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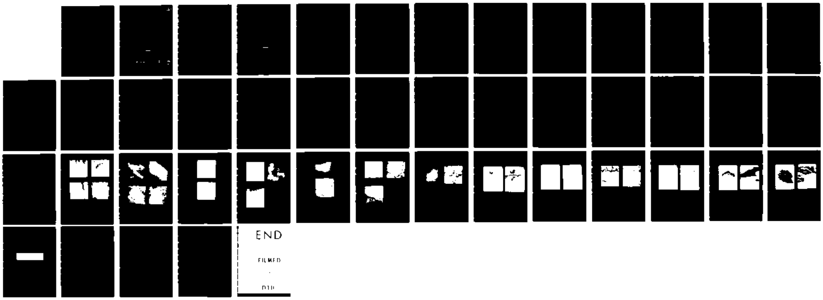

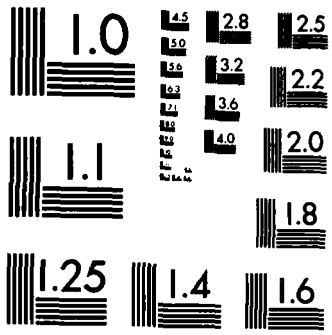

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Wear Behavior in Thin Layered Au/SS and Au/Mo Coatings

Final Report

E. L. Courtright
J. W. Patten

August 1982

Prepared for
the Office of Naval Research
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Battelle
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LEGAL NOTICE

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ABSTRACT

Principal objectives of this work were to (1) determine if the Delamination Theory of wear could be supported by experimentally observing improved wear resistance from samples coated with thin layers of gold at or below the critical thickness; and (2) to determine if laminate coatings made of alternate soft and hard materials could provide extended wear resistance.

Wear tests were performed on thin layers of sputtered gold against a 52100 steel slider. Both wear rate and debris particle size decreased with decreasing coating thickness in accordance with the Delamination Theory of wear. However, for thin coatings of 250 Å or less, the softer gold wore through exposing a harder stainless steel substrate. Much larger debris particles were produced when this occurred as the active shear zone apparently penetrated more deeply into the base material.

Protective laminate coatings prepared by sputtering alternate layers of Au/SS and Au/Mo did not wear by progressive attrition of each layer. Debris particles several layers in thickness were formed giving rise to apparent dislocation penetration, plastic deformation, and fracture across the interfaces.

SUMMARY

Decreasing the gold surface layer thickness from 10^{-3} cm to 100 Å resulted in rapidly decreasing wear rates and a corresponding decrease in the size, thickness, and laminar character of primary wear particles. Continued wear produced larger debris particles that penetrated several layers of the underlying deposit. Comparisons between as-cast gold and a thick deposit of sputtered gold produced similar wear rates and debris particles confirming that sputter deposited gold is representative of bulk material. Since no evidence of interlayer separation was observed, it was concluded that the as-deposited structure did not influence interpretation of the experimental results.

Once wear-through of the thin protective gold layer was achieved, more extensive subsurface deformation and delamination occurred. The fracture zone frequently penetrated numerous layers of Au and SS indicating that the crystallographic compatibility at these interfaces was adequate to support slip band movement across the interfaces.

Similar results were obtained when molybdenum was used as an underlayer in place of SS; however some Mo was detected in the primary platelet debris suggesting that dislocation penetration of the interface had occurred. Molybdenum had been expected to be a more effective barrier because of its higher modulus and differing crystal structure thereby making it more difficult for slip planes to achieve the required crystallographic orientations needed to transfer a slip zone from one material to the other.

Laminates produced by depositing alternate layers of soft and hard material did not provide wear resistance by gradual wearing away of successive layers. Rather, delamination occurred by subsurface plastic deformation and by the formation and removal of large particulate debris.

ACKNOWLEDGEMENTS

The authors wish to thank the Office of Naval Research for their support and Dr. Dick Miller and Prof. Ralph Burton for their guidance and patience. Darrell Hays helped to organize the experiments and interpret wear results and Harold Kjarmo performed most of the scanning electron microscopy and energy dispersive spectroscopy. John Prater and Darrell Hays reviewed the manuscript.

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FIGURES

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BACKGROUND

Sheet-like or layered wear particles were first observed in 1929[1]. However, early researchers in the area of wear mechanisms did not attach major significance to the shape of these particles[2]. In 1973 Suh published his initial observations of thin sheet wear particles and discussed his delamination theory of wear[3]. Since that time, Suh's group and others have conducted extensive investigations of wear debris and wear track morphologies in a variety of materials[4]. Although this area is clearly still in its infancy, the results are commonly incorporated into general discussion of wear[5-7]. In a recent review[8] Miyakawa discusses these theories with respect to gold.

In general, many wear couples produce debris characteristic of the materials involved and the normal and tangential loads at the wear surface. When this debris is examined at high magnification, typically in a scanning electron microscope (SEM), it is often found to consist of thin sheet-like particles. Much of the research conducted since Suh's initial observations has been empirical and has sought to relate particle shape and dimensions to material properties or loading conditions at contact points.

Suh's theory postulates interactions between dislocations generated by local stresses at the surface of a metal; for example, under sliding contact. These dislocations are driven into the metallic bulk by the applied stress at the surface. After this stress is relaxed, dislocations that are sufficiently close to the surface, i.e., within range of their image forces, return to the surface and disappear. Dislocations deeper than some critical distance remain in place after the stress at the surfaces passes. When the surface stress returns, the process is repeated, except that now some of the dislocations generated at the surface interact with the dislocations remaining from the last stress cycle. After several stress cycles, dislocations pile up along a plane parallel to the metal surface, leaving a dislocation-free zone between this plane and the surface. As the process continues, the dislocations coalesce to form a plane of voids. Eventually, fracture occurs along this plane and platelet wear debris is produced, with each platelet being a segment of this nearly dislocation-free material.

EXPERIMENTAL DESIGN

Suh's delamination theory of wear seems to depend on:

- A surface region free of dislocations due to image effects.
- Pile-up of dislocations in a subsurface plane parallel to the surface.
- Movement and coalescence of dislocations to form voids - an effect which is intensified by hard second-phase particles.

Thin laminate materials (layers $\lesssim$ 200 Å thick) offer a test of this theory. They should be very resistant to wear because restricted dislocation generation and movement would reduce large plastic deformation and subsequent failure by delamination. A layer of soft metal deposited on a harder substrate favors a "low dislocation density" region near the surface as a result of image forces. Dislocation propagation perpendicular to the surface should stop at the interface between the soft wear resistant outer layer and the harder less compliant underlayer, and then return to the surface.

The elastic modulus, shear modulus, and crystal structure of the thin soft outer layer and the hard underlayer are expected to influence the propensity for delamination. A strong bond is required between the two, but solubility and crystallographic compatibility should be reduced to prevent penetration of dislocations across the interface. If the shear modulus in the surface coating is less than the underlayer, then the dislocations generated during sliding wear should be repelled by the interface. If the coating is sufficiently thin (i.e., less than some critical thickness), most of these dislocations will be eliminated by returning to the surface once the slider induced force field has passed.

Thus, the coating should remain soft and continue to function as a protective layer.

It was proposed that these hypotheses be addressed by analyzing the unidirectional sliding wear behavior and debris generated in alternate layered materials. Initially, the proposed metal pairs were Au and Mo because of the large mismatch in mechanical properties (factor of 4 difference in modulus); dissimilar crystal systems (Au is fcc, Mo is bcc); insolubility; oxidation resistance; and well characterized behavior of gold. Later, 316 stainless steel (factor of 3 difference in modulus) was substituted for Mo because of difficulties in preparing stress free deposits. An oxidation resistant outer layer such as Au was considered essential to this evaluation so as not to restrict the return of dislocations to the free surface by image forces. A growing oxide film and attendant volume expansion could impose back stresses which would impede or otherwise reverse this process.

Cylindrical wear specimens of machined and hardened 1090 steel sputter coated with several layers of Au and either Mo or SS offered a unique method for experimentally testing the effects of layer thickness which could be varied over the expected critical range. In addition pure cast gold could be used for a control and reference material. These specimens could be subjected to unidirectional sliding wear and the wear debris and wear track appearance analyzed.

A layered type structure allows nearly independent variation in elastic and plastic properties and hence in the physical processes controlling dislocation propogation. The effectiveness of the layered structures for hardening has also been previously demonstrated in a similar (Cu-Mo) system[9,10]. There are several reasons to expect laminate hardening. Slip across a layer interface between two dissimilar metals should produce additional interface area[11], requiring additional energy to support propogation. In addition, the requirement for plastic compatibility at solid-solid interfaces may directly result in strengthening of solids[12]. Here, compatibility means accommodation of stresses and strains introduced at grain or phase boundary as a result of differences in elastic and plastic properties. These properties change nearly discontinuously at the interfaces of the proposed layered materials. The misfit decreases continuously with distance from the interface. As a consequence, a slipband intersecting a layer boundary requires either very concentrated long range slip or accommodating elastic strains for local compatibility, so that long range slip should be difficult. Thus, laminate structures have potential for providing increased wear resistance. As the soft outer layer wears through, the next harder under layer should become the wear resistant surface and then the next soft layer and so forth down through the stack. Resistance to slip across each interface provides the barrier that would enable each layer in succession to act as a protective coating. By varying the layer thickness, it may be possible to evaluate the critical thickness associated with maximum wear resistance. The critical thickness needed to prevent delamination has been estimated at less than 10,000 Å[13]. Since sputter deposition lends itself to accurate deposition thicknesses in the angstrom range, layers ranging from 100 Å to 2000 Å were selected for experimental purposes.

SPECIMEN PREPARATION

All the test specimens containing multilayered coatings were fabricated by high rate sputter deposition. This fabrication technique was chosen because of previously demonstrated ability to produce uniform and continuous layers of dissimilar materials with sharp atomically clean interfaces between layers.

