ANALYSIS OF SHORT AND LONG FATIGUE CRACKS GROWTH KINETICS UNDER NON-REGULAR LOADING

V. V. Panasyuk*, O. Ye. Andreykiv*, O. I. Darchuk* and P. S. Kun*

A mathematical model for description of the long and physically short fatigue cracks propagation kinetics under non-regular loading was proposed. It is based on the δ_c -model of fatigue plastic zone at the crack tip generalized for fatigue loading and the energetic fracture criterion. This model reflects the main features of the reverse elastic-plastic deformation of materials in the prefracture zone, particularly, the residual stresses presence at the crack tip due to plastic flow of material, partial crack closure during unloading etc. and takes into consideration their influence on the crack growth rate.

INTRODUCTION

Elaboration of the methods for evaluation of the structures integrity under time-variable random loading is one of the urgent problems of fracture mechanics. The recent experimental and analytical investigation allowed to obtain the main factors defining the peculiarities of the influence of the loading amplitudes variation influence on structural materials fracture at different stages of fatigue damages development. Residual stresses, arising near the crack tip due to plastic deformation of the material and crack closure - partial linkage of its edges during unloading (Budiansky and Hutchinson (1), Fuhring and Seeger (2), Russel (3), Wang and Blom (4)) stand for such factors primarily when considering the development of long and physically short cracks (sizes of which exceed the sizes of structural parameters of material). In this case thin strips in front of the crack are modelled by the lines of discontinuity in normal displacements within the framework of the known

* Karpenko Physico-Mechanical Institute of Academy of Sciences of Ukraine, Lviv, Ukraine

δ_c-model (Panasyuk (5), Dugdale (6)), generalized for a case of cyclic loading effect. This model is now most often used for evaluation of the effective SIF range ($\Delta K_{eff} = K_{max} - K_{op}$), which is the main calculational parameter that determines crack growth rate under regular loading. However, the employment of the dependence $v = f(\Delta K_{eff})$ describing kinetic diagram of fatigue fracture in the "effective" coordinates for evaluation of the crack increment at every loading cycle under non-regular loading is not sufficiently substantiated and does not provide reliable data. Particularly, this simplified approach does not illustrate the non-uniform (jump-like) character of the crack propagation, typical of non-regular loading. Energetic fracture criterion allows to account for these peculiarities more completely. In this case the calculation is based on determination of plastic strain energy which is adsorbed by the prefracture zone at every loading cycle, and a cycle number required for a subsequent crack increment (jump) is obtained from the energy balance equation.

In the present study, the deformation model of the cyclic plastic zone and energetic fracture criterion form the basis of the calculational model of fatigue crack growth under variable loading amplitudes.

ANALYSIS OF ELASTIC-PLASTIC DEFORMATION OF MATERIAL NEAR FATIGUE CRACK TIP

The main peculiarities of the stress-strain state at the fatigue crack tip are schematically illustrated in Figure 1. As a result of plastic deformation of the material in fracture, the crack growth is accompanied by formation of the plastic stretches $u_{res}(x)$ on its edges. During unloading the compressive stresses appear on the crack extension which are equal to the yield stress σ_y of the material within the plastic zone area. On some area adjacent the crack tip, the crack edges interact. If we use δ_c-model for description of the presented monotonous and cyclic plastic zones, the analysis of the stress-strain situation is reduced to the solution of some boundary value problem of the crack theory. Figure 2 shows the boundary conditions that are assumed as the additional ones on the external surface of a body and determine its loading conditions. The sought values are the size of maximum plastic zone l_{pmax}, cyclic plastic zone l_{pf}, contact zone l_{con}, and distribution of contact stresses $\sigma_{con}(x)$. Proceeding from a condition of smooth linkage of the crack edges in the contact zone

$$u_{min}(x) = u_{res}(x); \quad 0 < x < l_{con} \tag{1}$$

and using the Green's function, a problem is reduced to a Cauchy type singular integral equation. In the case of self-similar crack (plastic zone sizes are relatively small as compared with crack sizes) the equation takes the form:

$$\int_{0}^{l_{con}} \sigma_{con}(t)\frac{\sqrt{t+l_{cf}}}{x-t}\,dt = 2\pi\gamma\sqrt{x+l_{cf}}\,\frac{\partial}{\partial x}\left[u_{res}(x)-u^{*}_{min}(x)\right] \qquad (2)$$

where u^{*}_{min} is the crack edges displacement after unloading without accounting for contact stresses.

