# NITINOL 60 AS A MATERIAL FOR SPACECRAFT TRIBOELEMENTS

**Stephen V. Pepper[(1)], Christopher DellaCorte[(2)], Ronald D. Noebe[(3)], David R. Hull[(4)], Glenn Glennon[(5)]**

*[(1)]NASA-Glenn Research Center, Cleveland, OH 44135, (United States) Email: stephen.v.pepper@nasa.gov*
*[(2)]NASA-Glenn Research Center, Cleveland, OH 44135, (United States) Email: christopher.dellacorte@nasa.gov*
*[(3)]NASA-Glenn Research Center, Cleveland, OH 44135, (United States) Email: ronald.d.noebe@nasa.gov*
*[(4)]NASA-Glenn Research Center, Cleveland, OH 44135, (United States) Email: david.r.hull@nasa.gov*
*[(5)]Abbott Ball Company, Inc., West Hartford, Connecticut 06133-0100, (United States) Email: gglennon@abbottball.com*

## ABSTRACT

The mechanical properties of Nitinol 60, 60 w/o Ni, 40 w/oTi (55 a/o Ni, 45 a/o Ti) are sufficiently attractive to warrant its consideration as a lubricated spacecraft triboelement. 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 a 440C steel counterface in the vacuum spiral orbit tribometer. Test results consisting of the coefficient of friction versus time (friction traces) and relative degradation rates 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 spacecraft bearing applications.

## 1. 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 [1,2]. In the present paper, we present evidence that NiTi alloys can be tailored to avoid shape memory or superelastic behavior and that such alloys display excellent 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.

Traditional tool steel based bearing materials, such as M50 and 52100 enjoy widespread application due to their high hardness, ease of manufacture and good tribological properties. However, these alloys suffer from corrosion attack if not protected and though electrically conductive they are also highly magnetic. In addition, when used as bearing rolling elements, their high density leads to high centrifugal forces and limited fatigue life. These considerations have driven the search and development of alternate bearing and mechanical component alloys, namely stainless steels and ceramics. Stainless steels such as 440C are widely used in the bearing and gear industry where corrosion resistance and high hardness are required. These martensitic stainless steels are reasonably low cost, easy to machine prior to heat treatment and are dimensionally stable. When prepared through vacuum melting processes, they achieve very uniform, fully dense microstructures which lead to fine surface finishes and good fatigue behavior. Despite being referred to as stainless, however, the 400 series martensitic steels are prone to corrosion and are more accurately referred to as corrosion-resistant alloys rather than stainless. They are also highly magnetic which can be problematic in certain applications.

Silicon nitride ceramics, on the other hand, are essentially corrosion proof. They can be polished to very fine surface roughness and are quite wear resistant. Silicon nitride's low density compared to steels also makes it ideal for ultra high-speed applications because lower centrifugal stresses result. These attributes make silicon nitride the material of choice for high stiffness, high load, high-speed bearings and for applications that include corrosive conditions and aggressive sliding environments. Such applications include bearings for gas turbine hot sections, cryogenic oxidizer turbopumps and components for diesel engine fuel injection systems. Though nonmagnetic, silicon nitride is an electrical insulator. It is also more expensive to manufacture than steels owing to the complexity and cost of the high temperature, high pressure powder metallurgy processing required. Silicon nitride's low thermal expansion coefficient can present challenges in applications involving wide temperature variations.

This paper assesses the feasibility of using NITINOL 60 (60 w/o Ni, 40 w/o Ti (55 a/o Ni, 45 a/o Ti)) for bearings and mechanical components. 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.

Historically, metallic alloys with high concentrations of titanium are poor tribological materials in that they do not respond well to lubrication by organic fluids [3-5]. 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. 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 440C steel counterfaces in the vacuum spiral orbit tribometer. Test results consisting of the coefficient of friction versus time (friction traces) and relative degradation rates will be presented. Initial results have been reported [6].

## 2. MATERIALS

The NITINOL 60 balls evaluated in this work were manufactured via a high temperature proprietary powder metallurgy process roughly similar to that described in the literature [7]. The finished 12.5 mm diameter balls were bright and shiny in appearance and resembled conventional polished steel balls. Density was measured at 6.71 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. The elastic modulus is estimated to be 114 GPa, comparable to that of the Ti-6Al-4V alloy. Differential scanning calorimetry (DSC) indicated that the final hardened balls are microstructurally stable down to at least –100 °C. The 440C steel counterfaces on which the NITINOL 60 balls ran in the spiral orbit tribometer had Rockwell C hardness values about 60.

