Kovove Mater. 51 2013 183–188
DOI: 10.4149/km_2013_3_183

Sliding wear performances of 316 L, Ti6Al4V, and CoCrMo alloys

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Received 16 April 2012, received in revised form 8 October 2012, accepted 10 June 2013

Abstract

In this study, tribological performances of three alloys, 316 L, Ti6Al4V, and CoCrMo, used in manufacturing orthopedic implants, are compared. Wear tests were conducted on a reciprocating wear tester by rubbing an Al_2O_3 ball. It was found that the wear resistance of the 316 L and CoCrMo alloy was almost 2 and 24 times of the Ti6Al4V alloy, respectively, whose steady state friction coefficient lies between those of the 316 L and CoCrMo alloy. Examinations of wear tracks and contact surfaces of the Al_2O_3 ball revealed the dominant wear mechanisms as abrasive for CoCrMo and adhesive for 316 L and Ti6Al4V alloy. These observations confirmed that the favorably biocompatible characteristics of Ti6Al4V alloy was not accompanied by a reasonable sliding contact performance. In this respect, surface modification is a necessity for load bearing Ti6Al4V implants to extend their durability in the human body to the levels of 316 L and/or CoCrMo implants.

Key words: CoCrMo, 316 L, Ti6Al4V, wear

1. Introduction

Load bearing orthopaedic implants such as hip and knee joints are manufactured from stainless steels or cobalt-based alloys or titanium alloys owing to their enhanced corrosion and mechanical properties [1, 2]. Long-term durability of these implants in the human body depends on their wear resistance along with their static and dynamic strength. Wear not only leads to generation of debris ranging from nanometers to millimeters in the tissues near implants but also accelarates the rate of *in vivo* corrosion owing to the removal of the protective oxide layer from the surfaces [3–10].

Wear debris are found to be biologically active and cause local inflammation that leads to bone loss around the implant [10]. The resulting bone loss enlarges the interface and eases the flow of body fluid, causing higher transportation capacity of the wear debris, which finally leads to the loss of implant fixation [7, 10–14]. The consequence of this process is a revision surgery consisting of replacement of the implant with a new one, which can be traumatic and expensive for the patient.

In this work, sliding wear behavior of the alloys used in manufacturing orthopedic implants (316 L as the stainless steel, Ti6Al4V alloy as the titanium alloy, and CoCrMo alloy as the cobalt based alloy) was compared. More specifically, their tribological performances were evaluated under identical sliding contact conditions by considering the wear rate, the friction coefficient, and the dominant wear mechanism.

2. Experimental procedure

5 mm-thick disc-shaped samples of 316 L stainless steel (ø 10 mm), CoCrMo (ø 8 mm), and Ti6Al4V (ø 10 mm) alloys were used in this study. The chemical composition and the hardness of the investigated materials are provided in Table 1.

Reciprocating wear tester (Tribotech, France) was used to assess the tribological performance of samples under dry sliding contact conditions (in an air at 25 °C temperature and 35 % relative humidity). Before wear testing, the surfaces of the samples were mirror finished by grinding and polishing. 6 mm-diameter Al_2O_3 balls were used as the counterface, which were rubbed on the surfaces of the samples under three different normal loads (1 N, 3 N, and 5 N) at a sliding velocity of 0.01 $m\,s^{-1}$. The stroke and the total sliding

