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Key Words:
Wear
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Retention:
Permanent

WEAR TESTING OF STAINLESS STEELS IN HYDROGEN – EFFECTS OF COATING AND PRE-CHARGE (U)

Poh-Sang Lam
Thad M. Adams

MARCH 2010

Savannah River National Laboratory
Savannah River Nuclear Solutions
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DISCLAIMER

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1.0 EXECUTIVE SUMMARY

Phase I wear testing was previously conducted to evaluate the effects of hydrogen atmospheres on wear behavior of stainless steel materials. A Phase II wear testing campaign was run to investigate 1) effects of hydrogen pre-charge and increased load and 2) impact of surface coatings on wear behavior.

Testing was conducted with guidance from the ASTM G 99, “Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus,” test standard. Testing was conducted in air or in gaseous hydrogen at a pressure of 13.8 MPa (2000 psig) at room temperature. The hydrogen pre-charge samples were exposed to gaseous hydrogen at an elevated temperature to produce a minimum of 30wppm atomic hydrogen at the sample surface. For the coatings tests, samples were coated with either a plasma nitride or a diamond like carbon (DLC) surface coating applied by a commercial coating vendor.

Material loss due to wear was determined by (1) weighing the specimens (disks and pins) before and after the test; and (2) by tracing the specimen surface roughness across the wear region with a profilometer for both Phase I and Phase II campaigns. Testing was performed for all Phase II samples with a nominal travel distance of 2000 m and a unidirectional disk linear speed at nominally 800 mm/sec. The phase II test data indicate the following:

- Materials transfer and excrescence was observed for metal-to-metal test conditions. Examination of the surface finish of the post-test specimens was made with optical microscopy, scanning electron microscopy (SEM), and profilometer tracing. The results are consistent with previous Phase I results and are indicative of adhesive wear and galling characteristics of stainless steels.
- Similar to Phase I results, AUM10 had a higher wear rate than 316L. Pre-charging with hydrogen showed minimal effect. Increasing load from 45.4 g (0.1lb) to 91 g (0.2 lb) resulted in a small increase in wear.
- Surface coatings reduced the overall wear of the pin and disk materials. For tests with nitride coated disks and uncoated pins increased pin wear was displayed.
- DLC coating appears to offer the most potential as a wear reducing coating—it can be used for either case of both disk and pin coated or one coated and one non-coated, with improved wear resistance.

2.0 INTRODUCTION

Joint research between the Toyota Research Institute North America and the Savannah River National Laboratory (SRNL) was performed to characterize the effects of hydrogen for materials used in fuel cell vehicles. Mechanical equipment for high pressure gaseous hydrogen service includes moving parts where two surfaces may be in contact and slide against each other, resulting in wear that may damage the component. Consideration must be given to the wear characteristics of the alloys of construction; this is especially critical for valves, pumps, bearings, seals and fasteners.

The sliding wear mechanisms of metallic and ceramic components in hydrogen may be expected to be different from the wear experienced in air or inert atmospheres. The interactions of materials with similar hardness and surface reaction behavior could be more deleterious in a hydrogen environment than in air or other atmospheres where protective surface scales may form. Excessive adhesive transfer or fragmentation of these materials could also occur in hydrogen that would not occur in air applications.

Phase I wear testing of stainless steel materials in gaseous hydrogen was completed in FY09. A Phase II program was conceived, to evaluate the impact of pre-charging samples with hydrogen to ensure that the test surface was saturated in hydrogen. A second aspect to the Phase II effort was to evaluate selected commercial coatings to assess their impact on wear behavior in gaseous hydrogen.

Results from this Phase II study together with the initial Phase I results provide key information to designers for material selection for hydrogen service applications involving metallic components with mating dynamic surfaces.

3.0 TEST EQUIPMENT AND SAMPLES

A wear test apparatus has been designed by following the guidelines described in ASTM G 99-05, "Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus," as schematically shown in Figure 1. The system was designed to allow testing samples in high pressure hydrogen environment by providing a pressure boundary made of Super Alloy HASTELLOY® C276 with outside diameter of 12.7 cm (5 in.), thickness of 3.81 cm (1.5 in.), and the internal cavity height of 17.78 cm (7 in.).

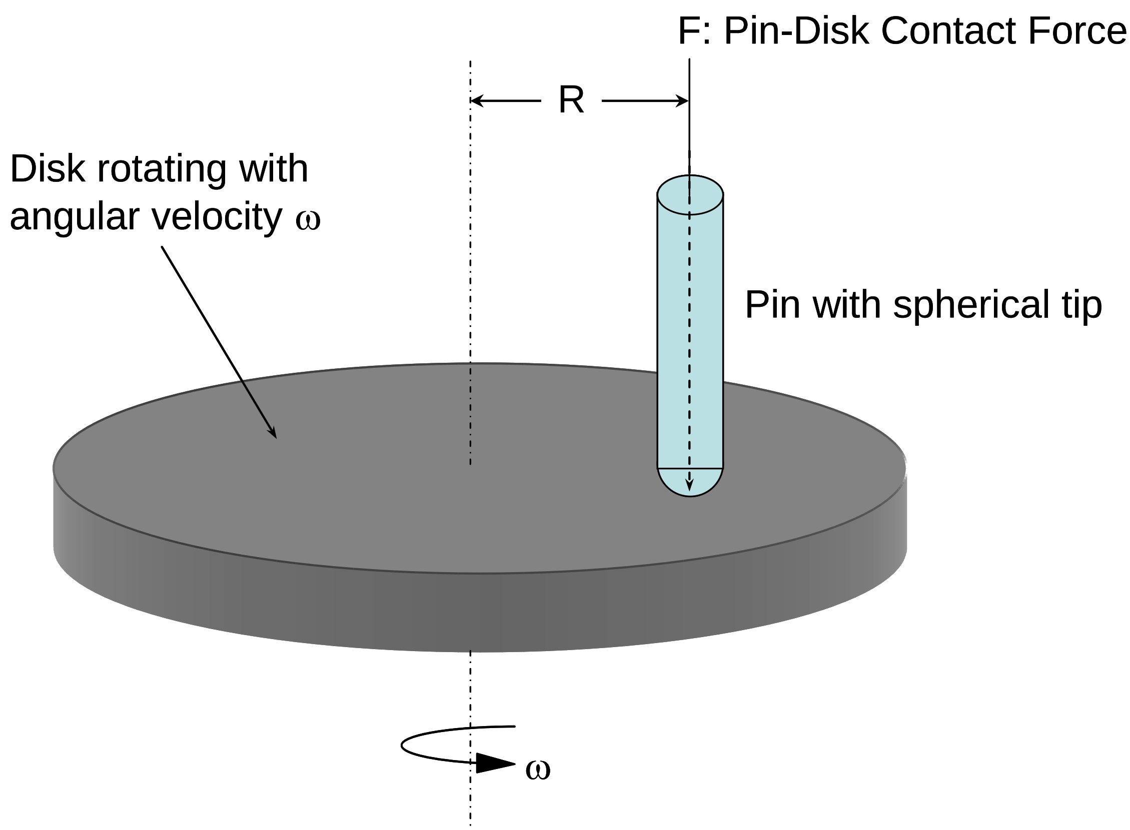

Figure 1. Schematic of disk-pin wear test system (R is the wear track radius).

