PERFORMANCE OF ULTRA HARD CARBON WEAR COATINGS ON MICROGEARS FABRICATED BY LIGA

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ABSTRACT

Stiction and friction are of concern for the reliable, long-term application of Ni-alloy micromachines. We have found that the application of a 30 - 70 nm hard carbon coating produces a significant reduction in the friction coefficient and wear rate of electroformed Ni substrates in reciprocating sliding contact under simulated MEMS operating conditions. To evaluate the performance of coated components, a series of 70-µm-thick microgears ranging in diameter from 0.2 to 2.2 mm were fabricated from electroformed Ni via standard LIGA processes and fixtured on posts in preparation for the coating procedure. A pulsed vacuum-arc deposition process was used to deposit a carbon coating on the gears with the plasma incident at a shallow angle to the gears' top surface. A sample bias of -2 keV was used in order to produce a coating with relatively low stress and good adhesion while maintaining high hardness. This coating process is known to be somewhat comformal to the component surfaces. The coating uniformity, particularly in the high-aspect-ratio areas between the gear teeth, was evaluated with micro-Raman spectroscopy. It is shown that the coating can be applied uniformly on the top gear surface. Between the gear teeth the coating was the same thickness as on top of the gear down to a point 50 µm below the top surface. Below that point (i.e. between 50 and 70 µm), the coating thickness is somewhat thinner, but is still present. These results demonstrate that it is possible to a deposit hard carbon coating on microgears to reduce friction and wear in micromachines.

INTRODUCTION

"Micromachines" made with lithographically fabricated moving parts are an area of considerable current technological interest [1,2]. Several applications involve the use of "microgears." These gears have several wear surfaces, including the gear faces, gear teeth, and the holes for their axles. The operation speed of some micromachines that use these gears exceeds 50,000 rpm, so that wear of critical contacting surfaces, such as the gear teeth, is of concern. In other applications, the machines must sit idle for extended periods of time. In this case, corrosion and stiction are of concern.

Some of the mechanical concerns in the design of reliable micromachines are similar to those encountered in computer hard disk drives [3]. During disk drive operation, the ceramic composite read/write head (slider) is supported approximately 50 nm above the disk surface by an air bearing. However, during starts and stops, the slider contacts the disk surface. Wear protection in this case is provided by "diamond-like carbon" (DLC) coatings on the surface of the disk and slider. There is an additional thin coating of fluorocarbon lubricant on the disk surface. Here, we investigate the feasibility of using DLC coatings to coat microgears made of electroformed Ni. With microgears, there is the additional constraint of

coating high aspect ratio surfaces, such as the gear teeth. For this reason, we used a vacuum arc deposition method that is known to be partially conformal, as opposed to a more line of sight method such as sputtering. The substrate bias helps directs the incident ions to the surface of the sample such that areas that are not in the direct line of the plasma stream are coated. We have shown previously that a layer of vacuum arc carbon provides substantial reductions in friction coefficient (down to 0.2) and wear in tests on bulk coupons of electroformed Ni [4].

EXPERIMENTAL

Eleven electroformed Ni microgears were fabricated at Sandia by the LIGA process. The gears are components of a gear reduction train, and are between 0.2 and 2 mm in diameter and are 70 μm thick. Figure 1 shows an SEM micrograph of a relatively large gear. Figure 2 is a side view of the edge of a smaller gear. The radius of curvature of the gear teeth is 8 μm; this makes the maximum aspect ratio (height/width) of the teeth 70/(2x8) or 4.4. As shown in Fig. 3, the gears were affixed to posts on a Cu plate in preparation for the coating deposition.