Deposition was performed in a sputtering apparatus schematically described in Figure 1. For further description of the basic phenomenon, the reader is referred to reference (14). Component A was Au and Component B was either Mo or Type 316 stainless steel. Difficulties in obtaining adherent thick coatings of Mo encouraged the use of 316 stainless steel as the principal hard surface material.

Substrates were fabricated from hardened 1090 steel. Several 0.5 inch diameter rods were mounted in the revolving substrate holder (Figure 1) for each coating experiment. In operation the substrates were rotated around the half-cylinder (A and B) targets so that a given area was exposed to the A target for the first half of a revolution and to the B target for the second half of the revolution. At the same time, each substrate rotated several revolutions about its own axis in the time required to pass in front of a single (A or B) target. Deposit layer thickness was determined by rotational speed and sputter deposition rates.

The sputtering system was typically evacuated with a liquid nitrogen trapped oil diffusion pump to 1.2×10^{-4} Pa for 18 hours before deposition began. High-purity krypton sputtering gas was admitted to the sputtering chamber until a pressure of 0.34 Pa was achieved. Each substrate was etched by ion bombardment with 100 V Kr^+ ions for approximately 10 minutes to produce an atomically clean surface. During sputter deposition the voltages applied to the A and B targets were adjusted independently to obtain the desired sputtering rates. It was found that substrate bias voltage could not be varied effectively in this apparatus. Substrate potential, therefore, was very close to -35 V (plasma-related or floating potential) for all deposits.

TESTING

The apparatus shown schematically in Figure 2 was assembled and used for wear testing. All tests were conducted in dry air. The oil flowing over the slide and wear specimen carried wear debris away from the slider-specimen contact area. The oil and entrained debris were collected in a clean glass dish below the wear specimen.

The oil was then diluted with filtered "Freon" FT* and vacuum-filtered thru cellulose acetate filter paper with a 0.5 μm pore size. Additional (pre-filtered) "Freon" FT was used to further clean the wear debris (trapped on the filter paper) and the filter paper by vacuum filtering approximately 1 liter of the solvent.

Samples of the filter paper were coated with carbon to provide a conductive film as well as anchor the wear debris, and these coated samples were examined in a scanning electron microscope (SEM)** to characterize debris particle size and shape. The SEM was also used to characterize the specimen wear tracks and along with energy dispersive spectroscopy to characterize material transferred to the slider. Energy dispersive spectroscopy was also used in an attempt to determine whether debris particles contained more than one sputter-deposited layer, i.e whether both Mo and Au (or Fe and Au) were present in each debris particle.

Several debris samples were collected on copper grids during filtration and examined in a 200 Kev transmission electron microscope (TEM). This voltage proved inadequate to penetrate the thick debris platelets in most instances.

At the conclusion of testing, wear specimens were metallographically sectioned along their axis, mounted, polished, and photographed. The depth of the wear tracks were then measured to determine wear rate.

* "Freon" TF in high purity trichloro-trifluoroethane. "Freon" is DuPont's trademark for its fluorocarbon compounds.

** All SEM photomicrographs in this report have been reduced 15% for reproduction.

RESULTS AND DISCUSSION

The sputtered deposits produced in this study are listed in Table 1. In addition one wear specimen was fabricated by casting from pure Au, so that the wear debris from non-sputtered Au could be compared. This wear specimen was labeled ONR-0. Table II lists typical wear test conditions. These include the sample load in grams, the surface speed in mm/sec, and the sliding distance in meters.

Cast Gold

Figure 3 shows an SEM characterization of wear tracks on specimen ONR-0 (cast Au). Note the smeared gold developing into overlayers. Figure 4 shows two wear particles on filter paper (background), obtained from this specimen. These particles seem to have developed from separation of an overlayer similar to the one shown in Figure 3, and include many layers of gold. Transmission Electron Microscope (TEM) examination of wear particles did not reveal any void formation. However, only 200 Kev was available and the particles were so thick that a definitive examination could not be conducted.

Figure 5 presents SEM photos of the slider surface that was used to produce the wear track in Figure 3 and the gold debris particle in Figure 4. As the arrows indicate, the slider was nearly completely covered with gold transferred from the wear specimen. Separation of similar gold layers transferred to the slider may be a source of debris particles. However, it was thought that debris particles were produced directly from the wear track in this experiment.

Sputtered Gold

The SEM photos in Figure 6 show a wear track from specimen ONR-2. This specimen was coated with 250 alternate stainless steel and gold layers, approximately 830 Å thick. However, the last layer deposited was gold and was 1.3×10^{-3} cm (5×10^{-4} in) thick. The result was a pure sputtered gold surface, thick enough to exceed the range of dislocation image forces, supported by an underlying structure with the elastic properties and dislocation barriers of a layered material. From these photos, it is apparent that the wear track is similar to the wear track on cast gold (Figure 3). Pending separation of debris particles is particularly evident. The multi-layered character of these particles suggests that delamination has occurred and the separated particle rebonded to the surface. Since only gold was detectable by energy dispersive spectroscopy in the areas under these large separating particles, it is hypothesized that individual wear particles were built up either by gross plastic deformation (smearing) of successive layers of gold during sliding contact or by cold welding these particles together in the wear track. A large wear particle, generally consisted of many layers. Each layer was probably produced by one sliding contact event or one smaller debris particle and then displaced over and welded to previously produced layers. Large platelet debris particles could be reduced in thickness by subsequent sliding contacts in a manner similar to the techniques used to produce thin foils by pack rolling. This would allow formation of multilayered debris particles as thick or thicker than the outer layer without delamination of this layer or fracture across the as-deposited interface.

Figure 7 shows typical gold debris particles, produced from specimen ONR-2. These particles clearly could have been produced by the above model. Some of the particles were estimated to be at least 1×10^{-3} cm (4×10^{-4} in) thick and were comprised entirely of gold. No iron was detectable in the wear track indicating that delamination was restricted to the gold layer and that the underlying stainless steel acted as an effective barrier to dislocation propogation. Fracture occurred, close but not adjacent to the Au-SS interface.

Layered Gold-Stainless Steel (1600 Å)

Figure 8 shows a wear track from specimen ONR-1. The outer gold layer of this deposit was thinner than for specimen ONR-2. The deformed areas of this wear track were similar to the track in pure gold, but the sheet thickness appeared to be less. Extensive ductility was still present in the layered deposit, as expected. Both the gold and the stainless steel layers were approximately 1600-1700 Å (1.6×10^{-5} cm) thick in the sample. This thickness should be greater than the range of dislocation image forces but is obviously less than the thickness of wear debris found in the sputtered outer layer of specimen ONR-2.

Figure 9 shows some of the wear debris particles from specimen ONR-1. Thickness of individual layers within large particles was approximately 500 to 1000 Å, clearly less than the sputtered layer thickness and less than the layer thickness within pure gold debris particles. However, the detailed structure was on a smaller scale than for pure gold and seemed to show less ductility. In addition, smaller debris particles were observed. Some of the details could not be easily resolved with the SEM. No evidence for such (individual) fine particles was found in the debris obtained from pure cast (ONR-0) or sputtered gold (ONR-2).

As wear continued on specimen ONR-1, the wear rates began to increase dramatically and the debris particles increased in both size and thickness. Figure 10 shows a debris particle on wear track ONR-1 3B at a sliding distance of 600 meters. This particle is approximately 7000 Å in thickness which is on the order of four to five layers of gold and stainless steel. Energy dispersive spectroscopy confirmed that both gold and stainless steel were present in this and other similar particles from this particular wear track. The surface of this particle is relatively clean and does not contain evidence of multiple compacted layers as previously observed in the all gold debris from ONR-2, see Figure 7. It was not possible to determine if the surface layer was Au or SS because penetration of the electron beam easily exceeds the layer thickness.

The wear track shown in Figure 8 shows the condition of the surface after 100 meters of sliding distance. Large areas of the stainless steel underlayer appear exposed. It was not possible to determine whether the increased wear rates and production of larger delamination particles began after the 1600 Å gold outer layer was completely removed and the stainless steel underlayer became the wear bearing surface, or if several layers were removed before the process accelerated. It is clear, however, that the delamination process changes once the soft gold outer layer has been penetrated.

Layered Gold-Molybdenum (250 Å)

Attempts were made to produce two specimens by sputter depositing alternate layers of Au and Mo. Poor adherence was obtained when the Mo was initially deposited directly on the 1090 steel substrate. Much better adherence was obtained when gold was used as the first layer. Specimen ONR-4 was made with 635 alternate layers of Au (225 Å) and Mo (250 Å).

Wear tracks of ONR-4 show little or no wear up to 75 meters in sliding distance as shown in Figure 11. The wear rates were too low to be measured and no useful wear debris could be collected. At 100 meters, very small debris particles were collected as shown in Figure 12. There were two types both of which appeared brittle in nature and exhibited radial cracking. It was not possible to determine thickness by scanning electron microscopy and attempts were made to examine some of these particles in a transmission electron microscope. The particles were thick enough to limit examination with a 200 kev microscope and resolution was inadequate to determine detailed structural features. Electron diffraction patterns contained faint Mo spots indicating that initial delamination penetrated the Au/Mo interface. This is unexpected since the thickness of these layers (~ 250 Å) should have been below the critical thickness and the difference in elastic molulus and crystal structure (fcc for Au vs. bcc for Mo) should have provided an effective barrier to dislocation propagation.

If the harder underlayer doesn't function as a barrier then many of the dislocations will not return to the free surface and disappear.

Figure 13 shows a wear track for ONR-4 after the load had been doubled and the surface speed increased by a factor of three. Catastrophic failure of the coating in the wear track region is observed. Evidence of columnar structure in the fragments shown along the edge of the wear track indicate that the layers did not separate by delamination, but rather by breaking off large chunks of deposit, thereby demonstrating that the inter-layer bonding was very strong. It is clear that the wear process in the Au/Mo coatings did not proceed by general layer by layer attrition. Failure apparently occurred at the coating/substrate interface as the loading conditions increased in severity.

