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Variations in erosive wear of metallic materials with temperature via the electron work function

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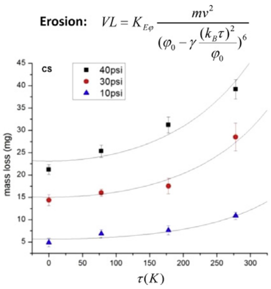
HIGHLIGHTS

- Metallic materials' wear resistance is influenced by temperature.
- Electron work function (EWF) intrinsically determines materials' wear resistance.
- An EWF-based temperature-dependent solid-particle erosion model is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Mechanical properties of metals are intrinsically determined by their electron behavior, which is largely reflected by the electron work function (*EWF or* φ). Since the work function varies with temperature, the dependence of material properties on temperature could be predicted via variations in work function with temperature. Combining a hardness − φ relationship and the dependence of work function on temperature, a temperature-dependent model for predicting solid-particle erosion is proposed. Erosive wear losses of copper, nickel, and carbon steel as sample materials were measured at different temperatures. Results of the tests are consistent with the theoretical prediction. This study demonstrates a promising parameter, electron work function, for looking into fundamental aspects of wear phenomena, which would also help develop alternative methodologies for material design.

1. Introduction

Though microstructure is a predominant factor governing the performance of materials, intrinsic mechanical properties of metallic materials, e.g., Young's modulus, yield strength and ductility, are fundamentally determined by their electron behavior [1–7]. The electron behavior is reflected by the electron work function (EWF), which is the minimum energy required to move electrons at Fermi level from inside a metal to its surface without kinetic energy [8]. This parameter may provide supplementary clues for material design and modification. For instance, EWF can be used to select appropriate alloying elements for solution-strengthening and to identify beneficial and detrimental phases in multiphase alloys. These capabilities of EWF have been demonstrated by recent studies [9–11]. It should be indicated that mechanical properties of realistic materials are strongly affected by

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their microstructure, which complicates the dependence of the properties on the electron behavior. However, the mechanical properties of a material can still be reflected by its overall electron work function to a certain degree, since the overall EWF is linked to EWFs of individual phases and interphase boundaries, which play roles in determining the overall properties. The correlation between the overall EWF and those of individual microstructure constituents has been under active study.

Electron work function varies with temperature [11–13]. Thus, the dependence of material properties on temperature could be established via EWF-temperature relationship. In this article, the dependence of material loss on temperature, caused by solid-particle erosion, is proposed by combining a simple erosion model, EWF-hardness and EWF-temperature relationships. Solid-particle erosion tests were performed for three sample materials, Cu, Ni and carbon steel, at various temperatures. The first two are single-phase pure metals and the third is a two-phase material consisting iron and cementite. The objectives of this work are 1) to determine if the effect of temperature on erosion is predictable based on the dependence of work function on temperature, and 2) to have a preliminary look into possible influence of the second phase (cementite) in the steel on the prediction.

As reported in the article, the trend of material loss of both the single-phase and two-phase materials with temperature is in agreement with the theoretical prediction. The second phase, cementite, affects the erosion resistance of the steel. Such effect could be included in or reflected by a relevant material coefficient, e.g., $K_{E\varphi}$ and γ in Eq. (7), so that the established model could also be applicable to two-phase or multiphase materials. However, the generality of the model for multi-phase materials need further studies, since influences of metallic and non-metallic phases on the overall work function should be different. The established erosion-temperature relation based on EWF may help develop new approaches for looking into fundamental issues of tribological phenomena.

It may need to indicate that the effect of temperature on the erosion resistance can be directly evaluated based on the dependence of hardness on temperature without involving the electron work function. However, the ultimate objective of this study is to reveal the correlation between the electron behavior and mechanical & tribological properties. Such correlation would provide supplementary clues for material design. As a matter of fact, considerable studies have been conducted with a long history to correlate mechanical properties with the electron behavior using quantum mechanics. However, the quantum theory is too complicated to be feasibly used in material development especially for structural materials. Studies have shown that the electron behavior is largely reflected by the work function, a simple but fundamental parameter, which much facilitates the efforts in correlating the tribological properties with the electron behavior.

Although in an early stage of study, this work has demonstrated the link between the intrinsic wear resistance of materials and their work functions, and also shown the promise of using work function in development of supplementary approaches or alternative methodologies for material design and modification on a feasible electronic base.

2. Temperature-dependent erosion model

For a ductile material, the contact created by the impingement of particle, Ac, is proportional to the impact contact force (F) and inversely proportional to the hardness of the material (H) as described in [14,15],

$$A_c \propto \frac{F}{H} \tag{1}$$

During erosion, the impact force comes from the kinetic energy of solid particle associated with its moment change when striking the target surface:

$$\mathrm{F} = -\mathrm{m}\frac{dv_y}{dt} \tag{2}$$

where m is the mass of the particle striking the surface, and v_y represents the vertical component of the velocity of the particle. Thus we have

$$\mathrm{m}\frac{dv_y}{dt} = -HA_c$$

$$\mathrm{m}\left(\frac{dy}{dt}\right)\cdot dv_y = -HA_c\cdot \mathrm{dy}$$

$$\therefore \int_v^0 mv_y dv_y = -\int_0^d HA_c dy = -\int_0^d HA_c(y)dy$$

If the particle strikes the surface at 90°, the above integration yields

$$\textit{Indention volume},\ V = A_c\cdot d = \frac{mv_y^2}{2H}$$

A_c is the average contact area and d is the depth of indent made by the particle. If the particle strikes the surface at a certain angle, the horizontal velocity needs to be taken into account. Thus, a general relation between the erosion volume loss (V) and material's hardness is expressed as

$$VL = K_E\frac{mv^2}{H} \tag{3}$$

where K_E is an erosion coefficient, which is related to the impingement angle of the particle and other factors such as the size and angularity of the particle. Hardness of a metal is its resistance to plastic deformation, dependent on the number of slip systems, elastic modulus and Poisson's ratio etc. It has been shown that H is related to the work function in the following form [16]:

$$H\left(1-\mu^2\right) = C\varphi^6 \tag{4}$$

where μ is the Poisson's ratio, C is a coefficient dependent on the crystal structure, the number of activated slip systems, Burgers vector, and the dislocation width, etc. Combining Eq. (4) and Eq. (3) yields

$$VL = K_E\frac{mv^2}{H} = K_{E\varphi}\frac{mv^2\left(1-\mu^2\right)}{\varphi^6} \tag{5}$$

When the hardness is converted to the work function, the coefficient K_E is replaced by $K_{E\varphi}$ Reza and Li [17] derived a relation between the work function and temperature, expressed as:

$$\varphi(\tau) = \varphi_0 - \gamma\frac{(k_B\tau)^2}{\phi_0} \tag{6}$$

where φ_0 is the work function at room temperature (i.e. 295 K), $\tau = T - 295$ and T is the absolute temperature (K). γ is a material