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Application of a Kinetic Indentation Technique to Estimate Wear and Fatigue Behaviors of Irradiated Specimens

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ABSTRACT

A method known as the "Kinetic Indentation Technique" was proposed to estimate wear and fatigue resistances by using small specimens and nano-indentation for irradiation study in HANARO. The method is theoretically based on both the proportion of elastic and plastic deformation and the values are obtained by the micro-hardness test. The parameters for the evaluation are obtained from the diagram indentation loading (P), indentation depth (h) and time (t). The relationship of hysteresis to diagram parameters was also obtained to evaluate wear and fatigue behaviors. The method is applicable to estimate wear and fatigue assessments considering the proportion of elastic-plastic deformations of the micro-asperities.

INTRODUCTION

It is necessary to estimate various mechanical properties such as wear and fatigue resistances by using small specimens, especially applying to irradiation study and nano-technology, because of the limited test conditions and facilities. Recently, a nano-indentation method has been an attractive consideration because of its statistical characteristics for indentation. The values are determined by measuring micro-hardness which is a function of indentation depth for a given indenter shape. Statistical parameters of the micro-hardness are generally expressed by a histogram such as indenter-loading vs. print depth. The relationship between indenter loading and print depth allow not only for the complex of mechanical properties of materials but also the characteristics of its structure. In this study, a method known as the “Kinetic Indentation Technique” was theoretically proposed and empirically applied to evaluate wear and fatigue behaviors.

THEORETICAL APPROACH

It is well known that the relationship between elastic and plastic deformation of micro-asperities can be described using the Hook's law for arbitrary elastic or plastic local contact loading. The friction coefficient (f_p) in the deformation is given as equation (1) by the ratio of elastic (W_e) and total (W) deformation works:

$$f_p = 1 - \frac{W_e}{W} \text{ ----- (1)}$$

The parameters of elastic (W_e) and total (W) deformation can be obtained by a continuous indentation loading test. Fig. 1 is the typical indentation loading (P) and indentation depth (h)-time (t) curve in which the parameters are given as respective areas inside the unloading curve 2 and portion 1 and 2 of the figure.

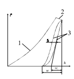

Fig. 1. Typical indentation diagram with three parts: 1 loading; 2 holding under loading; 3 unloading and repeated loading with registration hysteresis loop with the width.

The specimen may show more complete characteristics of the stress-strain state in the tribo-junction. For the ideal elastic loading the indentation diagram becomes reversible curve 3, while that for real quasi-elastic contact becomes the hysteresis loop with the width (δ). The width of hysteresis loop becomes an important parameter in determining the kinetics of wear and fatigue. With increasing plastic deformation in the micro-contact the diagram demonstrates the loading branch 1 in Fig. 1. The width (δ) in terms of dimensionless deformation (ε) can be obtained by normalizing the value with respect to parameters (h) or (W_1) of indentation in Fig. 1. If the net deformation in indentation of the depth (h) equals the width, the deformation (ε) in linear approximation can be expressed as the part of (δ/h) with respect to (ε). The stability on the surface of materials is strongly deformed under wearing. The diagram becomes a smooth plateau and shear of the micro-asperities occurs practically under the condition of constant hardening and elastic strain. Accordingly, the elastic strain can be expressed as follows [2]:

$$\varepsilon_W = \frac{2}{\sqrt{\pi}}\left(\frac{W_i}{\sqrt{A}}\right) = \frac{HM}{E_f} \text{-----(2)}$$

$$\frac{W_i}{\sqrt{A}} = \left(\frac{\sqrt{\pi}}{2}\right)\frac{HM}{E_f} \text{ ------ (3)}$$

where ε_W = HM/E_r,. The equality of ε_W = HM/E_r manifests the Hooks' law on local elastic-plastic loading. The true net contact pressure is less then traditionally measured Meier hardness especially in the region of small plastic deformation [3]. The value of δ depends on the plastic deformation of the micro-asperities. The parameter (δ) is described with the help of (ε) values in indentation. Since geometrically similar indentations (ε) do not depend on (h), a linear approximation in the region of ($\varepsilon_\delta < \varepsilon$) is assumed as follows $\varepsilon_\delta = \varepsilon(\delta/h)$. It is known that ε_δ for Vickers pyramid becomes $0.40\frac{\delta}{\sqrt{A}}$ [2, 3]. Due to the linear relation between (Wi) and ε_W, the hysteresis value is similarly expressed as equation (5) in terms of elastic deformation of indentation as followings

$$\varepsilon_{\delta W} = \varepsilon_W\left(\frac{\delta}{W_i}\right) \text{---- (5)}$$

Dividing the numerator and denominator in equation (5) by ($\sqrt{A}$) and taking into account equation (2) equation (5) becomes equation (6)

$$\varepsilon_{\delta W} = \frac{2}{\sqrt{\pi}}\left(\frac{\delta}{\sqrt{A}}\right) \text{----- (6)}$$

