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Elevated temperature tribology of cobalt and tantalum-based alloys

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ABSTRACT

This paper describes the friction and wear behavior of a Co–Cr alloy sliding on a Ta–W alloy. Measurements were performed in a pin-on-flat configuration with a hemispherically tipped Co-base alloy pin sliding on a Ta–W alloy flat from ambient to 430 °C. Focused ion beam-scanning electron microscopy (FIB-SEM) and cross-sectional transmission electron microscopy (TEM) were used to identify the friction-induced changes to the chemistry and crystal structure in the subsurface regions of wear tracks. During sliding contact, transfer of material varied as a function of the test temperature, either from pin-to-flat, flat-to-pin, or both, resulting in either wear loss and/or volume gain. Friction coefficients (μ) and wear rates also varied as a function of test temperature. The lowest friction coefficient ($\mu = 0.25$) and wear rate (1×10^{-4} mm^3/N m) were observed at 430 °C in argon atmosphere. This was attributed to the formation of a Co-base metal oxide layer (glaze), predominantly (Co, Cr)O with Rocksalt crystal structure, on the pin surface. Part of this oxide film transferred to the wear track on Ta–W, providing a self-mated oxide-on-oxide contact. Once the oxide glaze is formed, it is able to provide friction reduction for the entire temperature range of this study, ambient to 430 °C. The results of this study indicate that glazing the surfaces of Haynes alloys with continuous layers of cobalt chrome oxide prior to wear could protect the cladded surfaces from damage.

1. Introduction

Tantalum–tungsten refractory metal alloys are well known for their high temperature strength while cobalt–chromium alloys, such as Haynes 25, exhibit superior resistance to oxidation at elevated temperatures. Therefore, Co–Cr alloys are cladding candidates for providing elevated temperature oxidation protection for Ta–W structures. The major focus of this study was to evaluate the friction and wear behavior, especially during run-in, of Co–Cr/Ta–W contacts at elevated temperatures, and to analyze the tribochemistry (i.e., formation of protective oxide glazes), friction-induced structures and phase transformations in the surfaces and subsurfaces.

Friction and wear mechanisms at elevated temperatures are more challenging to evaluate than those at ambient temperature, as wear mechanisms typically change and can be more complex with increasing temperatures. Peterson et al. [1] performed one of the earliest studies on high temperature metallic wear with self-mated metallic pairs of cobalt, iron, copper, nickel and molybdenum. This study revealed that friction and wear could be significantly reduced whenever soft, low interfacial shear strength metallic oxide films form at elevated temperatures. High temperature (up to 800 °C) sliding tests on Ni-20% Cr-base alloys (Nimonic 80A) have been shown to induce the formation of oxide 'glaze' surface layers that resulted in lowering wear, compaction and sintering of wear debris [2]. There are also other studies that show softer oxide glazes form during high temperature sliding of Co-based alloys resulting in decreased wear rates [3–5]. Typically, wear rates as a function of sliding temperature exhibit non-linear behavior, deviating from Archard's adhesive wear equation that linearly relates hardness and wear resistance.

Recently, Blau [6] reviewed high temperature metallic wear and the effects of oxidation, its role in debris formation, and microstructural evolution during metallic wear. Depending upon the nature of oxide layer formation, the wear rate at elevated temperatures can either be enhanced or reduced. In the case of alumina sliding on nickel aluminide, the wear rate decreased by several orders of magnitude at 650 °C compared to room temperature, because of the combination of increased yield strength, work hardening of nickel aluminide, and formation of a protective NiO surface layer at this temperature [6]. Conversely, if the particle layers are not very well compacted (through sintering for example), the relatively loose hard particles are removed more easily and wear rates increase, as in the case of self-mated nickel-base alloy Nimonic 80A [7]. As the temperature increases, the tendency

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to form stable oxide transfer layers and mechanically mixed layers between rubbing counterbodies becomes paramount in protecting the underlying bulk alloy.

A common theme that emerges from these and other elevated temperature studies is the ability to form, maintain, and if necessary, self-replenish oxide films if long-lasting, low-friction, wear contacts at high temperatures are to be realized. In addition to external heat, frictional heat generated at the sliding contact needs to be considered, since both contributions can influence the high temperature tribological behavior and the ability to form and retain surface oxide layers. Therefore, the major objectives of this study were to 1) quantify the friction coefficients and wear rates of Co-base alloy sliding on Ta–W alloy from ambient to 430 °C 2) characterize the sliding-induced chemical and structural changes of the worn surfaces and subsurfaces that control the tribological properties, and 3) determine the friction and wear mechanisms, including tribochemical phases (oxide formation), wear-induced phase transformations, grain refinement, and dislocation structures. Understanding these phenomena and their role in controlling the friction and wear behavior of cobalt and tantalum-based alloys are the major focus of this study.

