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Evaluation of Friction Coefficient and Compressive Strength of Graphite Layers of Nuclear Fuel for HGTR by Kinetic Nano-Indentation Technique

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1. Introduction

It is necessary to estimate various mechanical properties such as wear and fatigue resistances of thin coated layers of coated fuel because of the limited test conditions and dimensions. In this study, a method so called "Kinetic Indentation Technique" was applied to evaluate wear and fatigue behaviors. The method is based on both the proportion of elastic and plastic deformation and values obtained by micro-hardness test. In this study, compressive strength and friction coefficient of graphite layers on nuclear fuel are obtained from the diagram of load-indentation depth-time and vilified the values.

2. Theoretical Approach

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 tests.[1] If the net deformation in indentation of the depth (h) equals then deformation (ε) in linear approximation should 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 to the smooth plateau and shear of 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 A is the area of indentation projection, ε_W = HM/E_r, HM is the Meier hardness, E_r is the contact elastic modulus, W_i is the elastic constant of plastic indentation with area of a and hardness of HM. 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 plastic deformation of micro-asperities. The parameter (δ) is described with the help of (ε) values in indentation. Since geometrically similar indentations (ε) does not depend on (h), a linear approximation in the region of ($\varepsilon_\delta < \varepsilon$) is assumed as follows $\varepsilon_\delta = \varepsilon(\delta/h)$. Due to the linear relation between (Wi) and ε_W, the hysteresis value is similarly expressed as equation (4) in terms of elastic deformation of indentation as followings

$$\varepsilon_{\delta W} = \varepsilon_W\left(\frac{\delta}{W_i}\right) \text{---- (4)}$$

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

$$\varepsilon_{\delta W} = \frac{2}{\sqrt{\pi}}\left(\frac{\delta}{\sqrt{A}}\right) \text{ ----- (5)}$$

Expression (5) differs from (4) only in coefficient, determined by different nature of elastic and plastic deformation. Comparing these expressions we obtain equation (6):

$$\frac{\varepsilon_{\delta W}}{\varepsilon_\delta} = 2.8 \approx \frac{HM}{\sigma} = 3 \text{ -----(6)}$$

where σ is respective true stress on simple extension. Equations (1-3) determine the relation between the diagram and friction coefficient.

To calculate the friction coefficient (f_p) with the help of the parameters of P-h diagram, the relationship between elementary increase of the works of elastic (dW_e) and total dW strain. If the loading branch is described by the dependence $P = ah^m$, where m is the constant for this diagram, then the equation (8) is satisfied.

$$\frac{dW_e}{dW} = m\frac{w_i}{h} = C_A\sqrt{A}\left(\frac{h_d}{h}\right)\left(\frac{HM}{E_f}\right) \text{----- (8)}$$

where the value of ratio $\frac{dW_e}{dW}$ is given by the slope angle of tangents of P-h diagram in the boundary point of $P = P_{max}$.

To determine the friction coefficient we should take the ratio of total strain works. The surface of equivalent micro-asperity is closer to spherical and conical one, $m \approx me \cong 1.3$ is satisfied. Hence, the friction coefficient (f_p) becomes equation (9).

$$f_p = 1 - \left(\frac{m}{m_e}\right)\left(\frac{w}{h}\right) \text{----- (9)}$$

where the power indices m and m_e describe loading and unloading brunches of P-h diagram. The net friction coefficient ($f = f_o + f_p$), where f_o is the value at purely elastic contact, is estimated by continuing experimental dependence f(p) up to p=0.

3. Results and Discussion

Fig. 1 is typical indenter-loading-time curve obtained from the buffer graphite layer of coated fuel. As shown in Fig. 1, it is clear that hysterisis curve is formed. Table 1 is hardness, density and strength of graphite layers on a coated nuclear fuel. As shown in Table 1, hardness increases from buffer, IPyC and OPyC in order, which values are 0.55, 0.874 and 2.726 GPa, respectively. The density and strength of the graphite layers estimated by kinetic indentation method are 1.08, 1.15 and 1.81 g/cm^3, and 174, 291 and 606 MPa, respectively.

Table 2 is friction coefficient of graphite on a coated fuel. As shown in Table 2, friction coefficients of the buffer, IPyC, and OPyC are 0.51, 0.45 and 0.4, respectively.

Tatsuo reported compressive strength of sintered graphite with 1.78 g/cm3 density is 87.6 MPa. Stephan also reported the coefficient of friction of sintered graphite is in the range of 0.2-0.6. Although the previous specimen is not equal to the coated layers on nuclear fuel, kinetic indentation method estimates reasonably strength and density, respectively. [2]

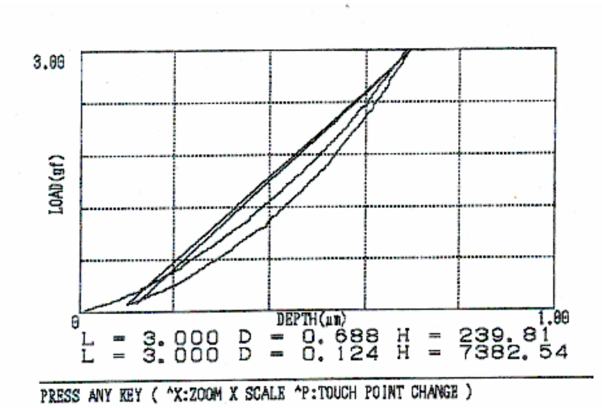

Fig. 1. Load-displacement-time Curve of Graphite Layer of a Coated Fuel.

Table 1. Hardness, Density and Strength of Graphite Layers on a Coated Fuel

	Hardness [GPa]	Density [g/cm^3]	Strength [MPa]
Buffer	0.522	1.08	174
I-PyC	0.874	1.15	291
O-PyC	2.726	1.81	606

Table 2. Friction Coefficient of Graphite Layers on a Coated Fuel

Sample-#	δ	Wi	W	fp
Buffer	11	35	72	0.51
I-PyC	6	11	20	0.45
O-PyC	5	42	70	0.40

4. Summary

Hardness of buffer, IPyC and OPyC are 0.55, 0.874 and 2.726 GPa, respectively. The density, strength and friction coefficient estimated by kinetic indentation method are 1.08, 1.15 and 1.81 g/cm^3, and 174, 291 and 606 MPa, and 0.51, 0.45 and 0.4, respectively.

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