Expression (6) differs from (4) only in coefficient, determined by different nature of elastic and plastic deformation. Comparing these expressions we obtain equation (7):

$$\frac{\varepsilon_{\delta W}}{\varepsilon_\delta} = 2.8 \approx \frac{HM}{\sigma} = 3 \text{ -----(7)}$$

where σ is respective true stress in a simple extension. Equations (1-3) determine the relation between the diagram and friction coefficient. Fig. 2 is obtained by experiment which shows two parts of the dependence *f*(p). Part 1 demonstrates low values of (*f*) and its slight dependency on specific pressure (p) to the area of normal exploitation of the tribo-junction. When increasing the pressure up to (p_k), the intensive growth of the friction coefficient will be observed. This means that on ($P > p_k$) the portion of plastic deformation of the micro-asperities sharply decreases. The tribo-junction becomes the schedule of intensive wear.

The second one of the main parameters is the geometry of micro-asperities determining (p_k). Let us further accept that the (p_k) corresponds to the transition from the region of quasi-plastic loading to the developed plastic strain in a micro-contact. For a spherical indentor with diameter (D) or its pressing up to the indentation diameter (d) the value of (p_k) increases proportionally to the ratio $\frac{HM}{E_r}$. For the values of (d/D < 0.2) which means characteristic of the stationary friction modes, the residual plastic deformation in a local contact is approximated as the equation (8) by the dependence: $\varepsilon = k\left(\frac{d}{D_f}\right)^\beta$ ----- (8)

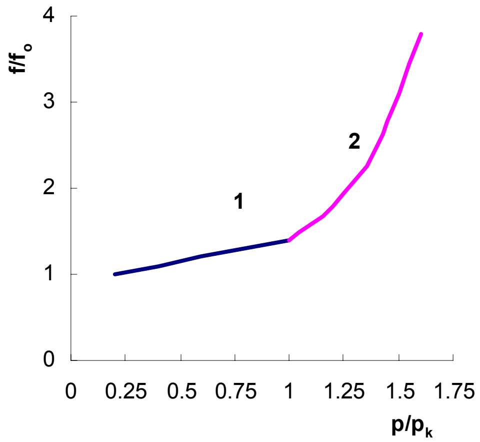

Fig. 2. Typical dependency of friction coefficient on specific mean pressure in the tribo-junction for crystalline solids

where D_f and β are the diameter of the surface of unloaded (recovered) indentation and constant to express plastic deformation, respectively. If there is no residual plastic strain in the indentation the D_f tends to be infinity. The accumulation of plastic strain depends only on hysteresis and its value is approximately equal to the elastic strain (the ratio tends to unity). More precise strain values in the indentation are given by the model of isostatic surface taking into account the dependency of deformation in indentation on the coefficient of material strain hardening (i.e. on Meier index). In this case the linear approximation of the strain inside the interval of $\frac{d}{D_f}$ at n=2.3 gives the value of k=0.134.

To calculate the friction coefficient (f_p) with the help of the parameters of the P-h diagram, the relationship between elementary increase of the works of elastic (dW_e) and total dW strain [5]. If the loading branch is described by the dependency $P = ah^m$, where m is the constant for this diagram, then the equation (9) is satisfied.

$$\frac{dW_e}{dW} = m\frac{w_i}{h} = C_A\sqrt{A}\left(\frac{h_d}{h}\right)\left(\frac{HM}{E_f}\right) \text{----- (9)}$$

where the value of ratio $\frac{dW_e}{dW}$ is given by the slope angle of tangents with respect to branches 1 and 3 of P-h diagram in the boundary point of $P = P_{max}$. To determine the friction coefficient we should take the ratio of the total strain works. If the surface of equivalent micro-asperity is closer to a spherical and conical one, m ≈ me ≅ 1.3 is satisfied. Hence, the friction coefficient (f_p) becomes equation (10).

$$f_p = 1-\left(\frac{m}{m_e}\right)\left(\frac{w}{h}\right) \text{----- (10)}$$

where the power indices m and m_e describe loading and unloading brunches of the P-h diagram. The net friction coefficient ($f = f_o + f_p$), where f_o is the value at a purely elastic contact, is estimated by continuing experimental dependency f(p) up to p=0. Let us denote diameter (radius) of micro-asperities' peaks of equivalent micro-asperity by symbol D_L. Its dimension is given by the Abbot curve. From the geometric consideration of an equi-lateral triangle in which real angles at the top of a conic asperity are much more than ϕ=60_/2, while the apex is rounded, the equation (11) is obtained.

$$D_L = \frac{2R_{\max}}{(1-\sin\phi)} \text{----- (11)}$$

The apex $\left(\frac{h}{R_{\max}}\right)$ is smeared or impressed down to the about value of less than 0.4. Substituting D_f by D_L in equation (8) and normalizing the current value of (ε) with the maximum value of ($\frac{h}{R_{\max}}$ = 1), equation (12) is obtained.

$$\frac{\varepsilon}{\varepsilon_{\max}} = \left(\frac{d}{d_{\max}}\right)^{\beta} \text{ ----- (12)}$$

Since the d_{max} implies that ($\frac{h}{R_{\max}}$ = 1 = ε_h), the relation of ($\frac{d}{d_{\max}}$) = ε_h^{β} is obtained, where ν is exponential coefficient.