The vacuum deposition method has been described in detail elsewhere [5]; only a summary will be presented here. C^+ ions are extracted from a vacuum-arc plasma and passed through a magnetic filter to remove macroparticles. The incident energy of the C^+ ions is ca. 20 eV. Additional ion energy is added by negatively pulse-biasing the substrate with a 25% duty cycle. We used a -2 kV substrate bias for these films because our previously reported tribology data [4] indicate that these films have a slightly lower friction coefficient compare to the harder films made at lower substrate bias. In addition, high bias films have better adhesion and can be grown to larger thicknesses due to their lower compressive stress. A calibration run was made to determine

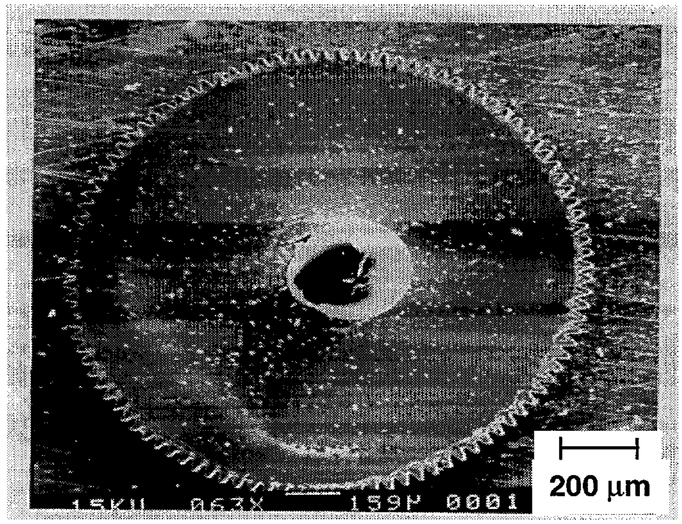

Fig. 1 SEM micrograph of a 1.97 mm diameter microgear, fabricated in electroformed Ni by the LIGA process. The radius of curvature of the gear teeth is 8 μm. (The high contrast distorts the center of the image.)

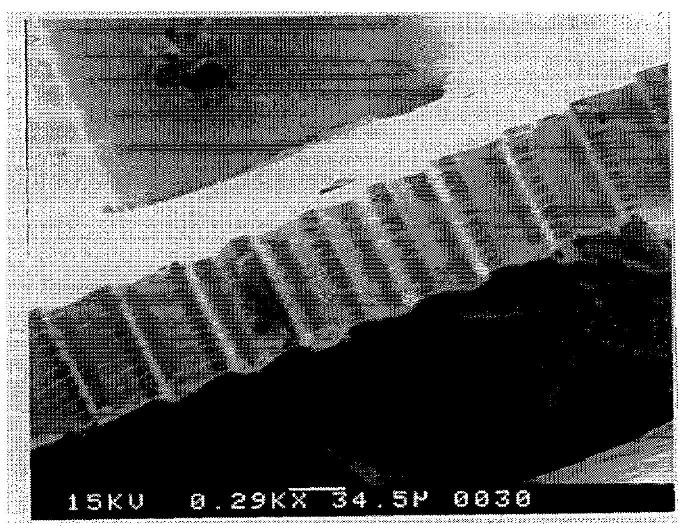

Fig. 2 SEM micrograph of a 980 μm diameter gear, side view. The gear is 70 μm thick. The fixturing post can also be seen above the gear.

the deposition rate at normal incidence angle (0.13 nm/arc pulse). Then the deposition was carried out with the plasma stream directed at 80° to the surface normal of the gears and 10° from normal to the gear edge as shown in Fig. 4. The Cu plate on which the gears were affixed was rotated during the deposition to coat uniformly around the edges. 4000 pulses were used for the carbon film deposition on the gears. If the coating method were strictly line of sight, and taking into account the deposition angle and the exposed area of the gear, this would produce a 90 nm coating on the gear surface. Because only half of the side of the gear is exposed to the plasma for a given pulse, the line of sight model predicts a 163 nm coating on the gear teeth. Application of a simple shadowing correction for the angle of the gear teeth (cf. Fig. 4) reduces this latter number to 71 nm. The thickness distribution of the coating was found to be different due to the conformal nature of the coating process, as discussed below.