Figure 1 shows the schematic diagram of the wear test mechanism for a stationary pin and a rotating disk with angular velocity ω (rad/sec). The linear velocity of the disk speed (v) is calculated in term of revolutions per minute ($\mathrm{RPM} = \frac{\omega}{2\pi} \times 60$) as $v = \omega R = \frac{\pi R \times \mathrm{RPM}}{30}$

Disk samples for wear testing were fabricated from 316L and AUM10 stainless steels. As shown in Figure 2, they are 4.76 cm (1.875 in.) in diameter and 0.635 cm (¼-in.) thick. The disks were machined from 2-inch diameter bar stock (see vendor certificate in Appendix A and Aichi Steel information sheets in Appendix B). Two parallel flat surfaces were machined on opposite edges of each disk to keep it from rotating in the sample holder. Each disk was engraved with a unique serial number. The test side of the sample is the non-engraved side and was machined to a minimum 0.81 μm (32 μ-in.) arithmetic average (Ra), per ASTM G 99.

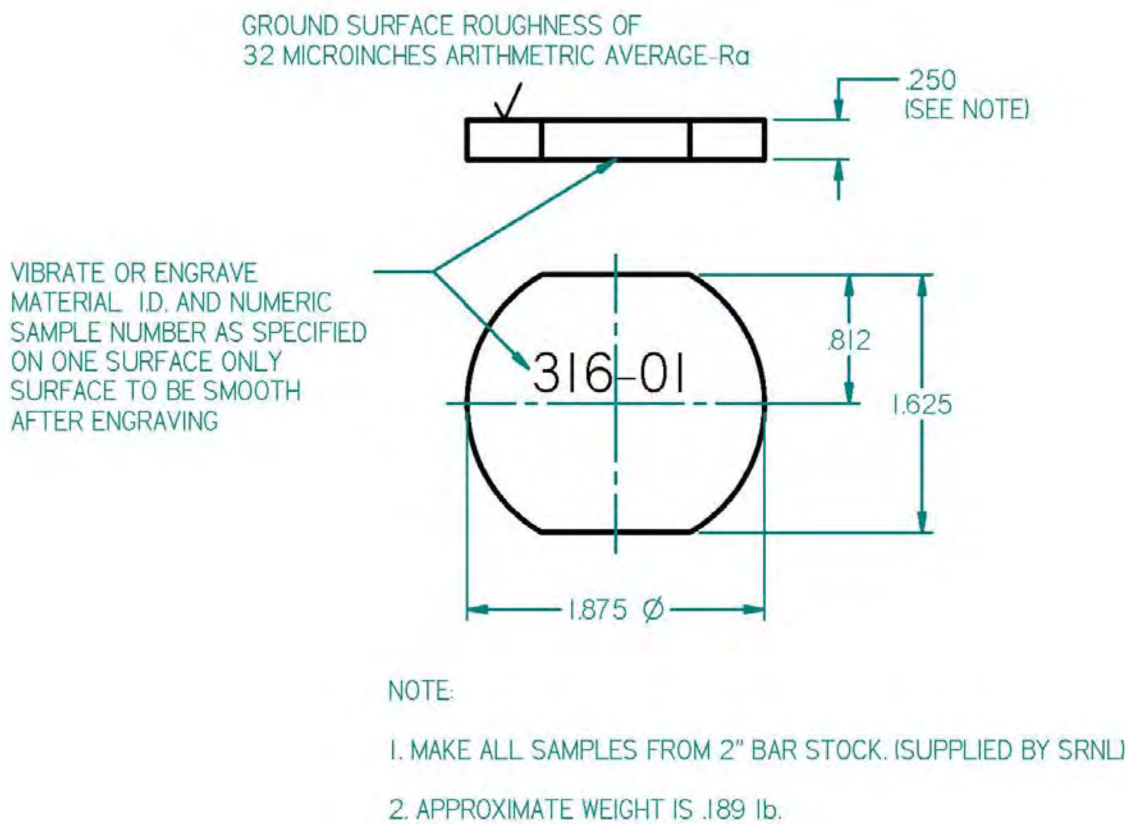

Figure 2. Wear sample disk design and dimensions.

Additionally, pin samples for wear were fabricated from 316L and A286 stainless steel materials. They were machined from 9.525 mm (3/8-in.) rod (see vendor certificates in Appendices B and C, respectively). Each pin is 7.94 cm (3[in., which is slightly longer than that used previously 2¾ in [9].) long with a spherical tip on one end and is threaded on the other (Figure 3). Each sample pin is engraved with a unique serial number. The spherical shape was machined on a lathe, so the tip at the end of the pin was not perfectly spherical. For this reason, the pin was mounted in the test machine at a slight angle to the vertical position so the point of contact with the disk would be made on a spherical pin surface.

To maintain the same surface finishing of the specimens as previously tested in the Phase I study [1], the same commercial fabrication vendor was used and the same fabrication instructions were provided. Typical as-finished sample disk and pin can be seen in Figure 4.