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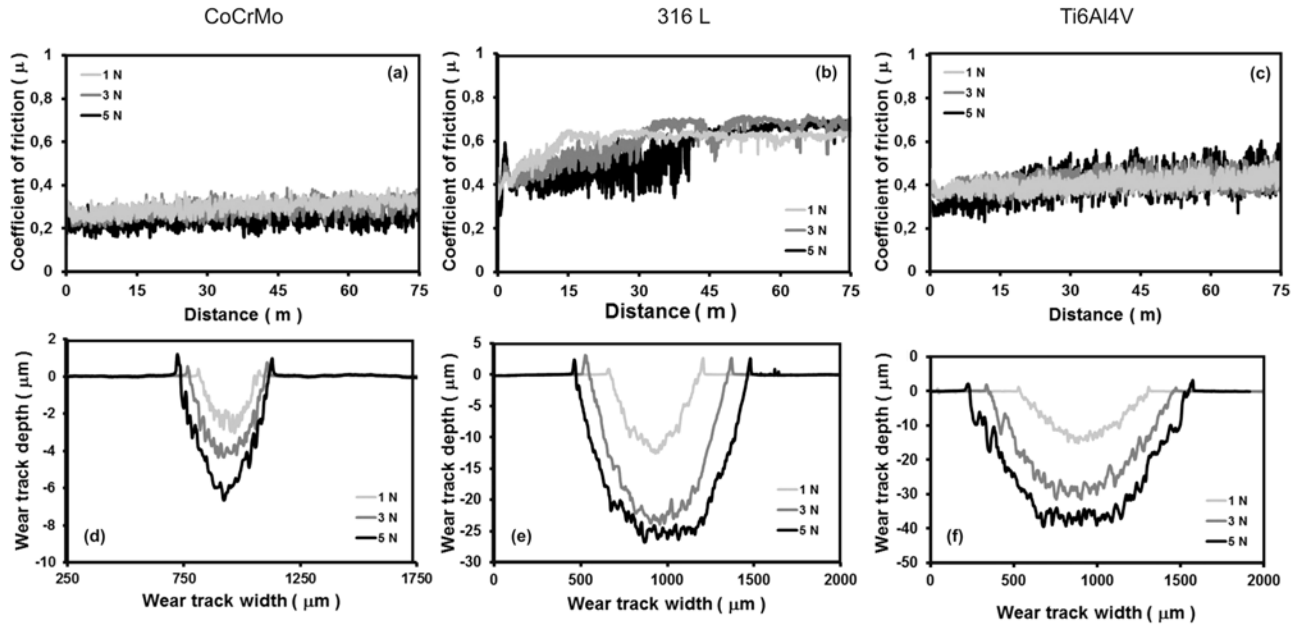

Fig. 1. (a–c) Friction curves and (d–f) 2D wear track profiles of the examined alloys.

Table 1. Chemical composition and hardness of the 316 L, CoCrMo, and Ti6Al4V alloys used in this study

Elements (wt.%)	316 L	CoCrMo	Ti6Al4V
Chemical composition			
C	0.014	0.042	–
Cr	16.83	27.56	–
Ni	10.29	0.17	–
Co	0.06	Bal.	–
Mo	2.30	5.13	–
Mn	1.80	0.40	–
Si	0.28	0.36	–
Ti	0.003	–	Bal.
Al	0.03	–	6
V	0.042	–	4
Fe	Bal.	0.24	–
Hardness			
HV	203	470	315

distance of the counterface on the surfaces of samples was 5 mm and 75 m, respectively. Frictional force data were continuously recorded during wear testing.

Wear tracks that developed on the surface of samples were analyzed using a 2-D profilometer (Dektak-6 M, USA) and a Scanning Electron Microscope (SFEG SEM, Philips-Holland), equipped with an energy dispersive X-ray spectrometer (EDX). Contact surfaces of Al_2O_3 balls were examined using a Light Optical Microscope (LOM-Leica-CTR 6000, Germany).

3. Results

The results of the wear tests are presented as the friction curves and the 2D wear track profiles in Fig. 1. The friction curves of 316 L tended to increase with respect to the sliding distance, while the friction curves of CoCrMo and Ti6Al4V alloys were almost stable throughout the testing period without any significant change in the average level associated with heavy fluctuations (Fig. 1a–c). Since the friction curves of the 316 L reached a steady-state value after a sliding distance of about 45 m, in the present study the steady state friction coefficient values of the examined samples were determined as listed in Table 2, for the sliding distances longer than 45 m. The steady state values of the samples did not change remarkably depending on the test load. In terms of their steady-state friction coefficients, the examined alloys can be ranked from low to high as CoCrMo, Ti6Al4V, and 316 L.

The depth, width, and ultimately the cross-sectional area of wear tracks formed on the surfaces of each sample during wear tests increased with increasing test load (Fig. 1d–f), as would be expected from increasing material removal by the rubbing action of the counterface. In the present study, results of the wear tests were quantified in terms of wear rate ($mm^3\,N^{-1}\,m^{-1}$) calculated by considering the per unit test load (N), and per unit sliding distance (m) for a given volume of wear tracks (cross-sectional area × length, mm^3). As presented in Table 2, the wear rates of each sample were in the same range even at different test loads. On the basis of the average specific wear rate values of Table 2, Ti6Al4V alloy possessed the worst wear resistance when compared to

Table 2. Steady-state friction coefficients, specific wear rates, and dominant wear mechanisms of the investigated samples

Test load	Steady-state friction coefficient	Specific wear rate ($mm^3 N^{-1} m^{-1}$)	Dominant wear mechanism
CoCrMo			
1 N	0.24	2.4×10^{-5}	Abrasive
3 N	0.29	2.3×10^{-5}	
5 N	0.30	2.5×10^{-5}	
Average	0.27	2.4×10^{-5}	
316 L			
1 N	0.60	33.1×10^{-5}	Adhesive
3 N	0.63	34.0×10^{-5}	
5 N	0.64	33.6×10^{-5}	
Average	0.62	33.5×10^{-5}	
Ti6Al4V			
1 N	0.41	58.3×10^{-5}	Adhesive
3 N	0.42	58.4×10^{-5}	
5 N	0.41	58.0×10^{-5}	
Average	0.41	58.2×10^{-5}	