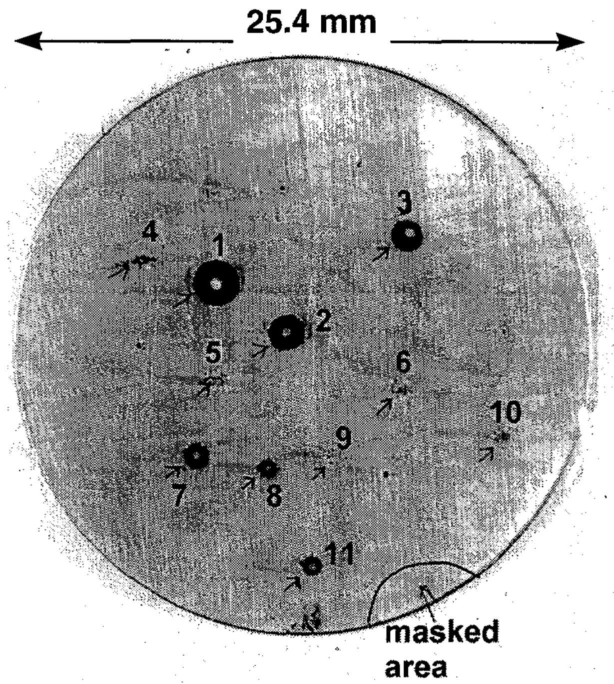

Fig. 3 Fixturing of microgears on posts in preparation for coating.

RESULTS AND DISCUSSION

The coating uniformity was evaluated with micro-Raman spectroscopy. A 10x microscopy objective was used to provide the requisite working distance to examine the top surfaces of the gears close to the fixturing pins and the sides of the gears. The laser spot size was 5 µm. The sample position was controlled with a x-y stage capable of 2 µm steps. The absorption coefficient α of vacuum-arc DLC films made under these experimental condition had been measured previously and is $9x10^4$ cm^{-1} at 488 nm, the laser wavelength used in the micro-Raman setup. The expected Raman intensity from an absorbing film as a function of film thickness h has the functional form

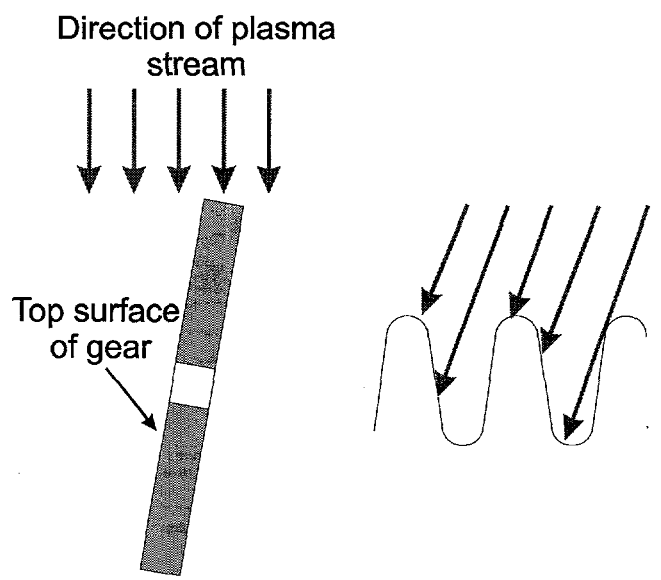

Fig. 4. Schematic of deposition geometry. Left (side view): the plasma stream was oriented 80° to the surface normal. Right: schematic of shadowing. At the angle of incidence shown (20°), the area between the gear teeth is not fully in the line of sight of the plasma.

