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Fundamental investigation of micro-scale wear characteristics of ultra-fine gold wires under low contact force and long sliding distance

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ABSTRACT

Micro-scale wear characteristics of ultra-fine gold wires with a diameter of ~28 μm was investigated under a low contact force over a long sliding distance up to ~200 km. The tip of the wire was slid against a silicon wafer under a low normal force of 5 μN. Wear of the gold wire was quantified from the images of the tip obtained by a 3D laser microscope and a scanning electron microscope before and after the wear test. The dimensionless Archard relationship wear coefficient was in the order of 10^{-7} which was extremely low considering that sliding was carried out in dry condition. Such a low wear characteristics was attributed to low contact pressure that could be achieved by formation of a conformal contact due to flattening of the wire tip as sliding wear progressed. Wear behavior of the gold wire could be characterized by formation of thin flakes of wear debris that were generated as a result of adhesive shear stress imparted at the sliding interface. As an effort to reduce the wear coefficient even further, octadecyltrichlorosilane self-assembled monolayer was deposited on the silicon to serve as a nano-lubricant. It was effective in improving the wear resistance by about two-fold.

1. Introduction

Gold, which is a precious transition metal, has several unique physical and chemical properties that make this material attractive in various industrial applications. In addition to good chemical stability, gold has a very high electrical conductivity with good ductility and malleability [1]. Also, owing to its excellent manufacturability, gold can be fabricated in a variety of physical forms such as bulk, films, coatings, and nanoparticles [2–4]. Particularly in applications related to tribology, gold has been extensively utilized in dentistry as dental restorative materials, in electronics as electrical contact junctions including slip rings and in mechanical systems as solid lubricant coatings. As such, the tribological properties of gold have been extensively investigated with respect to these application fields.

In dental application of gold, basic concerns have been the chemical stability and wear resistance of gold as a dental restorative material. Also, the wear incurred by the tooth enamel due to the use of gold compared to other materials has been a major issue. In one of the earlier works, Hacker et al. have shown that wear of enamel was the least when gold alloy was used as the restorative material compared with porcelain-based ceramic materials [5]. This work also showed that wear of the gold was lower than that of the ceramic materials. However, the mechanism of wear of gold was not investigated in detail though adhesion was mentioned as the most likely mechanism. A similar work performed by Al-Hiyasat et al. also showed that gold was the least abrasive material and most resistant to wear among several candidate materials when tested against human enamel in *in vitro* wear tests [6]. In a recent study, the wear characteristic of gold restorative material was compared with that of zirconia when tested against enamel [7]. It was determined that gold was superior to zirconia with respect to wear incurred by enamel which led to the conclusion that gold is a good restorative material if esthetics is not a concern. Despite the advantages of using gold as a dental restorative material, a most recent study has raised concerns that wear of gold due to long usage can lead to health risks [8]. In this regard, there is still a need to better understand the fundamental wear mechanism of gold with the aim to improve its wear resistance.

Gold is also used extensively in electrical contact applications [9,10]. To assure proper operation of electrical systems with switches or relays, the contact resistance at the junctions should be low. However, due to vibration, thermal fluctuation, and

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mechanical impact the contact resistance often increases over time due to oxidation and wear of the contact surfaces. In this regard, gold has been used extensively as electrical contact materials owing to its anti-oxidation property, high conductivity, and good solderability. In an earlier work conducted by Antler and Drozdowicz it was shown that fretting wear is a major mechanism of failure of electrical contacts [11]. As a remedy to enhance the durability of gold electrical contacts, increasing the thickness of the gold coatings was recommended in this work. In other studies, the addition of hard metal oxide nanoparticles in gold was suggested to increase the wear resistance of gold electrical contacts [12,13]. However, there was a concern regarding the increase in the electrical resistance due to inclusion of the oxide particles. In this regard, Mogonye et al. have proposed that implantation of He ions into gold electrical contacts can improve the tribological properties of the contact without compromising the electrical resistivity [14]. As efforts to understand the wear characteristics of gold electrical contacts in various operating conditions, the effects of current load [15], temperature [16] and vibration [17] have also been investigated. Results showed that all these factors have a significant effect on the fretting wear behavior of gold electrical contacts. These findings emphasized the importance to minimize vibration and temperature increase to prolong the durability of electrical contacts as well as the need to enhance the wear resistance of gold contacts.

In other applications related to electrical contacts, gold is also used as a coating material for printed circuit board terminals and mobile phone connectors in which similar surface degradation issues exist as those experienced in electric switches or relays [18,19]. Gold is also used as a material for brushes and coatings for slip rings for rotating machinery with electrical connectors. Slip ring brushes are typically comprised of multiple wires with a small diameter that slide against a rotating slip ring while conducting electric current across the contact interface. Lubricant is often used to reduce the friction and wear of the slip ring system. However, Ueno et al. showed that the use of lubricant increased the contact resistance of the slip ring significantly and also caused the voltage–current relationship became non-linear [20]. Therefore, for better performance of slip rings for precision devices, the wear resistance of the gold brushes should be sufficiently enhanced to eliminate the need for a lubricant.

