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Lubrication of Nitinol 60

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Abstract

The mechanical properties of Nitinol 60, 60 wt.% Ni, 40 wt.% Ti (55 at.% Ni, 45 at.% Ti) are sufficiently attractive to warrant its consideration as a lubricated triboelement. Triboelements are always run lubricated. The ability to lubricate Nitinol 60 by the oils usually used on spacecraft mechanisms—Pennzane 2001A, Krytox 143AC and Castrol 815Z—was experimentally determined. These oils were run in the boundary lubrication regime for Nitinol 60 balls running against Nitinol 60 counterfaces in the vacuum spiral orbit tribometer. Test results consisting of the coefficient of friction versus time (friction traces) and relative degradation rates of the oils are presented. Contrary to the inability to successfully lubricate other metal alloys with high titanium content, it was found that Nitinol 60 is able to be lubricated by these oils. Overall, the results presented here indicate that Nitinol 60 is a credible candidate material for bearing applications.

Introduction

Binary nickel-titanium (NiTi) alloys are in widespread use in the medical and dental industries in applications where their biocompatibility and unique superelastic or Shape Memory Effect (SME) characteristics are readily exploited (Refs. 1 and 2). In a previous paper (Ref. 3), the authors presented evidence that NiTi alloys can be tailored to avoid shape memory or superelastic behavior. Under these circumstances, such alloys may prove to have attractive tribological properties under oil-lubricated contact conditions.

Materials for high performance bearings, gears and other mechanical components require a number of specific properties and characteristics. Among these key attributes are high strength and hardness, high thermal conductivity, and the ability to be manufactured to very high levels of precision with regards to final dimensions and surface finish. In addition, excellent corrosion resistance and good tribological properties are often of importance especially for applications in extreme environments.

This paper assesses the feasibility of using Nitinol 60 (60 wt.% Ni, 40 wt.% Ti (55 at.% Ni, 45 at.% Ti)) for bearings and mechanical components. This material has a unique combination of properties. As noted, Nitinol 60, when appropriately heat-treated, does not exhibit SME properties at normal ambient and anticipated use temperatures and is dimensionally stable. It has high hardness when properly heat-treated and yet can be readily machined prior to final heat treatment. Like silicon nitride, Nitinol 60 is nonmagnetic and is intrinsically highly resistant to corrosion. Unlike ceramics, Nitinol 60 is electrically conductive.

Tribological devices are always run lubricated, and metallic alloys with high concentrations of titanium historically do not respond well to lubrication by organic fluids (Refs. 4 to 6). For example, alloys such as Ti-6Al-4V exhibit galling behavior in dynamic contacts even under conditions well lubricated by oils and greases. There is presently no understanding at the fundamental level of why metallic titanium alloys perform so poorly under lubricated tribological conditions. A consideration of Nitinol 60 as a tribological material thus requires an *experimental* study of its performance in a lubricated configuration and is the motivation for this study. This paper reports the results of tests with oils commonly used on spacecraft tribological systems—Pennzane 2001A, Krytox 143AC and Castrol 815Z—running in the boundary lubrication regime for a Nitinol 60 ball against Nitinol 60 counterfaces in the vacuum spiral orbit tribometer. Test results consisting of the coefficient of friction versus time (friction traces) and relative degradation rates of the oils will be presented. A comparison of Nitinol 60 running against Nitinol 60 with either 440C or 52100 steel running against 440C or 52100 steel will be made. Results of Nitinol 60 balls running against 440C steel counterfaces have been previously reported (Refs. 3 and 7).

Materials

The Nitinol 60 balls evaluated in this work were manufactured by Abbott Ball (Ref. 8) via a high temperature proprietary powder metallurgy process roughly similar to that described in the literature (Ref. 9). The finished 12.7 mm diameter balls were bright and shiny in appearance and resembled conventional polished steel balls. Density was measured at 6.7 g/cc, about 13% percent lower than steel, and microhardness measurements indicated values in the range of 58 to 62 on the Rockwell C scale in the hardened condition. Differential scanning calorimetry (DSC) indicated (Ref. 3) that the final hardened balls are microstructurally stable down to at least –100 °C.