Layered Gold-Stainless Steel (100 Å Layers)

The specimen ONR-6 with alternating 100 Å layers of Au/SS was expected to provide a solid test of Suh's delamination wear theory. The 100 Å layer thickness is well below the expected critical thickness needed for image forces to return dislocations to the free surface. This specimen was similar in characteristics to ONR-1 except that the individual layer thicknesses were a factor of ten less.

Wear rates remained consistently low over an extended period of time and although the particle debris generated did not produce a large volume of material, the individual wear particles as shown in Figures 14 and 15 were much larger in size and in thickness than expected. These particles ranged from 5000 to 8000 Å in thickness and thereby consisted of 50 to 80 as-sputtered layers. Energy dispersive spectroscopy confirmed the presence of both Au and SS. The surface of some particles, see Figure 15, were somewhat rougher than those observed from ONR-1 (compare Figure 10) and some of the step-like features most likely contain more than one as-sputtered layer.

If there is a consistency between ONR-1 and ONR-6, it seems to be that when the soft gold outer layer is consumed, then a more severe delamination process begins which penetrates vertically through the multi-layered interfaces. Examination of platelet edges reveal that vertical shear is occurring and there is no evidence of the multiple layers or ragged fracture surfaces. The lack of columnar features left from the as-deposited microstructures suggest that there was sufficient slip band penetration and localized ductility to accommodate the vertical shearing process.

Energy dispersive x-ray analysis could not be used to prove that the horizontal fracture layers were gold. However, if the subsurface shear zone produced by the slider was trapped in one or more soft gold underlayers, then dislocations propogating within these zones would be reflected at the stainless steel boundaries located above and below. Continual movement would lead to void formation and coalescence. As delamination starts within a zone, the stress concentration at the interface is apparently sufficient to force propogation across the interface leading to the type of edge ductility observed in Figures 14 and 15.

Wear Rate

Optical cross sections of wear tracks similar to those shown in Figure 16 were used to measure the volume of material removed and to calculate wear rates. This was done at periodic intervals. The result shown in Figure 17 include only comparisons made for test conducted with similar loads (550 grams), speed (83 mm/sec) and geometry.

There are too few data points in Figure 17 to be conclusive and the scatter reflects the measurement uncertainty; however, a consistent trend of decreasing wear rate as a function of gold thickness was recorded. A weak correlation between wear rate and the type of debris was observed. In general, the very large multilayered wear debris particles were found in conjunction with higher rates. Particle size and thickness decreased when the gold layer thickness decreased as did the wear rates. At longer times, wear rates either increased again or stayed constant but, in general, the particles increased in size.

Soda, et al[15] observed a relationship between the number of wear fragments and the load. In this work, catastrophic failure occurred at higher loadings for Au/Mo. For thin Au/SS layers, i.e. ONR-6, failure was observed in the subsurface layers, but produced a lower volume of larger debris particles. In both of these cases, the very first particles were either not collected or could not be measured. It may be that the wear rates and the particles were initially small, but as the protective outer layer wore through, a transformation in the wear process occurred.

CONCLUSIONS

Coatings made by depositing thin alternate layers of soft (Au) and hard (SS, Mo) have been used to test the Delamination Theory of wear and to determine if the principles would extend to laminates and thereby offer a means of increasing wear life. The following conclusions resulted from varying the thickness of Au/SS and Au/Mo coatings and studying the debris generated in a sliding wear track.

The primary wear debris generated from thick gold layers were aggregated by cold welding in the wear track into much larger secondary particles. No difference in behavior between cast gold and thick sputtered gold was observed indicating that sputtered deposits are representative of bulk material.

Both the primary particle debris and wear rates initially decreased with decreasing layer thickness. These results are in accordance with the Delamination Theory of wear.

Very thin Au coatings less than 250 Å in thickness and below the expected critical thickness did not further reduce wear of effectively prevent penetration of the underlayers. There was evidence that the zone of maximum plastic shear penetrated several layers into the deposit once the soft gold outerlayer started to wear through. Delamination may not be restricted by soft thin layers if enough imperfections and discontinuities exist to cause localized delamination. As more underlayer is exposed, a rapid change in the failure process occurs as seen by greater subsurface penetration.

Laminates do not appear to provide increased resistance to wear or do they extend wear life. The wear process does not proceed by gradual wearing away of successive layers, but rather by delamination in underlying layers.

REFERENCES

1. Füchsel, M., 1929. "Über Berschleibbarkeit der W Werkstoffe bei trockenei Reibung," Orgon Fortschr., 84, 413.

2. Bowden, F. P., and D. Tabor. 1971 (first print 1950). "The Friction and Lubrication of Solids," Oxford University Press, Ely House, London.

3. Suh, Nam P., 1973. "The Delamination Theory of Wear," Wear, 25, 111-124.

4. Suh, Nam P., 1980. "Update on the Delamination Theory of Wear," ASM Materials Science Seminar on Fundamentals of Friction and Wear of Materials, pp. 43-71.

5. Czechos, Horst, 1978. "Tribology - A Systems Approach to the Science and Technology of Friction, Lubrication, and Wear," Tribology Series, Vol. 1, Elsevier, New York, 111-112, 207.

6. Engel, Peter A., 1978. "Impact Wear of Materials," Tribology Series, Vol. 2, Elsevier, New York, 15-17.

7. Barwell, F. T., 1979. "Treatise on Materials Science and Technology," Wear, Vol. 13, Douglas Scott, editor, Academic Press, New York, 37-39.

8. Miyakawa, Y., 1980. Gold Bulletin, 13, 21-30.

9. Patten, J. W., 1975. "Stability of Composites Formed by Sputter Deposition of Thin Copper and Molybdenum Layers," PhD Thesis, Washington State University, Pullman, WA. 1975. Research supported by the Advanced Research Projects Agency under Contract No. F44 620-73-0071.

10. Patten, J. W., S. A. Duran, 1981. "Composites Formed by Sputter Deposition of Thin Copper and Molybdenum Layers," presented at the International Conference on Metallurgical Coatings, AVS, San Francisco, April 6-10, 1981, to be published in conference proceedings and in Thin Solid Films.

11. Hull, Derek, 1969. "Introduction to Dislocations," Permagon Press Ltd., New York, pp. 220-230.

12. Murr, Lawrence E., 1975. "Interfacial Phenomena in Metals and Alloys," Addison-Wesley Publishing Co., Reading, Massachusetts, p. 338.

13. Jahanmir, S., E. P. Abrahamson and N. P. Suh., 1976. "Sliding Wear Resistance of Metallic Coated Surfaces," Wear 40, 75-84.

14. Patten, J. W., R. W. Moss, E. D. McClanahan and W. T. Pawlewicz, 1981. "Recent Advances in Materials Synthesis by Sputter Deposition at Pacific Northwest Laboratory," Invited Paper, presented at the International Conference on Metallurgical Coatings, AVS, San Francisco, April 6-10, 1981, to be published in Conference Proceedings and in Thin Solid Films.

15. Soda, N., Y. Kimura and A. Taraba. 1975. "Wear of Some FCC Metals During Unlubricated Sliding Part II: Effects of Normal Load, Sliding Velocity and Atmospheric Pressure on Wear Fragments," Wear 35, 331-343.

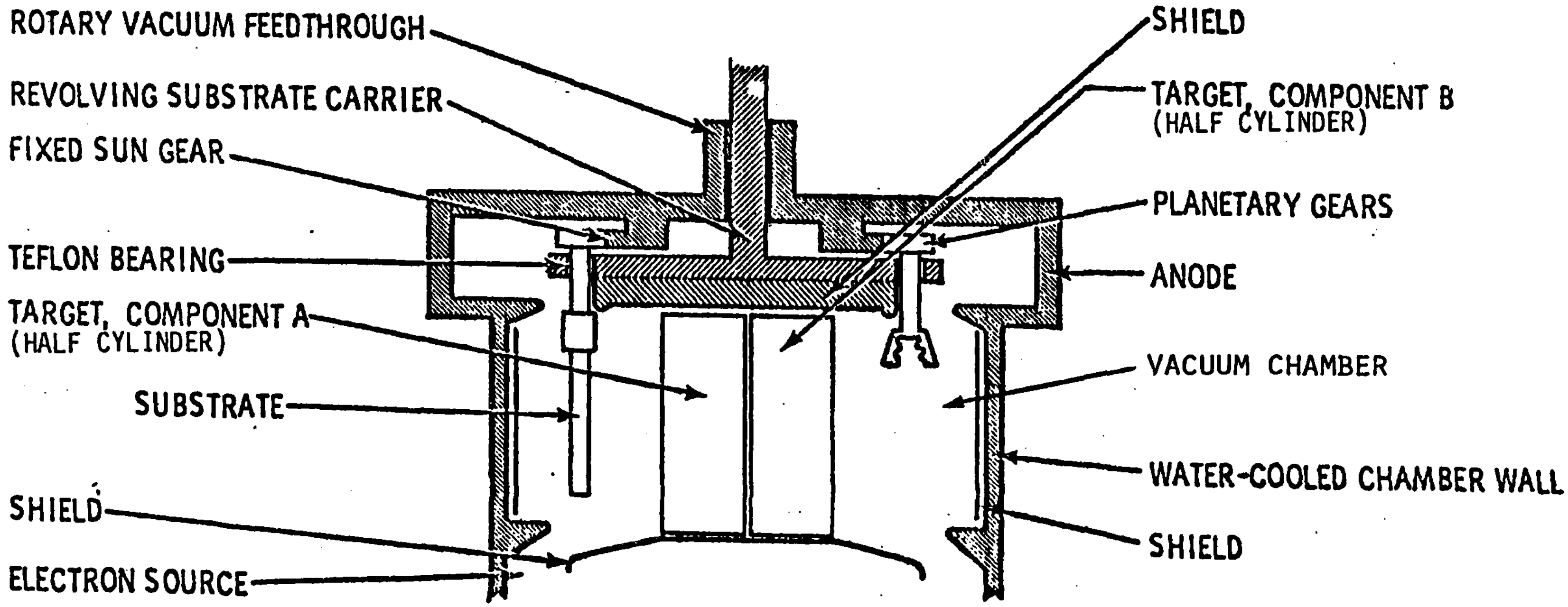
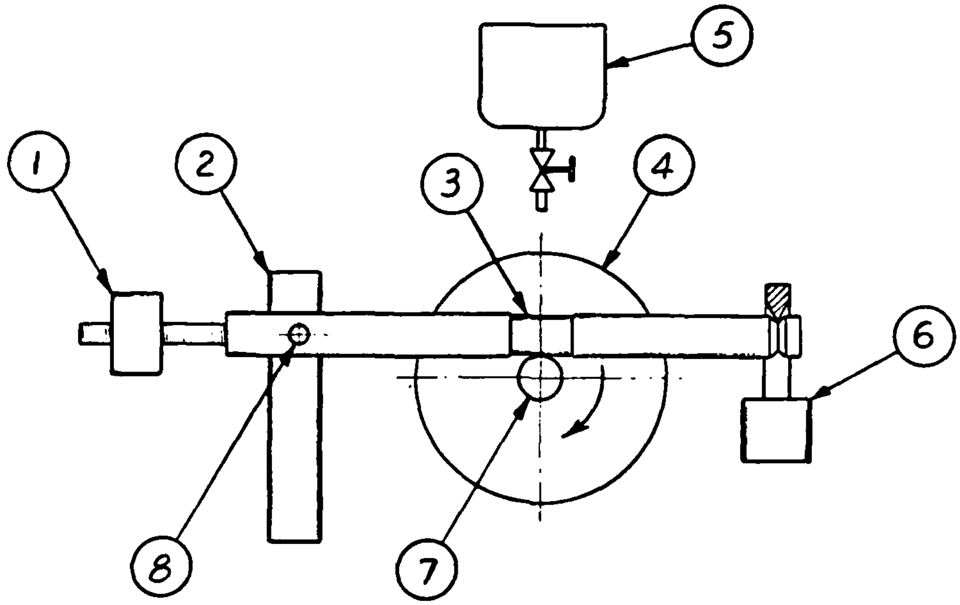


