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EFFECT OF MATERIAL HARDNESS ON ENERGY DISSIPATION FROM A MOVING CRACK IN FIRST MODE

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Abstract. Fatigue crack growth is the reason of failure of mechanical parts under cyclic loading. When a crack forms in material a plastic zone surrounds the tip of the crack. In this paper, a model based on HRR singularity is utilized to find the strain energy dissipation from a crack tip. Material hardness effect on the dissipated strain energy is investigated. It is found that the strain energy dissipation decreases with hardness. The results also show the direct logarithmic relation between the stress intensity factor and strain energy dissipation of fatigue crack propagation.

Keywords : Fatigue, Crack propagation, Plastic dissipation

1. INTRODUCTION

When a component is under cyclic loads, it experiences a degradation process. This degradation is responsible for the final failure of the material when accumulated damage initiates micro cracks which eventually ends up in cracks and the propagation of the macro cracks causes the failure of the part[1].

The crack propagation behavior has been the subject of study for many years. In early days, the propagation of crack was directly related to the loads on the part under cyclic forces. These investigations were started by the well-known Paris law. The problem which can arise in utilizing the concept of load and stress intensity factor (SIF) is the fact that the conventional relations are restricted to small regions of propagation. This has been the incentive for researchers to be after methods which are capable of quantifying the propagation behavior on account of observable system parameters including temperature [2, 3].

The strain dissipation is the source of the heat which is a representation of the degradation occurring during the propagation of the crack. This dissipation is mainly because of the plastic work in the plastic zone ahead of the crack tip. Fig. 1 shows the schematic of a crack loaded in the first mode[4].

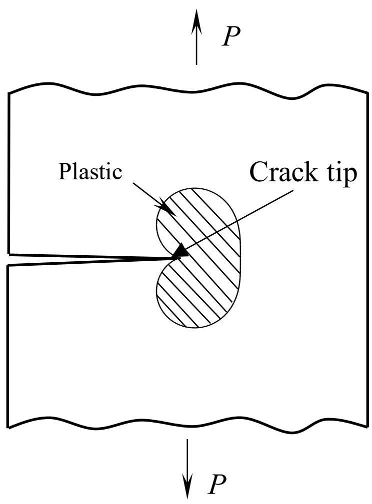

Figure 1. Crack faces loaded in the first mode of crack propagation.

As it is seen in Fig. 1, The butterfly plastic region around the crack is symmetric in respect with the plane of the crack. The plastic strains combined with stresses in the zone act as a source of heat by generating the plastic work. The stress strain distribution around the crack is given by Hutchinsone, Rice and Rosengren [5] which is commonly called HRR singularity.