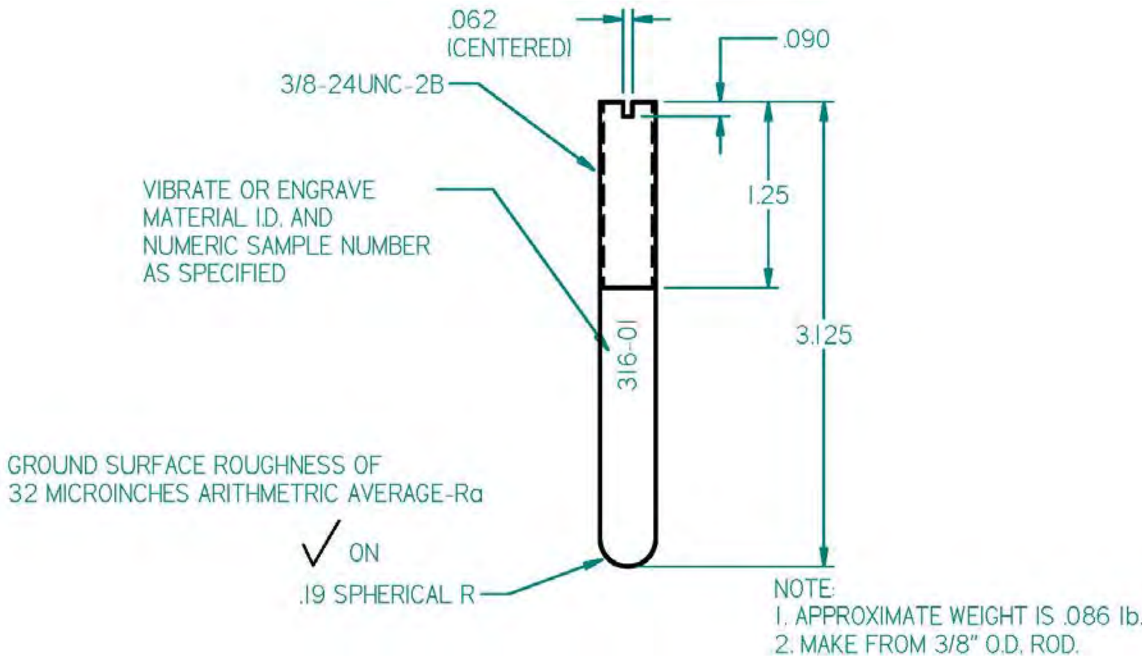

Figure 3. Wear sample pin design and dimensions.

Figure 4. The disk and pin wear test samples**.**

Tensile properties and material hardness values for the as-received disk and pin materials can be found in the vendor certificates or the material information sheets (Appendices A to D) and are summarized in Table 1.

Table 1. Mechanical properties of disk and pin sample materials

	316L Disk (Appendix A)	AUM10 Disk (Appendix B)	316L Pin (Appendix C)	A286 Pin (Appendix D)
Bar Stock Diameter cm (in.)	5.08 (2)	5.486[1] (2.16)	9.525 (3/8)	9.525 (3/8)
0.2% Yield Stress MPa (ksi)	269 (39)	390[2] (57)	561 (81.43)	924 (134)
UTS MPa (ksi)	593 (86)	530[2] (77)	688 (99.84)	1158 (168)
Elongation (%)	66	37[2]	46.01	23
RA (%)	73	74[2]	75.2	39
Hardness	HB 185	HV 183[1] (3mm below surface) HV 186[1] (D/4) HV 183[1] (D/2) HRB 88[2]	HB 212	HRC 34 HB 321

Note 1: Information provided by Toyota Motor Company.
The heat treatment is 920 °C x0.5 Hr, furnace cool to 650 °C (2.5 Hr), 650 °C x 0.5 Hr, air cool.
HV 183 is equivalent to HB 174.

Note 2: See Appendix B for the information sheets from Aichi Steel Co. (Japan) [2].
The heat treatment is 900 °C x 2 Hr which is different from that in Note 1.
HRB 88 is equivalent to HB 175.

4.0 COATING

Two types of coating were selected to be evaluated for their wear performance in hydrogen service:

(1) Diamond-like-carbon (DLC)

This is a surface coating of diamond like carbon that exhibits a very low sliding friction and high surface hardness. It is possible to mask with areas and selectively coat a substrate. The coating is deposited using a combination of a physical vapor deposition process (PVD) and plasma enhanced chemical vapor deposition process (PECVD). The PVD process will deposit and initial adhesion layer and the PECVD deposits the DLC coating. In the process a carbon carrying gas is introduced into the chamber and a power supply accelerates electrons and cracks the gas breaking the carbon and hydrogen bonds and ionizing the gas as well. The ions are then drawn to the fixture holding the substrates with a negative bias potential forming a coating with a diamond like structure.

The resulting diamond-like coating is structurally amorphous and chemically inert, and may be self-lubricating with very good wear resistance. This coating will replicate the surface finish of the substrate. The typical thickness of the coating is 2 to 5 microns (8×10^{-5} to 2×10^{-4} inches) with Vickers hardness between HV 1000 and 3500 [3].

(2) Plasma nitriding:

Plasma Nitriding is a thermo-chemical diffusion process that will create a hard case several thousandths deep. Unlike a surface coating which will provide properties independent of the substrate being coated, the results from the plasma nitriding process are dependent on the composition of the steel being nitrided. Case depth and hardness will vary depending on the nitriding forming elements present in the alloy. The processing temperature is fixed to between 900 and 950 degrees F. The hardness achieved will generally increase depending on the chromium content in the steel. The surface roughness will increase after nitriding. During the initial heating step of the plasma nitriding process, a hydrogen gas is introduced into the chamber and a pulsed DC bias is supplied to the product to be nitride. The product's surface is bombarded with hydrogen ions during the initial heating cycle. This helps elevate the temperature and cleans the surface as well. When the product reaches the required processing temperature, a gas mixture of nitrogen and hydrogen is introduced and the nitriding cycle begins. The nitrogen will diffuse into the substrate reacting with nitride forming elements and create a hard layer that will continue for up to several thousandths into the steel. On the surface of the product, a compound layer will form and again will vary in thickness depending on the alloy being nitride. This is sitting on the surface and is the primary cause for the uniform growth you receive from the nitriding process. This layer is comprised of epsilon or gamma prime depending on the gas mixture used. If a small amount of carbon is included in the nitrogen and hydrogen gas mixture during the nitriding cycle, the compound layer will be an epsilon layer.

The surface hardness for the plasma nitrided 304 or 316 stainless steels is HRC 62-66 with a total hard case depth 50 to 200 microns (0.002 to 0.008 inches) [3].

Based on the test matrix, nitride coating was applied on twenty AUM10 disks and four 316L pins, and DLC was coated on twenty AUM10 disks and four 316L pins. The DLC-coated disks and pins have a bright black finish (Figure 5) that appears to have the same surface configuration (machine marks) as the original, non-coated specimens except for the black color. The nitride-coated disks (Figure 5) have a dull satin finish that masks the nitrided surface. This soft and rough layer could easily be removed with a Scotch-Brite™ pad, or would quickly wear away at the beginning of the wear test. However, the surface condition of the nitride-coated pins looks similar to that of the DLC-coated pins (Figure 5). This indicated that the nitride surface finish is sensitive to the original substrate surface roughness, and to the curvature of the surface being coated.

