ABSTRACT

Nanoscale fretting can be studied by using scanning probe microscopy (SPM) and a newly proposed “slip index” which provides unified approach to fretting on different scales. Various relevant issues such as production of colloidal probes and SPM calibration will be presented. Partial and gross slip nanoscale fretting tests with displacement amplitude from 5 to 500 nm and normal load from 15 to 28 µN will be described. Experiments show a substantial increase of the friction at the transition from partial to gross slip and a significant difference of damaged surfaces in the two fretting regimes.

INTRODUCTION

Fretting is a relative cyclic motion between two surfaces, having a non-uniform distribution of local relative displacement at their contact [1]. Depending on loading conditions, material properties and environment, fretting causes fretting wear or fretting fatigue, which can arise in any assembly of engineering components if a source of vibration is present [2]. Fretting damage is identified as the plague of modern machinery [3] and is likely to be found in various micro electro mechanical systems (MEMS) that are extensively developed today.

Due to development of the scanning probe microscopy (SPM), it became possible to study fretting at the nanoscale. However, research effort of nanoscale surface damage was concentrated so far on abrasive wear mechanism using sharp tip SPM probes [4,5] and fretting was never studied at the nanoscale. In light of the above lack of information, it is the purpose of the present work to study nanoscale fretting of a sphere on flat with the SPM.

EXPERIMENTAL DETAILS

All tests were performed on a NanoScope III Dimension 3100 SPM with silicon rectangular cantilevers that were supplied without tips. A SiO$_2$ microsphere with a diameter of 3.1 µm was glued to the end of each cantilever to produce colloidal probes that enable to test a well-defined sphere-on-flat contact. An inverted light microscope and a three-axis manual micromanipulator were utilized to produce the colloidal probes.

Prior to each test, after installing a colloidal probe in the SPM, the system was adjusted to eliminate cross-talk problem [6] and then calibrated for the specific probe. An improved wedge calibration method [7] was used for the lateral (friction) force calibration. The bending stiffness required for exact measurement of the applied load and adhesion force was determined experimentally by deflecting the probe with a reference cantilever of a known stiffness. The original method [8] was slightly modified for better reliability and easier usage.

Colloidal SiO$_2$ probes were fretted against a Si (100) surface within indexed square test zones of 15 µm sides. These test zones were produced on a Si wafer using a photolithography technique and were used to allow easy identification of the fretted areas during a post-test surface analysis. The mating surfaces had a roughness average of less than 1 nm. Tests were carried out with oscillation frequency of 1 Hz, displacement amplitude ranging from 5 to 500 nm, and a normal load defined as the sum of the applied load and the adhesion force ranging between 15 and 28 µN. The adhesion (pull-off) force required to determine the normal force was measured immediately following the termination of each test. The temperature and relative humidity were 21 °C and 50 %.

The output voltage signals of the SPM piezo scanner as well as the probe bending and torsion were sampled with an external 16-bit analog-to-digital converter and processed with a LabVIEW software package to provide on-line monitoring of the contact response. Each test was carried on until steady state friction conditions were obtained and shortly after was stopped. Only the steady state friction portion of the test was analyzed.

RESULTS AND DISCUSSION

The present tests were carried out mostly in the partial slip and gross slip fretting regimes that were characterized by the unified approach of the slip index [1].

The friction coefficient was obtained from the dissipated friction energy by integrating the friction force over the tangential displacement and dividing by the total sliding distance and the normal load. The steady state friction coefficient was 0.29-0.39 for the gross slip conditions. The transition from gross slip to partial slip conditions was characterized by high friction coefficient values between 0.39 and 0.71. The partial slip conditions led to a much lower friction coefficient of 0.20. The surprising behavior of the friction coefficient, which rises sharply at the transition from partial to gross slip regime, is not well understood yet and this issue requires further in-depth study.

Surface damage of the flat Si test zones was quantitatively...
analyzed by SPM using a regular integrated probe in a contact mode. It showed nanoscale wear scars as well as loose wear particles outside the scars. It is very clear from the SPM images that fretting wear does exist even on the nanoscale.

The loose wear particles that were found outside the wear scars had a characteristic flake-like form of about 5-20 nm thick and 50-120 nm wide. It is interesting to note that flake-like wear particles of similar dimensions were also associated with wear in magnetic storage head-disk interface [9] and in conventional microscale fretting wear tests [10].

![Figure 1. SEM images of damaged colloidal probes that were fretted under (a) gross slip, (b) mixed gross/partial slip and (c) partial slip conditions.](image)

Figs. 1(a)-(c) present SEM images of three microspheres fretted under different sliding conditions that led to different surface damage. The gross slip conditions shown in Fig. 1(a) resulted in material transfer and formation of wear debris that covered the entire contact zone on the sphere. The mixed gross/partial slip conditions shown in Fig. 1(b) resulted in two forms of damage: material transfer in the central portion of the contact area that possibly appeared during the initial gross slip conditions and surface degradation in a surrounding annular portion of the contact area that possibly appeared during the following partial slip conditions. Fig. 1(c) demonstrates some surface degradation in a surrounding annular contact area that appeared under partial slip conditions.

Similar to wear rate increase with displacement amplitude observed in conventional microscale fretting tests, the wear rate in the nanoscale gross slip fretting also increases with increasing slip index. Also, it seems that nanoscale reciprocal sliding wear rate is higher than that in nanoscale fretting.

**CONCLUSION**

The existence of nanoscale fretting wear was demonstrated by using scanning probe microscopy with colloidal probes. These probes provide a well-defined sphere-on-flat contact for nanoscale fretting research and can allow future study of nanoscale fretting wear with almost any pair of materials.

**ACKNOWLEDGMENT**

This research was partially supported by The Israel Science Foundation.

**REFERENCES**