FAILURE LIFE PREDICTION BY SIMPLE TENSILE TEST UNDER DYNAMIC LOAD

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ABSTRACT

This paper introduces a method to predict the fatigue life of mechanical system either pre-cracked or un-cracked part of a mechanical system on the basis of dynamic failure characteristics by the tensil test. Because of its complex behavior of fatigue in mechanical structures, the analysis of fatigue needs much research on their life prediction. The method presented here for the dynamic tensile strength analysis uses simple tensile test to predict the failure life of various materials. Then that is numerically simulated to analyze the failure life prediction of mechanical system by virtue of its material fracture. Thus the dynamic tensile strength analysis is performed to evaluate the life parameters with a numerical example using the developed method.

KEYWORDS

Fatigue Fracture, Simple Tensile Test, Dynamic Tensile Strength, Failure Life Prediction

INTRODUCTION

The failure of material structures or mechanical systems is likely to cause problems as direct or indirect result of fatigue. To best estimate its reliability in designing a mechanical system, the prediction of failure life is one of the most important failure mode to consider. However, because of its complicated behavior of fatigue in mechanical structures, its analysis requires more study on their life prediction.

Recently the optimum design concept has been widely applied to mechanical design as result of the reduction of its size and weight of mechanical structure. Also today's safety factor of mechanical system is much lower than before. The components are to be more fragile and at the end of their product life cycle they can bring fatal damage to the whole system if latent defects existed in any part of the components. In most related literatures of mechanical structures, the estimation of their safety were studied through the fatigue failure test and the fault finder system such as the expert system using the finite element method at the initial design (Paik, 1990). But the method is complicated, costly and takes long time in finding out the failure effect and devising solutions. Therefore, this paper presents a method to predict the fatigue life of mechanical system either pre-cracked or un-cracked part of mechanical system on the basis of the consideration of the dynamic failure characteristics by the tensil test. This method can be used to obtain the failure characteristics from fatigue in the estimation of failure-safety with a dynamic strength analysis. First, the life prediction equations are derived to evaluate the safety of mechanical system. Then the proposed method is applied to one part of mechanical system for the validation with the numerical calculation and simulation.

THEORY OF STATIC LIFE PREDICTION

For the case of a constant absolute temperature T (K), under a constant tensile stress σ loaded on the small specimen of materials, the failure life (Zhurkov, 1965) can be predicted as the form

$$\tau = \tau_o \exp\left(\frac{U_o - \gamma\sigma}{kT}\right) \qquad (1)$$

where τ is the life time (sec.), τ_o is the life coefficient, U_o is the bonding energy (kJ/mole) on the atomic scale, k is the Boltzmann constant (kJ/mole K), and $\gamma\sigma$ is the function of a tensile stress loaded an uni-axial force.

In a view of statistical dynamics, Eq.(1) gives a probability of failure energy obtained on a mechanical part (i.e., it represents a relationship between the life and the influence parameters for the failure of materials or parts). However, Eq. (1) has a conflict, and it could be happened a bond rupture despite of $\gamma\sigma = 0$. So the equation of life prediction should be used for a big enough given stress (Kim, 1994).

The bonding energy U_o, determinated by the probability of bond rupture for strength from the equation of prediction of static failure as shown in Eq. (1), is essentially needed to separate energy from a material 1 mole of atom, ion or molecular. In other words the bonding energy U_o is equal to the binding energy of atoms in the crystal lattice of metals as listed in Table 1. Also it is in accordance with the activating energy in polymer materials.

Since the life coefficient τ_o is formd in the order of magnitude, its constant value may be taken as 10^{-13}sec. for all different materials in the chemical

Table 1. Bonding Energy (U_o [kJ/mole])

Element	Bonding Energy	Element	Bonding Energy	Element	Bonding Energy
All	309.6	Ni	364.0	Ge	313.8
AgCl	127	Pb	175.7	LiF	1004.2
Cd	117.2	Si	351.5	Mg	142.3
Cu	338.9	Ti	506.3	$NaCl_2$	765.7
Fe	418.4	V	539.7	Nb	627.6

characteristics of structures. The Boltzmann constant k has its value of 8.314 $\times 10^{-3}$ kJ/mole K. Also the loading uni-axial stress is generally expressed in terms of the material coefficient γ and the stress σ (Lee, 1982).

THEORY OF DYNAMIC LIFE PREDICTION

For the function of temperature and time in Eq.(1), the equation of static life prediction can be used for the dynamic life prediction. Before this modification, the validity of this concept must be examined as the following steps:

① The probability of a supplied energy U_o is $e^{-\frac{U_o}{kT}}$ with thermal fluctuation of atoms.

② Under the action of mechanical stress σ, the probability becomes $e^{-\frac{F}{kT}}$. In a stressed body, the interatomic binding energy is reduced in the magnitude of the energy of F. The magnitude of tensile stress inducing thermal fluctuation strongly relates to the chemical bond disrupture through thermal fluctuation.

③ The probability can be written as $e^{-\frac{W}{kT}}$ under the consideration of the consumption energy W in pre-craked one.