The plate specimens were machined from a cast and hot rolled plate obtained from a commercial source (Ref. 10). The specimens were subjected to a proprietary heat treat by Abbott Ball before final polishing. Their microhardness was determined to be about 55 on the Rockwell C scale.

The elastic modulus of the specimens was determined indirectly from the width of the track made by the ball on the plate in the tribometer described below. The track width was about 450 μm for a 30 lb. load. Using the equations for the Hertz pressure for a sphere on flat contact, a value of 101 GPa was obtained for the effective elastic modulus of the Nitinol 60 system considered here. This value is comparable to the elastic modulus of the titanium alloy Ti-6Al-4V, 114 GPa.

Tribometer

For the tribological evaluations, Nitinol 60 balls were lubricated with a few tens of μg (micrograms) of the different oils and subjected to a rolling-sliding contact lubricant life test in a Spiral Orbit Tribometer (SOT), described before (Refs. 11 and 12). The SOT, depicted in Figure 1, is basically a thrust bearing with one ball and flat races (plates). It may be regarded as a simplified version of the usual angular contact ball bearing.

The upper plate is stationary and the lower plate rotates to drive the ball into an orbit that is an opening spiral. The ball contacts a guide plate at the end of each orbit, which forces the ball back into its initial orbital radius. The ball then exhibits, for a given coefficient of friction (CoF), a stable orbit, repeatedly over-rolling the track on both flat race plates and guide plate. The spiral's pitch and the length of the contact on the guide plate increases with the increase in the CoF. A piezoelectric force transducer supporting the guide plate senses the frictional force developed on the ball as it slides on the rotating plate during the contact of the ball with the guide plate. As explained in (Ref. 11), during this contact, the coefficient of friction is obtained from this force and the load imposed on the system. The tribometer is housed in a stainless steel chamber that can be evacuated by a turbomolecular pump to $\leq 2\times10^{-8}$ torr.

The surface cleaning procedure for all ball and plate specimens was by lightly rubbing with an aqueous slurry of silicon carbide polishing powder, followed by sonication in deionized water. This preparation results in a surface on which water exhibits zero contact angle (spreads) and which exhibits an XPS spectrum a) devoid of impurities other than a small feature due to adventitious carbon and b) in which the Fe^0 feature for a 440C steel specimen is clearly evident, indicting a native oxide only a couple of nm thick for that material. XPS analysis of Nitinol 60 indicated a similar surface condition after this cleaning procedure.

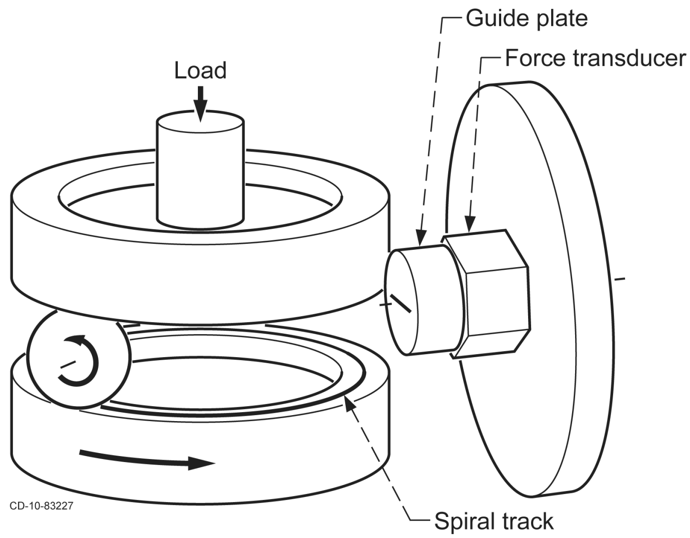

Figure 1.—Components of the Spiral Orbit Tribometer (SOT).