2. Materials

Hemispherically tipped Co-base Haynes 25 alloy pins (~1.59 mm diameter) with a tip radius of ~0.6 mm were lapped to achieve an average surface roughness (R_a) of 0.094 μm. Table 1 lists the composition and room temperature mechanical properties of the Haynes 25 alloy. A representative 3D optical white light interferometer image of the polished pin surface is shown in Fig. 1a. A focused ion beam (FIB) cross-section of the pin taken at the spherical cap surface was used to determine if there were any polishing-induced subsurface structural changes. Fig. 1b shows the corresponding cross-sectional bright field transmission electron microscopy (BFTEM) image. Grain refinement due to polishing is localized in the top ~50 nm resulting in a very thin superficial layer suggesting minimal surface deformation occurred due to polishing. Furthermore, the inset in Fig. 1b shows a selected-area electron diffraction pattern (SADP), which along with the BFTEM image, confirmed that there was no evidence of a FCC to HCP stress-induced transformation in the Co-base alloy due to polishing often observed when such alloys are mechanically cold worked [8]. The Ta–W alloy flats (22 × 22 mm^2 size) were also polished to a R_a=0.25 μm against the surface lay and 0.05 μm with the lay. Table 1 also lists the composition and room temperature mechanical properties of the Ta–W alloy. Fig. 2a shows a representative 3D optical white light interferometer image of the polished Ta–W flat surface. The slight surface lay due to polishing is evident from the image. A corresponding cross-sectional BFTEM image of the Ta–W flat after polishing is shown in Fig. 2b. Similar to the Co-base alloy pins, there is minimal subsurface plastic deformation due to polishing. The image was acquired within a Ta–W grain and shows some evidence of dislocation substructure. These images of the Co-base alloy pin and Ta–W flat will serve as a baseline when compared to the subsurfaces generated during the wear processes.

3. Experimental methods

Sliding friction and wear tests were conducted using a home-built linear wear tester (LWT) that was retrofitted to accommodate the heating stage, shown in Fig. 3. The pin (Co-base alloy)-on-flat (Ta–W) configuration within the LWT is indicated on Fig. 3. Experiments were performed at 25 °C (room temperature), 170 °C, 430 °C, and thermal cycled from 430 °C→40 °C→170 °C. These conditions are referred to hereafter as ambient, 170 °C, 430 °C, and thermal cycled, respectively. The ambient tests were run in either laboratory air with approximately 15% relative humidity (RH) or in Ar (0.3% RH, < 10 ppm O_2, and < 100 ppm H_2O) in an environmental chamber, while the elevated and thermally cycled temperature tests were conducted in Ar only. Reciprocating/bidirectional sliding was performed so that the pin never left contact with the flat thus minimizing any heat losses and pre-oxidation effects. The sliding speed was 3.7 mm/s, track length was ~1.7 mm, and each test was

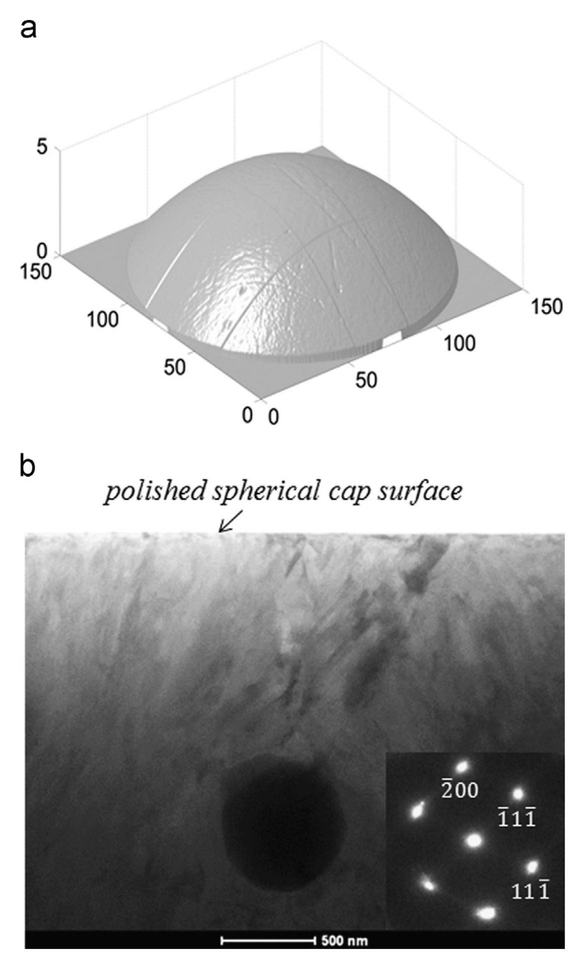

Fig. 1. (a) 3D scanning white light interferometry image (units in μm) and (b) cross-sectional BFTEM image of Co-base alloy pin after polishing (pre-wear). A spherical WC particle is also shown in the subsurface. Inset is a SADP pattern acquired from near surface showing the FCC structure viewed down ZA=[011].

Table 1
Compositions and room temperature mechanical properties of Co-base (Haynes 25) and Ta–W alloys.

Alloy	Compositions (wt%)	Hardness HV10 (GPa)	Elastic modulus (GPa)	Poisson's ratio	Tensile strength UTS (MPa)
Haynes 25[a]	51 Co, 20 Cr, 15 W, 10 Ni, 1.5 Mn, < 3 Fe, < 0.4 Si, 0.1 C	2.55	225	0.31	1015
Ta–W[b]	90 Ta, 10 W	1.88	207	0.30	620

[a] Analyses supplied by Haynes International, Inc.
[b] Analyses supplied by Cabot Supermetals.

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