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Physical meaning of the wear volume equation for nitrogenated diamond-like carbon based on energy considerations

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ABSTRACT

A modified Archard–Holms type of wear volume equation was reconsidered in terms of its energetic aspects. Both the wear volume equation and the friction coefficient are treated in terms of frictional energy. A theoretical approach to the wear volume-frictional energy equation proposes that the wear coefficient consists of the wear particle size and surface energy as well as the ratio of the wear energy to the frictional energy. The value of the wear coefficient of nitrogenated diamond-like carbon was estimated using the measured hardness, wear particle size and surface energy and compared to the wear coefficient obtained by the wear volume-frictional energy test on the ball-on-disk method. The wear volume equation, using the Young's modulus instead of the hardness, was introduced based on fracture theory, and the wear volume equation is shown to be equivalent to the conventional wear volume equation for nitrogenated diamond-like carbon.

1. Introduction

The no-friction condition is used in learning Newtonian mechanics at school to predict the motions of bodies. There are very few descriptions regarding tribology in physics textbooks. However, Newtonian mechanics only effectively works for planetary motion. There is no situation where a body moves without friction in the living world. In fact, it is very difficult to imagine the world without friction. Humans would not be able to hold objects by hand. We could not even walk on the ground.

Sliding and rolling motions have been used for a long time to build constructions and transfer materials because they are effective in moving objects though friction. After the Industrial Revolution, mechanical industry has struggled to reduce the heat generation due to friction and the corruption of components due to wear. The friction effect must be added to Newtonian mechanics to predict the accurate motion of objects in the living world.

The Coulomb–Amontons law [1] concerns friction, which states that the frictional force for objects is:

> "When the force exerts for the body to slide on the surface the opposite force in the slide direction, which is proportional to the normal load, exerts the body simultaneously."

Wear is a tribological behaviour. The definition of wear is serial volume loss on a surface due to friction. It seems that the surface is scraped off by the frictional force. Although wear is strongly related to friction, there are no equations to represent the relationship between them. The representative wear volume equation is the Holm–Archard equation:

$$V = k\frac{mgl}{H} \tag{1}$$

where V (m^3) is the wear volume, k is the wear coefficient, m is mass (kg), g is acceleration due to gravity (m/s^2), l is the sliding distance (m) and H is the hardness of the worn material (N/m^2). This equation simply explains general wear behaviour such as wear volume being proportional to the applied load and moved distance, and inversely proportional to the hardness. However, it is relatively unpopular because of the diversity of hardness measurements. There are several methods to measure bulk hardness in industry; for example, the indenter shapes of Rockwell, Vickers and Brinell are conical, pyramidal and spherical, respectively, and so on. The measurement values are not practically unified, though there are some conversion tables. The wear coefficient in each examination using the various hardness indices cannot be compared. In the other words, because the hardness is realised not as a physical property but as a mere measurement value due to its unclear physical meaning, the Holm–Archard equation still does not prevail. When Holm [2] and Archard [3] derived this equation separately, the resistance stress of plastic flow was used in the first instance. However, there was no convenient measurement method

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for the wear volume equation. Khruschov proved that the wear resistance of materials is proportional to the hardness [4]. It is thought that the hardness was used in the place of the resistance stress of plastic flow for the equation, due to the simple measurement method of the hardness after the relationship was disclosed. The other significant issue in tribological behaviour is heat generation on the sliding surface. Civilisation only began to grow after man learnt to make fire using friction. In modern industry, heat generation due to sliding motions is recognised not only as consuming energy but also as degrading tribological performance. Softening of the sliding components or chemical reactions on the sliding surface caused by frictional heat make the tribological behaviours more complicated. An energetic approach is required to investigate the heat effect on the tribological behaviours, and to develop energy-saving technology.

Energetic consideration of the wear mechanism has been widely discussed. Rabinowiez [5] explained the wear volume equation for abrasive wear using a geometrical model, and for adhesion wear based on the surface energy concept. Jahanmir [6] investigated the wear mechanisms due to delamination, adhesion and polishing from an energetic point of view. Kallas [7] investigated the relationship between the injection energy of glass particles and the abrasive wear loss of the metal using the static and kinetic penetration energy of an indenter to a metal surface. Ouadou et al. [8] invented a piece of equipment for a scratch test, hardness test and measurement of three dimension shapes automatically, to evaluate wear energy, wear speed, scratch hardness and scratch toughness. Mohrbacher et al. [9–11] developed a fretting wear mechanism based on an active energetic approach; they concluded that the total dispersion energy was linearly proportional to wear volume in the fretting contact. Fouvry et al. [12–15] further interrogated the fretting wear mechanism in terms of the dispersion energy. Liskiewicz et al. [16] investigated the lifetime of surface coatings using the dispersion energy. This dispersion energy is equal to the frictional energy, because the latter is dispersed as other energetic forms.

