HARD FILM COATINGS FOR HIGH-SPEED ROTARY MEMS SUPPORTED ON MICROBALL BEARINGS

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Abstract: Titanium Nitride (TiN) and Silicon Carbide (SiC) coatings deposited on the surface of silicon raceways are evaluated in a microturbine. Nanoindentation is employed to study the properties of the hard-thin-film/silicon raceway system and the tribological platform is evaluated through turbine operation curves. TiN films are shown to stay intact over the speeds and forces in the range relevant to future power and energy applications applications, (500-10,000rpm and 10-50mN, respectively), while SiC films wear almost instantaneously. Evaluation of the dynamic friction torque versus normal load relationship between the TiN and bare Si systems suggest the gradual generation of wear debris, comprised of either the raceway or microballs, is negating the benefits of enhanced mechanical properties in TiN.

Keywords: tribology, friction, microturbine, microball bearing

INTRODUCTION

Silicon microfabrication technology has allowed researchers to scale rotary machines such as pumps, generators and motors to continuum and microscale structures for compact power systems. A major challenge in realizing robust power micro-electromechanical systems (PowerMEMS) is providing high-performance mechanical support for surfaces under load in relative motion. Microball bearings have been demonstrated to be viable for micromotors and micropumps across a large speed range [1,2]. In the case of the [2], SiC was applied on the surface of the micromotor to act as low friction, low wear material and thought to enable lower friction operation than bare silicon, however no tribology has been performed and was only limited to operation at low speed/load.

Measurements of friction force (or torque), COF, and wear are, by-in-large, limited to the sliding regime for microsystems [3]. Randomly distributed micro rolling contact bearings have been studied in [4]. Ghodssi, *et al.*, first explored the frictional behavior of steel, 285 µm diameter, ball bearings within a microfabricated ball/raceway system [5]. This work presented a statistical analysis of the static COF for bare silicon (μ=0.0560), thin film silicon nitride (μ=0.0290), and chromium (μ=0.0235) micromachined surfaces with steel balls. A microscale analog to a full compliment planar thrust bearing was first demonstrated in a MEMS device in [6]. McCarthy, *et al.*, reported a load and speed dependant dynamic COF values for a planar contact bearing from 0.0005-0.025 [7].

This study aims to illuminate the potential for hard film coatings in a rolling bearing configuration realized within a high-performance rotary microsystem. This work focuses on the enhancement of a previously reported microturbine [7] by using SiC and TiN hard film coatings on the raceways of the hybrid ceramic/metal thrust ball bearings with the improved bearing design from [8].

EXPERIMENT

Microturbine Design

The microfabricated silicon test device, shown in Fig. 1, consisted of two main components: a radial inflow turbine layer for actuation, and the encapsulated ball bearing.

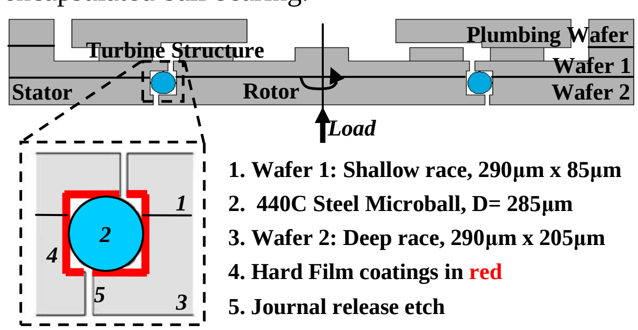

Fig. 1: Cross section schematic of the microturbine tribology test device with a close-up of the raceway.

The bearing is encased by two bonded silicon layers with an asymmetrical raceway deep-reactive-ion etched into each layer. The bearing depths are offset so that the balls do not contact the silicon bond interface during operation. Before bonding, the raceway surfaces were coated with either SiC or TiN films, or left bare. A journal is etched completely through each wafer to create a rotor that is supported only by the microball bearings. After bonding, turbine blades and vanes are etched into the top structure with a height of 250 µm, simultaneously reaching the journal etch and releasing the turbine side of the device. Similarly, the thrust-side release structure is etched into the backside of the bonded test device, completely releasing the rotor. A complete fabrication schematic can be found in [1]. The packaging of the test device allowed for turbine flow and a thrust plenum to be operated independently, allowing for the decoupling of thrust and actuation loads as described in [7].

