,cyc}$	stress intensity factor in Mode I due to the fatigue cyclic loading	$\mathcal{E}$	dissipated energy per unit length of crack front during one cycle
$K_{I,temp}$	stress intensity factor in Mode I due to the temperature gradient	ϑ	temperature variation field depending on time t and radius r
$K_{I,max}$	maximum stress intensity factor in Mode I	ΔK_I	range of the Mode I stress intensity factor
$K_{I,min}$	minimum stress intensity factor in Mode I		

the heat source within the reverse cyclic plastic zone is identified from temperature field measurement (with an infrared camera) at the surface of a central cracked specimen. In this case the thermal losses due to convection cannot be neglected like in the previous theoretical problem (infinite plate with a central through crack). A finite element analysis including the thermal losses (convection) allows the authors to compute the temperature field on the specimen, to estimate the thermal stresses due to this heterogeneous temperature field and to quantify their effect on the Mode I stress intensity factor. It is shown that the crack tip is under compressive thermal stresses which reduce the crack driving force. Finally, some recommendations for further theoretical and experimental investigations are proposed.

2. An infinite plate with a semi-infinite through crack

2.1. The temperature field due to the heat source within the reverse cyclic plastic zone

During crack growth under cyclic loading, the cyclic plastic strains at each cycle are confined within the reverse cyclic plastic zone. A portion of the plastic strain energy is dissipated in heat and generates a temperature variation. Generally, the size of this reverse cyclic plastic zone is very small. In order to determine

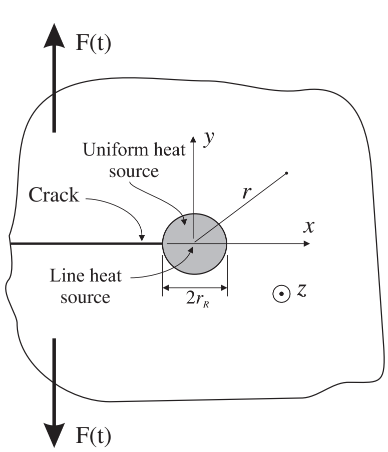

Fig. 1. Schematic of the thermodynamical problem of a semi-infinite crack in an infinite plate under cyclic tension (Mode I) caused by a remote mechanical loading $F(t)$.

the temperature field, it is possible to consider the thermal problem associated with the fatigue crack propagation as a line heat source centered in the reverse cyclic plastic zone along the crack tip in an infinitely thick body. Ranc et al. [6] have compared the numerical solution (by finite element analysis) of the thermal problem in the case of a uniform heat source in a cylinder with a radius equal to the radius of the reverse cyclic plastic zone (Fig. 1) and the analytical solution of the thermal problem with a line heat source. The temperature variation fields obtained with the line heat source or the uniform heat source hypothesis are very close to eachother outside the reverse cyclic plastic zone: the relative difference is equal to about 0.03%. However, the temperature inside the reverse cyclic plastic zone can be very differently distributed, but this is not the aim of this paper. This study is focused on the effect of the temperature gradient on the stress state outside this plastic zone, in order to calculate the consequences on the stress intensity factor.

The dissipated power per unit length of crack front is assumed to be proportional to the surface area of the reverse cyclic plastic zone and the loading frequency f [7]:

$$q = f\mathcal{E} = f\eta r_R^2, \tag{1}$$

with $\mathcal{E}$ the dissipated energy per unit length of crack front during one cycle, r_R the radius of the reverse cyclic plastic zone and η a material-dependent proportionality factor.

It is well-known in the literature that, both in plane stress and plane strain, the reverse cyclic plastic zone radius is proportional to ΔK_I^2, where ΔK_I is the range of variation of the Mode I stress intensity factor. Consequently, the dissipated power per unit length of crack front is proportional to the stress intensity factor variation to the power four:

$$q = q_0 \Delta K^4, \tag{2}$$

with

$$q_0 = \frac{\eta f}{8^2 \pi^2 \sigma_y^4} \tag{3}$$

for plane stress conditions and,

$$q_0 = \frac{\eta f}{24^2 \pi^2 \sigma_y^4} \tag{4}$$

for plane strain conditions.

These results have been already shown analytically [7] and numerically [8]. Furthermore it is important to note that Pippan

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