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Elastomer vs. ceramic in cyclically loaded contact: What wears less?

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ABSTRACT

Here we compare the wear performance of silica and polyurethane in a vacuum gripper. The problem is modeled numerically by evaluating the energy dissipated at the interface, and experimentally by examining surface damage in contact subjected to cyclic normal loading. In the numerical model, the energy dissipated during unloading is found to be negligible with respect to that of loading. Changing the contact geometry has a good effect in terms of frictional work reduction, but this is not as significant as the effect obtained by changing the material. Replacing silica with polyurethane reduces the frictional work by a factor of at least 20. The latter finding is qualitatively validated in experiments.

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1. Introduction

Friction is a dissipative process in which a portion of mechanical work done by external forces is expended to generate structural defects, stored as a result of elastic strains, emitted in the form of phonons, photons and electrons, and transmitted into heat [1–3]. This process takes place within the topmost layers of contact surfaces, raising the free surface energy and bringing these layers into an activated unstable state [4]. When a surface transits to an equilibrium state as a result of interaction with the environment and transformation of the subsurface material structure, the change manifests itself in various types of wear [5], while the amount of energy involved in this process actually determines the form of surface damage [6].

Based on the above, many efforts were made to relate the wear volume to the amount of energy dissipated in a tangentially loaded sliding contact [7]. Because it is hardly possible to measure local friction and relative displacement, experimental works correlated wear volume with cumulative dissipated energy, determined by integrating global friction force over the total sliding distance [8–12]. Numerical modeling, however, has made it possible to resolve the spatial distribution of shear traction and relative displacement, allowing the local cumulative energy dissipation to be computed, and the spatial wear distribution to be predicted [13,14].

The case of wear in a contact repeatedly loaded in the normal direction presents another interesting topic. Here, the damage is related to the energy that is dissipated through slip at the periphery of contact between dissimilar bodies [15]. This type of motion is commonly referred to as radial fretting [16–18], and the resulting surface damage, though small, may constitute a significant problem for work that is conducted in a clean environment. One example of this problem arises in semiconductor manufacturing, where backside wafer contamination degrades flatness and creates “hot spots” leading to lithography defects on the front side of the wafer [19,20]. One of the main reasons for this contamination is wear of vacuum and electrostatic grippers due to cyclic normal loading in chucking and releasing incoming wafers.

While investigating this problem, we learned that the contact posts used to support gripped wafers are usually made of ceramics, in order to prevent chemical contamination of the wafers. However, ceramics are prone to interfacial slip, even at very small relative displacements, due to their high stiffness [21], which should inevitably lead to wear as a result of mechanical energy dissipation. Interfacial slip and shear stresses can be reduced significantly in a system that deforms easier and accommodates relative displacement within the bulk of contacting bodies by allowing their elastic deformation. Driven by this idea, we here compare the wear resistance of ceramic and elastomer, which can also be chemically inert and vacuum-compatible. To evaluate spatial wear distribution, the problem is modeled numerically by computing the mechanical energy dissipated at the interface. It is also investigated experimentally to examine actual surface damage in a contact that is subjected to cyclic normal loading and unloading.

The gripping system chosen for modeling is a vacuum chuck consisting of a few tens of nipples that each have toroidal shape with a flat contact area of 10.2 mm^2 and that share a plane of

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contact that is lapped to a mirror-like degree of surface finish. The chuck utilizes silica (SiO_2) as a contact material and works with a pressure drop of 90 kPa acting over an area of 28.3 mm^2 within each nipple to grip incoming silicon (Si) wafers. In both the numerical and experimental parts of this work, we modeled the behavior of a single nipple in contact with a corresponding wafer fragment. The elastomer employed for comparison was polyurethane (PU), which was chosen due to its wide industrial use based on its high resistance to wear and its long fatigue life [22].