The cleaned Nitinol 60 plate specimens were installed in the tribometer and only the ball was lubricated with a few tens of μg of oil. Tests of the Nitinol 60 system were run at a load of 30 lb, corresponding to a Hertz pressure of .84 GPa. Comparative tests with steel specimens were run at 43 lb. load, for a Hertz pressure of 1.5 GPa. Under these conditions, the system is obviously operating in the boundary lubrication regime. The characteristic of a test in which boundary lubrication is operative is a low and constant coefficient of friction for a number of orbits and then an eventual transition to a much higher value of the CoF. This eventual increase has been attributed to the consumption of the organic lubricant by tribochemical attack on the lubricant molecules in the ball/plate contact by the bearing materials between which the lubricant is captured. Each member of the ball/plate contact can exhibit tribochemical activity that degrades molecular structure, consuming the lubricant and leading to high CoF in the absence of lubricant and the end of the test. A normalized lifetime, $\mathcal{L}$, in orbits per μg, is obtained by dividing the number of orbits for the CoF to reach 0.2 by the weight in μg of lubricant applied to the ball. This lifetime is a relative measure of the degree of the specimen's tribochemical aggressiveness that destroys, or consumes the lubricant. It is an inverse relative degradation rate of the lubricant oil undergoing the tribological test. The case of extreme tribochemical aggressiveness results in the lack of any lubrication at all, since the lubricant is totally destroyed in the contact without being able to provide any lubrication. Such is the case for chemically aggressive materials such as titanium, as is well known in engineering practice, and will also be shown below to be the case here for Nitinol 60 specimens coated with a thin film of titanium.

Results

A typical friction trace obtained with this tribometer is shown in Figure 2 for 440C steel lubricated with Pennzane 2001A. A friction trace for Krytox 143AC lubricating 52100 steel is shown in (Ref. 12, Fig. 3). The characteristic of the friction trace of a system that can be successfully lubricated with a few μg of liquid lubricant is a low, constant and noise-free CoF for at least a few hundred orbits. Eventually the CoF rises to high values (>0.2) as the lubricant is consumed and the test is concluded. The transition to high CoF is gradual with Pennzane 2001A and rather abrupt with the perfluoropolyethers (PFPEs) Castrol 815Z and Krytox 143AC. The "jog" in the CoF at about 30,000 orbits sometimes occurs and is often absent in friction traces in the SOT. The presence of these "jogs" does not seem to correlate with the lifetime of a test and no particular significance is attributed to them.

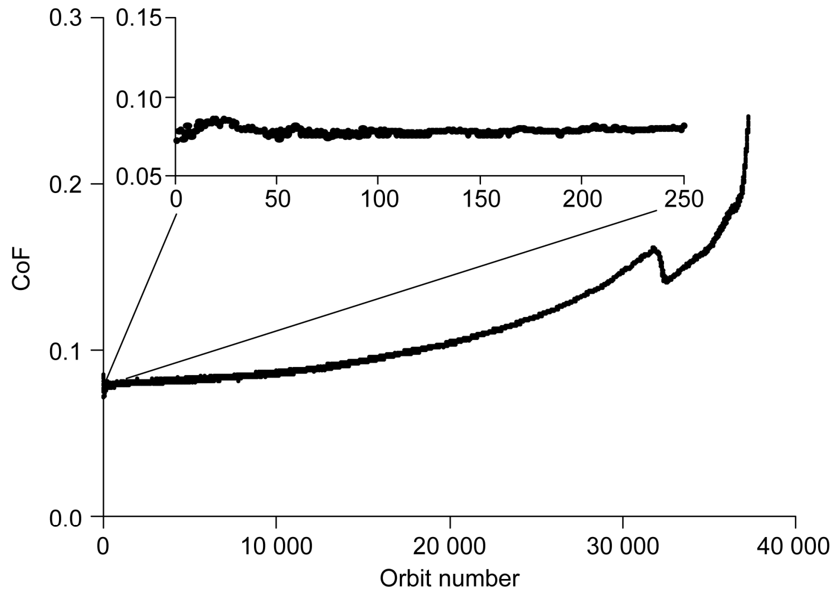

Figure 2.—Friction trace of 440C steel lubricated with 16 μg Pennzane 2001A. The normalized lifetime, $\mathcal{L}$, for this test is 2307 orbits per μg. The friction trace for the first 250 orbits is inset.