FIGURE 1. SCHEMATIC OF SPUTTER DEPOSITION SYSTEM USED TO DEPOSIT LAYERED COATINGS.



1. Counterweight
2. Pivot post
3. AISI 52100 slider. Rockwell C-62 machined to 16rms after hardening
4. Lathe chuck
5. Oiler
6. Loading weight
7. Wear specimen
8. Pivot

FIGURE 2. APPARATUS FOR PRODUCING AND COLLECTING WEAR DEBRIS.

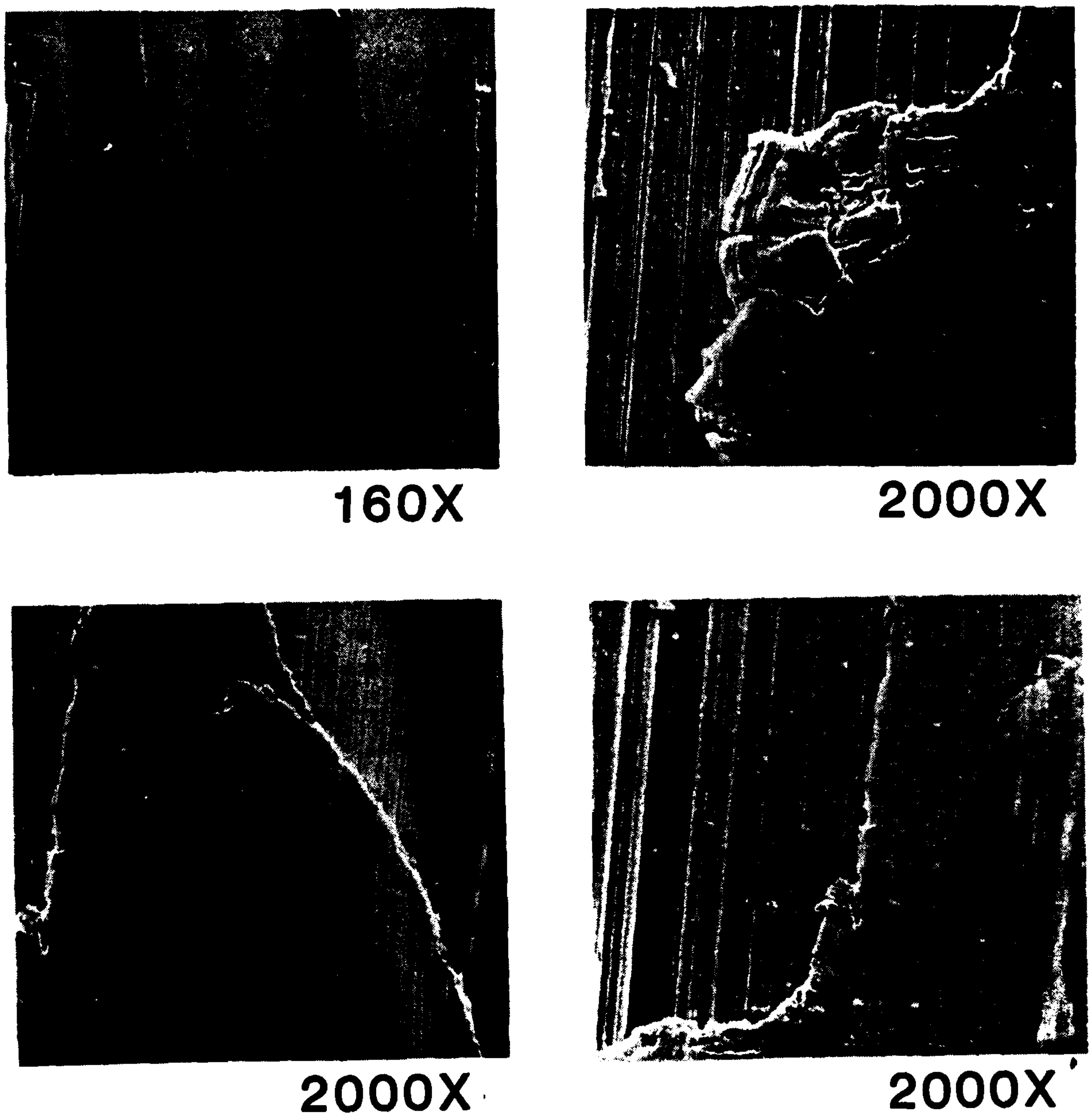


FIGURE 3. SEM MICROGRAPHS OF WEAR TRACKS ON CAST Au WEAR SPECIMEN ONR-0.

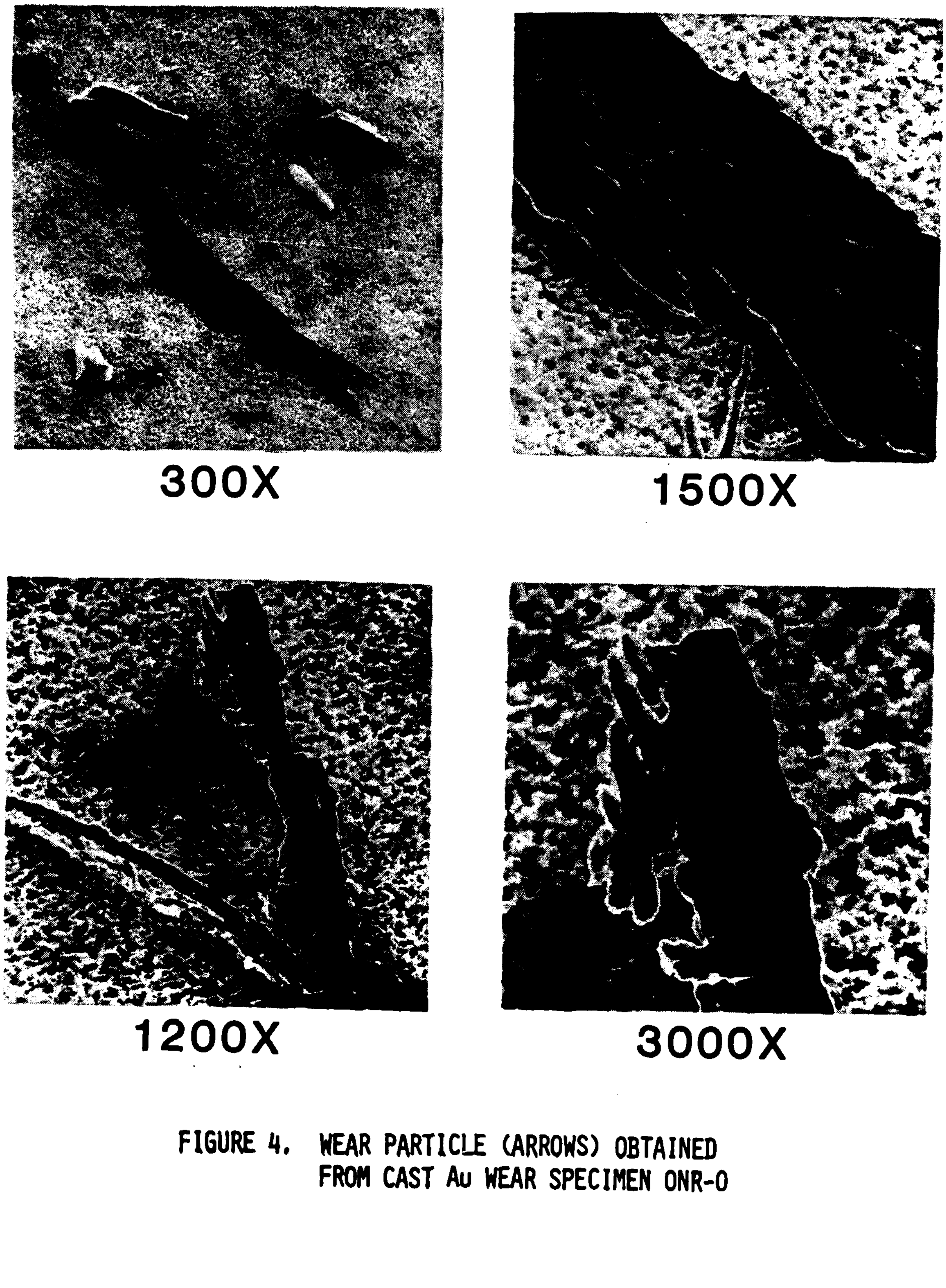
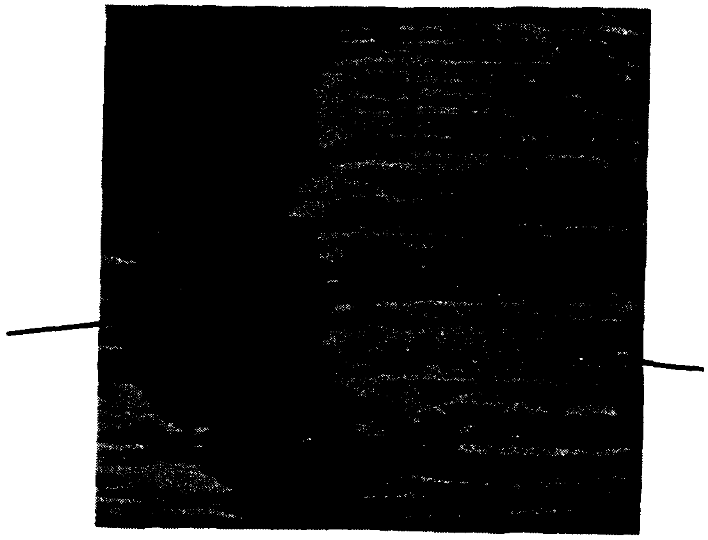


