Wear 312 (2014) 58–69

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Wear characteristics of large aspect ratio silicon microbearing systems

S. Demiri [a], S. Boedo [b,*], L.S. Holsen [b]

[a] Microsystems Engineering, Rochester Institute of Technology, Rochester, NY 14623, United States
[b] Department of Mechanical Engineering, Rochester Institute of Technology, Rochester, NY 14623, United States

ARTICLE INFO

Article history:
Received 11 November 2013
Received in revised form
25 January 2014
Accepted 31 January 2014
Available online 11 February 2014

Keywords:
MEMS
Microsystems
Tribology
Journal bearings
Wear

ABSTRACT

This paper addresses the wear characteristics of large aspect ratio (length-to-diameter) silicon microbearing systems using an enhanced experimental test rig. The test system is comprised of a rigid rotor which has been manually assembled onto a fixed hub to form the microbearing. CMOS-based lithographic and etching processes, including deep-reactive ion etching, are employed in the construction of the rotor and hub with length to diameter ratio of approximately 0.5 and radial clearance values in the range from 3.5 to 9.2 μm. The rotor is pneumatically driven by nitrogen gas at a constant supply pressure delivered through a rectangular microchannel.

A new methodology for measuring wear was developed by digitizing optical microscope images of the rotor system, and the rotor load was calculated from CFD models of the entire rotor-hub system. It was found that the tested silicon microbearings have a wear coefficient (based on the well-known Archard relation) which falls within a relatively narrow band bounded by previously published values for polysilicon materials tested at the macroscale and microscale. The wear coefficient is also observed to be relatively unchanged during the wear process which is more characteristic of macroscale wear processes.

1. Introduction

Advancements in integrated-circuit (IC) processing have led to the introduction of silicon-based microelectromechanical systems (MEMS). Silicon's prominence within MEMS is attributed to its strength, electrical, and oxidation characteristics [1]. The range of MEMS applications has been rapidly expanding in response to increasing demands for mobility and multifunctionality at low cost. A key incentive fueling the development of microsystems such as microturbines, micropumps, microgears, and lab-on-chip systems is the low unit cost resulting from mass-fabrication of complex, integrated, silicon-based microsystems by borrowing from many established precision IC processing techniques. In the quest for commercialization, the primary inhibitor to date has been bearing reliability. This is particularly true for high speed operation (on the order of tens of thousands to millions of revolutions per minute) where seizure, high wear rates [2], and complete destruction [3] have been observed.

Surprisingly, relatively little is understood about the wear behavior of large aspect ratio microbearings. In the past, researchers have worked primarily on surface micromachined polysilicon electric-driven rotating machinery. The design space available for employing this fabrication methodology has resulted in bearings with length-to-diameter (L/D) aspect ratios on the order of 0.05. This ultra-low aspect ratio is due to limitations of surface micromachining planar fabrication technology. More recently, wear characteristics of larger aspect ratio (∼0.6) plain cylindrical journal bearings fabricated using X-ray lithography, Ni electroplating, and tungsten alloy coatings were reported [4]. Results indicated that coated microbearings had lower wear rates than uncoated bearings.

Recently, the authors reported on the first published study which investigated the wear behavior of large-aspect ratio silicon-based microbearings [5]. The experimental system, denoted as Phase 1, is shown in Fig. 1. The system is characterized by a rigid rotor which has been manually assembled onto a fixed hub to form the microbearing. Rotor (out-of-plane) thickness ranges from 150 to 200 μm, and the rotor diameter is approximately 400 μm, resulting in a relatively large length to diameter ratio of 0.38–0.5. The rotor is pneumatically driven by nitrogen gas which enters a drilled access hole from the backside of the hub and flows through one of the rectangular microchannels.

It was found that wear progression was substantially dependent on bearing geometry for bearing configurations with similar average clearance values. Observed wear morphology was strongly suggestive of impact damage, as shown in Fig. 2, and could not be attributed to an adhesion or abrasion wear model. Moreover, the

* Corresponding author. Tel.: +1 585 475 5214; fax: +1 585 475 7710.
E-mail addresses: sxd3544@rit.edu (S. Demiri), sxbeme@rit.edu (S. Boedo), lsh1471@rit.edu (L.S. Holsen).

http://dx.doi.org/10.1016/j.wear.2014.01.016
0043-1648

Nomenclature

A_w	debris area [L^2]
B	hub length [L]
C	radial clearance [L]
D	rotor diameter [L]
F	radial load [F]
H	material hardness [FL^{-2}]
K	wear coefficient [–]
L	rotor out-of-plane thickness [L]
L_s	wear path length [L]
N	number of thrust pads [–]
P_0	ambient pressure [FL^{-2}]
R	hub nominal radius [L]
R_1	hub radius, top surface [L]
V	volumetric wear [L^3]
W	thrust load [F]
a	pad effective inner radius [L]
b	pad effective outer radius [L]
e	journal eccentricity [L]
h	film thickness [L]
r_1	rotor radius, top surface [L]
t_w	wear particle size [L]
x,y,z	system reference frame [L]
Δ	pad etch depth [L]
α	taper angle [–]
δ	rotor axial position [L]
ε	journal eccentricity ratio [–]
θ	rotor rotation angle [–]
μ	dynamic viscosity [FTL^{-2}]
σ	surface roughness [L]
ψ_0	sector angle [–]
ω	rotor angular velocity [T^{-1}]

observed impact damage was thought to be associated more with the physical limitations and test protocol of the Phase 1 experimental rig, characterized by large clearance specifications and lack of thrust bearing surfaces, compared with what would be expected in an actual application.