Since the frequency of thermal oscillations of atoms is written as dt/τ_o during the time interval dt, the probability becomes

$$e^{(-\frac{U_o - F - W}{kT})}\frac{dt}{\tau_o} \qquad (2)$$

Here, as indicated, there exists a direct relationship between the kinetics of fracture of solids under the action of mechanical stress and the rupture of interatomic bonds. And that relationship enables the mechanism of fracture of solids to be explained as a kinetic process described in Eq.(2). Thus it has a chance to eliminate an atom from lattice by thermal oscillation. The total of these probabilities makes 100%, that is, one atom is fully eliminated from the safety zone on the lattice. Then it is fully broken in a part within a period so called the life of the part.

From Eqs.(1) and (2), the prediction of static failure life yields the dynamic failure life as follows:

$$\int_0^L \frac{dt}{\tau_o \exp\left(\dfrac{U_o - F(t) - W(t)}{kT(t)}\right)} = 1 \qquad (3)$$

This equation shows that the upper-bound of the integral L indicates the life of a part. In the right-hand side of this equation the failure possibility of a part is unity. Therefore this equation can be applied to the part with an initial crack and without one.

Rewriting the parameters in Eq.(3) as $F(t) = \gamma\sigma(t)$, $\sigma(t) = (\bar{\sigma} + \hat{\sigma}\cos\omega t)$, $W(t) = \dfrac{2\gamma_s a(t)}{B}$, with $a(t) = a_i \exp(t)$, and $T(t) = T = \text{const.}$, the equation of the dynamic failure life is

$$\int_0^L \frac{dt}{\tau_o \exp\left(\dfrac{U_o - \gamma\sigma(t) - \dfrac{2\gamma_s a(t)}{B}}{kT}\right)} = 1 \qquad (4)$$

The parameters of Eq.(4) may be replaced by the following variables:
$L = \dfrac{2\pi N}{\omega}$, $\quad \omega t = x$, $\quad t = \dfrac{x}{\omega}$, $\quad \omega = 2\pi f$.
Substituting these variables into Eq. (4), we have

$$\frac{2N}{\tau_o \exp\left(\dfrac{U_o - \gamma\bar{\sigma}}{kT}\right)} \times \int_0^\pi \left(e^{\frac{\gamma\hat{\sigma}}{kT}\cos(x) + \frac{2\gamma_s}{kT}\frac{a_i}{B}\exp\left(\frac{x}{\omega}\right)}\right)\frac{dx}{\omega} = 1 \qquad (5)$$

Then the life time can be obtained as follows :

$$L = \frac{\tau_o \exp\left(\dfrac{U_o - \gamma\bar{\sigma}}{kT}\right) \times \pi}{\displaystyle\int_0^\pi \left(e^{\frac{\gamma\hat{\sigma}}{kT}\cos(x) + \frac{2\gamma_s}{kT}\frac{a_i}{B}\exp\left(\frac{x}{\omega}\right)}\right)\frac{dx}{\omega}} \qquad (6)$$

Therefore, the number of iteration to exhaust the life time can be derived as

$$N = \frac{\tau_o \exp\left(\dfrac{U_o - \gamma\bar{\sigma}}{kT}\right) \times \pi \times f}{\displaystyle\int_0^\pi \left(e^{\frac{\gamma\hat{\sigma}}{kT}\cos(x) + \frac{2\gamma_s}{kT}\frac{a_i}{B}\exp\left(\frac{x}{\omega}\right)}\right)\frac{dx}{\omega}} \qquad (7)$$

where $\bar{\sigma}$ = mean stress (N/mm^2),
$\hat{\sigma}$ = fluctuation stress (N/mm^2),
γ_s = plastic deformation energy (kJ/mole),
a_i = initial defect (mm),
B = thickness of specimen (mm),
f = frequency (Hz), and
N = life cycle (cycle) .

Generally the value of γ_s is 6.02×10^{-1} kJ/mole in most metals. The frequency of failure f (Hz) is related to the bonding energy caused by a fluctuation stress $\hat{\sigma}$ and a mean stress $\bar{\sigma}$. It is a well known fact that in its early stage the failure is localized in defects, and later growth divides the body into parts. The material constant can be interpreted as the magnitude of defects determining the probability of breaking the bonds responsible for its strength: it can be determined by a simple tensile test. From the experimental results as shown in Fig.1, the material constant can be calculated

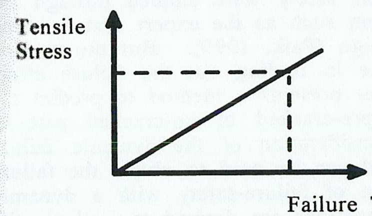

Fig. 1 Tensile fracture with constant loading rate failure time

$$\gamma = \frac{U_o}{\sigma_u}(1 - \eta) \qquad (8)$$

with

$$\eta = \frac{\ln\left(\dfrac{\tau_u}{\tau_o}\right)}{\dfrac{U_o}{kT}} \times \left(1 - \frac{\ln\left[\left(\dfrac{U_o}{kT} - \ln\left(\dfrac{\tau_u}{\tau_o}\right)\right]}{\ln\left(\dfrac{\tau_u}{\tau_o}\right)\left[1 - \left(\dfrac{U_o}{kT} - \ln\dfrac{\tau_u}{\tau_o}\right)^{-1}\right]}\right) \qquad (9)$$

where τ_u is the failure time (sec.) and σ_u is the tensile stress (N/mm^2) . It is very simple process that the material constant γ is obtained from simple tensile test with only two quantities: the tensile strength σ_u and the failure time τ_u .

