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Comparison of interface mechanics characteristics of DLC coating deposited on bearing steel and ceramics

Chongyang Nie, Dezhi Zheng, Le Gu*, Xiaoli Zhao, Liqin Wang

Harbin Institute of Technology, Research Lab of Space & Aerospace Tribology, Hei Longjiang Province, Harbin 150001, China

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ABSTRACT

The load response of a coating and substrate system was built using interface mechanics theory. The characteristics of interface mechanics of diamond-like carbon (DLC) coatings deposited on bearing steel (M50) and ceramics (silicon nitride, Si_3N_4) were calculated, where the results showed that Si_3N_4 substrate could bear greater stresses along the interface than M50 under similar surface load and DLC coating conditions. Since the elastic modulus of ceramics is greater than that of the steel's, when a thicker coating is deposited, there will be a greater increase of interface normal stress for ceramics than for steel, as well as a greater elastic modulus of coatings meaning a greater interface normal stress. The interface transverse stress can be small when the difference of elastic modulus between coating and substrate is minor, meaning a better match. From the scratch test results, the interface bonding capacity of DLC coating with Si_3N_4 and M50 substrate were verified.

1. Introduction

Today, bearing steels are used in high-speed, high-temperature, and heavy-load, as well as other extreme environments [1]. To make a breakthrough of 3.0×10^6 mm r/min in the *dn* value which defines the limit speed of bearings and to indicate their qualities (*dn* = Diameter × Speed), engineering ceramics have been used to create hybrid bearings. A novel bearing material, silicon nitride (Si_3N_4) is harder than steel and its density is only 40% of the latter. Moreover, the Si_3N_4 can withstand both abrasion wear and high temperatures; the dimensions of hybrid bearings are hardly changes with different environments [2]. Hybrid bearings are usually made by a combination of Si_3N_4 and M50, and are suitable to be used in aerospace engines under high temperatures, high speeds, and heavy loads [3]. In other applications, such as gas turbines and air compressors [4], Si_3N_4 is chosen for some mechanical components because of its ability to resist distortion, corrosion, and fracturing.

The results of Tong et al. [5] showed that, the tribo-pair of Si_3N_4 and M50 has a excellent resistance to adhesive wear, on the other hand, the primary failure modes of ceramic and steel were adhesive wear, brittle fractures, and plough wear. Oxidation films were found on the surfaces of the tribo-pair, so the contact stresses and lubricating condition would be changed if low friction and/or wear resistant coatings, such as noble metal, graphite, molybdenum disulfide, and diamond-like carbon (DLC), etc. were deposited on the surface of tribo-pair. Hence the service life and reliability of bearings will just depend on the coatings [6–8] and there is a lot of space for their performance improvement and optimization. Using macroscopic mechanical, microscopic mechanical, nano-mechanical, tribo-chemistry, and material transfer theory, etc., many scholars researched and designed varying coatings for different applications and environments [9–11] aiming to improve stress level in the substrates and enhance bonding strength along the interface.

Scheibert et al. [12–16] investigated the characteristics of coating-substrate systems using the analytical method of coating stresses, while Hauert [17–19], Dearnaley and Arps [20] researched the application technique of DLC coating. Because load-carrying ability and interface bonding strength vary according to different substrates as well as different thicknesses or/and hardness of the coatings, there is a lack of consistent approach to test or evaluate all kinds of coatings. The most common ways to analyze the coatings are qualitative by experiences and trials. For example, Mittal [21] created a stripping experiment to measure the adhesion of the thin film; Teer's group estimated the characteristic of coating by indentation [22–24] and scratching [25–27]. In addition, Allen and Senturia [28] brought about the blister method to measure

* Corresponding author. Tel.: +86 451 86403712; fax: +86 451 86403712.
E-mail address: gule@hit.edu.cn (L. Gu).

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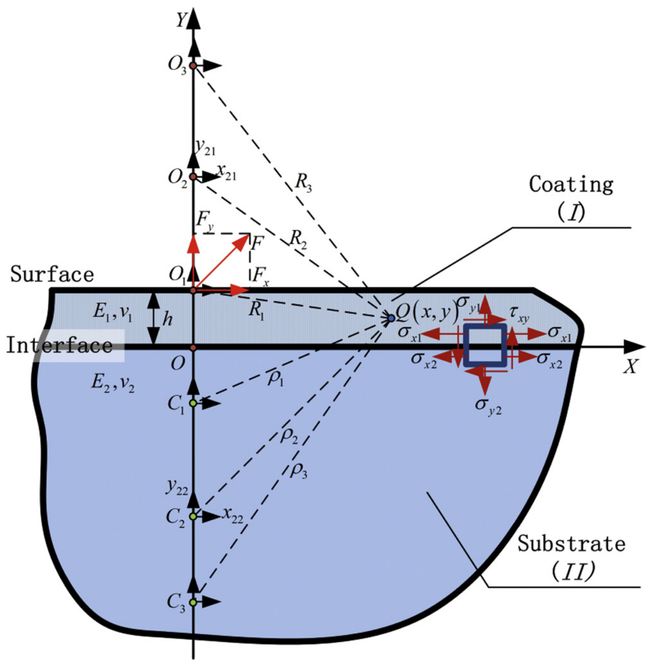

Fig. 1. The analytical model of interface mechanics.

the critical stresses as soon as the coating experienced adhesion failure from the substrate. These experiments were totally reliant on the test samples, instruments, environments, operations, and manipulators, so the results and criterions in these experiments were significantly diverse and impossible to compare with another. Sometimes a conclusion from one test would even contradict the other ones found in different tests.