2. Theoretical model

2.1. Numerical model

A commercial FE package, ANSYS, was used to solve the axisymmetric static elastic contact problem shown in Fig. 1(a); it is characterized using the parameters summarized in Table 1 (data on Si and SiO_2 were taken from [23,24], the mechanical properties of PU were provided by a local PU supplier, the friction coefficient of PU was measured in a ball-on-flat contact under the normal load of 0.4–1.6 N with a custom one-pass-slide tribometer described elsewhere [25], and the fillet radii were chosen to cover as wide range as possible given the available contact width of 0.5 mm). The model consisted of six-node triangular elements PLANE183, three-node surface-to-surface contact elements CONTA172 and three-node contact target elements TARGE169. Boundary conditions were defined as follows. The nipple base was clamped, which corresponds to the nipple/chuck connection. The external radius of the wafer fragment was allowed to move freely in a vertical direction and prevented from moving in a radial direction. The latter condition applies because there are several tens of nipples on one chuck, and a wafer fragment that is gripped by any nipple located not on the chuck's edge is constrained by the surrounding wafer fragments that are subjected to the same conditions (periodicity). Based on that the choice of friction model was not expected to affect much the spatial distribution of the mechanical energy dissipated in contact, the nipple/wafer interface was modeled as a simple frictional contact with local friction governed by Coulomb's law: sliding occurred when tangential stress reached a threshold value of normal stress multiplied by friction coefficient. Since the contact problem is nonlinear, it cannot be solved immediately by applying the total load. To this end, during loading, the pressures shown in Fig. 1(a) were reached by, first, bringing both external and internal pressures to 100 kPa and then decreasing the internal pressure to 10 kPa incrementally. Unloading was performed by incrementally increasing internal pressure back to 100 kPa. At each loading/unloading increment, displacement and stress fields inside the contacting nipple and wafer were evaluated (Fig. 1(b) and (c)). Tangential stresses (local specific friction force) and incremental variation of the local sliding distance at the interface between the nipple and the wafer were used as output parameters.

Table 1
Properties of materials and geometry tested.

	Young's modulus, E (GPa)	Poisson's ratio, υ	Friction coefficient	Fillet radius, R (μm)
Si	165	0.28	Counterface	0, 10, 20, … 310
SiO_2	73	0.17	0.33	
PU	0.04	0.5	2.3	

2.2. Energetic wear criterion

To determine the spatial wear distribution, at each contact point we evaluated the specific work done by the local friction force by integrating the tangential stress over the relative displacement (slip) between the mating surfaces of the nipple and the wafer. The stress distribution and sliding distance fields at the interface of the frictional contact were obtained from the FE model at each solution step. These values were processed in the MATLAB numerical computing environment to evaluate the local friction work (dissipated energy) according to the following expression

$$W(\mathbf{x}) = \int_{\delta(\mathbf{x})} \tau(\mathbf{x}, \delta(\mathbf{x}))\, d\delta \tag{1}$$

where $\tau(\mathbf{x})$ is the tangential stress and $\delta(\mathbf{x})$ is the sliding distance at point $\mathbf{x}$ of the interface. After evaluating the spatial distribution of the frictional work for both the loading and the unloading parts of a chucking cycle, we have found the maximum local specific work and the location at which it was reached. Given that our toy model cannot predict actual wear-induced changes in contact geometry in the course of repetitive loading and unloading, the work obtained upon completion of one loading cycle is the same for any subsequent repetition. Therefore, a maximum value of cumulative work, which represents the actual surface damage in our model, is proportional to the work done in one cycle. This may seem to be unrealistic; however, because the spatial wear distribution does not change much in a conformal contact, and because the wear volume, which is proportional to the dissipated energy, increases monotonically (to a first approximation) with the number of cycles [13], the results that are obtained for the first cycle can be (qualitatively) extrapolated to the rest of the surface life. Based on this rationale, the maximum local specific work was used as a comparative criterion to analyze the effects of material and surface geometry on wear.

3. Experimental details

3.1. Preparation of specimens and test conditions

The specimens used to model the wear performance of the

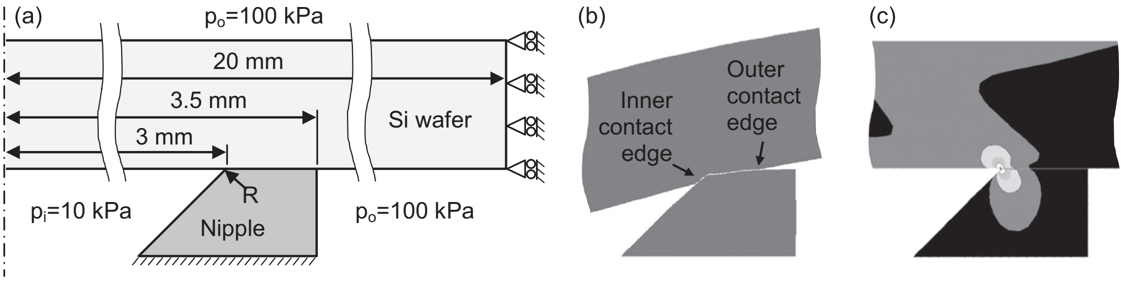

Fig. 1. Modeled vacuum nipple. (a) Loading and boundary conditions. (b) Deformation (not to scale) in loaded (activated) state. (c) Von Mises stress distribution in loaded state.