Hard Film Coating

The improvement of raceway hardness, considered to be the principle mechanical property of interest, through the use of thin films is the focus of this study. TiN and SiC thin films were chosen because of their promising mechanical properties and their compatibility with microfabrication techniques.

SiC and TiN films are sputtered onto a bare silicon substrate after successive O_2 plasma and Ar plasma cleaning steps. The SiC films were sputtered to a thickness of 250nm from a SiC target in an Ar atmosphere. The chamber pressure is held at 2.5 mTorr and the DC sputtering source is operated at 1 kW without any external substrate heating. These conditions most likely produced an amorphous film, although the morphology was not studied. TiN films were deposited in a reactive sputtering process. First, a thin Ti adhesion layer was deposited at 5 mTorr, and 1kW, in pure Ar. Next, TiN was sputtered from a Ti target in a N_2 plasma at 2-5 mTorr and 1 kW after a 30 min pre-sputter that nitrides the surface of the target. TiN sputtered in this manner typically has a columnar grain structure. The total film thickness of the Ti/TiN stack is 250nm.

Fig. 2 shows the load/displacement curves obtained for the three materials systems in a nanoindentation study. A *Hysitron Triboindenter* was used to probe the mechanical properties of the films and substrate. Table 1 summarizes the mechanical properties of interest for all three materials systems, extracted from the curves shown in Fig. 2.

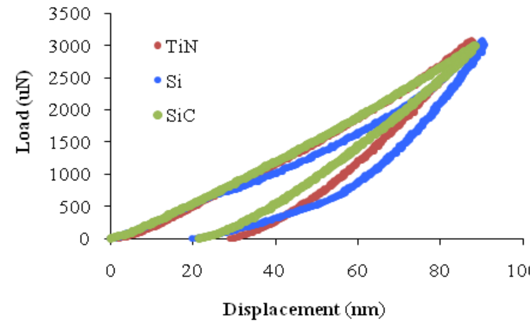

Fig. 2: Characteristic load/displacement curves obtained for Si, SiC and TiN

Table 1: Summary of mechanical properties obtained from nanoindentation.

Properties	Si	250nm TiN	250nm SiC
Stiffness (GPa)	169	155.9	127.1
Hardness (GPa)	13.4	15.7	15.5-17.7

Testing Methodology

Friction torque measurements were taken for each material system using spin-down deceleration tests at variable normal loads. First, the thrust plenum pressure is set to provide normal load (5-50mN) to the bearings. The independent turbine flow then actuates the released rotor structure via the deep-etched turbine structures. Because of leakage through the journals, the normal force on the bearing during operation is the sum of the thrust pressure and actuation pressure at the journal. After the turbine has equilibrated to a steady rotational speed, the actuation flow is cut-off and the turbine is left to decelerate under only the pressure of the thrust plenum. Friction torque over the speed range of 1,000-10,000 rpm, or dynamic friction torque (DFT), is obtained from the second derivative of a power law fit to the position data from the spin-down. A more in-depth description of this methodology can be found in [6].

Turbine operation curves were taken for each of the three materials systems. For these tests, rotation speed was measured as a function of input power provided by the turbine flow. All three materials systems were tested after an initial run in. Bare Si and TiN turbines were also tested after every 500,000 revolutions to determine if wear had significantly altered the operating conditions of the turbines.