FIGURE 4. WEAR PARTICLE (ARROWS) OBTAINED FROM CAST Au WEAR SPECIMEN ONR-0

2000X



7600X

FIGURE 5. SEM PHOTOS OF THE SLIDER USED TO PRODUCE THE WEAR TRACK IN FIGURE 3 AND THE GOLD DEBRIS PARTICLE IN FIGURE 4 (FROM CAST GOLD SPECIMEN ONR-0). THE LEFT ARROW INDICATES THE SURFACE OF THE A1S1 52100 STEEL SLIDER. THE RIGHT ARROW INDICATES GOLD TRANSFERRED TO THE SLIDER FROM THE WEAR SPECIMEN.

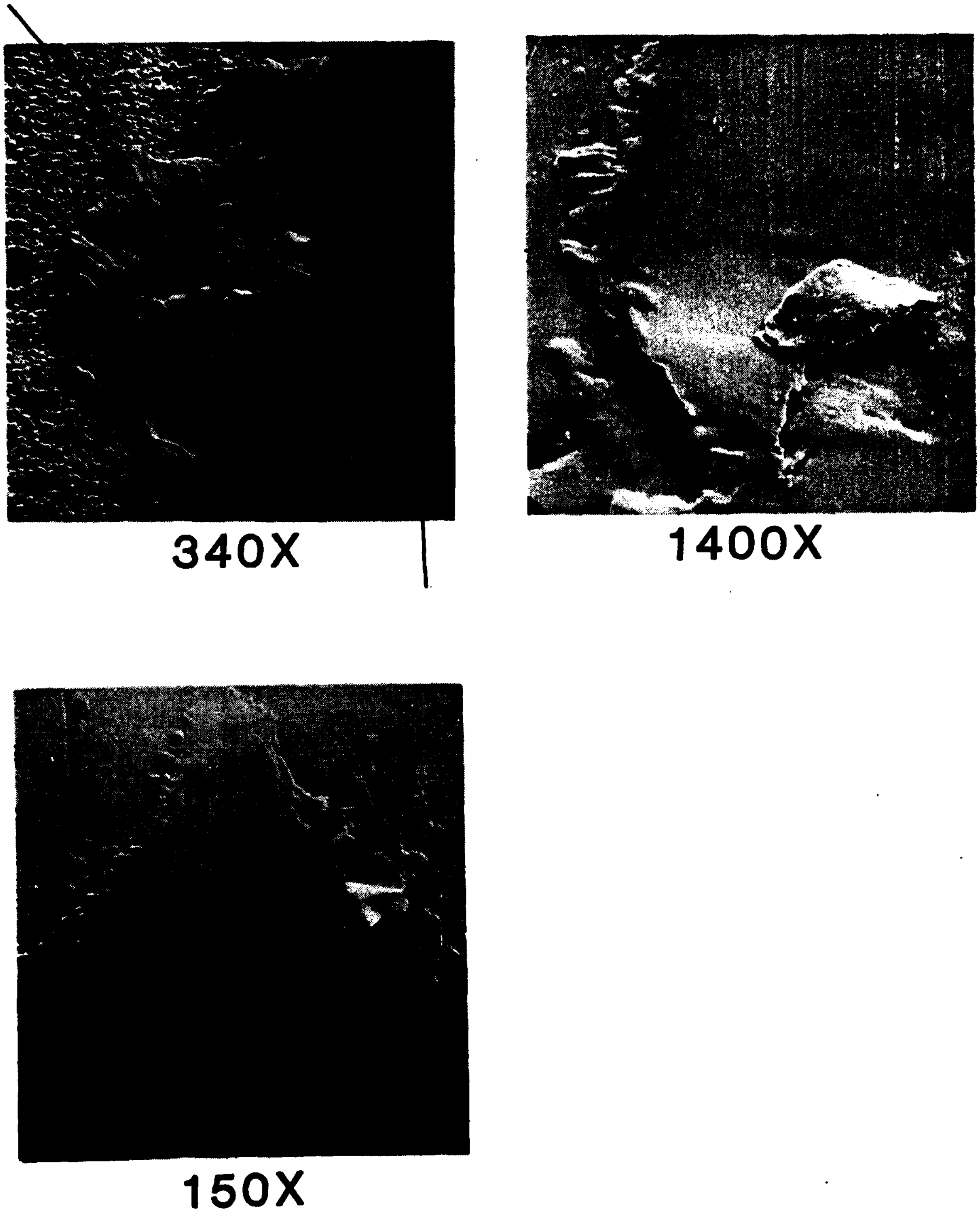
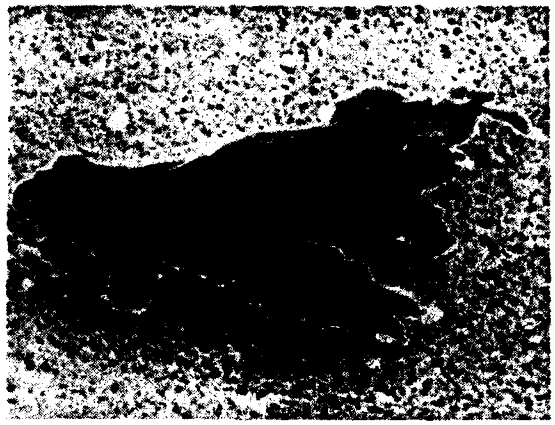
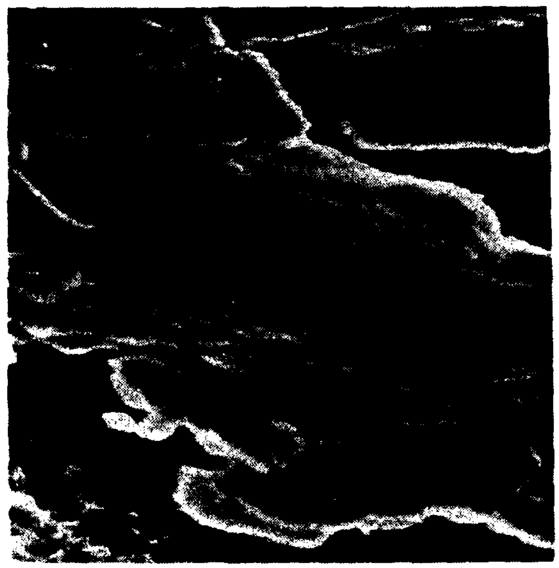


FIGURE 6. SEM PHOTOS OF A WEAR TRACK ON SPECIMEN ONR-2 (THICK SPUTTERED GOLD SURFACE). (A) LEFT ARROW INDICATES AS-SPUTTERED SURFACE. RIGHT ARROW INDICATES SLIDING DIRECTION.



1500X



6000X

FIGURE 7. SEM PHOTO OF A SPUTTERED Au WEAR PARTICLE FROM SPECIMEN ONR-2.