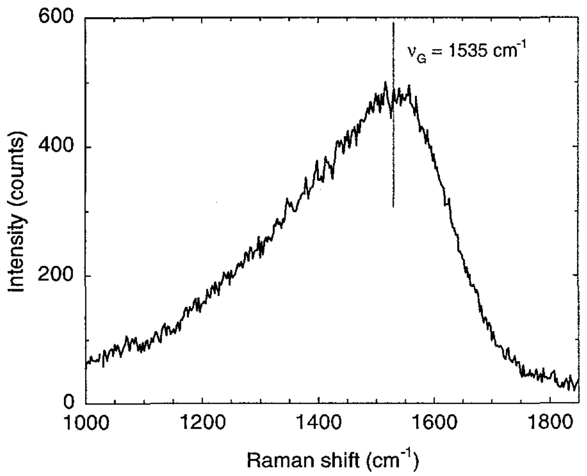

Fig. 5. Raman spectrum of DLC coating on a microgear obtained with a 10x microscope objective, 10 mW laser power, and 30 s integration time. The height of the so-called "G-band" feature is used to evaluate the coating thickness.

$$I(h) = \int_0^h \exp(-2za)dz \qquad (1)$$

where the factor of 2 reflects the fact that the laser must penetrate to a certain depth z and the Raman scattered light must travel back to the film surface for a signal to be detected. Examination of Eq. (1) reveals that the Raman signal will be approximately linear in film thickness up to 100 nm, somewhat sensitive to thickness from 100 - 200 nm, and not very sensitive to coating thickness from 200 - 300 nm. The Raman signal is essentially constant for $h > 300$ nm. In what follows, the intensity of the Raman signal will be used to evaluate the film thickness. A constant signal as a function of position will indicate that either the coating is uniform in thickness or is thicker than about 200 nm, or both. A Raman signal that varies with position indicates that the film is less than 200 nm thick and is varying in thickness.

Figure 5 shows the Raman spectrum of the DLC coating obtained from the top surface of a microgear. Based on our previous calibration of the Raman peak position and the sp^3 content of the film [6], the peak maximum, 1535 cm^{-1}, corresponds to an sp^3 content in the film of about 50%. Such a film is expected to have a hardness of about 30 GPa. Figure 6 shows the variation in Raman peak intensity as a function of position across the top of the 1.97 mm diameter microgear depicted in Fig. 1. The fluctuations in the signal strength are within the experimental uncertainty of the measurements indicated by the error bars. As discussed above, this indicates that the coating is at least 100-200 nm thick at all the measured points or it is uniform in thickness across the surface of the gear. Figure 6 shows that the Raman

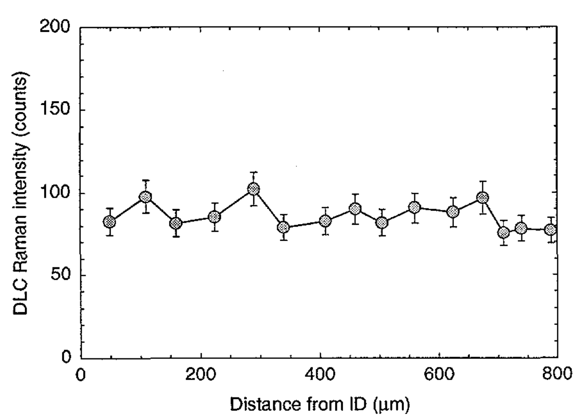

Fig. 6. Raman intensity measured on the top surface as function of distance from the inner diameter (ID) of a 1.97 mm diameter microgear (cf. Fig. 1).

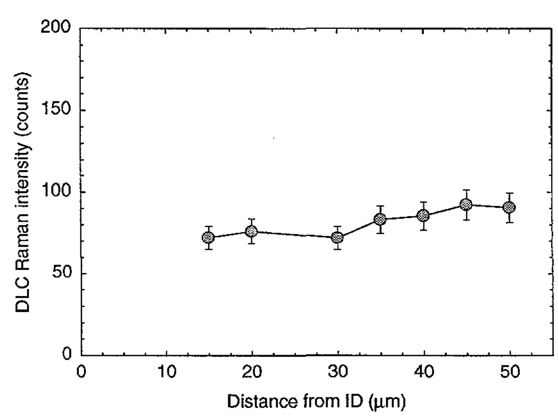

Fig. 7. Raman intensity measured on the top surface as function of distance from the inner diameter (ID) of a 200 μm diameter microgear.