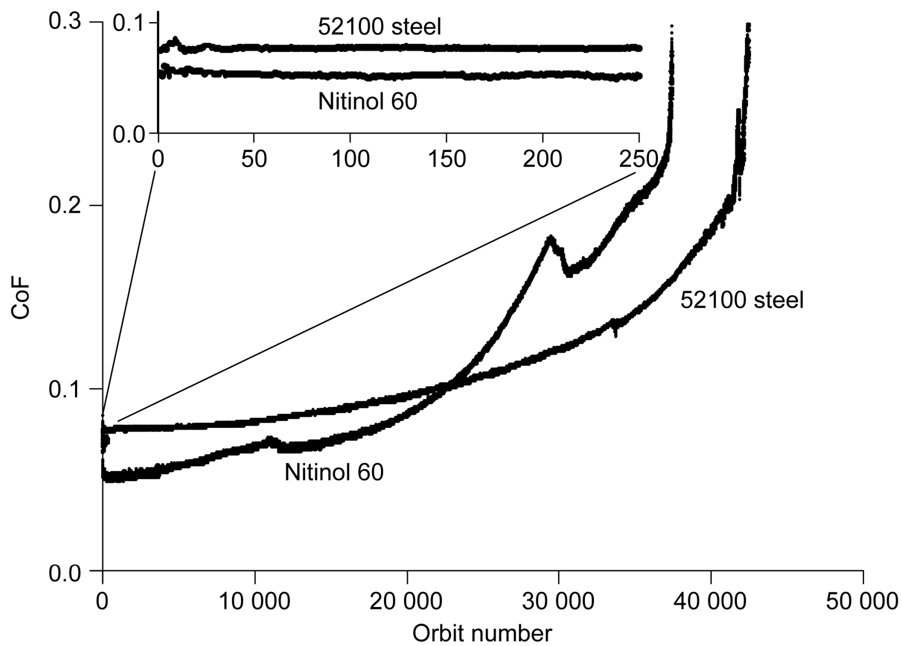

Figure 3.—Friction traces for 52100 steel lubricated with 13 μg Pennzane 2001A and Nitinol 60 lubricated with 25 μg Pennzane 2001A. The traces for the first 250 orbits are inset.

A friction trace of Nitinol 60 lubricated with Pennzane 2001A is shown in Figure 3. A trace of 52100 steel lubricated with Pennzane 2001A is also shown in the figure for comparison. It is seen that the trace for the Nitinol 60 system is quite similar to that for 52100 steel (although in this case, the “jog” appears in the Nitinol system instead of the steel system). The inset shows that both the Nitinol 60 and the 52100 steel exhibit the low, constant friction characteristic of a successfully lubricated system.