Based on the analysis of interface mechanics [29–31] in this paper, a coating-substrate system model was built using mathematical formulations, while the interface mechanics characteristics were compared theoretically and experimentally by the amount DLC coating deposited on M50 bearing steel and Si_3N_4 ceramics.

2. Calculation model

Suppose the coatings and the substrates were uniform, isotropic, and linear in elasticity. In the analytical model of interface mechanics of Fig. 1, a straight interface was formed along the adjacent of coating and substrate.

From Fig. 1, coating *I* was used to cover the surface of substrate *II*, connected only by the interface. Above the coating there was a free surface and force marked *F* was applied at point O_1 on said surface. *X*-axis (real axis) was along the interface, and *Y*-axis (imaginary axis) was perpendicular with *X*-axis and passed through O_1. The two axes intersected at *O*, namely the global origin point and the reference frame *XOY*. The elastic modulus of coating *I* and substrate *II* were defined as E_1 and E_2, Poisson's ratio v_1 and v_2, respectively. *h* was the thickness of the coating and, as it was extremely thin in regards to the substrate, was therefore semi-infinite. The force resolution of *F* said $F = F_x + iF_y$ in the *XOY* coordinate.

The interface stresses shown in Fig. 1 could be calculated by the method of images from the complex variable function. The boundary conditions and the constraints of the model were equivalent; furthermore, equations were composed using the relationship between stress and strain. As a method of images, the interface and the surface were imagined as mirrors that reflected point *O* or O_1 and that would generate infinite points of mirror images. These images influenced the interface stresses as a superposition form in order to fulfill the boundary conditions and constraints. Namely, the conditions of interface continuum and free surface were satisfied and interface stresses were gained by superposing the stress solutions of these image points.

When dealing with the isotropic materials, the theory of linear elasticity was chosen and bulk forces neglected. So the Goursat's stress functions in the form of complex variable were written as

$$\begin{cases} \sigma_x - i\tau_{xy} = \varphi' + \overline{\varphi'} - \bar{z}\varphi'' - \psi' \\ \sigma_y + i\tau_{xy} = \varphi' + \overline{\varphi'} + \bar{z}\varphi'' + \psi' \\ 2\mu(u + iv) = \kappa\varphi - z\overline{\varphi'} - \overline{\psi} \end{cases} \quad (1)$$

φ and ψ are Airy's potential functions in Eq. (1). $\overline{X}$ means the conjugate of *X*. μ is shear elasticity modulus, and its relationship with *E* and v is in the form of $\mu = 0.5E/(1+v)$. κ is Kappa parameter by $\kappa = 3\text{–}4v$ for plane strain and $\kappa = (3-v)/(1+v)$ for plane stress, respectively. The model of this paper is concerned with plane stress.

With respect to plain equations and convenient programming, the iterative expressions will be written in the form of polynomials [32].

Denote $m_1 = (\beta - \alpha)/(1 - \beta)$ and $m_2 = (\alpha + \beta)/(1 + \beta)$

Supposing A_k and B_k are $A_k = u_0 + u_1 \ln z_k + \sum_{j=1}^{N} \frac{u_{j+1}}{z_k^j}$ and $B_k = v_0 + v_1 \ \ln \ z_k + \sum_{j=1}^{N+1} \frac{v_{j+1}}{z_k^j}$. Then the potential functions of Eq. (1) are

$$\Phi_k = m_1 \left\{ \begin{aligned} & \overline{u_1} + \overline{v_0} + \overline{v_1} \ln s_k + \frac{1}{s_k}[\overline{v_2} - \overline{u_2} - ih(2k-1)\overline{u_1}] \\ & + \sum_{j=2}^{N} \frac{1}{s_k^j}[\overline{v_{j+1}} - j\overline{u_{j+1}} + ih(j-1)(2k-1)\overline{u_j}] + \frac{1}{s_k^{N+1}}[ih(2k-1)N\overline{u_{N+1}} + \overline{v_{N+2}}] \end{aligned} \right\} \quad (2)$$

$$\begin{aligned} \Psi_k = & -(m_2\bar{u}_0 + m_1\bar{v}_1) - m_2\overline{u_1}\ln s_k + \frac{1}{s_k}[ihm_1(2k-1)(\overline{v_1} - \overline{u_1}) \\ & + m_1\overline{v_2} - (m_1 + m_2)\overline{u_2}] + \frac{1}{s_k^2}[2m_1\overline{v_3} \\ & - (4m_1 + m_2)\overline{u_3} - m_1(2k-1)^2h^2\overline{u_1} - ihm_1(2k-1)(\overline{v_2} - 3\overline{u_2})] \\ & + \sum_{j=3}^{N} \frac{1}{s_k^j}\{jm_1\overline{v_{j+1}} - (j^2m_1 + m_2)\overline{u_{j+1}} - ihm_1(2k-1)(j-1)[\overline{v_j} \\ & - (2j-1)\overline{u_j}] + m_1(j-1)(j-2)(2k-1)^2h^2\overline{u_{j-1}}\} \\ & + \frac{m_1}{s_k^{N+1}}\{(N+1)\overline{v_{N+2}} + N(N-1)(2k-1)^2h^2\overline{u_N} - ih(2k-1) \\ & \times[N\overline{v_{N+1}} - N(2N+1)\overline{u_{N+1}}]\} + \frac{m_1}{s_k^{N+2}}\{(2k-1)^2h^2N(N+1)\overline{u_{N+1}} \\ & - ih(2k-1)(N+1)\overline{v_{N+2}}\} \end{aligned} \quad (3)$$