NUMERICAL CALCULATION AND DISCUSSION

The process for the estimation of life prediction from the equation of dynamic life prediction, derived in Eq. (7), are discussed as follows :

First, find the lifetime (τ_u) by simple tensile test for arbitrary part, and calculate the material constant (γ) by substitution with effective factors tensile strength (σ_u), bonding energy (U_o), life coefficient(τ_o), temperature (T) and etc.

Second, as shown in Fig. 2, compute the value for the prediction of failure life (N) using by the material constant and the equation of prediction of dynamic life.

Finally, compare the values between calculated and experimental result.

SS41 WITH INITIAL CRACK

For the structural steel, SS41 (tensile strength $450.8 N/mm^2$), with the initial crack 4mm, the failure time was measured with simple tensile test and then the material constant is calculated by substitution those known quantities into Eqs. (8) and (9) . As shown in Table 2, the value of prediction life 2.3×10^4 from the numerical failure life is approximately the same of the reference value (Kwon, 1991), 1.99×10^4. Thus the validity for this study has been proved.

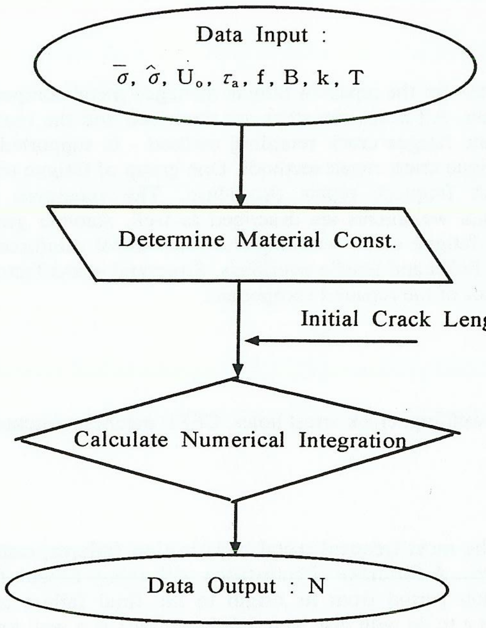

Fig. 2 Flow chart for life prediction

Table 2. Prediction results of pre-cracked SS41 for the simulation (Initial crack = 4 mm)

Bonding Energy	418.4	(kJ/mol)	Fluctuation Stress	132.3	(N/mm^2)
Life Coefficient	10^{-13}		Mean Stress	299.39	(N/mm^2)
Boltzmann Const.	8.384×10^{-3}	(kJ/mole K)	Tensile Strength	450.8	(N/mm^2)
Temperature	R.T 300	(K)	Initial Crack size	4	(mm)
Frequency	15	(Hz)	Thickness	3.2	(mm)
Failure Time	103	(sec.)	Plastic deformation energy	6.02×10^{-1}	(kJ/mole)

	Experimental	Prediction	Error (%)
Life	2.3 e+004	1.99 e+004	15.6

SS41 WITHOUT INITIAL CRACK

In the case of without initial crack, evaluating the failure life to the specimen SS41, with tensile strength $472.36 N/mm^2$, under the simple tensile test and computing the prediction life by substitution those known quantities into Eq. (9), the prediction life obtained 5.03×10^5. The validity of this numerical method is proved by the comparison, as shown in Table 3, this prediction value being approximated with the experimental value (Kwon, 1991), 5.35×10^5.

Table 3. Prediction results of un-cracked SS41 for the simulation (Initial crack = 0 mm)

Bonding Energy	418.4	(kJ/mol)	Fluctuation Stress	183.26	(N/mm^2)
Life Coefficient	10^{-13}		Mean Stress	262.64	(N/mm^2)
Boltzmann Const.	8.384×10^{-3}	(kJ/mole K)	Tensile Strength	472.36	(N/mm^2)
Temperature	R.T 300	(K)	Initial Crack size	0	(mm)
Frequency	15	(Hz)	Thickness	10	(mm)
Failure Time	103	(sec.)	Plastic deformation Energy	6.02×10^{-1}	(kJ/mole)

	Experimental	Prediction	Error (%)
Life	5.35 e+005	5.03 e+005	6.36

CONCLUSION

Under the action of a fluctuation load on SS41, the following conclusions are drawn from the result of this paper for the failure life :

① The failure life is easily obtained by the analysis of the dynamic strength using a simple tensile test and furthermore time and cost are drastically reduced through the computational simulation in use with the simple experiment.

② The method of failure-life prediction under the dynamic load, being introduced in this paper, is used to solve time-dependant problem for the strength of any materials.

Thus this paper made at least several contributions toward the design of advaced mechanical and structural system.

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