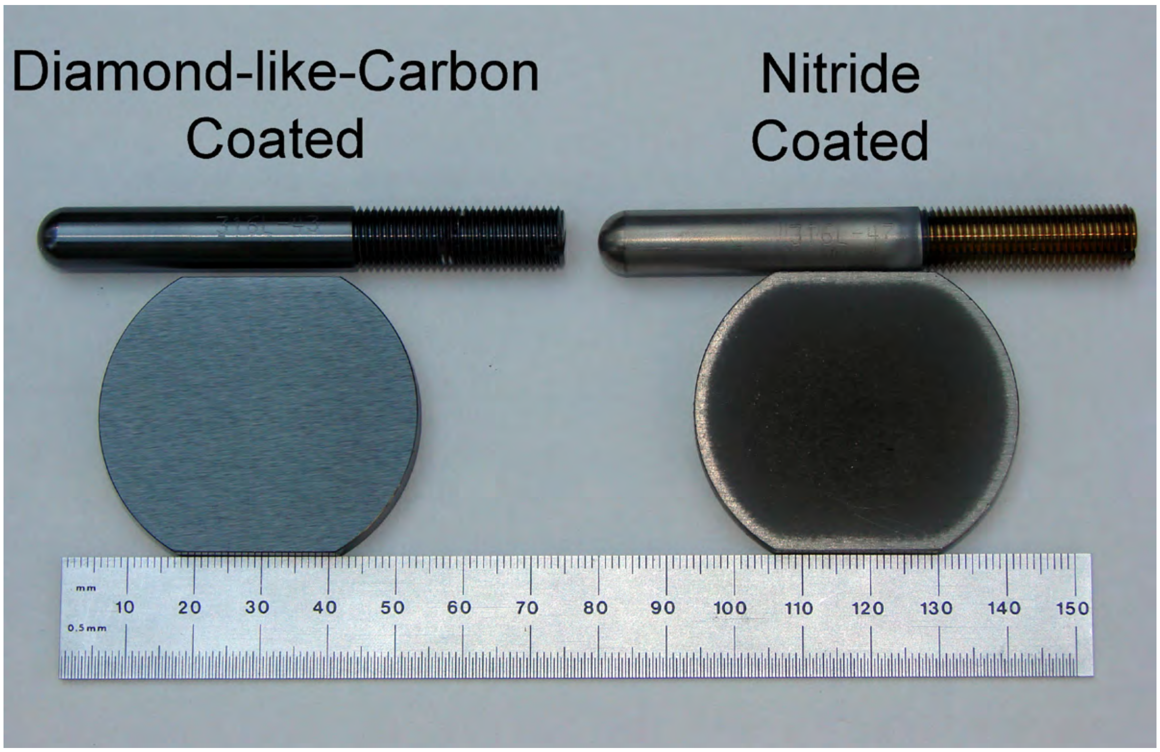

Figure 5. As received DLC and Nitride coated samples.

5.0 HYDROGEN PRE-CHARGE

The test matrix required that five 316L disks and 39 pins (26 316L and 12 A286) be pre-charged with hydrogen for the wear test. None of the coated samples were pre-charged. Note that AUM10 is a soft magnetic ferritic stainless steel based on Type 410L martensitic stainless steel. The hydrogen diffusivity is high in this alloy so pre-charge was also not conducted for AUM10 samples.

The SRNL hydrogen charging facility has a capability of 68.9 MPa (10,000 psi) charge pressure. For these wear samples, an optimum charge condition was determined by SRNL in-house software such that the criterion of 30 wppm (1680 appm for typical stainless steels) at the sample surface could be met. All the samples were nominally pre-charged with 17.2 MPa (2500 psig) research grade hydrogen gas (Appendix E) at 350 °C for one week. The atomic hydrogen concentrations in a disk and at the tip of a pin are shown in Figure 6. It can be seen that the condition of 30 wppm is exceeded everywhere at the tip pf a pin, and within 1.5 mm (0.06 inch.) from the surface of a disk. Note that the boundary condition of the numerical calculation maintained at 2531 appm based on the hydrogen charge parameters. A detailed discussion on diffusion properties can be found in Reference [4].

The charge temperature (350 °C) has been shown not to alter the microstructure of the steels. After each charge, the specimens were immediately cooled with liquid nitrogen (−196 °C at 1 atm) and removed from the charge vessel, then transported in dry ice (-78 °C) to a freezer for temporary storage at -44 °C until wear testing was conducted. The length of the freezer storage and a short term exposure to room temperature prior to initiating wear testing will not affect the hydrogen concentration in the samples.

The SRNL charge container has an effective length of 20-23 cm (8-9 inch.) and 3.18 cm (1¼ inch.) in diameter. As a result, the standard disk sample with a diameter of 4.76 cm (1.875 in.) (see Figure 2) must be re-designed for hydrogen pre-charge. An adaptor was fabricated for the smaller pre-charged disks so the wear testing can be conducted normally. Due to the size of the charge tube, only 10 pins (or 5 disks and 5 pins) could be charged at each time.