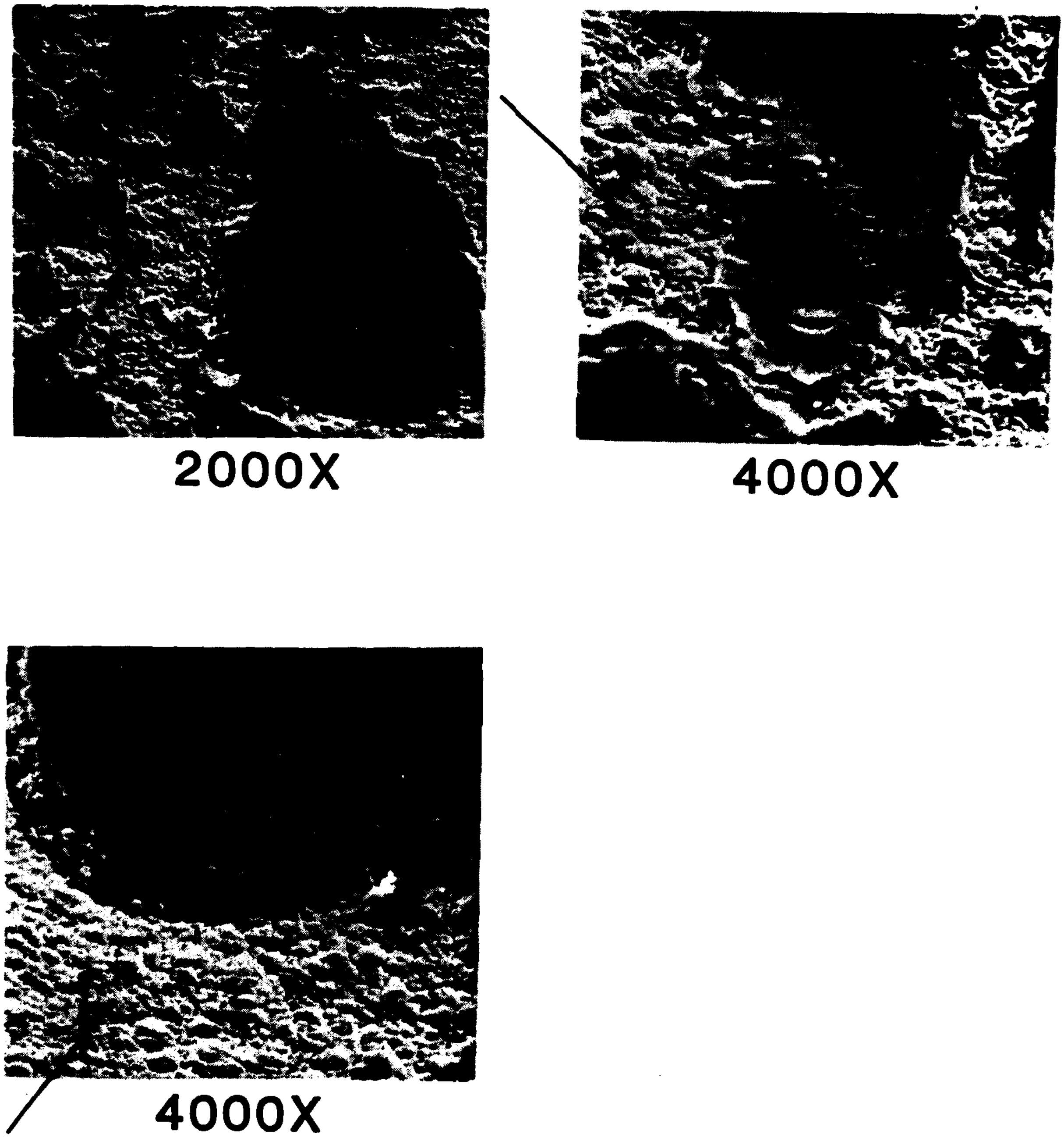
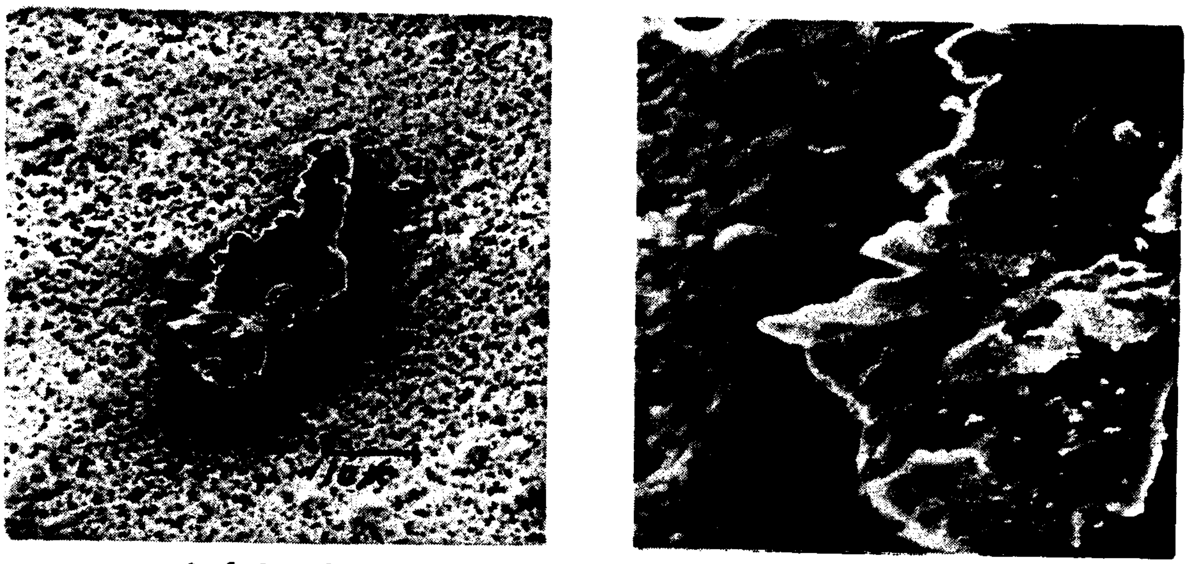
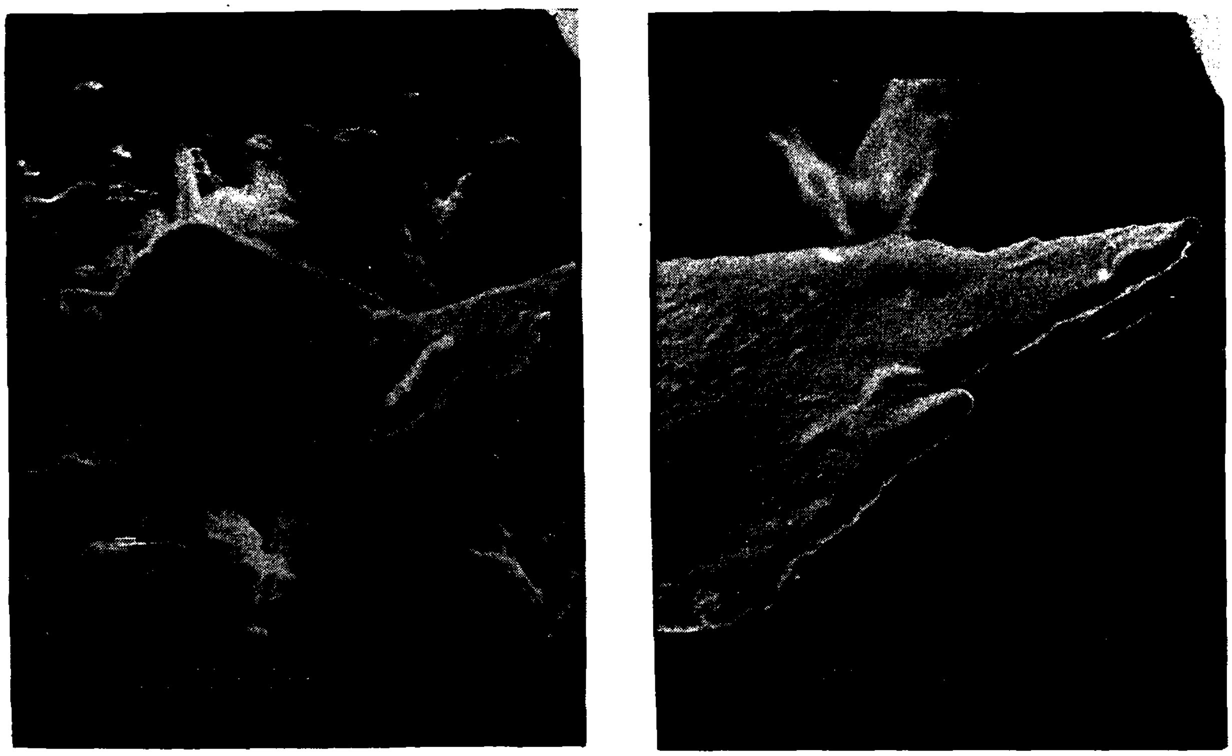


FIGURE 8. SEM PHOTOS OF A WEAR TRACK FROM SPECIMEN ONR-1. THE ARROWS POINT TO THE STAINLESS STEEL UNDERLAYER.



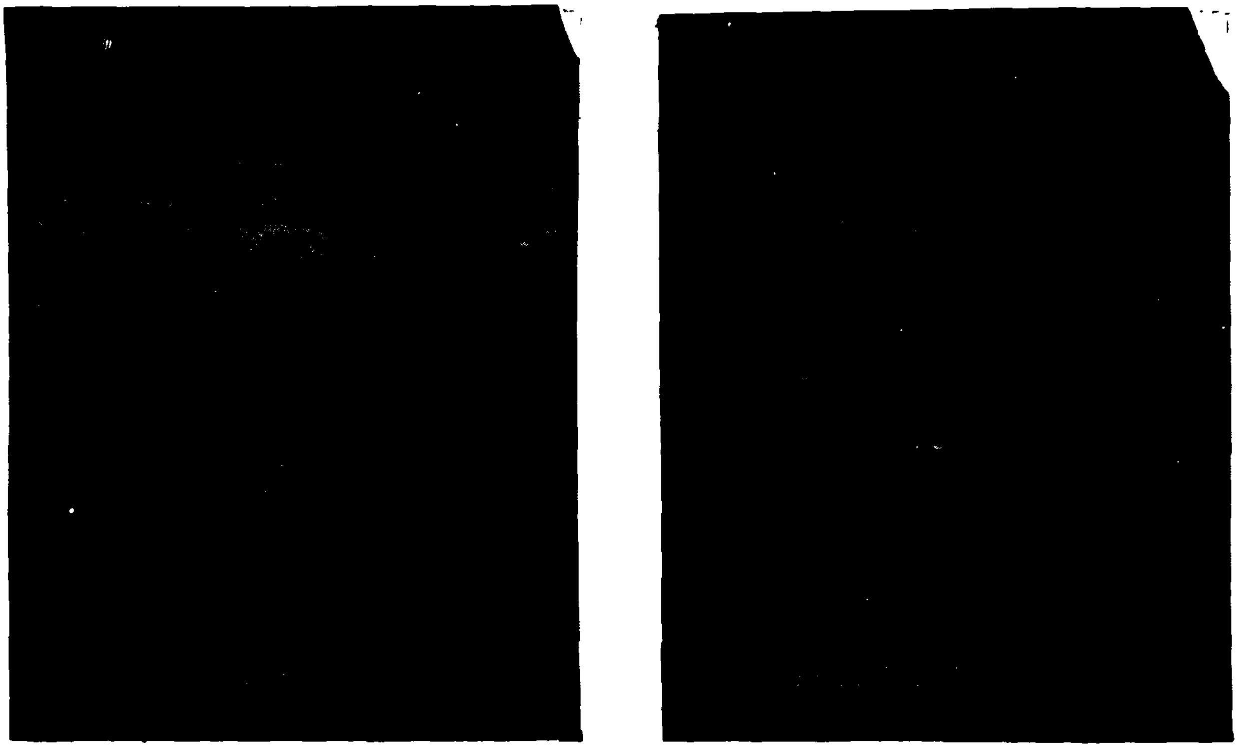
1400X   5600X

FIGURE 9. SEM PHOTOS OF WEAR DEBRIS PARTICLES FROM SPECIMEN ONR-1. SLIDING DISTANCE 25 METERS.