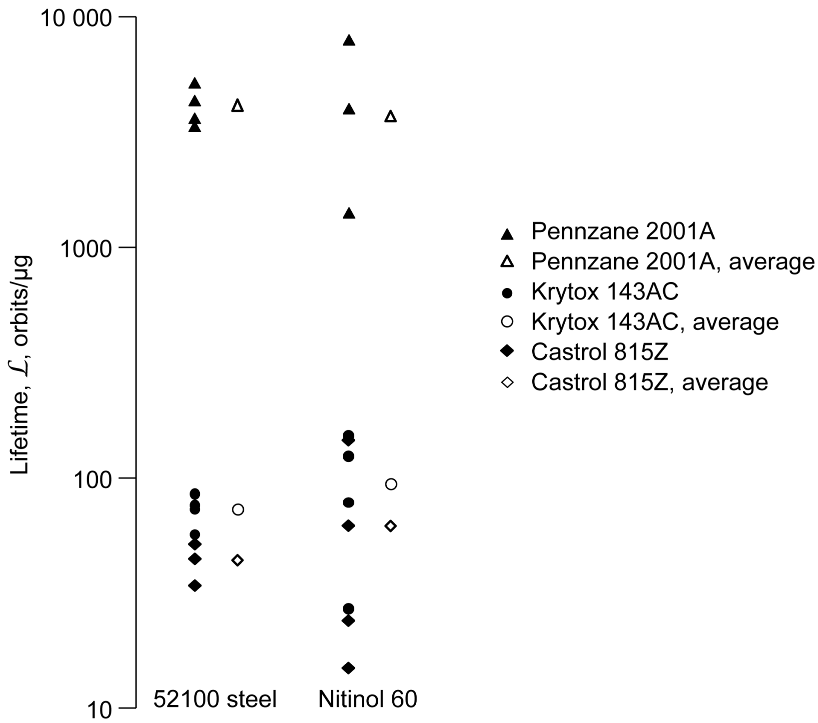

Figure 4.—Graphical view of the normalized lifetime $\mathcal{L}$ data in Table 1. Average normalized lifetimes for four tests are indicated by open symbols.

Four tests of each of the three lubricants on the Nitinol 60 system were conducted. The initial CoF and normalized lifetime $\mathcal{L}$ for each test are given in Table 1 together with the average value for the four tests. The values for the tests on 52100 steel from (Ref. 12) are also given in the table. A graphical view of these results is shown in Figure 4.

TABLE 1.—INITIAL COEFFICIENTS OF FRICTION (CoF_{ini}) AND NORMALIZED LIFETIMES $\mathcal{L}$ (ORBITS/μg) FOR TESTS OF CASTROL 815Z, KRYTOX 143AC AND PENNZANE 2001A ON BOTH NITINOL 60 AND 52100 STEEL (FROM REF. 12). AVERAGE VALUES ARE INDICATED ALSO

Lubricant	52100 Steel				Nitinol 60			
	CoF_{ini}	$CoF_{ini,ave}$	$\mathcal{L}$	$\mathcal{L}_{ave}$	CoF_{ini}	$CoF_{ini,ave}$	$\mathcal{L}$	$\mathcal{L}_{ave}$
Castrol	.13	.12	34	44	.1	.09	24	62
	.12		52		.06		145	
	.12		45		.08		62	
	.12		45		.11		15	
Krytox	.13	.13	85	73	.15	.15	78	95
	.13		73		.14		152	
	.13		57		.14		124	
	.14		76		.15		27	
Pennzane	.075	.077	5188	4113	.052	.054	1400	3701
	.078		4313		.052		4000	
	.077		3325		.052		8000	
	.081		3625		.058		1413	