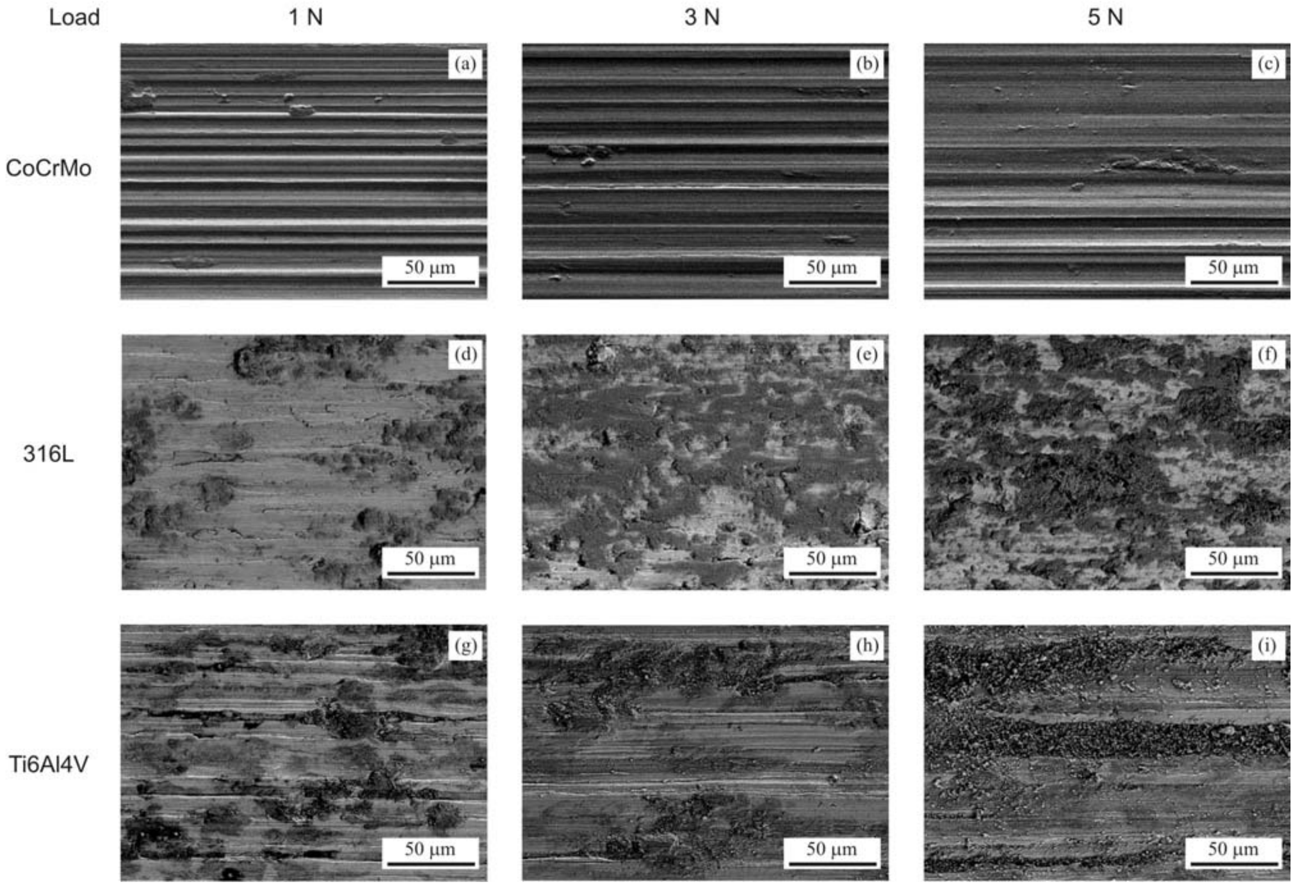

Fig. 2. SEM micrographs of the wear tracks formed on the surfaces of (a–c) CoCrMo, (d–f) 316 L, and (g–i) Ti6Al4V samples.

other investigated samples. Thus, wear resistance of the CoCrMo and 316 L alloys is approximately 24 and 2 times of that of the Ti6Al4V alloy.

