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Electron work function, adhesion, and friction between 3d transition metals under light loads

Yanping Li*, D.Y. Li

Department of Chemical and Materials Engineering, University of Alberta, Room 536, Edmonton, Alberta, Canada T6E 2G6

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Abstract

Adhesion and friction between metallic materials are of importance to many dynamic mechanical systems, particularly to those at nano- or micro-scales. Under light loads, friction is mainly dependent on the adhesion between two surfaces in contact, to which valence electrons have the predominant contribution. However, the correlation between the electronic behavior and adhesion as well as friction has not been well established.

This paper reports the authors' recent studies on the correlation among electron work function (EWF), adhesion and friction of transition metals. The EWF is the minimum energy required to remove an electron from the Fermi level. This parameter characterizes the electronic behavior of metals and can be determined experimentally. In this study, the metal–metal friction under light loads was evaluated employing a micro-tribometer. It was demonstrated that adhesion and friction of the transition metals were closely related to their electron work functions. The adhesion between two different metals in contact could be expressed as a function of their EWFs and electron densities. Consequently, the friction between the two metals under light loads could be estimated based on these two parameters.

Keywords: Electron work function; Adhesion; Friction; Metals

1. Introduction

Adhesion has attracted extensive interest because of its importance to many surface processes, such as friction, wear, and adsorption [1]. Adhesion could be particularly important to nano/micro devices. In this case, the light contact force and smooth contact surfaces render the friction to be dominated by adhesion, and mechanical plowing is less important [2,3]. Fundamental understanding of adhesion between two metals could therefore be necessary for operation and optimization of nano/micro-devices.

Considerable efforts have been made to fundamentally investigate adhesion and friction between two metals using experimental and theoretical approaches. Rabinowicz correlated friction coefficients of clean metals to their ratios of adhesion energy to hardness [2]. Buckley examined the adhesion between (0 1 1) face of iron and surfaces of other metals, and showed that the chemical reactivity of the metals was directly related to their adhesion behavior [4]. He also demonstrated that metals with larger percentages of d valence bond character had lower friction coefficients [1]. Sikorski [5] investigated the adhesion of different metals by applying the twist-compression bonding method under normal atmospheric conditions and showed that high friction was always accompanied with strong adhesion, which was influenced by melting point, crystal structure, mutual solubility and hardness, etc. Calculations of adhesive force from first principles have also been made [6–11], which shed light on the adhesion mechanism; however, clear correlation between adhesion of metals and their fundamental properties, e.g., the electron behavior, has not yet been established.

Different mechanisms have been proposed regarding the adhesion between two metals; it is undoubted that the intrin-

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* Corresponding author. Tel.: +1 780 4925157; fax: +1 780 4922881.
E-mail address: yanpingl@ualberta.ca (Y. Li).

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sic adhesion largely depends on the surface electronic configuration and properties [4,12–14]. The electron behavior of a metal can be characterized by its electron work function (EWF), the minimum energy required for an electron to escape from the Fermi level to a point just outside the bulk metal [15]. The EWF is one of fundamental electronic properties of a metallic surface, which can be measured quantitatively and is related to various properties of metals and semiconductors as well as many surface processes, such as adsorption, contamination, surface segregation and friction [16–18]. Studies have been conducted to investigate the relationship between EWF and metal–ceramic adhesion. It was observed that higher EWF corresponded to lower adhesive force for metal–ceramic contact [19,20]. Since ceramic is relatively inert, the EWF of the metal therefore largely determined the adhesion and friction for the metal–ceramic contact. For metal–metal contact, the situation is complicated. In this case, the EWFs of both metals are of importance to adhesion because charge transfer exists between the two different metals, which results in an internal electric field [6,9,21].

The objective of this work is to investigate the relationship between the EWF and adhesion for 3d transition metals. Transition metals and their alloys are widely used in engineering practice, often involving dynamic metal–metal contact [22]. The interaction between transition metals is more complicated than simple metals because of their electronic configurations [6]. The adhesion behavior of transition metals is a topic of both practical and theoretical interests. Due to the difficulty in direct determination of adhesion between the metals, in this work, friction was used as a parameter to evaluate the adhesion behavior. This is acceptable when the contact load is light. It is known that the friction force is the summation of two contributions: the adhesive force and the deformation force. The ratio of these two contributions varies with the contact condition especially the contact force [23–25]. Our previous study has demonstrated that under light loads, adhesion plays a predominant role in controlling the friction force [20].

2. Experimental procedure

2.1. Samples preparation

Materials under the study were 3d transition metals provided by Alfa Aesar and Strem Chemicals Companies (Table 1), respectively. All metal samples (plates) were annealed in Argon atmosphere at temperatures above their recrystallization points for 1 h and slowly cooled down in furnace. The annealing temperatures for the metals are listed in Table 2 .

Table 1
Composition of 3d transition metals under study

Metal	Purity (%)
Ti	99.2
V	99.5
Cr	99
Mn	99.9
Fe	+99.97
Co	+99.9
Ni	+99.9
Cu	+99.9

The samples were then lightly polished using a slurry containing aluminum oxide powder (0.05 μm). After polishing, the samples were ultrasonically cleaned in reagent grade acetone (10 min) and reagent alcohol (5 min). All tests were carried on the polished surfaces without etching in order to (1) reduce the probability of formation of surface films, and (2) to minimize the orientation effect on friction measurement. Friction tests were performed under unlubricated condition in ambient environment [(22 ± 2 °C, 45 ± 5% relative humidity (RH)].

2.2. Friction measurement

Coefficients of friction of the metals in contact with Fe were measured using a universal micro-tribometer (UMT) provided by CETR, California, USA. Before the friction test, a small plate of iron with dimensions 4 mm × 4 mm × 1.2 mm slid reciprocally on a bigger dissimilar or similar metal sample under a load of 40 mN for six passes. The bigger samples had various dimensions (plates) with their surface areas large enough for the sliding process. The sliding distance was 6 mm for each pass and the sliding speed was 4 mm/s. The aim of this reciprocal sliding process was to remove a possible oxide scale or an adsorption layer on the surface. Single-pass sliding tests were then performed under different constant loads from 1 to 40 mN at a sliding speed of 3 mm/min over a sliding distance of 6 mm. Both normal load (F_N) and frictional force (F_L) were measured during the single-pass sliding process. Friction coefficients ($\mu = F_L/F_N$) of the transition metals against iron were obtained by averaging three measurements or more to ensure the consistency of the friction measurements.

3. Results and discussion

3.1. Friction measurement under light loads

Adhesion and friction of metals are surface phenomena and depend on physical and chemical properties of the met-

Table 2
Annealing temperature

Metal	Annealing temperature (°C)
Ti	500
Fe	500
Co	500
Ni	500
V	630
Cr	630
Mn	390
Cu	390