Solid lubrication is another important tribological application of gold [21,22]. Solid lubricants are typically used in situations where liquid lubricants cannot be applied due to high temperature or vacuum conditions [23,24]. These lubricants need to provide low shear strength at the sliding interface, and therefore, relatively soft materials are used. They also function by providing a transfer film to the counter surface such that low friction can be maintained even with the occurrence of wear. In this regard, gold can be effectively utilized as a solid lubricant either as a coating or as a filler in other materials. Deepthi et al. showed that solid lubrication performance of gold can be enhanced by mixing with WS_2 to form a nano-composite coating [25]. It was shown that smooth transfer film was successfully formed on the counter surface by combining these two materials. Miyake et al. employed gold together with diamond-like carbon (DLC) to create a multilayer solid lubricant film [26]. The results showed that the multilayer films comprised of DLC/Au exhibited lower friction and wear than the individual monolayer films.

Considering the wide applications of gold that are concerned with electrical contacts and sliding components as discussed above, it is important to clearly understand its wear characteristics in order to improve the tribological properties. Though there have been numerous studies that address the wear characteristics of gold for specific applications, fundamental studies on the micro-scale wear characteristics of gold have not been performed sufficiently. In this work, the approach taken to gain this fundamental understanding was to conduct wear tests using a thin gold wire under relatively low contact forces over a long sliding distance against an extremely smooth surface such as a silicon wafer. This approach was taken in order to limit the wear mechanism to adhesion by minimizing the abrasive interaction between the gold wire and the counter surface. Adhesion is thought to be the basic wear mechanism between two contacting surfaces that would always occur to a certain extent whereas abrasive wear due to asperity or particle interaction may be mostly eliminated by maintaining a low contact force and by using extremely smooth surfaces. Also, since gold is not readily oxidized, its fundamental micro-scale wear behavior may be probed without the concern for oxidation wear.

Wear tests were conducted by contacting the tip of a gold wire specimen with a diameter of $\sim 28\ \mu m$ against a silicon wafer which was made to rotate at a certain angular velocity. Force was applied by the elastic deflection of the gold wire. Following the wear test, wear of the gold wire specimen was characterized using a 3D laser microscope and a scanning electron microscope (SEM). Furthermore, the effect of using octadecyltrichlorosilane ($CH_3(CH_2)_{17}SiC_{13}$) self-assembled monolayers (OTS-SAM) in reducing the wear of gold wire was investigated. The results of this work are expected to lead to better understanding of wear mechanisms of gold that would ultimately aid in improving its tribological performance in various applications.

2. Experiment details

2.1. Specimen preparation

For the wear tests performed to understand the fundamental characteristics of micro-scale wear of gold, commercialized gold bonding wires (MK Electronics Co., Ltd.) with a purity of 99.99% that are used in the semiconductor industry were utilized. These wires are typically fabricated through a series of processes that include casting, multiple drawing, annealing, refinement, and winding [27]. The wires were cut using a sharp blade to 5 mm lengths and were attached to a silicon piece ($2 \times 3\ mm^2$) that served as a mount to allow easy handling of the wire specimens. Care was taken to cut the wires such that a flat and smooth cross-section was obtained. After viewing the cut wires under a microscope, only the ones with relatively intact cross-sectional profiles were selected to be used in the experiments. For the counter surface, a very smooth and flat silicon wafer was used to minimize the effects of surface roughness on the wear behavior of gold. Though silicon is not typically used as a sliding material against gold in practical applications, it was thought to be adequate as a counter surface material to assess the fundamental wear behavior of gold. In the wear experiments, $40 \times 40\ mm^2$ square pieces cut from silicon (100) wafers were utilized. Prior to the wear test the silicon specimens were cleaned in an ultrasonic bath while immersed in acetone, ethanol and deionized water for 10 min each to remove the contaminants.

As an effort to reduce the wear of gold wire, OTS-SAM was deposited on the silicon specimen. OTS-SAM readily forms a tightly-packed monolayer coating on silicon with the head group of the OTS-SAM chain bound tightly to the silicon surface by covalent bonds [28]. OTS-SAM has been effectively utilized in increasing the hydrophobicity and reducing the surface energy as well as adhesion of silicon [29]. It was also shown that friction of silicon can be lowered by using OTS-SAM as a lubricant [30]. Prior to deposition of OTS-SAM, the silicon specimen was ultrasonically cleaned with acetone, ethanol and deionized water for 10 min each to remove the contaminants. Then the silicon specimen was