DISCUSSION

Silicon Friction Torque

A power-law relationship between DFT and normal load was presented for a silicon high-speed microball bearing supported microturbine in [7]. The empirical power law relationship implies that friction torque approaches zero as normal load becomes zero. In this work, a linear relationship of the form (1):

$$D = f^{*}L + v, \tag{1}$$

where D is the DFT, f is a constant representing the linear dependence of DFT on normal load, L is the normal load in mN and v is the load independent component of DFT. The value v is significant because it represents the theoretical minimum friction torque in an encapsulated microball bearing turbine for a perfectly thrust-balanced system. Fig. 3 illustrates the DFT values from spin-down tests taken at successive normal loads for a silicon raceway tested through progressive levels of run-in (fresh, 1 M revolutions, and 2 M revolutions).

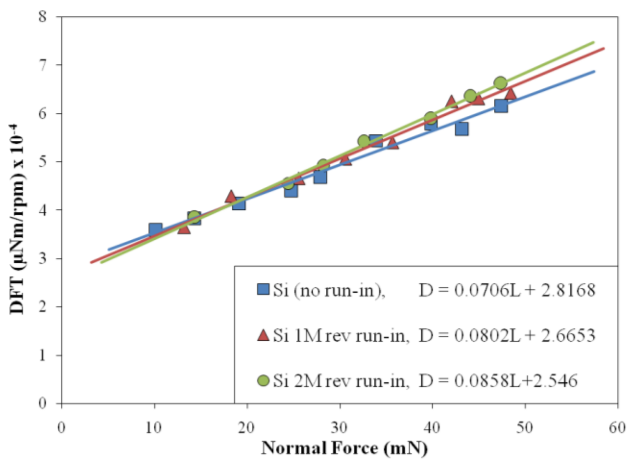

Fig. 3: DFT relationship from 10mN-50mN normal load in a silicon raceway/steel ball microturbine system.

Wear, or lack thereof, can be indirectly observed in the consistent values of DFT through the lifetime of the device. Future microball bearing supported MEMS devices can utilize the empirical, linear DFT relationship over this range of operating loads. Bare silicon raceways with the modified bearing design from [8] exhibit consistent behavior up to, and more than likely beyond 2M revolutions of run in, at typical MEMS operating loads. This makes the simple fabrication of an uncoated silicon/steel bearing attractive to applications that can accept current levels of friction torque where minimal wear can be tolerated.

Coated Raceway Performance

TiN and SiC film coatings are sputtered on to silicon raceways of identical geometry to those previously discussed. The mechanical properties of these films are determined through nanoindentation of the film-substrate system. Hardness is increased over bare silicon by 17% and 32% for TiN and SiC coated raceways, respectively. The higher hardness of the coated systems should be more resistant to plastic deformation from a contact load compared to bare Si, leading to lower friction.

Operating curves of each microturbine/coated raceway system are taken as an initial metric and periodic assessment of turbine performance. Input power, the product of flow and pressure drop across the turbine, is measured within the packaging. Turbine speed is measured in a tachometer style with a high-rate optical displacement sensor. Fig. 4 shows the operation curves taken with less than 10,000 revolutions for the three materials systems.

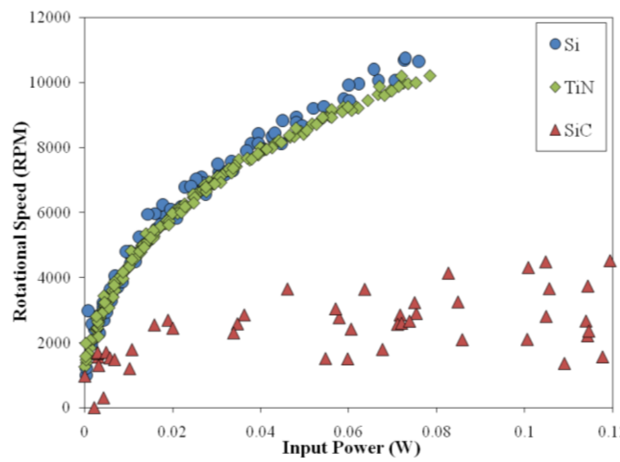

Fig. 4: Initial operation curves taken for each material system.