The contact surface appearances of the examined

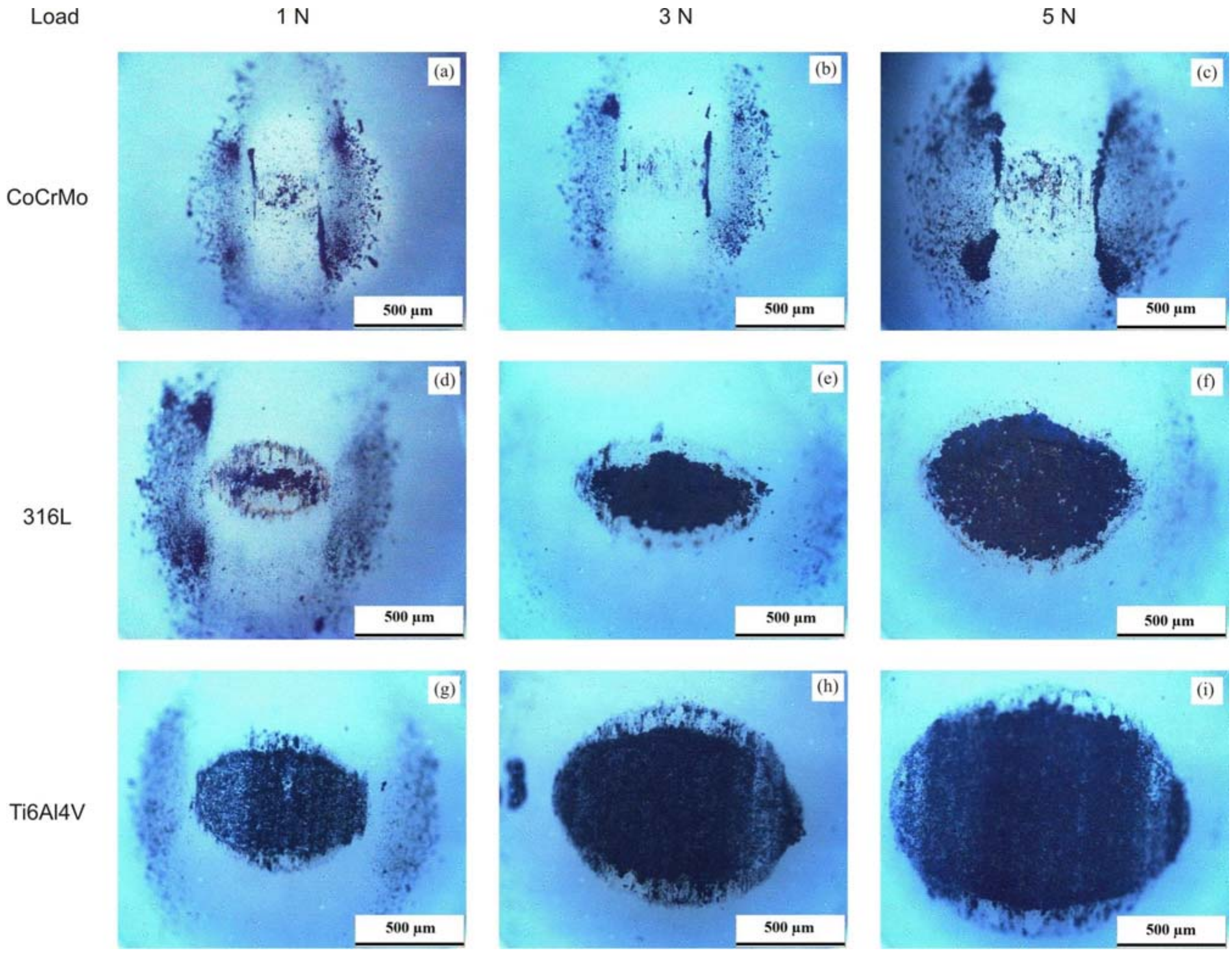

Fig. 3. Contact surfaces LOM micrographs of the Al_2O_3 balls rub on (a–c) CoCrMo, (d–f) 316 L, and (g–i) Ti6Al4V samples.

samples and the Al_2O_3 ball counterfaces are depicted in Figs. 2 and 3, respectively. The contact surface topography of CoCrMo alloy showed characteristics of abrasive wear due to the presence of number of fine grooves aligned parallel to the sliding direction (Fig. 2a–c). Although the increase of test load induced relatively deeper and larger grooves, material transfer to the contact surface of the counterface was not evident clearly. Wear debris seemed to be ejected from the contact surface of the counterface and located outside the contact surface (Fig. 3a–c).

