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On the inhibition of metal transfer through ion implantation

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ABSTRACT

The impact of N⁺, C⁺, and S⁺ ion implantation on Al metal transfer to the implanted Interstitial Free Steel (ISF) was investigated using single-pass wear tests. The metal transfer was quantified by evaluating the Al coverage area from EDS maps taken from the wear tracks. The ISF steel had three different dose levels from each ion. It was concluded that S⁺ implantation provided the best resistance to metal transfer. The metal transfer resistance increased with dose for all the implanted species except for the S⁺ where the results plateaued after a 1e17 ions/cm² dose due to sputter limitations. Argon purging reduced the effectiveness of the N⁺ and C⁺ implants in reducing metal transfer while having little effect on the S⁺ implantations. This indicates that the N⁺ and C⁺ implanted ISF steel wear elements rely on tribo-oxidation to optimize their metal transfer resistance effectiveness while tribo-oxidation provides no benefit for the S⁺ implantations. In all cases, ion implantation increased the amount of tribo-oxidation taking place where C⁺ and S⁺ showed increasing amount of oxygen take-up with dose. The N⁺ implantations showed little dependence of oxygen take-up with dose, which indicates that the C⁺ and S⁺ implantations alter the low-temperature oxidation kinetics differently than the N⁺ implantations. The friction coefficient did not depend on oxygen concentration in the environment, which enforces the importance of surface film chemistry for friction generation. The tribochemical reduction of the natural iron oxide by aluminum facilitates metal-on-metal contact, and creates the adhesion forces responsible for the measured friction coefficient whose generation is characterized by a stick-slip mechanism. Ion implantation reduced the friction and noise with the sulfur implantations providing the best benefit. The mechanisms for the reduction of metal transfer based on surface chemistry were proposed from the view point of Sasada's Mutual Material Transfer model.

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1. Introduction

Ion implantation is a surface modification technique that since the late 1970s has been investigated for improving the tribological properties of surfaces [1]. Some of the oldest of these studies involved nitrogen [2,3] implantation where implantation into steel surfaces improved the wear resistance when slid against a harder counter-material during dry sliding studies. More recently, carbon [4] and sulfur [5,6] implantations into steel surfaces have been carried out to improve their tribological properties. In general, ion implantation has had a positive impact in reducing the wear of steel surfaces; however, there are cases where implantation does not have an impact on wear resistance. For specific material cases such as hardened 52100 steels, nitrogen implantation had no measureable impact on wear resistance during reciprocating tests against hard counter materials [3] demonstrating that already hard materials may

benefit less from ion implantation. In the case of environmental effects, Tarkowski [7] showed that the test atmosphere could affect the tribological effectiveness of nitrogen-implanted iron when slid against a tungsten-carbide ball after many cycles. In particular, it was demonstrated that no significant difference in wear characteristics between implanted and unimplanted were observed in argon atmosphere or vacuum wear tests, while tests in oxidizing environments showed that nitrogen implantation lowered friction coefficients relative to the unimplanted samples after many cycles. The tribo-oxidation of the debris and wear-surface were enhanced by ion implantation, which presumably reduced the impact of adhesive wear. Those examples demonstrate that the hardening and chemical benefits of ion implantation can be negated for certain testing conditions.

The goal of this article is to evaluate the impact of ion implantation in regards to metal transfer. Metal transfer is an insidious process occurring during sliding of metallic contacts that can result in galling [8]. The traditional model of metal transfer usually starts with adhesive wear events between interacting asperities [9]. Fractured metal from the cohesively weaker material transfers to the stronger material. As a result, small particles or “wear elements”

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are initially stuck on the harder materials surface, which act like additional asperities. As a wear element rubs the opposing surface, another wear element may form on the original one to form a debris particle. The debris particle continues to build up through a process known as “Mutual Material Transfer” [10,11]. The debris is constantly obstructing the sliding surfaces, and this produces normal and tangential forces on the particle. Once the debris reaches a critical size, the resultant tangential obstruction force overcomes the adhesive force of the debris at the surface, which results in the debris being swept off the track. Ploughing or micro-grooving is commonly associated with metal transfer due to the normal obstruction forces. The mechanical locking from the ploughing should provide resistance to motion in the tangential direction. This could allow additional build-up of the debris. The other evidence that mechanical locking plays a role is that a higher percentage of debris tends to stick to the surface that is more resistant to ploughing.

According to the prescribed mechanism for metal transfer, either the transfer element forming mechanism and/or build-up process needs to be disrupted in order to reduce it. One process that should address both mechanisms is tribo-oxidation enhancement. Tribo-oxidation, generally, is the oxidation that occurs during the wear process, where the oxidation takes place on the contacting surfaces during sliding and in the debris during mechanical mixing. The heavier presence of oxidized transfer elements in the debris should disrupt the transfer element growth process as proposed by Sasada [12]. Oxidized transfer elements can form through one of two processes: the fracturing of the implanted surfaces native oxide film or through tribo-oxidation of an already-formed implanted-surface wear element. In addition to disrupted debris growth, enhanced tribo-oxidation should also reduce the adhesive wear between the surfaces. For example, Glascott [13] in his review on low-temperature oxidative effects on reducing wear of Ni-based superalloy sliding components shows that wear testing at 200–300 °C gave lower friction coefficients than testing at room temperature because of the faster oxidation kinetics at higher temperatures. Increasing the oxidation rate will reduce friction by reducing direct metal-on-metal contact and disrupt the build-up of wear elements.