The SiC coated raceway system wore almost immediately upon testing and caused the turbine to behave erratically. Visual inspection of the SiC raceway surfaces revealed minimal fracture of the film on the surface, but rather a smooth worn interface that was within the estimated contact area of the balls. This suggests that the mechanism of wear took place within the film, rather than at the film/substrate interface. Film properties, rather than adhesion properties dominated the failure mechanism of this film, suggesting that crystalline 3C-SiC with higher harness and stiffness, but similar adhesion to silicon could be a candidate for future study.

TiN coated raceways were tested using spin-down friction testing in the same manner as described in the *Silicon Friction Torque* section. Fig. 5a compares the DFT of TiN and Si raceways with little run-in (within the range of 5,000-10,000 revolutions). In contrast, Fig. 5b compares the DFT of TiN and Si raceways after 2M revolutions of run-in. Initally TiN coated races perform almost identically to bare Si systems.

At 2M revolutions the TiN raceways begin to exhibit erratic behavior when compared to the consistent performance of the bare Si raceways. Inspection of the raceway after testing revealed localized delamination of the TiN coating over ~ 25% of the bearing surface within the contact area of the ball. Fatigue at the interface of the film/substrate system could lead to sub-surface crack initation and growth, causeing a gradual delamination of the film. The film adhesion properties could be tuned to avoid fatigue induced delamination, although the friction of the film from the onset of testing showed no significant improvement over bare silicon. This suggests that other phenomena, such as ball-on-ball sliding friction, may dominate over rolling friction dictated by raceway mechanical properties. The ball packing and surface properties present an interesting avenue to reduce system friction as opposed to tuning the properties of the raceway.

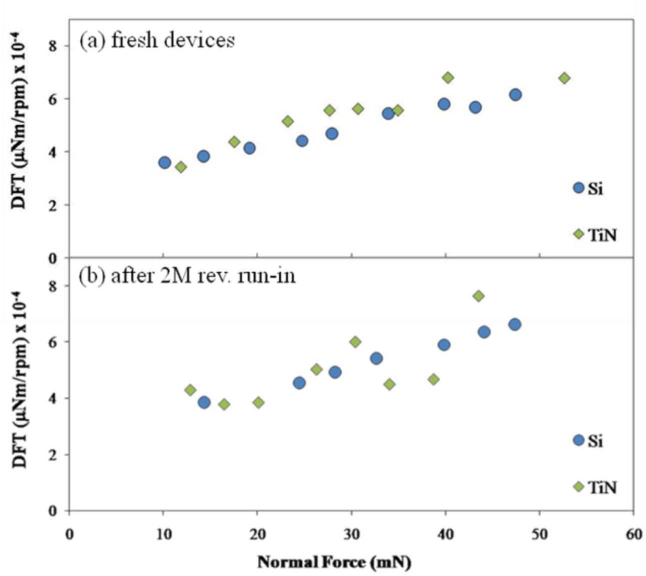

Fig. 5: (a) DFT values for bare Si and TiN coated systems. Both systems follow the linear relationship between DFT and normal load. (b) DFT values for raceways after 2M revolutions of run-in. Si raceways remain consistent, while the TiN coated systems begin to exhibit erratic behavoir.

CONCLUSION

A linear DFT/normal load relationship was established for bare Si and TiN coated raceways within fabricated microturbines. The linear relationship (Eq. 1) accounts for load independent contributions to friction torque and establishes a theoretical minimum operating torque. Friction testing was repeated and the DFT values re-evaluated at various intervals of turbine wear up to two million revolutions (fig. 3,5b). Despite having a superior hardness, the TiN coated turbines exhibited similar values of friction torque for the range of normal loads and film thickness tested. An increasingly erratic behavior of the TiN turbines with increased run-in suggests the microball/raceway system is wearing and generating debris. Further testing will investigate the other potential contributions to friction within the coated raceway systems, such as ball-on-ball sliding. A greater understanding of the wear mechanisms present in both the coated and bare-Si systems, including a study of the ball wear, will help elucidate the fundamental mechanisms dictating the tribological properties of the microball bearing platform.

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