## 3. TRIBOMETER

For the tribological evaluations, NITINOL 60 balls were lubricated with a thin film of the different oils and subjected to a rolling-sliding contact lubricant wear life test in a Spiral-Orbit-Tribometer (SOT), described before [8,9]. The SOT, depicted in Fig. 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

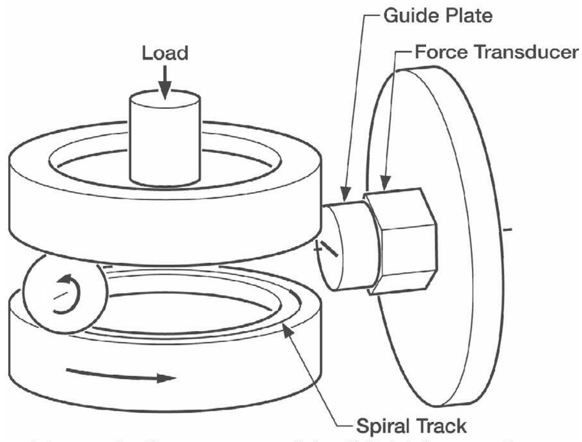


*Figure 1. Components of the SOT. The top plate and guide plate are stationary, while the bottom plate rotates to drive the ball.*

contact ball bearing. One of the plates is stationary and the other 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. 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 440C plate specimens were initially clean and only the ball was lubricated with about 25 µg of oil. Tests were run at a load of 30 lb, corresponding to a Hertz pressure of 1.06 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. In a symmetric system, 440C steel/440C steel for example, each member in the ball/plate contact contributes equally to the tribochemical attack rate and a normalized lifetime (orbits to failure per µg of lubricant initially applied) is obtained. In the asymmetric system considered here where members of the contact may have different tribochemical activities, smaller or greater lifetimes may occur. An extreme case is one in which one of the partners exhibits such great tribochemical aggressiveness that the lubricant does not survive thecontact at all and failure of the lubrication is immediate, with no observable lifetime. The other extreme case is that in which one of the partners exhibits no tribochemical activity at all and the test's (longer) lifetime is determined only by the activity of the other partner. The goal in this report is to provide an assessment of the ability to lubricate the NITINOL 60 via vacuum SOT tests with the NITINOL 60/440C steel/oil system.

## 4. TRIBOLOGY RESULTS

Determination of the ability of NITINOL 60 to be lubricated is best illustrated by first referring to a test of Pennzane 2001A on specimens that are all 440C steel. This is an oil/metal combination that is well established as a system that can be successfully lubricated. The friction trace of a typical test shown in Fig. 2 illustrates the basic characteristic—a low constant CoF illustrated for the first 250 orbits. The sensitivity of the SOT test to the surface chemical constitution of the ball is also illustrated in Fig. 2, which shows a test with a 440C ball coated with a thin film of titanium. It is evident from the high erratic CoF of the test with the titanium-coated ball that the system is not operating in a lubricated manner. This is attributed to the destruction of the Pennzane's molecular structure and attendant loss of lubrication capability by the tribochemically aggressive titanium film with which it is in contact. This test demonstrates that only one partner of a tribological pair needs to be tribochemically aggressive to prevent effective lubrication. Such highly aggressive tribochemical behavior was also observed with a NITINOL 60 ball coated with titanium, so that the effect is not dependent on the particular mechanical properties of the ball, but is really of chemical origin. Fig. 2 thus illustrates the extreme cases within which a test of the capability of lubricating a particular material falls—successful lubrication, indicated by low and constant CoF and lack of lubrication, indicated by high and erratic CoF.

The friction trace of a test with a NITINOL 60 ball lubricated with Pennzane 2001A and running on 440C plates is also shown in Fig. 2 and is seen to exhibit the same low and constant CoF typical of a successfully lubricated contact as does the all-440C steel system. Tests of all three oils with the NITINOL 60 balls running on 440C steel plates exhibited this behavior in the first few hundred orbits, indicating that NITINOL 60 is definitely not so tribochemically aggressive so as to preclude its lubrication by these oils.

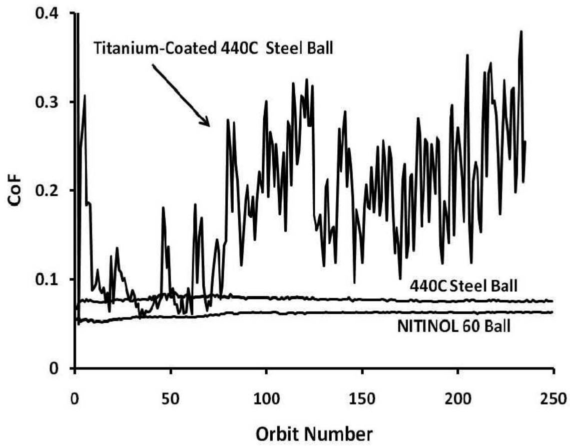


*Figure 2. Friction traces for a 440C steel ball, a 440C ball coated with a thin film of titanium and a NITINOL 60 ball, all lubricated with Pennzane 2001A and running on 440C steel plates.*