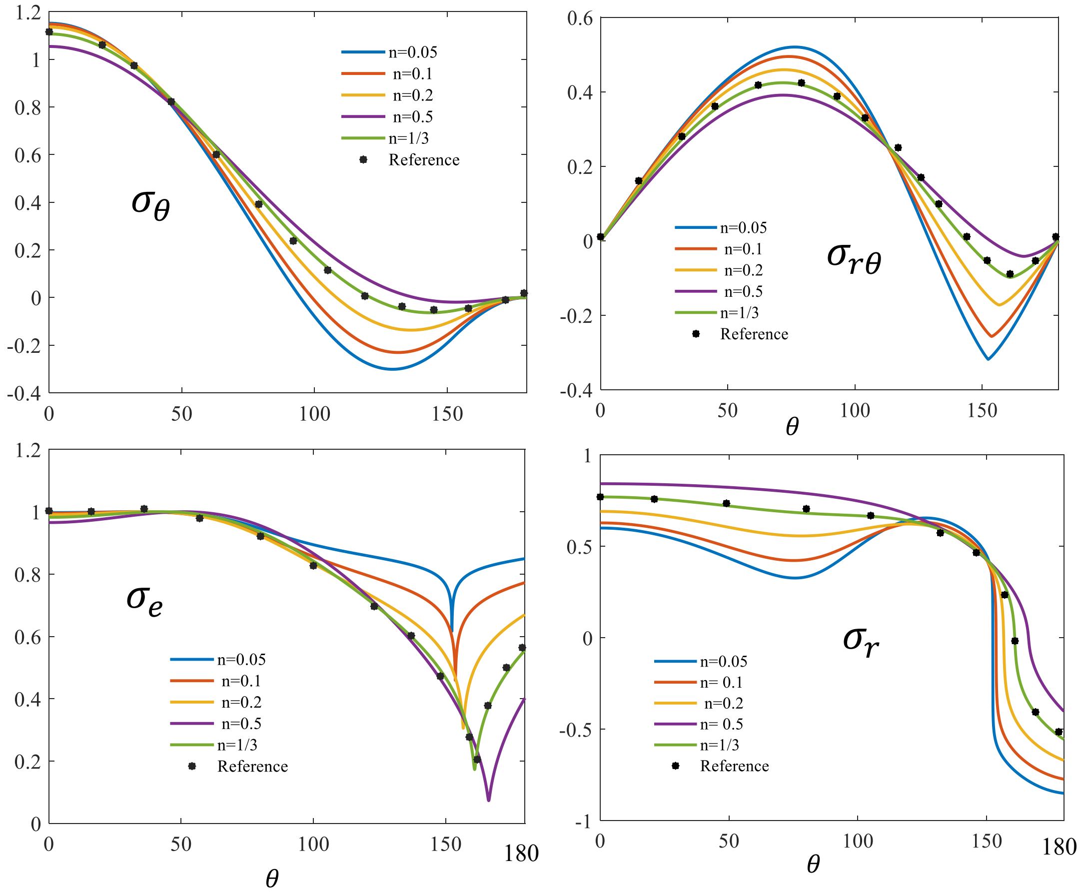

Figure 2. the angular stress distribution solved by Hutchinson

2. METHODS

2.1 Model description

The plastic behavior of a material under uniaxial tension/compression can be given by the following relation [6].

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2k'}\right)^{1/n} \tag{1}$$

In this equation, Δϵ denotes the range of strain, Δσ is stress range. n is the hardening exponent and E is young modulus. According to Hutchinson [3] the stress ahead of crack tip can be presented by the following relations.

$$\Delta\sigma_{ij} = \Delta\sigma_0 \left(\frac{\Delta K_I^2}{\alpha\Delta\sigma_0^2 I_n r}\right)^{\frac{n}{n+1}} \tilde{\sigma}_{ij}(n,\theta) \tag{2}$$

$$\Delta\epsilon_{ij} = \frac{\alpha\Delta\sigma_0}{E}\left(\frac{\Delta K_I^2}{\alpha\Delta\sigma_0^2 I_n r}\right)^{\frac{1}{n+1}} \tilde{\epsilon}_{ij}(n,\theta) \tag{3}$$

where $\tilde{\sigma}_{ij}$ and $\tilde{\epsilon}_{ij}$are functions that give the angular distribution of stress and $I_n$is an integration constant. the cyclic yield stress is shown by σ_0 and α is a dimensionless constant given by Eq. 4.

$$\alpha = \frac{2E}{(2k')^{\frac{1}{n}} \Delta\sigma_0^{\frac{n-1}{n}}} \tag{4}$$

Fig. 2 illustrates the plastic zone ahead of a fatigue crack. Each point in the plastic zone acts as a heat source. A point like A is shown in this figure. For this point, the heat source is given by the following relation.

$$W_p = \left(\frac{n-1}{n+1}\right)\sigma_{eq}\varepsilon_{eq}^{p} \tag{5}$$

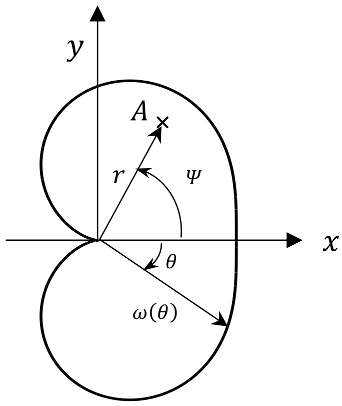

Figure 3. Cyclic plastic zone in front of the plastic zone.