Quantitative Image Analysis of EDS maps provide a convenient way of evaluating the chemistry over large areas. In this study, Al, Fe, and O EDS maps are generated over sections of the wear tracks. When an EDS map is generated, each pixel acquires an intensity level for a given color; there are 256 different levels (channels) of intensity. The histogram of a color’s intensity can be analyzed to determine the total fraction of an element within a given area. The mean color intensity is:

$$I_{ave} = \frac{\sum_{i=0}^{255} i \cdot n_i}{N} \quad ; \quad N = \sum_{i=0}^{255} n_i \quad (1)$$

where N is the total number of pixels in the EDS map. i is the pixel intensity. For this study, the total coverage of an element X is defined by:

$$C_X = \frac{(I_{ave}^X \cdot N_X)_{sample}}{(I_{ave}^X \cdot N_X)_{ref}} \quad (2)$$

The total coverage is a ratio of mean color intensities between the X on the wear surface and an X reference. The area coverage of element X is obtained by multiplying C_X by the area of the image. The reference is an EDS map of the pure material. In the present case, the reference for Al is taken from an Al EDS map of an 1100 Al surface, and the reference for oxygen is taken from an O EDS map of an 1100 Al surface. In a similar manner, the as-implanted ISF steel is used as a reference for Fe. This method provides a way to

quantify metal transfer in terms of the fraction of total possible amount of coverage. To be clear, the ratio C_{Al} is *not* related to the fraction of area covered by the wear debris because wear debris has different amounts of Al contents, but each unit area of debris is counted the same. This means that C_{Al} should always be smaller than the fraction of area covered by the debris. The degree of oxidation provides a measure of the oxide concentration in the wear debris. The degree of oxidation R is defined by:

$$R = \frac{C_O}{C_{Al}} \quad (3)$$

The intensities used in (3) are the average color intensities as defined by (1). The reference sample for C_O is the untested, Fe-surface, and the as-implanted surface was used for determining R for the implanted samples. The aim of this study is to report on the effect of N+, C+, and S+ implantations on metal transfer from the viewpoint of tribo-oxidation. The results of this article are divided up into two sections: The first section characterizes the implanted layers and the native oxides formed on N+, C+, and S+ implanted surfaces, and the second section characterizes the tribological performance of these surfaces under ambient and oxygen-lean conditions.

2. Methodology

The implantations were carried using two separate ion implantation laboratories: The University of Michigan Ion Beam Laboratory (MIBL) and the University of Albany (SUNY) Ion Beam Laboratory. The ion implanter used at the University of Michigan was a 400 kV piecemeal implanter with the ion source manufactured by Danfysik, the ion accelerator manufactured by National Electrostatics Corp, and the implantation stage manufactured by High Voltage Engineering Europa. The implanter used at the SUNY Ion Beam Laboratory was a 400 kV Varian (Extrion) 400-10A Implanter. Nitrogen gas was used as the N+ ion source material. Carbon Dioxide gas was used as the C+ ion source material. Sulfur-dioxide was used for the S+ source gas. The current were kept between 50–75 μ A. At those currents, the sample temperature wasn’t expected to exceed 200C; this prediction was based on a heat balance using the beam-energy as the heat input and blackbody radiation as the heat output. Several doses were used for these experiments. Ion doses ranged from 5e16 ions/cm2 to 2e17 ions/cm2. Two acceleration energies were used: 100 kV for the N+/C+ implantations and 150 kV for the S+ implantations.

The samples used for this experiment were Interstitial Free Steel (ISF) with a chemistry of (in Wt %) 0.0014% C, 0.12% Mn, 0.034% Al, 0.038% Ti, and the balance Fe. The measured knoop hardness (HK) of this material was 92 +/- 6 (Kgf/mm2). The 1100 Al had chemistry of (in Wt%) 0.05% Cu, 0.35% Fe, 0.25% Si, and the balance Al with a HK of 48 +/- 4. The ISF Steel was ground with 600 grit, and chemically polished using a 7% (by Vol.) HF solution with a balance of a H₂O₂ (30% vol.)/H₂O solution. The solution was kept at temperature between 25C–20C using packed ice. The resulting finish (RMS) of the samples (as checked by an optical profilometer) was between 0.01–0.08 μ m when inspected over 50 μ m lengths. The 1100 Al samples were received in the form of 1/8” Dia. balls. Prior to testing, the samples were chemically polished by a solution composed of 75% (by vol.) Phosphoric Acid, 5% Nitric Acid, and 20% H₂O. The temperature of the solution was kept between 200F–210F during the process. The resulting RMS of the samples was between 0.05–0.11 μ m when inspected over 50 μ m lengths. Wearing gloves during handling, and storing the samples in dry desiccators under 0.5-atm pressure controlled the surface chemistry variation.

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