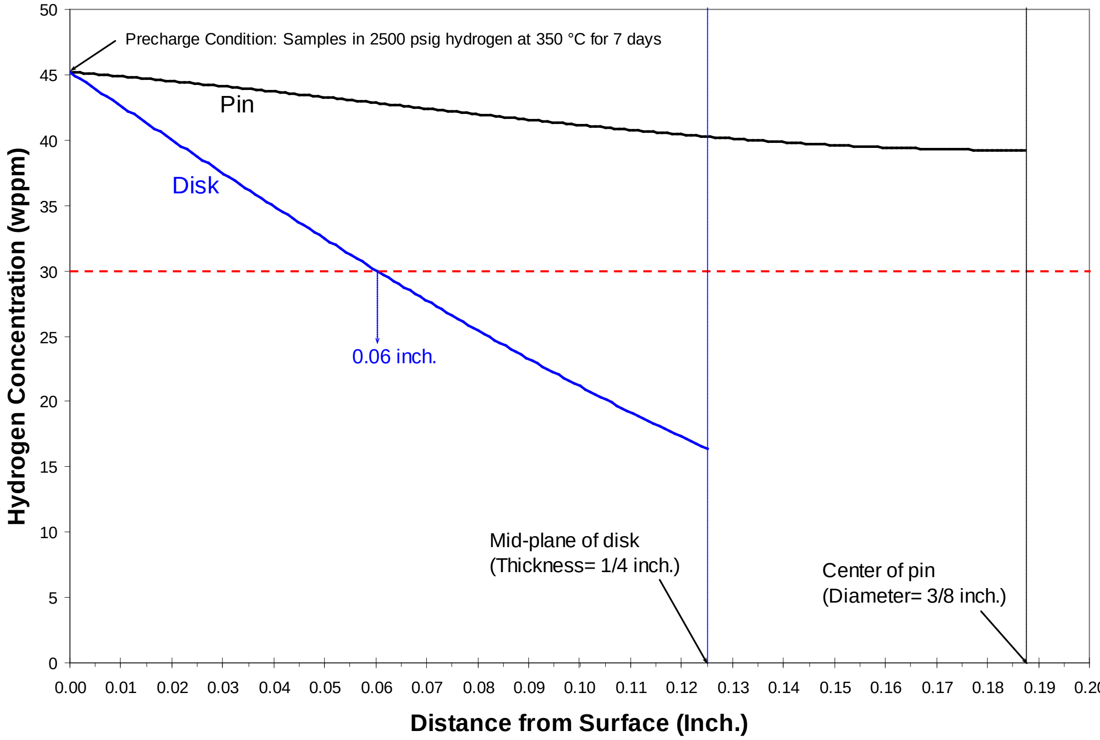

Figure 6. Hydrogen concentration in pre-charged disk and pin samples

6.0 TEST PROCEDURE AND EQUIPMENT

The non-coated sample disks and pins were cleaned in an ultrasonic cleaner, handled without any type of surface contamination, and stored in plastic bags prior to testing. The coated samples were tested with the as-received condition, except the superficial layer on the nitride-coated disks was removed with the Scotch-Brite™ pad. A four- place balance is used to obtain the pre/post-test weights of the samples.

The overall layout of the wear test laboratory can be seen in Figure 7, with the wear mechanism and its components shown in Figure 8. The threaded end of the pin (Figure 3) is screwed into a threaded hole in one end of a first class lever (Figure 9). The pin is prevented from moving by the addition of a lock nut. The fulcrum of the lever is supported by two ball bearings and the other end of the lever is threaded to hold a movable weight. The entire pin-holding assembly is designed to be positioned over the pan of a balance for setting the pin loads. The surface of the balance pan is in the same relative position as the surface of the disk in the test machine. A weight is adjusted until the force of the pin on the balance is exactly 45.4 g (0.1 lb) or 91 g (0.2 lb).

The pin-holding assembly is then mounted over the sample disk (Figure 9-Figure 10) with the load preset to either 45.4 g (0.1 lb) or 91 g (0.2 lb), the radial distance from the center of the disk to the point of contact with the pin is approximately 2.45 cm (1 in.). As discussed earlier, the pin is slightly tilted when the disk rotates because the apex of the pin head is not exactly on a spherical surface due to machining constraints. However, the contact point between the disk and the pin remains on a spherical surface as recommended by ASTM G 99-05.

Figure 11 displays the wear system with the pressure vessel lowered to enclose the disk-pin test mechanism for tests run in a hydrogen atmosphere. The pressure chamber (enclosure) is first evacuated, filled with helium, evacuated again and then filled to the desired pressure with gaseous hydrogen. The hydrogen gas used in this experiment was research grade with a purity of 99.9995% (Appendix E). Pressure is measured simultaneously by two independent pressure gages.

The disk-pin sample holder is rotated by a Magnedrive®. No high pressure rotating seals are required in the system so the leak path is eliminated. The Magnedrive® is driven by a V-belt connected to a variable speed DC motor (Figure 8). The rotational speed is measured by a non-contact laser tachometer connected to a computer which records speed vs. time during each test.

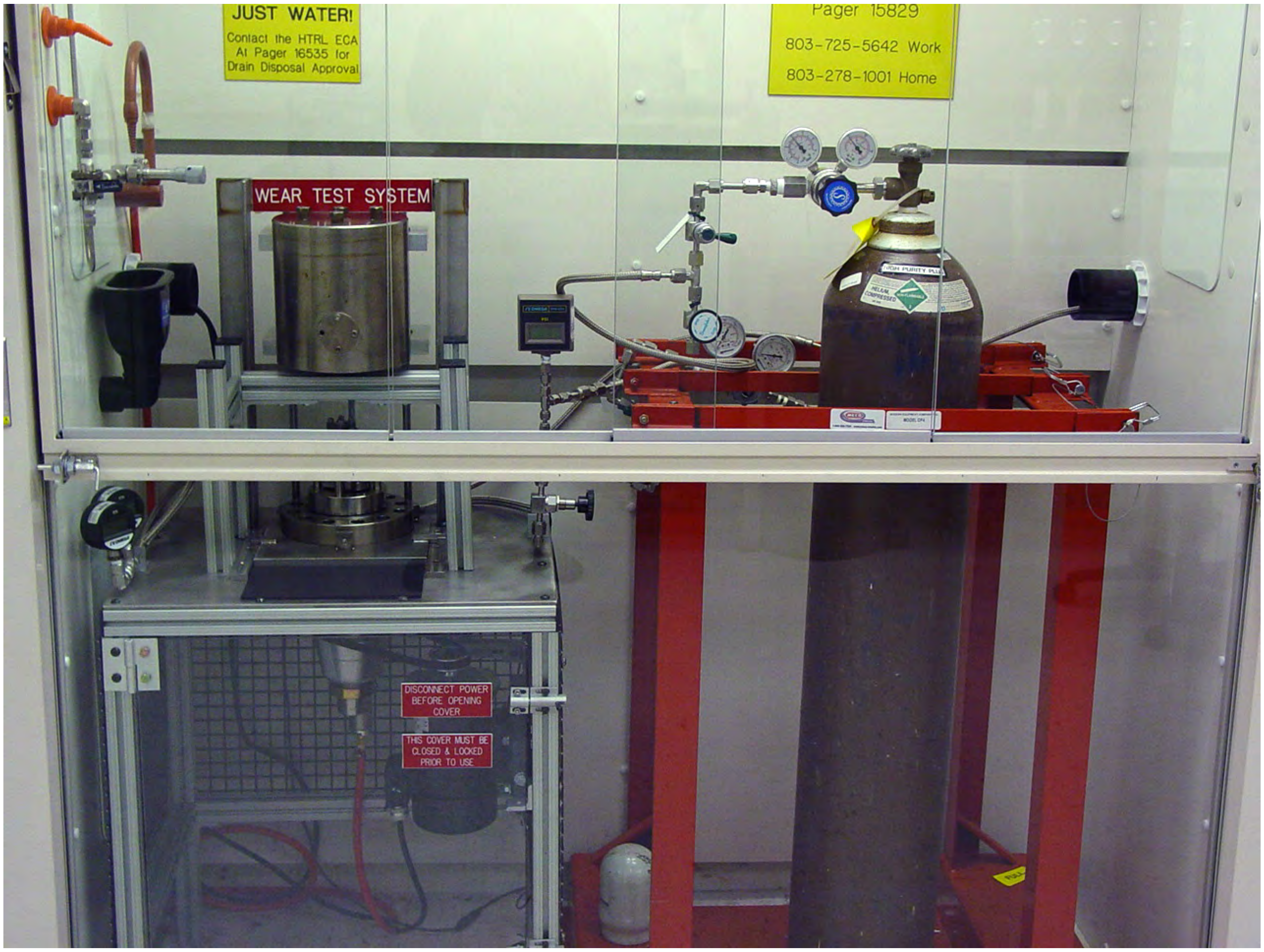

Figure 7 Wear test facilities: Disk-Pin System (left) and hydrogen gas supply cylinder (right).