The size of the plastic zone is given by the following relation for plane stress condition.

$$\omega(\theta) = \frac{1}{16\pi}\frac{\Delta K_I^2}{\sigma_0'^2}\left(1 + \frac{3}{2}sin^2\theta + cos\theta\right) \tag{6}$$

W_p given by Eq. 5 can be found for point A shown in Fig. 2.

$$W_p = f\beta\left(\frac{n-1}{n+1}\right)\frac{\Delta K_I^2 \tilde{\sigma}_{eq}(n,\theta)\tilde{\varepsilon}_{eq}(n,\theta)}{EI_n r} \tag{7}$$

$\tilde{\sigma}_{eq}$ and $\tilde{\varepsilon}_{eq}$ are equivalent plastic stress and strain angular distribution respectively and β is the ratio of the plastic strain converted to heat. Frequency is shown by *f*.

Equivalent stress and strain for plane stress condition are given by the following two equations.

$$\tilde{\sigma}_{eq} = (\tilde{\sigma}_r^2 + \tilde{\sigma}_\theta^2 - \tilde{\sigma}_\theta\tilde{\sigma}_r + 3\breve{\sigma}_{r\theta}^2)^{\frac{1}{2}} \tag{8}$$

$$\tilde{\varepsilon}_{eq}^{p} = \frac{2}{\sqrt{3}}(\tilde{\varepsilon}_r^2 + \tilde{\varepsilon}_\theta^2 + \tilde{\varepsilon}_r\tilde{\varepsilon}_\theta + \tilde{\varepsilon}_{r\theta}^2)^{\frac{1}{2}} \tag{9}$$

According to Eq. 5, the local heat generation can be found for each point is plastic zone. The total heat generation is the summation of each point heat sources in this region. This total amount is given by the following relation.

$$W_p = \iint_{plastic\ zone} f\beta\left(\frac{n'-1}{n'+1}\right)\frac{\Delta K_I^2 \tilde{\sigma}_{eq}(n',\theta)\tilde{\varepsilon}_{eq}(n',\theta)}{EI_{n'} r}dA \tag{10}$$

The integration is calculated over the closed area of the plastic zone. Eq. 10 reduces to the following relation.

$$W_p = \int_0^{2\pi}\int_0^{\omega(\varphi)} f\beta\left(\frac{n-1}{n+1}\right)\frac{\Delta K_I^2 \tilde{\sigma}_{eq}(n,\theta)\tilde{\varepsilon}_{eq}(n,\theta)}{EI_n}drd\varphi \tag{10}$$

2.2 Numerical Procedure

The solution procedure is carried out by a MATLAB script. The angular distribution functions of HRR singularity is found by a series of numerical integration using Runge-Kutta approach combined with the shooting method. A Simpson scheme is used for numerical solution of the integration in Eq. 10.

3. RESULTS AND DISCUSSION

Fig. 4 shows the strain energy dissipation as a function of first mode stress intensity factor. It can be seen that the stress intensity directly increases the dissipation and there is a logarithmic relation between the SIF and the dissipated energy. Furthermore, it is seen that by increasing the hardening exponent, the dissipated energy decreases.