There is an energy balance between the frictional energy induced by sliding motion and the dispersion energy consumed by heat, strain, plastic deformation and so on [17]. The motions of the bodies are analysed from a Lagrangian or Hamiltonian energetic standpoint. Generally, the former is described by the kinetic energy T and the potential energy U as:

$$L=T-U \tag{2}$$

How is the dispersion energy D (frictional energy) added in the Lagrangian? The Lagrangian including frictional energy was considered under the simple slope sliding model as shown in Fig. 1. For the slope angle α, the frictional force exerted on the object along the slope is $\mu N \cdot \cos\alpha$. The frictional energy for sliding distance r by the frictional force is

$$D=\mu N\cos\alpha \cdot r=\mu \overrightarrow{N}\cdot\overrightarrow{r} \tag{3}$$

The dispersion energy is added as a negative term in the Lagrangian because the direction of the frictional force is opposite to the sliding direction:

$$L=T-U-D=T-U-\mu\overrightarrow{N}\cdot\overrightarrow{r} \tag{4}$$

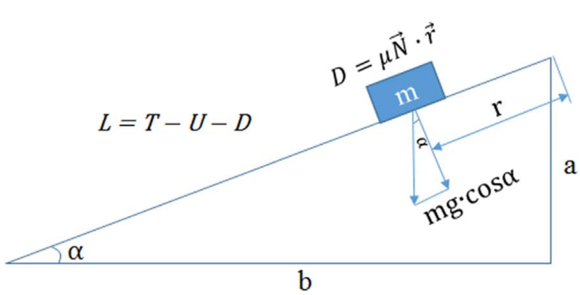

Fig. 1. Slope sliding model.

The kinetic energy of the body in Fig. 1 is $T=\frac{1}{2}m\dot{r}^2$ and the potential energy U is $-mgr\cdot\sin\alpha$, because downward is the negative direction. The Lagrangian for sliding motion in one dimension due to a constant angle α is:

$$L=\frac{1}{2}m\dot{r}^2+mgr\cdot\sin\alpha-\mu mgr\cos\alpha \tag{5}$$

The equation of this motion is

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial L}{\partial \dot{r}}\right)-\left(\frac{\partial L}{\partial r}\right)=m\ddot{r}-mg\sin\alpha+\mu mg\cos\alpha=0 \tag{6}$$

$$m\ddot{r}=mg(\sin\alpha-\mu\cos\alpha) \tag{7}$$

when the object either remains at rest or continues to move at a constant velocity by the end ($\ddot{r}=0$), the friction coefficient μ is

$$\mu=\frac{\sin\alpha}{\cos\alpha}=\tan\alpha \tag{8}$$

The motion equation of the object exerted by the external force F_x on a flat plane ($\alpha=0$) is

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\partial L}{\partial \dot{r}}\right)-\left(\frac{\partial L}{\partial r}\right)=m\ddot{r}-mg\sin\alpha+\mu mg\cos\alpha=F_x \tag{9}$$

$$m\ddot{r}=F_x-\mu mg \tag{10}$$

The required energy for moving the object over the distance l at constant velocity ($\ddot{r}=0$) is:

$$Fx\cdot l=E_f=\mu mgl \tag{11}$$

$$\mu=\frac{E_f}{mgl} \tag{12}$$

The frictional energy E_f is generated by energy input from the power train to operate the sliding motion [18]. Yamamoto et al. introduced a measurement method for frictional energy [19]. Frictional energy is calculated as the summation of the product of the frictional force and the sliding distance in a segment; that is, $\Sigma F(i)\cdot l(i)$. The frictional force and sliding distance data are logged in a tribometer. The energy consumption modes were proposed to be classified as 1) frictional heat: E_h, 2) wear energy: E_w, 3) elastic strain energy: E_e, 4) plastic deformation energy: E_p, and 5) chemical reaction energy: E_c. Therefore, the friction coefficient is described as follows:

$$\mu=\frac{E_f}{mgl}=\frac{(E_h+E_w+E_s+E_p+E_c)}{mgl}=\mu_h+\mu_w+\mu_s+\mu_p+\mu_c \tag{13}$$

where μ_h is the heat factor, μ_w is the wear factor, μ_e is the elastic strain factor, μ_p is the plastic deformation factor and μ_c is the chemical reaction factor [20]. Each consumption energy was also quantified: most frictional energy transforms into heat. That is to say, the substance of friction is related to heat generation.

The reciprocal of the friction coefficient $\varepsilon=1/\mu=mgl/E_f$ is defined as the energy efficiency of the movement over the distance l for an object of the mass m with respect to the energy input (frictional energy) E_f, which can expand the concept of the friction. The energy E_f is not restricted as the frictional energy. The energy efficiency $\varepsilon=1$ ($\mu=1$) is the equivalent to the work of lifting the mass m up to the height l against gravity vertically. In the case of $\varepsilon=10$ ($\mu=0.1$), the horizontal movement distance of the mass m is 10 times greater than the height l on the same energy input. The