Let us assume that wear in the tribo-junction is of a mechanical nature. The ultimate number of cycles N_c of repeated loading on the region of the local contact site is determined by critical value of accumulated plastic deformation ε_c. For a single loading cycle the deformation $\varepsilon = 0.134(\frac{d}{D_f})$ is satisfied. To determine the similarity coefficient, one should take into account the probability of repeated loading of the same micro-asperity on indentation. Let us consider the contour area of contact as A_c (in the model of nominally smooth plane surfaces the contour and nominal area coincide). For this area the net specific pressure equals p. For ($p > p_k$), the local pressure at the equivalent micro-asperity equals HM. If the net contact area of micro-asperities equals (A_r) the probability of their repeated loading in our model equals $\frac{A_r}{A_c} = \frac{p}{HM}$. For the number of cycles with $\frac{A_r}{A_c}$, the probability of related loading of arbitrary micro-asperity tends to 1. This means that the total contour area has been subjected to one loading. Then the process repeats up to an accumulation of N_c cycles. The layer with thickness equal to the dimension of the micro-contact is eliminated from the surface. Therefore the designation of similarity in the expression should be substituted for that of equality so introducing the coefficient of $\frac{A_r}{A_c} = \frac{p}{HM}$. Taking into account this notion, equation (13) is obtained.

$$N_c = \left(\frac{HM}{p}\right)\left(\frac{D_f}{d}\right)\left(\frac{\varepsilon_c}{0.134}\right) \text{ ----- (13)}$$

Hence, the N_c is related to the linear wear with the help of contact diameter in the micro-asperity (d). On reaching the number of repeated cycles, the material layer proportional to (d) is removed from the surface area (Ac). The proportionality coefficient is close to unity. Fig. 3 is the dependency of hysteresis deformation δ/w_1 on the number N of repeated loading cycles of pressure vessel steel and industrial glass, which were obtained by an indentation diagram. As shown in figure 3, the deformation on crystalline materials such as steel gets stabilized after twelve loading cycles, whereas the hysteresis on glass does not depend on N, which means that the steel has fatigue resistance, whereas industrial glass does not have fatigue resistance.[7]

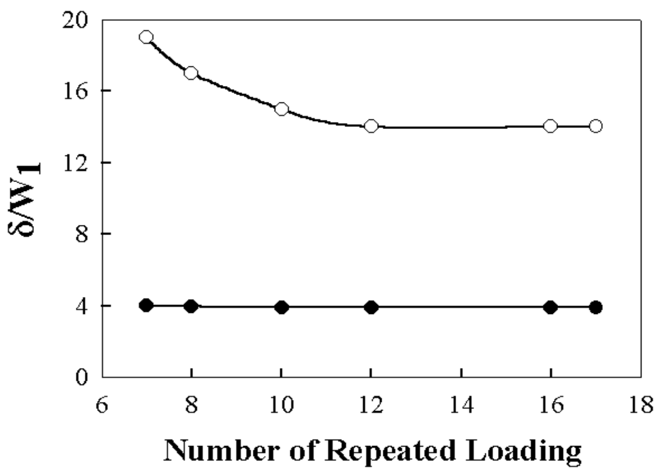

Fig. 3. Dependence of hysteresis deformation δ/w_1 on the number N of repeated loading cycles of pressure vessel steels (•)and industrial glass(•)

SUMMARY

A method known as the "Kinetic Indentation Technique" was proposed to estimate wear and fatigue resistances by using small specimens for irradiation study and nano-indentation. The method is theoretically based on both the proportion of elastic and plastic deformation and the values obtained by a micro-hardness test. The parameters for the evaluation are obtained from the diagram indentation loading (P) indentation depth (h) time (t). The relationship of hysteresis to diagram parameters was also obtained to evaluate wear and fatigue behaviors. The method is applicable to estimate wear and fatigue assessments considering the proportion of elastic-plastic deformations of micro-asperities.

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NOMENCLATURE

W : total deformation
$W_{e:}$ elastic deformation
δ: width
H: indentation depth,
A: area of indentation projection,
HM: Meier hardness,
E_r: contact elastic modulus,
W_i: elastic constant of plastic indentation with area of A and hardness of HM,
σ: true stress
f_p : friction coefficient,
P : typical indentation loading,

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