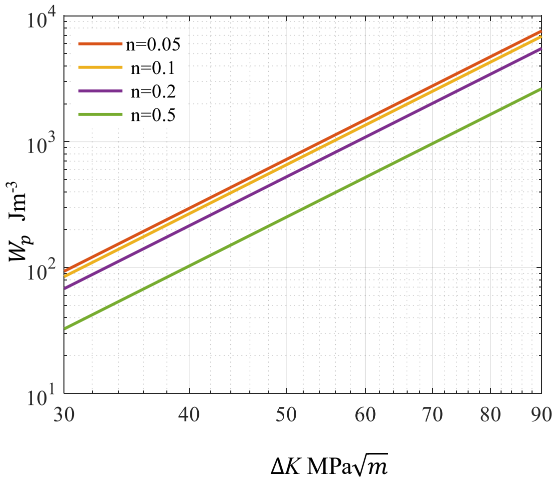

Figure. 4. Strain energy dissipation as a function of stress intensity factor for different strain hardening values *n*.

According to Fig. 4, The strain energy dissipation increases with the stress intensity factor. It is also seen that as the hardness increases, dissipation become smaller. Since the stress intensity factor is directly related to the propagation speed, this result means that heat dissipation increases with propagation rate. This implies that in order to control the propagation speed it is recommended to use material with higher hardness value.

Fig. 5 shows the Dissipated energy as a function of the hardening. It can be seen how hardening exponent is reversely affecting the dissipated strain work

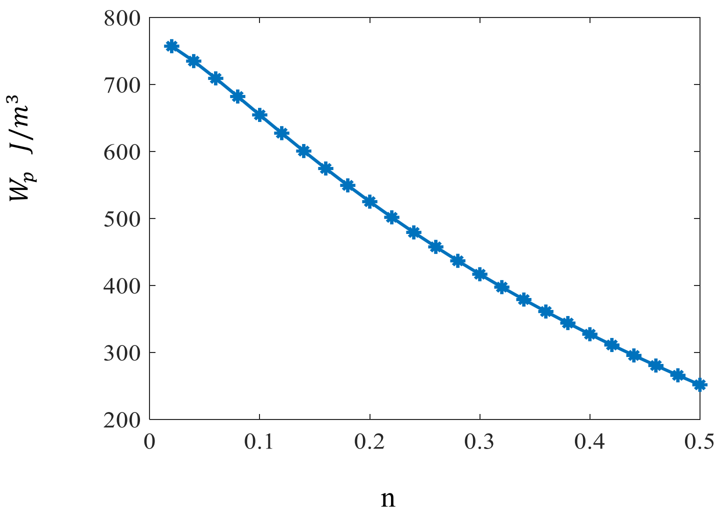

Figure. 5. Strain energy dissipation as a function of hardening exponent *n*.

The result shown in Fig. 5 denotes that in materials with larger hardness, the strain energy dissipation is smaller. This means that temperature rise due to crack propagation is smaller in these materials for the same stress intensity factor.

4. CONCLUSION

A model is presented to calculate the strain energy dissipated from a fatigue crack in cyclic loading. It was found that increasing stress intensity factor is responsible for elevation of dissipated energy, in addition, hardening exponent decreases the strain dissipation. This means that fatigue process is directly related to the material plastic parameter *n* which decide on the degradation happening during the propagation stage of fatigue crack growth.

5. NOMENCLATURE

n	Plastic hardening exponent	$\omega(\theta)$	Plastic region radius at angle θ (m)
r	Coordinate of radius	W_p	Plastic strain energy density (J/m^3)
ΔK_I	First mode stress intensity factor range (MPa.m$^{1/2}$)	k'	Cyclic strength coefficient (MPa)
β	Heat portion of plastic strain	$\tilde{\sigma}_{ij}(n,\theta)$	Dimensionless function of stress
α	Dimensionless constant	$\tilde{\epsilon}_{ij}(n,\theta)$	Dimensionless function of strain
$\Delta\sigma$	Range of stress (MPa)	σ_0'	Cyclic yield stress (MPa)
E	Elastic modulus (GPa)	σ_{eq}	Equivalent stress (MPa)
f	Load frequency	ε_{eq}^{p}	Equivalent strain

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