The additional conditions that provide the single-valued solution of a problem are these of continuity at the ends of the maximum and cyclic plastic zones and at the end of contact area.

Equation (2) admits of the closed-form solution in quadratures both in the case of mentioned self-similar crack and rectilinear crack, which length is rather small as compared to those of the plastic zones (physically short crack). This substantially simplifies the future analysis of crack growth as compared with the similar numerical solutions by the finite element method, the most frequently used in literature.

For example, this solution is realized in the case of crack propagation under regular loading with a given stress ratio. The obtained results, in particular, dependence of the SIF range on stress ratio R (Figure 3) check well with the known theoretical and experimental data.

ENERGETIC FRACTURE CRITERION

Fatigue fracture energetic criterion is founded on the hypothesis that the required plastic deformation energy for the formation of new surface area (crack increment) unit is a constant value for a given material. According to the mentioned above, the fatigue crack increment Δl after ΔN cycles of loading is obtained from the energy balance equation:

$$W_{0} + \frac{1}{\Delta l}\sum_{i=1}^{\Delta N} G_{f}^{(i)} = W_{fc} \qquad (3)$$

where W_{fc} is the specific energy of fatigue fracture; W_0 is a quasistatic part of the specific energy in the prefracture zone, i.e. the energy accumulated during one-time loading to the level of maximum loading; G_f is the energy accumulated in the cyclic plastic zone during the i-th cycle of loading:

$$G_f^{(i)} = 2\sigma_Y \int_0^{l_{pf}^{(i)}} \left(u_{max}^{(i)} - u_{min}^{(i)} \right) dx \qquad (4)$$

The energy criterion is the basis for modelling of a real elastic-plastic material with hardening by an elastic-perfectly plastic material. The σ_Y value of the model material is obtained from the condition that the specific fracture energy of the model material is equal to the energy, obtained from the fracture curve for a given material.

The presented dependencies allow to analyse cycle by cycle the fatigue crack growth under arbitrary variation of the loading amplitude. The effectiveness of these dependencies is proved, first of all, by the results of fatigue crack growth rate calculations in 9Х4Ф steel under regular loading with a constant stress ratio (Figure 4).

CONCLUSION

In this paper a complete system of criterial dependencies for description of fatigue cracks kinetics in elastic-plastic bodies under non-regular loading was established using the generalized model of the prefracture zone near the fatigue crack tip, solution of the corresponding boundary value problems of the crack theory for evaluation of the stress-strain state parameters in this zone and energy fracture criterion.

REFERENCES

(1) Budiansky, B. and Hutchinson, J., J. Appl. Mech., Trans. ASME, Vol.45, 1978, pp.267-276.

(2) Fuhring, H. and Seeger T., Eng. Fract. Mech., Vol.11, No.1, 1979, pp.99-122.

(3) Russel, S.G., Eng. Fract. Mech., Vol.33, No.6, 1989, pp.839-854.

(4) Wang, G.S. and Blom, A.F., Eng. Fract. Mech., Vol.40, No.3, 1991, pp.507-533.

(5) Panasyuk, V.V. Dopovidi AN URSR, No. 9, 1960, pp.1185-1189 (in Ukrainian).

(6) Dugdale, D.S., J. Mech. and Phys. Solids, Vol.8, No.2, 1960, pp.100-104.