In the case of the Ti6Al4V alloy, which exhibited the lowest wear resistance, the worn surface topography of the samples can be characterized by rough and delaminated nature with the indications of plastic deformation along with grooves parallel to the sliding direction (Fig. 2g–i). In general, worn surfaces exhibited typical characteristics of adhesive wear, which can be associated with material transfer to the counterface. Material transfer from the Ti6Al4V alloy caused darkening at the contact surface of the counterface, which became more intense at higher test loads (Fig. 3g–i).

The worn surface topographies of 316 L can be characterized by relatively smooth bright colored regions with dark colored oxide islands (Fig. 2d–f). EDX analysis also confirmed that these islands were rich in oxygen concentration. This result indicates the clear contribution of oxidation to the progression of wear process. Even though some oxide islands were smeared, they did not completely avoid the destructive action of the counterface, resulting in heavy plastic deformation in the oxide free bright regions associated with local delamination. The materials detached were then transferred to the contact surface of the counterface. Higher test loads provided high amount of material transfer (Fig. 3d–f). Contact surface appearances of the 316 L and the counterface indicated the dominant wear mechanisms as adhesive wear.

4. Discussion

According to the results of the wear tests conducted in this study, the examined three alloys can be ranked low to high as Ti6Al4V, 316 L, and CoCrMo in terms of wear resistance and as CoCrMo, Ti6Al4V, and 316 L with respect to the steady state friction coefficient (Table 2).

The considerably lower wear rate and friction coefficient of the CoCrMo alloy can be associated with its higher hardness (Table 1) as well as the progression of surface degradation by abrasive wear mechanism. Its relatively low steady state friction coefficient that suggests heavy destructive action of the counterface was partially prevented by the rolling of the wear debris at the interface, thus limiting the extent of abrasive wear at the highest test load of 5 N. This statement is in accordance with the reports of Yan et al. [15], Sun et al. [16], Pourzai et al. [17], and Julian et al. [18], who tested the wear performance of CoCrMo alloy against metal and ceramic counterfaces.

The relatively higher wear rate and the moderate friction coefficient of the Ti6Al4V alloy can be correlated with the inherent characteristic of titanium for low shear strength and high tendency to scuffing arising from its hexagonal closed packed crystal structure. In agreement with this notion, severe adhesion of Ti6Al4V alloys has been reported in many studies as the result of heavy material transfer to the counterface during sliding contact [19–21].

Although 316 L has the hardness almost half of the Ti6Al4V alloy (Table 1), it exhibited better wear resistance along with higher steady state friction coefficient than Ti6Al4V alloy. It is suggested that oxide islands generated during sliding contact reduced the material transfer to the counterface. Therefore, adhesive wear progressed in mild regime on the 316 L as compared to the Ti6Al4V alloy, under identical wear testing conditions. This observation is consistent with the data provided by Farias et al. [22], who correlated the low wear rate of stainless steels with oxide island formation on the worn surfaces. On the other hand, the crystal structures should also be considered when comparing the friction characteristics of 316 L and Ti6Al4V alloy. In this perspective, it is suggested that higher resolved critical shear strength of face centered cubic 316 L provided higher friction coefficient as compared to that of the hexagonal closed packed Ti6Al4V alloy having low separation between basal planes [23].

Although titanium alloys have many advantages over stainless steels and cobalt based alloys from the viewpoints of biomedical requirements, including high strength to weight ratio, close modulus of elasticity to that of bone, and enhanced biocompatibility, this study confirmed the necessity of surface modification processes for titanium based load bearing implants in order to extend their durability in the human body. It must be noted that any surface modification process that could be applied with the aim of providing high wear resistance should not sacrifice other requirements such as high dynamic strength and enhanced biocompatibility.

5. Conclusions

Sliding wear performances of three different alloys used in manufacturing of orthopaedic implants (316 L, CoCrMo, and Ti6Al4V) were compared in this study, wherein the basic findings can be summarized as follows:

– The wear resistance of the examined materials increased in the order of Ti6Al4V, 316 L, and CoCrMo. The dominant wear mechanisms were identified as abrasive for CoCrMo and adhesive for 316 L and Ti6Al4V alloy.

– Adhesive wear led to darkening at the contact surface of the counterface by material transfer. The contact surface of the counterface used in testing of the Ti6Al4V alloy was more markedly darkened as compared to that of the 316 L. Similar darkening has not been detected on the contact surfaces of the counterface rub on CoCrMo alloy, which was worn by abrasive wear mechanism.

Acknowledgements

I would like to express my sincerest appreciation and acknowledgement to Prof. Dr. H. Cimenoglu (Department of Metallurgy and Materials Engineering, Istanbul Technical University) for his invaluable support and insightful comments on my study.

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