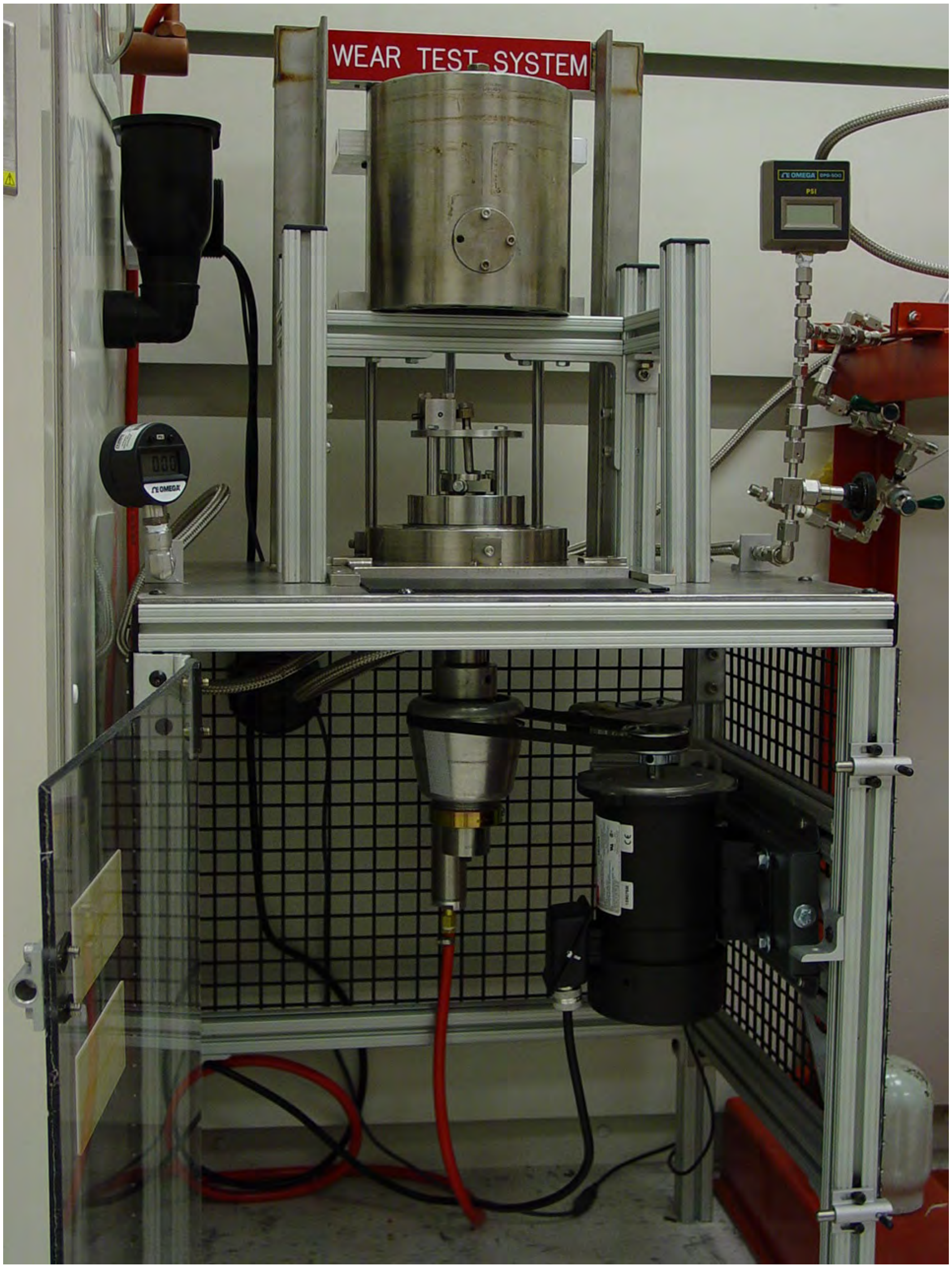

Figure 8. Wear hydrogen test system from top to bottom: pressure vessel enclosure for hydrogen test (to be lowed when testing), disk-pin holding assembly (samples are mounted), and Magnedrive® with V-belt connected to a DC motor (a non-contact laser tachometer is visible above the motor and behind the V-belt).

Figure 9. Sample disk on a rotating platform and the sample pin mounted in a fixed position.

Figure 10. Sample pin in contact with the disk.

Figure 11. Pressure vessel lowered to enclose the wear test mechanism ready for testing in hydrogen gaseous environment.

7.0 WEAR MEASUREMENT

After the samples were run in the test apparatus at a specified speed and travel distance (nominally 2000 m) under the load of 45.4 g (0.1 lb) or 91 g (0.2 lb), the wear track on the disk and the wear area on the pin were visually examined and photographed (Appendix F). The wear track diameter on the disk and the wear spot diameter on the pin were measured with a Ram Omis II Video Microscope. The wear surface morphology is obtained from a contact profilometer (Model: Rank Taylor-Hobson S5 Form Talysurf Profilometer). For this measurement, a diamond tip stylus is moved in a straight line from a virgin undisturbed area, across the wear region, and ending in the virgin undisturbed area on the other side of the wear track. The trace of each surface profile can also be found in Appendix F. From the trace on the chart, the wear width may be identified by noting a difference in surface finish. Typically, the wear region exhibits higher peak to valley variations, signaling that the surface has been disturbed as a result of testing. However, for some coated disks, especially DLC coated samples, visual examination and the profilometer traces were unable to identify a distinct wear region due to insignificant wear.

The individual disk and pin sample weight changes were obtained by direct measurement (i.e., with a four-place balance). The weighing procedure was as follows:

1. Weigh the test pin and record the weight.
2. Weigh the standard 50 gram weight and record the weight.
3. Weigh the "standard" pin and record the weight.
4. Repeat these three measurements a total of five times.
5. Weigh the test disk and record the weight.
6. Weigh the standard 100 gram weight and record the weight.
7. Weigh the "standard" disk and record the weight.
8. Repeat these three measurements a total of five times

After each test, a repeat of the above measurement process was performed to develop the wear test weight change data.

The wear volume of the samples after wear testing was obtained from the weight change data combined with typical mass density for the stainless steels (7.98 g/cc). In the case of DLC and nitride coatings, their densities are approximated by the pure diamond density (3.5 g/cc) and the typical density for nitriding steels (H7 g/cc).

