I1 (초청강연)

DETERMINATION OF FRACTURE TOUGHNESS BY UNIAXIAL TENSILE TEST

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ABSTRACT

The dynamic fatigue life equation is applied to uniaxial tensile test. The resultant equations for the surface energy and fracture toughness are calculated with the data from the tensile test and compared with the ones from ASTM E399 test. During the crack propagation under model loading, the material of the crack tip undergoes the process of the elastic-plastic deformation in the uniaxial tensile test. The surface energy per unit area is proportional to the ratio of plastic and elastic elongations. The calculated fracture toughness of the metals are very well coincident to the ASTM E399's test results.

1. INTRODUCTION

The preparation of the ASTM E399 specimen for fracture toughness measurements is tedious and difficult because of precise machining and crack formation by fatigue.
The measured data are also very scattered if not careful.
The surface energy per unit area for metals can not have been calculated by an exact formula contrary to for brittle materials(Ref. 1).
The tedious fracture toughness test can be completely omitted if the surface energy can be measured from tensile test result.
The dynamic fatigue life equation(Ref. 2) is applied to uniaxial tensile test. The resultant equations for the surface energy and fracture toughness are calculated with the data from the tensile test and compared with the ones from ASTM E399 test(Ref. 3).

2. DERIVATION OF EQUATION FOR SURFACE ENERGY AND FRACTURE TOUGHNESS FROM LIFE EQUATION OF UNIAXIAL TENSILE TEST

Arrhenius model for life equation and S. N. Zhurkov's static fatigue equation are of same type as follows.

$$\tau = \tau_0 e^{\frac{U_0 - \gamma\sigma}{kT}} \tag{1}$$

where τ is life of the material, τ_0 is material constant, T is Kelvin's temperature, k is Boltzman constant, U_0 is bonding energy constant of the material, γ is lethargy coefficient of the material, and σ and T are function of time in dynamic fatigue model, the fracture of the life already passed by as follows.

$$\frac{dt}{\tau_0 e^{\frac{U_0-\gamma\sigma(t)}{kT(t)}}} = \text{fraction of the life passed in } dt \text{ time interval} \tag{2}$$

The whole life is integrated like

$$\int_0^{\tau} \frac{dt}{\tau_0 e^{\frac{U_0-\gamma\sigma(t)}{kT(t)}}} = 1 \tag{3}$$

In ordinary uniaxial tensile test, it is assumed that temperature is constant and stress is linearly increased

$$\begin{aligned} \sigma(t) &= \dot{\sigma} t \\ T(t) &= T = \text{constant} \end{aligned} \tag{4}$$

Equation(3) becomes as (Ref. 2),

$$\int_0^{\tau_f} \frac{dt}{\tau_0 e^{\frac{U_0-\gamma\dot{\sigma}t}{kT}}} = 1 \tag{5}$$

where τ_f is the time from start of loading to fracture finish.

Because the fracture starts at ultimate tensile strength, the stress is maximum at σ_u

$$e^{\frac{\gamma\dot{\sigma}_{N=1}}{kT}} \cong 1 + \frac{\gamma\left(\frac{P_u}{A}\right)}{kT} \cdot \frac{\tau_0}{\tau_f} \cdot e^{\frac{U_0}{kT}}$$

$$e^{\frac{\gamma\dot{\sigma}_{N=1}}{kT}} \cong \gamma \cdot \frac{\sigma_{ut}}{kT} \cdot \frac{\tau_0}{\tau_f} \cdot e^{\frac{\gamma\dot{\sigma}_{N=1}}{kT}} \tag{6}$$

The equation (6) is simplified as

$$\gamma = k\mathrm{T}\frac{\tau_f / \tau_0}{\sigma_{ut}} \tag{7}$$

The surface energy per mole γ_p is

$$\gamma_p = k\mathrm{T}\frac{\tau_f}{\tau_0} \tag{8}$$

The surface energy per unit area is

$$\gamma_p = \gamma_s \frac{\tau_f}{\tau_0} \tag{9}$$

where γ_s is surface energy per unit area for elastic brittle fracture and τ_0 is the time for elastic brittle fracture at σ_u.
If the displacement of the test is linearly increasing with time

$$\gamma_p = \gamma_s \frac{(\Delta\ell)_f}{(\Delta\ell)_{e\ at\ \sigma_u}} \tag{10}$$

Equation (10) can be rewritten as follows.

$$\gamma_p = \gamma_s \frac{(\frac{\Delta\ell}{\ell_0})_f}{(\frac{\Delta\ell}{\ell_0})_{e\ at\ \sigma_u}} = \gamma_s \frac{(\frac{\Delta\ell}{\ell_0})_f}{\frac{\sigma_u}{E}} \tag{11}$$

The best method is to find τ_0 and τ_f in the stress-time curve of the test directly.
Finally the fracture toughness is as follows.

$$\mathrm{K_{1C}} = \sqrt{\tfrac{2}{\pi}\gamma_p \mathrm{E}} \tag{12}$$

3. MICROSTRUCTURAL PROCESSES DURING CRACK PROPAGATION

During the crack propagation under mode 1 loading the material of the crack tip undergoes elastic deformation, yielding, advancing forward strain hardening, ultimate tensile stress and from start of necking to breaking off.
It seems that it simulates elastic-plastic deformation of the uniaxial tensile test.
The crack tip opening is seemingly equivalent to necking in tensile test being advancing.
The development of the theory for fracture mechanics and the understanding of the process of crack propagation in fatigue to describe the behavior of bodies which contain crack are quite useful in reaching to an idea about material's life process together with tensile test.