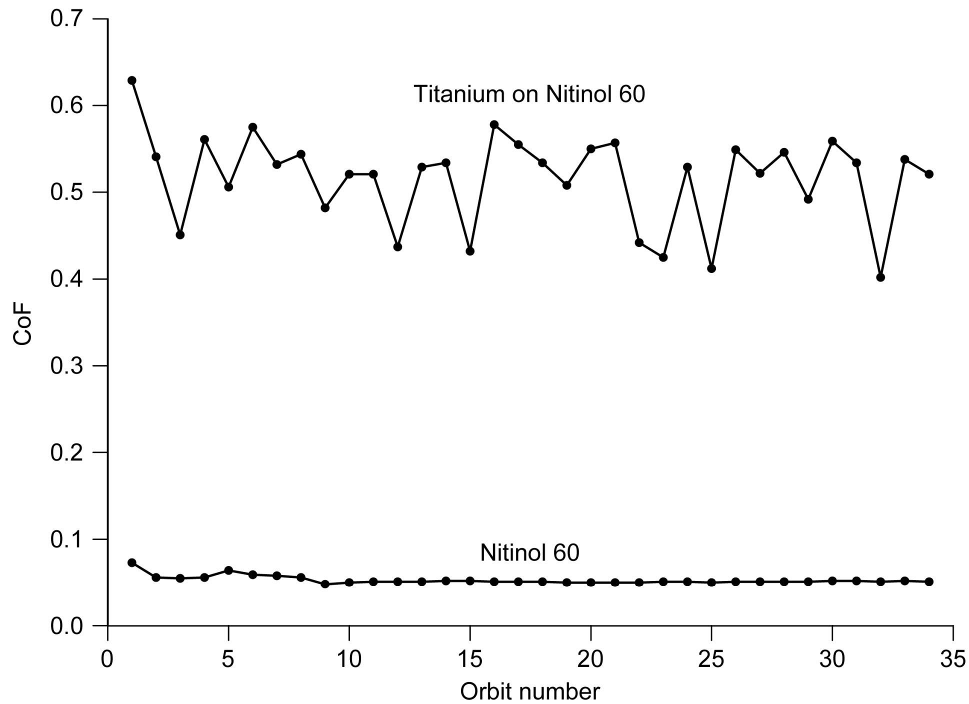

Figure 5.—Friction traces of Nitinol 60 lubricated with 28 µg Pennzane 2001A and Nitinol 60 coated with 200 nm titanium and then lubricated with 32 µg Pennzane 2001A.

The effect of tribochemical activity of the specimens on lubrication by the oils used here was demonstrated by testing with Nitinol 60 specimens that had been sputter-coated with 200 nm of titanium. All three oils were tested and the friction trace for Pennzane 2001A is shown in Figure 5 together with a friction trace for the uncoated Nitinol 60. In contrast to the low, constant CoF for the uncoated Nitinol 60, the CoF for the coated Nitinol 60 is very high and erratic, typical of the lack of lubrication. The same result for Pennzane 2001A was shown in Figure 2 of (Ref. 7) for a titanium-coated 440C ball running against uncoated 440C steel plates. Thus it appears that the tribochemical activity of only one surface of the contact is sufficient to prevent lubrication. Similar results were also obtained for Castrol 815Z and Krytox 143AC running on titanium-coated Nitinol 60 specimens.

Discussion

This paper reports the study of the feasibility of lubricating Nitinol 60. The test oils used here have proven to be effective lubricants for steel in both ambient air and vacuum environments. The conditions chosen for the tests—vacuum and the boundary lubrication regime—may be considered to be quite severe. No lubricant EHD film is present to physically separate the triboelements in the boundary lubrication regime. There is solid-solid contact in this regime. The lack of continuous reformation of protective oxide scales in the vacuum environment allows metal to metal tribo-contact in which the lubricant must be effective. It is probable that if Nitinol 60 survives these severe test conditions then it would also survive service in ambient air with macroscopic amounts of oil.

The comparison of Pennzane on Nitinol 60 with Pennzane on steel in Figure 3 shows a great similarity in behavior for the two triboelements—low, constant initial CoF and a normalized lifetimes $\mathcal{L}$ of similar magnitude. This is direct evidence for successful lubrication of Nitinol 60 by Pennzane 2001A. Similar results were obtained for Krytox 143AC and Castrol 815Z. As indicated in Table 1, there were no “zero lifetimes” as in Figure 5 for titanium-coated triboelements. No test failed to behave in a lubricated manner. In fact no test with these three oils for Nitinol 60 on Nitinol 60 or Nitinol 60 on steel ever failed to behave in a lubricated manner. The lack of a single failure of lubrication in all the tests reported here and reported previously (Refs. 3 and 7) leads to the strong conclusion that Nitinol 60 can in fact be lubricated by these commonly used oils in spite of its high content of titanium.

The data in Table 1 (and Fig. 4) permit a semi-quantitative comparison of the lubrication of Nitinol 60 to the lubrication of 52100 steel. First note that the data, both CoF and $\mathcal{L}$, is rather more repeatable, test to test, for 52100 steel than it is for Nitinol 60. For example, there is overlap in the lifetimes of Krytox 143AC and Castrol 815Z in the tests on Nitinol 60 but not in the tests on 52100 steel. Although the reason for this greater variability for the Nitinol 60 tests is not known, the *average* values for both CoF and $\mathcal{L}$ have the same ordering in both cases.