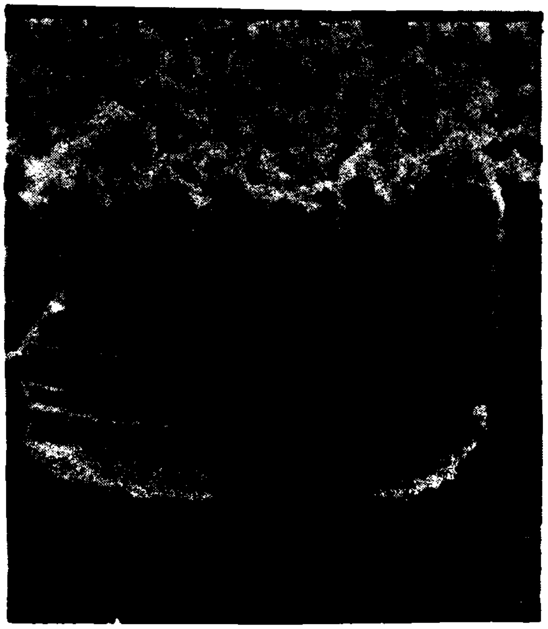
2000X 9000X

FIGURE 10. DEBRIS PARTICLE FROM SPECIMEN ONR-1
SLIDING DISTANCE 600 METERS.



400X 1500X

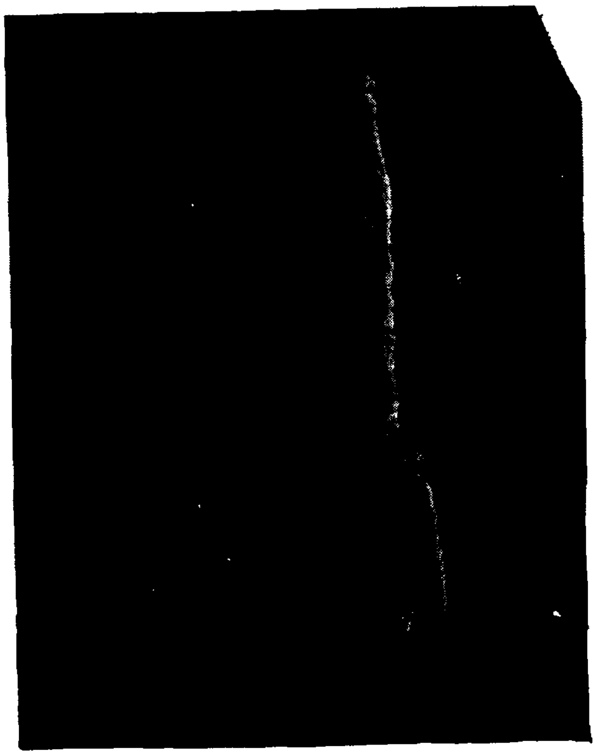
FIGURE 11. WEAR TRACK FOR Au/Mo SPECIMEN ONR-4. SAMPLE LOAD 550 GRAMS, SURFACE SPEED 83 MM/SEC, SLIDING DISTANCE 25-75 METERS.



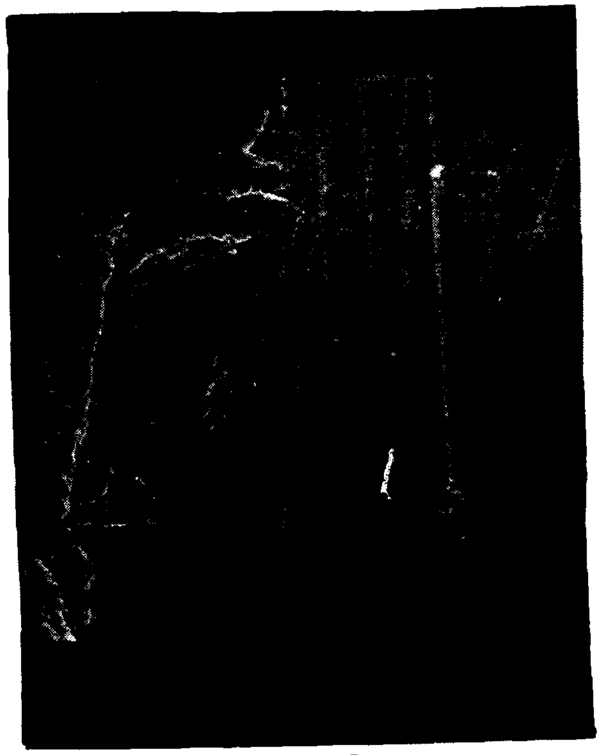
4000X

6000X

FIGURE 12. DEBRIS PARTICLES FROM WEAR TRACK OF SPECIMEN ONR-4. THE PARTICLE AT LEFT IS FOR A 550 GRAM LOAD, 83 MM/SEC SURFACE SPEED, AND 50 METER SLIDING DISTANCE. THE PARTICLE AT RIGHT IS AFTER 100 METER SLIDING DISTANCE.