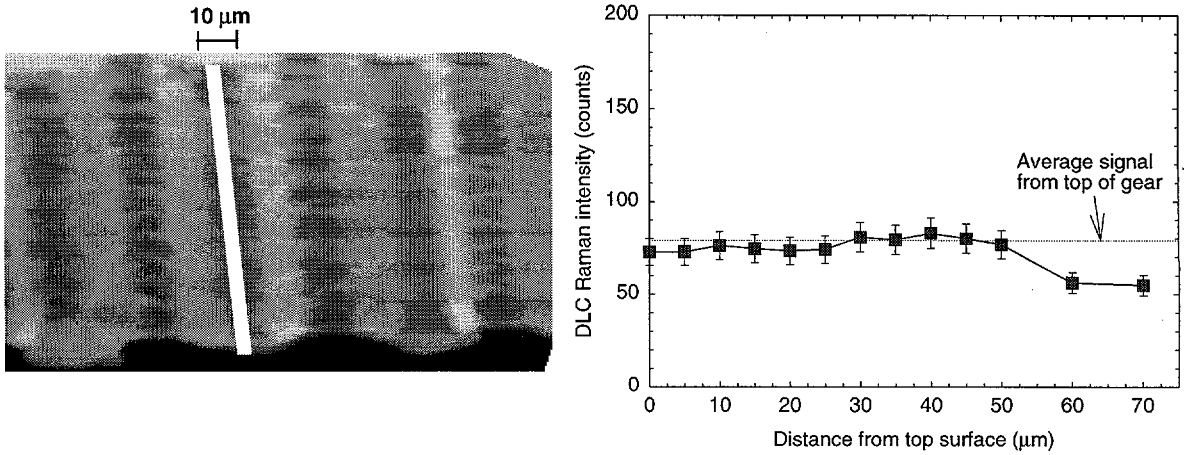

Fig. 8. Left: SEM detail of area between gear teeth (magnified from Fig. 2). The width of the Raman microprobe (5 μm) and the probed region are indicated by the white line. Right: Raman intensity between gear teeth as a function of distance from the top surface of the microgear. The intensity observed from scans on the top of the gear is indicated by the solid straight line.

signal intensity also does not vary significantly across the smallest gear (200 μm diameter) that was coated.

The Cu plate on which the gears were mounted was turned 90° to allow the sides of the gears to be examined with the Raman microprobe. Figure 8 shows the results from scanning the micro-probe between two gear teeth on a 900 μm diameter microgear. There are two important deductions to be made from these observations. First, the Raman intensity in the 0 - 50 μm region (0 μm marks the top surface of the microgear edge) is both uniform and the same as that observed on top surface of the gear. From 50 - 70 μm (i.e. the bottom of the gear edge), the signal level is reduced to 80% of the original level. Using Eq. (1), we obtain an estimate of 90 nm for the (reduced) thickness of the film in this area (i.e. the thickness at which a 20% drop in signal from the maximum possible would be observed). We further infer that the coating on in the 0 - 50 μm region and on top of the gear is at least in the thickness range where the observed Raman intensity less sensitive to thickness (100 - 200 nm) and may be thicker. A comparison of Figs. 6, 7, and 8 reveals that we observed a similar Raman intensity from the tops of all the gears. We therefore infer that the coating thickness there is at least in the 100 - 200 nm range and possibly could be thicker.

CONCLUSIONS

Application of the line-of-sight model predicted a coating thickness of 71 nm on the gear teeth and 90 nm on the gear surface. In contrast, we observed a coating thickness of at least 100-200 nm on the top of the gears and in most of the high aspect ratio between the gear teeth. The bottom 20 μm between the gear teeth had a thinner coating, estimated at 90 nm. We conclude that, with appropriate fixturing and the use of the vacuum arc process, it is possible to coat the complex surfaces of the microgears with a continuous coating of hard carbon. We expect, based on our previous tests on coated substrates of electroformed Ni [4], that coating microgears with DLC should reduce friction and wear (and possibly stiction) in micromachines.

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