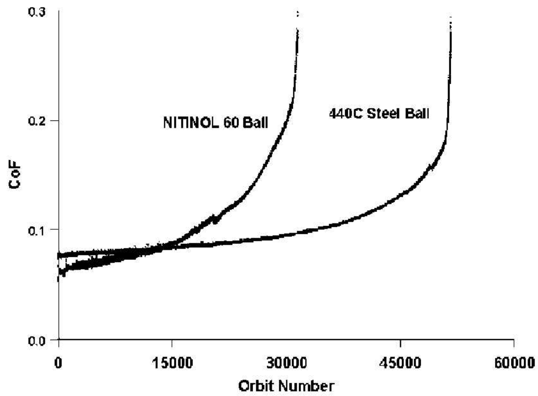


*Figure 3. The complete friction traces of the NITINOL 60 ball and 440C steel ball lubricated with Pennzane 2001A in Figure 2.*

The complete friction traces to failure of both the NITINOL 60 ball and 440C steel ball lubricated with Pennzane 2001A is shown in Fig. 3. The progressive increase in CoF exhibited by NITINOL 60 is typical of Pennzane in all tests with 440C steel. In fact the similarity of friction traces with NITINOL 60 and 440C steel balls was found for all three lubricants used here.

The normalized lifetime of a lubricant is an inverse measure of its consumption rate and thus of the tribochemical aggressiveness of a bearing material combination. These lifetimes for tests for NITINOL 60 balls on 440C steel and also for tests with an all-52100 steel system already published [9] are given in Tab. 1. It has been found that the lifetimes of the lubricants on 52100 steel are similar to those on 440C steel, thus justifying the comparison to the results of NITINOL 60 on 440C steel.

*Table 1. Normalized lifetime(orbits/μg) of 3 lubricants for tests with NITINOL 60 on 440C steel (average of 3 tests with each lubricant) and for tests with 52100 steel (average of 4 tests with each lubricant).*

| Lubricant | NITINOL 60 on 440C Steel | 52100 Steel on 52100 Steel |
|---|---|---|
| Castrol 815Z | 100 | 45 |
| Krytox 143AC | 68 | 73 |
| Pennzane 2001A | 1100 | 4100 |

The normalized lifetimes with the PFPE oils—Krytox and Castrol—on the NITINOL 60 ball are rather similar to those of the 52100 steel system, indicating that NITINOL 60 is, generally, no more tribochemically aggressive for those oils than either 440C or 52100 steel. The lifetime of Pennzane on NITINOL 60 is an order of magnitude greater than that of Castrol or Krytox, similar to the ordering of lifetimes of these lubricants for the all-steel system. However, the average lifetime of Pennzane on the NITINOL 60 ball is noticably shorter than the lifetime with steel, indicating a possibly more aggressive tribochemistry of NITINOL 60 for this oil. The differences observed between tests with and without NITINOL 60 may be due to (a) differences in tribochemistry (b) differences in the Hertz pressure at which the tests were run or (c) simply due to statistical scatter in the test values.

## 5. CONCLUSION

It is shown here by vacuum spiral orbit tribometry that the bearing system consisting of a NITINOL 60 ball and 440C steel plates *can* be successfully lubricated by Castrol, Krytox and Pennzane oils that are used on spacecraft bearing systems. Such a hybrid system, however, does not take full advantage of the unique combination of properties of NITINOL 60, such as being highly resistant to corrosion, nonmagnetic, electrically conductive and less dense than steel. NITINOL 60 plates for the SOT will soon be available. Tests with these oils are planned for an all-NITINOL 60 system and the results will be reported in the near future.

## 6. REFERENCES


1. Hodgson, D.E., Wu, M.H. & R.J. Biermann. (1990). Shape Memory Alloys. *Metals Handbook* **2**, 10th edition, 897–902.
2. Shabalovskaya, S.A. (2002). Surface, Corrosion and Biocompatibility Aspects of Nitinol as an ImplantMaterial. Bio-Medical Materials and Engineering, 12(1), 69–109.
3. Rabinowicz, E. (1954). Frictional Properties of Titanium and Its Alloys. *Met. Prog.,* **65**(2), 107–110.
4. Rabinowicz, E. & Kingsbury, E.P., (1955) Lubricants for Titanium. *Met. Prog.* **67**(5), 112–114.
5. Roberts, R.W. & and R.S. Owens, R.S. (1963) Titanium Lubrication, *Nature*, **200,** 357–358.
6. DellaCorte, C, Pepper, S.V., Noebe, R., Hull, D.R. & G. Glennon, (2009) Intermetallic Nickel-Titanium Alloys for Oil-Lubricated Bearing Applications. *NASA/TM—2009-215646.*
7. McNeese, M.D., Lagoudas, D.C., & Pollock, T.C. (2000). Processing of TiNi from ElementalPowders by Hot Isostatic Pressing, *Materials Science and Engineering* **A280**(2), 334–348.
8. Pepper, S.V. & Kingbury, E.P. (2003). Spiral Orbit Tribometry—Part I: Description of the Tribometer. *Trib. Trans.* **46**(1), 57–64.
9. Pepper, S.V. & Kingbury, E.P. (2003). SpiralOrbit Tribometry—Part II: Evaluation of Three Liquid Lubricants in Vacuum. *Trib. Trans* **46**(1), 65–69.