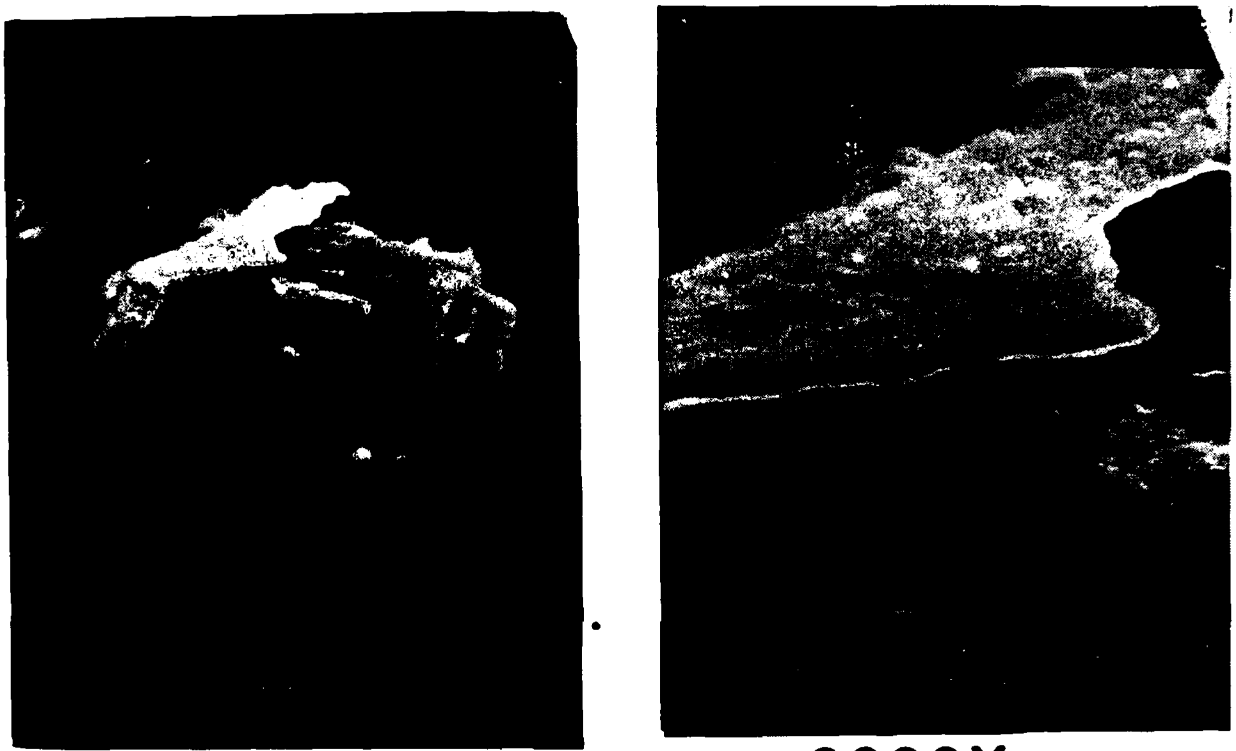


400X



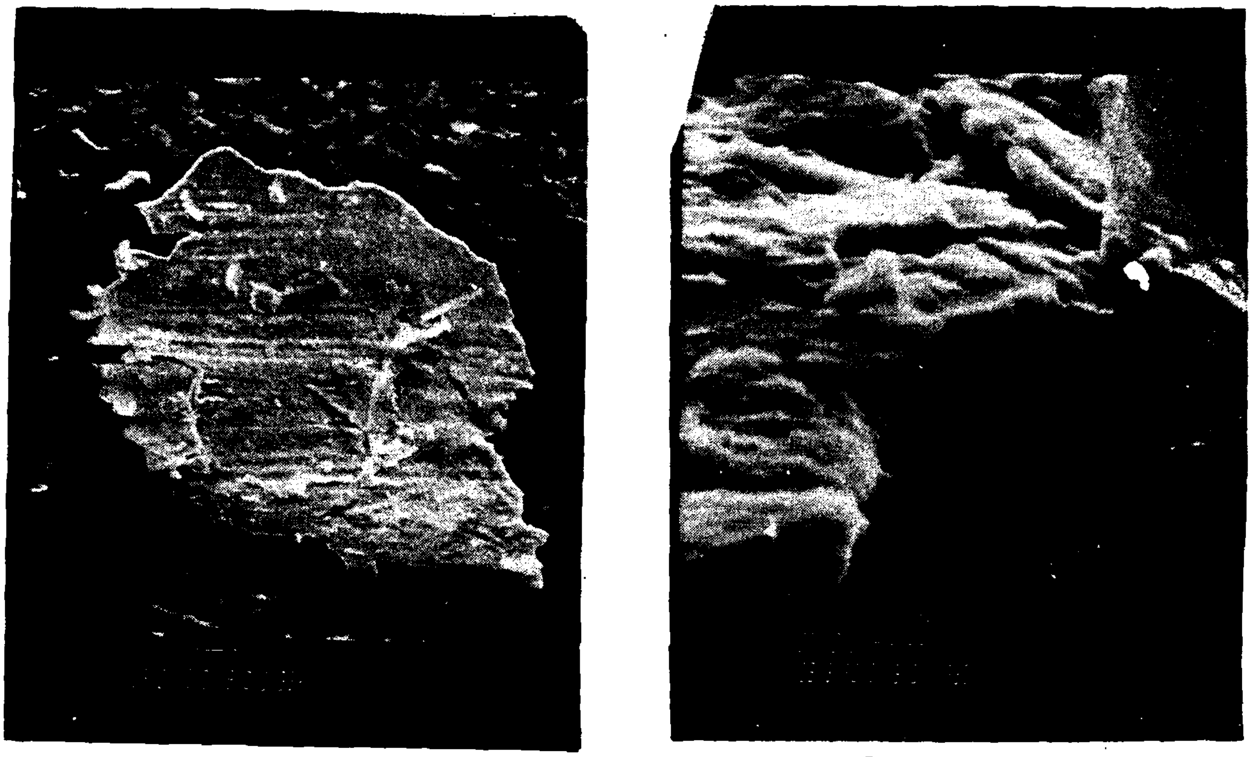
400X

FIGURE 13. WEAR TRACK FOR Au/Mo SPECIMEN ONR-4. SAMPLE LOAD 1100 GRAMS, SURFACE SPEED 250 MM/SEC (LEFT), 83 MM/SEC (RIGHT), SLIDING DISTANCE 100 METERS.



2000X 9000X

FIGURE 14. WEAR DEBRIS FROM Au/SS SPECIMEN ONR-6. SAMPLE LOAD 550 GRAMS, SURFACE SPEED 83 MM/SEC, SLIDING DISTANCE 300 METERS.



600X 9000X

FIGURE 15. WEAR DEBRIS FROM SPECIMEN ONR-6. SAMPLE LOAD 550 GRAMS, SURFACE SPEED 83 MM/SEC, SLIDING DISTANCE 1200 METERS.

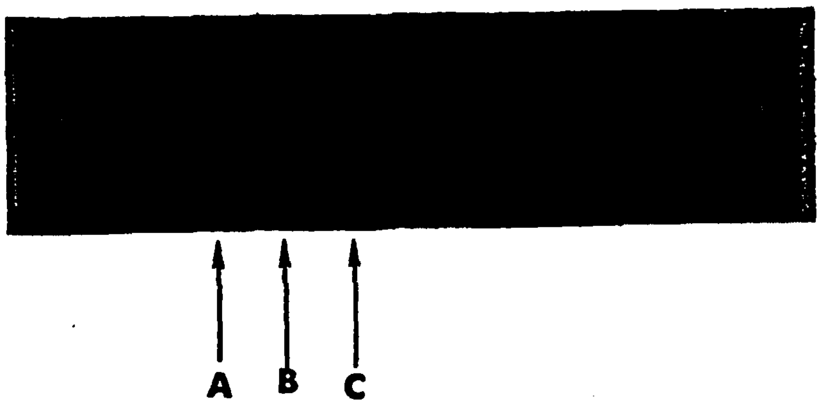


FIGURE 16. TYPICAL COATED WEAR SPECIMEN. A, B, AND C REPRESENT DIFFERENT WEAR TRACKS. OPTICAL CROSS SECTIONS WERE USED TO DETERMINE WEAR RATES.

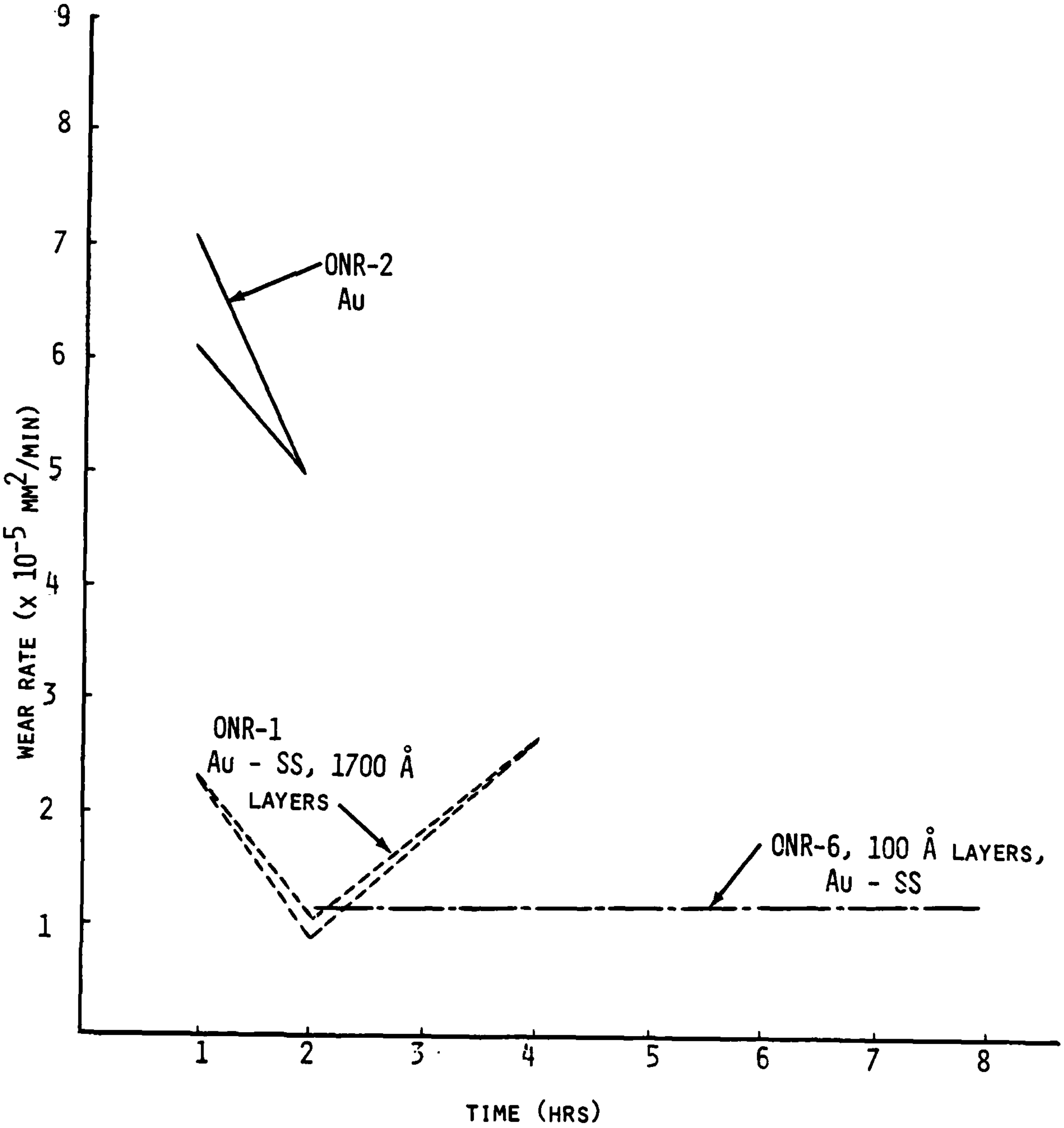


FIGURE 17. WEAR RATES AS A FUNCTION OF TEST DURATION.

TABLE II. TEST CONDITIONS FOR WEAR SPECIMENS

SAMPLE	WEAR TRACK	SAMPLE LOAD (GRAMS)	SURFACE SPEED (MM/SEC)	SLIDING DISTANCE (METERS)
ONR-0	1A	550	83	25
ONR-0	1B	550	83	50
ONR-1	1A 5	550	83	25
ONR-1	1A 15	550	83	50
ONR-1	1A 35	550	83	100
ONR-1	3B	550	83	600
ONR-2	1A	550	83	25
ONR-2	1B	550	83	25
ONR-4	2B-5	550	83	25
ONR-4	2B-15	550	83	75
ONR-4	2D&F	1100	250	100
ONR-6	1A	550	83	300
ONR-6	1B	550	83	1200

TABLE I. WEAR SPECIMENS PRODUCED BY SPUTTER DEPOSITION

RUN	LAYER MATERIAL	NUMBER OF LAYERS	THICKNESS/ LAYER (CALCULATED)	TOTAL THICKNESS (MEASURED)	COMMENTS
ONR-0	CAST GOLD	N/A	N/A	N/A	THIS IS THE ONLY SAMPLE TESTED THAT WAS NOT PRODUCED BY SPUTTER DEPOSITION
ONR-1	SS*	125	1600 Å	4.2×10^{-3} CM	GOOD ADHERENCE
	AU	125	1700 Å	(1.65 MILS)	
ONR-2	SS*	250	830 Å	5.6×10^{-3} CM	GOOD ADHERENCE
	AU (THIN LAYERS)	250	850 Å	(2.2 MILS)	
	AU (THICK OUTER LAYER)	1	1.2×10^{-3} CM (.5 MILS)		
ONR-4	MO	635	250 Å	3×20^{-3} CM	GOOD ADHERENCE. DEPOSITED AU AS INITIAL LAYER. A POWER FAILURE SHUT DOWN RUN EARLY.
	AU	635	225 Å	(1.2 MILS)	
ONR-6	SS*	2500	100 Å	5×10^{-3} CM	GOOD ADHERENCE
	AU	2500	100 Å	(2.0 MILS)	

* SS REPRESENTS 316 STAINLESS STEEL.