This paper provides an assessment of the effects of bearing clearance on the wear behavior of large aspect ratio silicon-based gas microbearings using a new Phase 2 test apparatus. Tighter clearances, constant supply pressure, and the use of gas thrust bearing surfaces are employed in the new design.

2. Material and methods

As in Phase 1, rotors and hubs are fabricated on separate silicon wafers and are manually assembled to form the microbearing system. In this manner, radial clearances as small as 1 μm are possible for bearing aspect ratios considered here. Novel "sprue" and "float" etching techniques involving KOH and deep reactive ion etching (DRIE) processes are employed in the fabrication of the hub and rotor, as described in detail elsewhere [5,6]. Phase 2 nominal rotor thickness and diameter specifications are 190 and 400 μm, respectively, resulting in an L/D ratio of 0.48 which is similar to that employed in Phase 1.

Fig. 3 shows several new features which are incorporated into the Phase 2 hub design. A single straight microchannel which is shorter than the Phase 1 design reduces the pressure drop from the source to the hub teeth. As discussed below, nitrogen gas is supplied from the top surface of the hub to the microchannel, eliminating the need for wafer dicing and drilling access holes into the brittle silicon. Sectored thrust pads are incorporated into the bottom of the hub base using a separate photolithographic mask pattern. The design intent of the pads is to promote full-film gas lubrication between the bottom of the rotor and the base of the hub, which in turn reduces contract friction, increases rotational speed, and stabilizes out-of-plane rotor motion. Fabricated hubs are shown in Figs. 4 and 5. The hub is now formed as a hollow shaft to assist in the alignment of a fiber optic cable for rotor speed measurements.

Figs. 6 and 7 show an exploded view schematic and assembly of the Phase 2 microbearing test fixture. The entire undiced wafer is placed on a precision ground 8 mm thick stainless steel plate. A polycarbonate plate and silicone sheet, each 1 mm thick, and each containing drilled access holes are aligned over the hub wafer. A top steel plate with access holes is bolted to the bottom plate which compresses the silicone sheet and seals the fixture. "Push-quick" gas feed connections are threaded into the top steel plate. The use of these fittings eliminates the potential for metallic debris during assembly, and the time required to connect the gas feed is substantially reduced.

As in the Phase 1 test rig, the emitting end of an optical fiber is oriented perpendicular to the top surface of the rotor. As a tooth traverses the light path, a fraction of the light is reflected back into the optical fiber and back through the coupler to be picked up by the light meter via another optical fiber. The result is a fluctuating power signal as each tooth passes over the light path, which when transmitted to an oscilloscope determines the rotor speed.

Fig. 8 shows the geometry of the assembled bearings in conformal and non-conformal configurations as defined previously [5,6] with the rotor positioned in contact with the thrust pad. A radial clearance parameter C_0 is defined as

$$C_0 = r_1 - R_1 + \alpha(B - L) \quad (1)$$

where a small, common axial taper α on rotor and hubs is a result of the DRIE etching process. In the conformal configuration, C_0 is essentially constant over the entire clearance space, and in the non-conformal configuration C_0 is the radial clearance at the top of the rotor. This radial clearance C_0 is the kinematic limit of rotor translation in the x–y plane provided rotor and hub are axially aligned.

A surface roughness value $\sigma_1 = 300$ nm was measured on the hub channel walls (perpendicular to the channel flow) using a WYKO optical profilometer and validated using atomic force microscopy (AFM). A surface roughness value of $\sigma_2 = 100$ nm was measured on the hub base which includes the thrust pads. Since rotor and hub employ the same fabrication process, the corresponding composite surface roughness σ_c of the contacting wall and thrust surfaces are given by

$$(2)^{1/2} \bullet \sigma_1 = 424 \text{ nm and } (2)^{1/2} \bullet \sigma_2 = 141 \text{ nm},$$

respectively.

3. Experimental results

A total of four test case studies, each with progressively larger clearances, were completed for microbearings in non-conformal (NC4, NC5) and conformal (C4, C5) configurations. Table 1 lists the dimensional bearing specifications for the case studies.

Figs. 9 and 10 show the progression of wear for each of the four tests at a common number of cumulative cycles. Each test case was driven at a constant 68.80 kPa (gauge) gas supply pressure for a