4. CALCULATION OF FRACTURE TOUGHNESS

(a) For 4340 steel annealed state

$\tau_0 = 8, \tau_f = 58, E = 2.11 \times 10^4\,(kg/mm^2)$

$\gamma_s = \frac{1}{20} \cdot E \cdot b = \frac{1}{20} \times 2.11 \times 10^4 \times 2.87 \times 10^{-7} = 3.03 \times 10^{-4}\,(kg \cdot mm/mm^2)$

$K_{1C} = \sqrt{\frac{2}{\pi} \times 3.03 \times 10^{-4} \times \frac{58}{8} \times 2.11 \times 10^4} = 5.43\left(kg \cdot \sqrt{mm}/mm^2\right)$

K_{1C} *by ASTM E399* $= 5.30$ (Ref. 3)

(b) For 2024 T3 Aluminum

$$\sigma_u = 49.2\ kg/mm^2$$

$$\left(\frac{\Delta\ell}{\ell_0}\right)_{e\ at\ \sigma_u} = \frac{49.2}{E} = \frac{49.2}{7.46\times10^3} = 6.60\times10^{-3}$$

$$\left(\frac{\Delta\ell}{\ell_0}\right)_f = 2.0\times10^{-1}$$

$$\gamma_s = \tfrac{1}{20}\times0.746\times10^4\times4.05\times10^{-7} = 0.15\times10^{-3}$$

$$K_{1C} = \sqrt{\tfrac{2}{\pi}\times0.15\times10^{-3}\times\tfrac{2.0\times10^{-1}}{6.60\times10^{-3}}\times0.746\times10^4} = 4.65$$

$$K_{1C}\ by\ ASTM\ E399 = 4.59\ (\mathrm{Ref}.3)$$

(c) For 7075 T6 Aluminum

$$E = 0.746\times10^4\,(kg/mm^2)$$

$$\gamma_s = \tfrac{1}{20}\cdot E\cdot b = 0.15\times10^{-3}$$

$$\sigma_u = 56.7\ kg/mm^2$$

$$\left(\frac{\Delta\ell}{\ell_0}\right)_{e\ at\ \sigma_u} = \frac{56.7}{0.746\times10^4} = 7.60\times10^{-3}$$

$$\left(\frac{\Delta\ell}{\ell_0}\right)_f = 1.15\times10^{-1}$$

$$K_{1C} = \sqrt{\tfrac{2}{\pi}\times0.15\times10^{-3}\times\tfrac{1.15\times10^{-1}}{7.60\times10^{-3}}\times0.746\times10^4} = 3.29$$

$$K_{1C}\ by\ ASTM\ E399 = 3.16\ (\mathrm{Ref}.3)$$

5. FRACTURE TOUGHNESS UNDER DIFFERENT MEAN STRESS FROM TENSILE TEST

If plastic deformation occurs under different mean stress from tensile test, the elongation, the surface energy per unit area and the fracture toughness are changed because the atomic bonding force reduces or increases with the variation of mean stress.

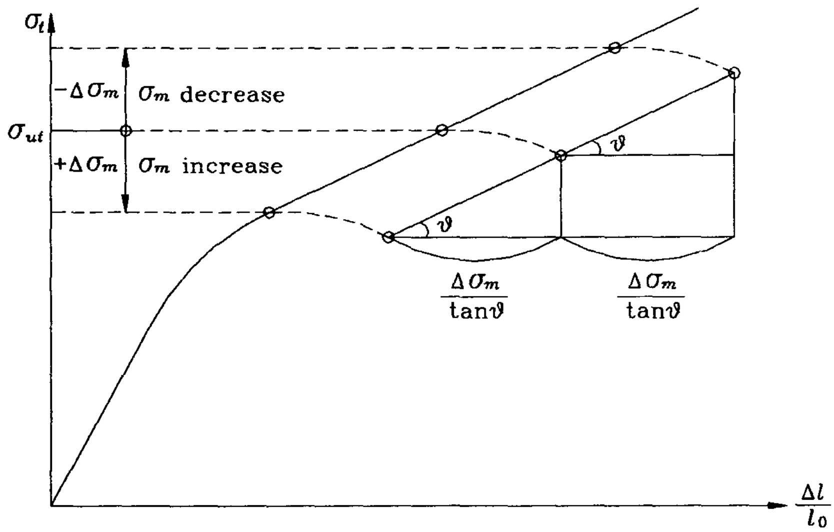

Fig. 1. True stress-elongation curve in uniaxial tensile test with varying mean stress

Because the mean stress in uniaxial tensile test is one third of the axial stress, variation of mean stress is equivalent to three times effect in uniaxial stress.
The elongation change caused by mean stress variation is $(-\Delta\sigma_m / \tan\theta)$ in Fig. 1.
The changed surface energy per unit area is as follows

$$\gamma_p = \gamma_s \frac{\left\{ \left(\frac{\Delta\ell}{\ell_0} \right)_f - \frac{\Delta\sigma_m}{\tan\theta} \right\}}{(\sigma_u - \Delta\sigma_m) / \mathrm{E}} \tag{13}$$

The changed fracture toughness is calculated by equation (12).

6. CONCLUSION

(1) During the crack propagation under mode 1 loading, the process of the elastic-plastic deformation in the uniaxial tensile test.

(2) The surface energy per unit area is proportional to the ratio of plastic and elastic elongations.

(3) The calculated fracture toughness of the metals are very well coincident to the ASTM E399's test results.

(4) The change of elongation caused by different mean stress from tensile test can theoretically be estimated because the atomic bonding force reduces or increases with the variation of mean stress.

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