For CoF_{ave}: Pennzane 2001A<Castrol 815Z<Krytox 143AC

For $\mathcal{L}_{ave}$: Pennzane 2001A>Krytox 143AC>Castro 815Z

It thus appears that, for these lubricated systems, it is the oil that controls these tribological properties (CoF) and the triboelements determine the oil’s eventual consumption ($\mathcal{L}$). It is also to be noted that the normalized lifetimes for the tests with Nitinol 60 cannot be directly compared to the tests with 52100 steel since the former were run at a Hertz pressure of .82 GPa while the latter were run at a Hertz pressure of 1.5 GPa. Higher Hertz pressure leads to shorter lifetimes in SOT tests (Ref. 13). It is thus expected that the normalized lifetimes for these oils run on Nitinol 60 would be considerably less than the lifetimes run on 52100 steel if the Nitinol was run at a Hertz pressure approaching 1.5 GPa. This may have to be considered in a practical application using Nitinol 60 as a bearing element.

As mentioned in the Introduction, metallic alloys with high titanium content such as Ti-6Al-4V cannot be lubricated with the usual organic fluids. The point of view taken here is that this inability to lubricate is due to a chemical reaction of the bearing material with the lubricant molecules in the ball/plate contact that effectively destroys the chemical structure of these molecules, rendering them unable to act as lubricants. The chemical reactivity of the bearing material is a function of its electronic structure, since it is the electrons in the bearing material that destructively interact with the orbital electrons of the lubricant molecules. This electronic structure and its relationship to (tribo)chemical reactivity is presently not understood well enough to provide a prediction of the ability to lubricate Nitinol 60 as opposed to the inability to lubricate Ti-6Al-4V. Somewhere between the 45 at.% titanium in Nitinol 60 (capable of being lubricated) and 86 at.% titanium in Ti-6Al-4V (*in*capable of being lubricated) there must be a value of the titanium content and the associated electronic structure of the alloy that marks the transition between these two lubrication regimes. The relationship between titanium content, electronic structure and tribochemical aggressiveness has not been studied at the fundamental level, either theoretically or experimentally. Perhaps the localized covalent nature of the electronic structure of the intermetallic compound Nitinol 60 (Ref. 14 and references contained therein) (as opposed to free unlocalized electrons in metallic alloys) is the aspect of this alloy that results in its capability of being lubricated. This may also be the reason that the covalent/ionic compounds TiC and TiN can be lubricated. However, no rigorous theory of tribochemical activity related to the electronic structure and covalency/free electron nature of the material as a function of titanium content has yet emerged. Similarly, an electron spectroscopic experimental characterization of a material to provide a characterization and/or prediction for its general chemical aggressiveness and possibly specific tribochemical aggressiveness has not been developed. Thus each candidate material/lubricant system must be approached anew on the *experimental* tribological level to determine its tribological compatibility.

Conclusion

Spiral orbit tribometry tests of Castrol 815Z, Krytox 143AC and Pennzane 2001A on Nitinol 60 in vacuum have shown that Nitinol 60 can be successfully lubricated. The coefficients of friction and relative degradation rates of the oils were similar to the values for these oils running on steels. Steel bearings and gears are generally lubricated with oils formulated with additives to reduce corrosion, wear and oxidation. The results presented here indicate that the development of formulated oils for lubrication of Nitinol 60 should also be successful.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The mechanical properties of Nitinol 60, 60 wt% Ni, 40 wt% Ti (55 at.% Ni, 45 at.% Ti) are sufficiently attractive to warrant its consideration as a lubricated triboelement. Triboelements are always run lubricated. The ability to lubricate Nitinol 60 by the oils usually used on spacecraft mechanisms--Pennzane 2001A, Krytox 143AC and Castrol 815Z--was experimentally determined. These oils were run in the boundary lubrication regime for Nitinol 60 balls running against Nitinol 60 counterfaces in the vacuum spiral orbit tribometer. Test results consisting of the coefficient of friction versus time (friction traces) and relative degradation rates of the oils are presented. Contrary to the inability to successfully lubricate other metal alloys with high titanium content, it was found that Nitinol 60 is able to be lubricated by these oils. Overall, the results presented here indicate that Nitinol 60 is a credible candidate material for bearing applications.

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