Volume loss was unable to be measured from the profilometer scans because for most of the samples the surface roughness of the wear track and the virgin area outside of the wear track were very similar—indicating minimal wear. However, the volume loss for the pins could be calculated from the measured wear spot diameter by assuming that it is nearly circular and using the following relationship:

$$\text{Volume Loss} = (\pi R^3/3)\bullet(2\text{-}3\cos\theta + \cos^3\theta)$$

with $\theta = \sin^{-1}(b/R)$, where R is the pin tip radius (3/16 inch.), and b is the wear spot radius.

The accuracy of the above relationship was evaluated and is demonstrated by the comparison shown Figure 12. This also indicates that the weight measurements of the pin (and the disk) are accurate.

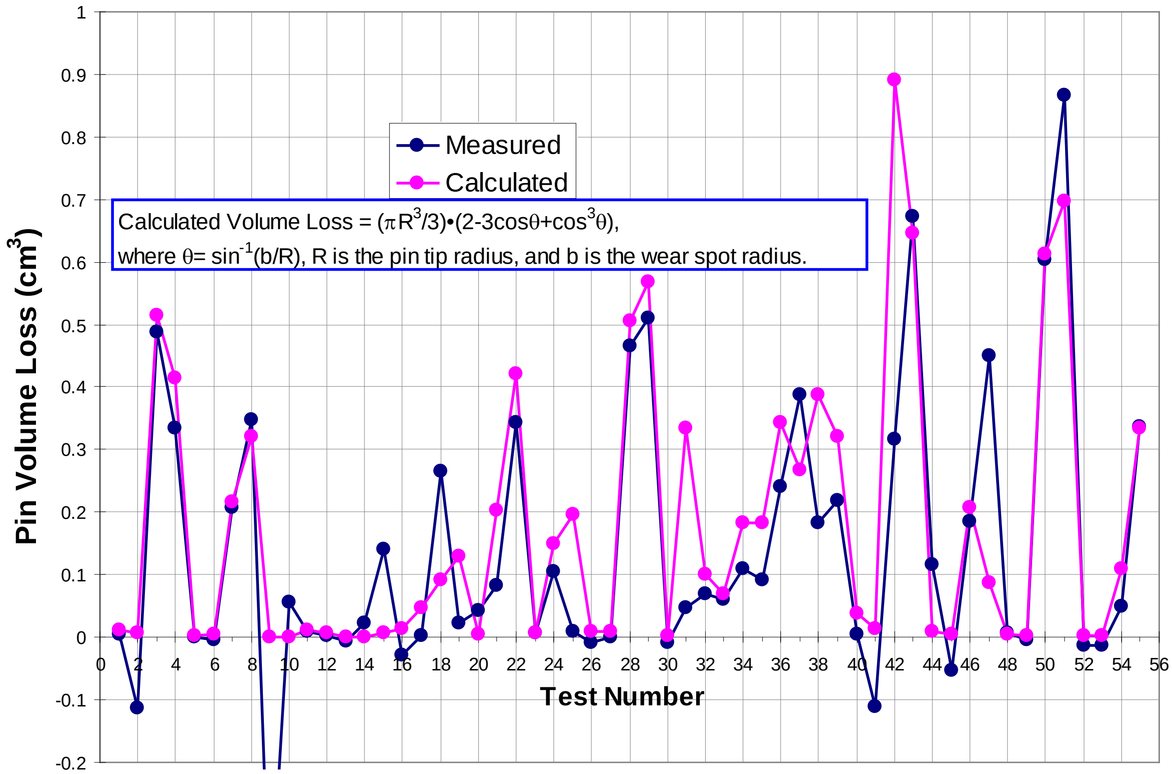

Figure 12. Comparison of pin volume change by weight measurement and by calculation.

Tables 2 to 4 list the test matrix for the Phase II study and the requested test parameters. For the Phase II testing, the nominal test speed is 800 mm/s and the total traveling distance is 2000 m. Note that the actual disk speed and the actual travel distance may vary slightly from the nominal (or target) values, because the actual distance from the center of the disk to the center of the wear track may not coincide exactly with the designed distance of R= 2.54 cm (1 in.).

Table 2. Test Matrix for Non-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Priority	Disk Material	Pin Material	Test Environment	Disk Number	Pin Number
1	1	DLC AUM10	316L	Air	AUM10-02	316L-06
2	1	DLC AUM10	316L	Air	AUM10-01	316L-05
3	1	Nitride AUM10	316L	Air	AUM10-05	316L-01
4	1	Nitride AUM10	316L	Air	AUM10-06	316L-35
5	1	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-04	316L-08
6	1	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-03	316L-07
7	1	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-08	316L-04
8	1	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-07	316L-03
9	2	DLC AUM10	DLC 316L	Air	AUM10-09	316L-41
10	2	DLC AUM10	DLC 316L	Air	AUM10-10	316L-42
11	2	Nitride AUM10	Nitride 316L	Air	AUM10-12	316L-48
12	2	Nitride AUM10	Nitride 316L	Air	AUM10-16	316L-47
13	2	DLC AUM10	DLC 316L	Hydrogen 2000 psig	AUM10-33	316L-43
14	2	DLC AUM10	DLC 316L	Hydrogen 2000 psig	AUM10-34	316L-44
15	2	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	AUM10-15	316L-46
16	2	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	AUM10-14	316L-45

Table 3. Test Matrix for Pre-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Priority	Disk Material	Pin Material	Test Environment	Disk Number	Pin Number
17	1	316L	316L	Hydrogen 2000 psig	316L-04	316L-34
18	1	316L	316L	Hydrogen 2000 psig	316L-02	316L-14
19	1	316L	316L	Hydrogen 2000 psig	316L-03	316L-15
20	1	AUM10	316L	Hydrogen 2000 psig	AUM10-60	316L-25
21	1	AUM10	316L	Hydrogen 2000 psig	AUM10-61	316L-26
22	1	AUM10	316L	Hydrogen 2000 psig	AUM10-62	316L-18
23	1	AUM10	A286	Hydrogen 2000 psig	AUM10-63	A286L-14
24	1	AUM10	A286	Hydrogen 2000 psig	AUM10-41	A286L-19
25	1	AUM10	A286	Hydrogen 2000 psig	AUM10-42	A286L-01
26	2	DLC AUM10	316L	Air	AUM10-13	316L-22
27	2	DLC AUM10	316L	Air	AUM10-22	316L-23
28	2	Nitride AUM10	316L	Air	AUM10-28	316L-20
29	2	Nitride AUM10	316L	Air	AUM10-27	316L-21
30	2	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-25	316L-29
31	2	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-26	316L-30
32	2	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-31	316L-27
33	2	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-32	316L-28