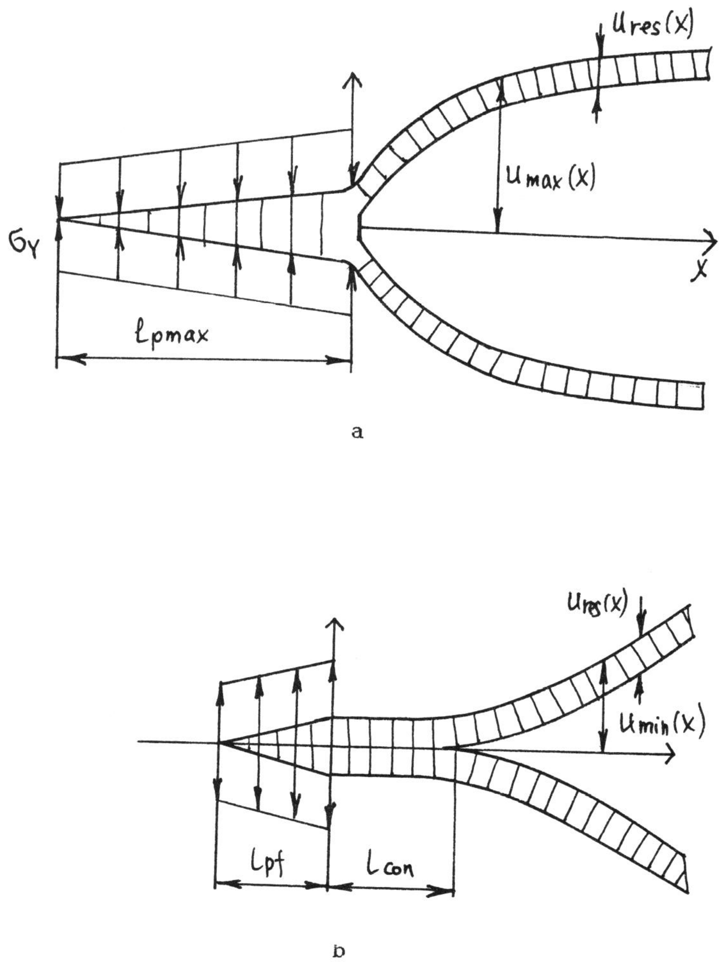

Figure 1 Geometry of crack-tip deformation at maximum (a) and minimum (b) applied loads.

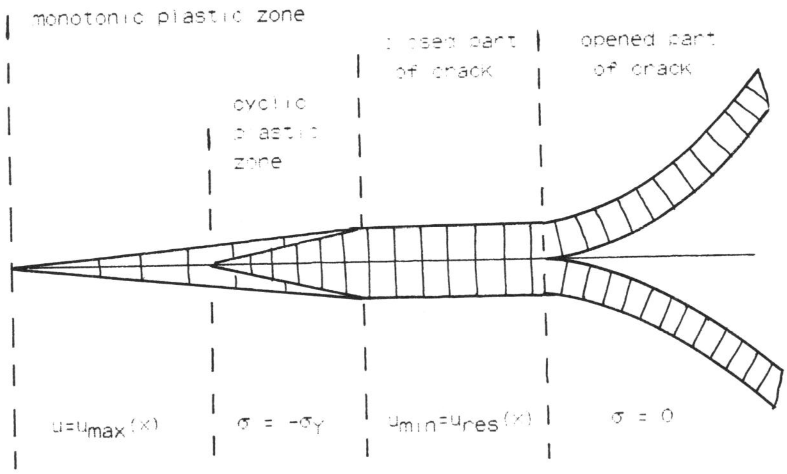

Figure 2 Boundary conditions near fatigue crack tip

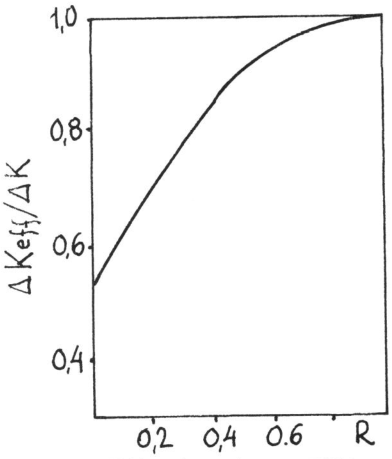

Figure 3 Effective stress ratio as a function of load ratio

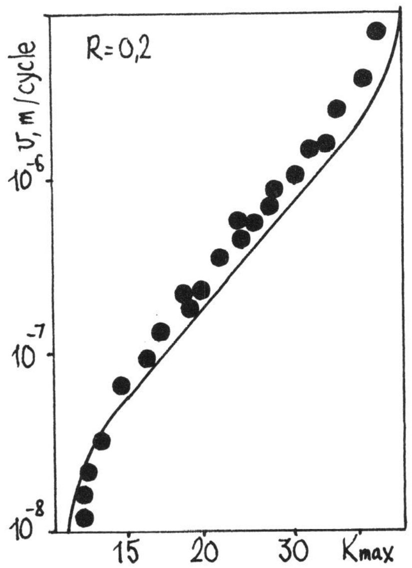

Figure 4 Comparison of experimental and calculated crack growth rates