Table 4. Test Matrix for Pre-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 91 g or 0.2 lb)

Test No.	Priority	Disk Material	Pin Material	Test Environment	Disk Number	Pin Number
34	1	316L	316L	Hydrogen 2000 psig	316L-01	316L-16
35	1	316L	316L	Hydrogen 2000 psig	316L-05	316L-17
36	1	AUM10	316L	Hydrogen 2000 psig	AUM10-43	316L-32
37	1	AUM10	316L	Hydrogen 2000 psig	AUM10-44	316L-33
38	1	AUM10	A286	Hydrogen 2000 psig	AUM10-45	A286-02
39	1	AUM10	A286	Hydrogen 2000 psig	AUM10-46	A286-03
40	2	DLC AUM10	A286	Air	AUM10-11	A286-11
41	2	DLC AUM10	A286	Air	AUM10-17	A286-12
42	2	Nitride AUM10	A286	Air	AUM10-19	A286-13
43	2	Nitride AUM10	A286	Air	AUM10-40	A286-04
44	2	DLC AUM10	A286	Hydrogen 2000 psig	AUM10-18	A286-05
45	2	DLC AUM10	A286	Hydrogen 2000 psig	AUM10-21	A286-06
46	2	Nitride AUM10	A286	Hydrogen 2000 psig	AUM10-20	A286-07
47	2	Nitride AUM10	A286	Hydrogen 2000 psig	AUM10-24	A286-08
48	2	DLC AUM10	316L	Air	AUM10-29	316L-24
49	2	DLC AUM10	316L	Air	AUM10-30	316L-11
50	2	Nitride AUM10	316L	Air	AUM10-23	316L-12
51	2	Nitride AUM10	316L	Air	AUM10-37	316L-13
52	2	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-36	316L-31
53	2	DLC AUM10	316L	Hydrogen 2000 psig	AUM10-35	316L-52
54	2	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-38	316L-49
55	2	Nitride AUM10	316L	Hydrogen 2000 psig	AUM10-39	316L-50

8.0 POST-TEST WEAR CHARACTERIZATION

8.1 WEAR SURFACE CHARACTERIZATION

Following the initial visual examination of the disk and pin samples after testing, photographs were used to document the wear tracks and post-test surfaces. They are displayed along with the traces from contact profilometer in Appendix F. Selected sample photographs and profilometer traces are shown in Figure 13-Figure 26. From these micrographs a few general conclusions can be drawn:

1. Tests conducted with non-coated disk and non-coated pin combinations displayed the most significant wear tracks visually
2. Coated disk-pin samples—either coated disk-coated pin or coated disk-non-coated pin—displayed minimal to no wear tracks visually

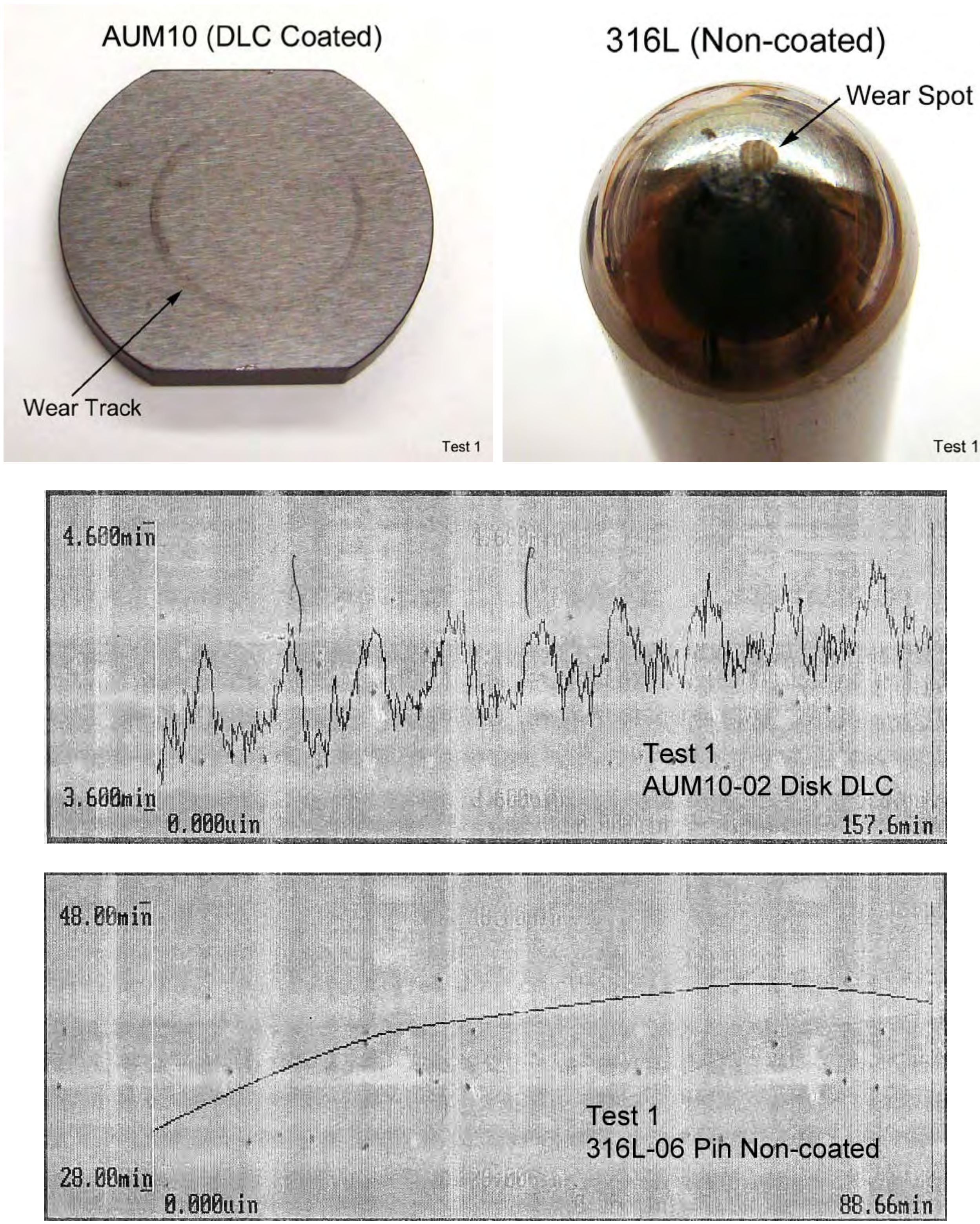

Figure 13. Post-Test Wear Surface Photographs and Profilometer Data for Test #1

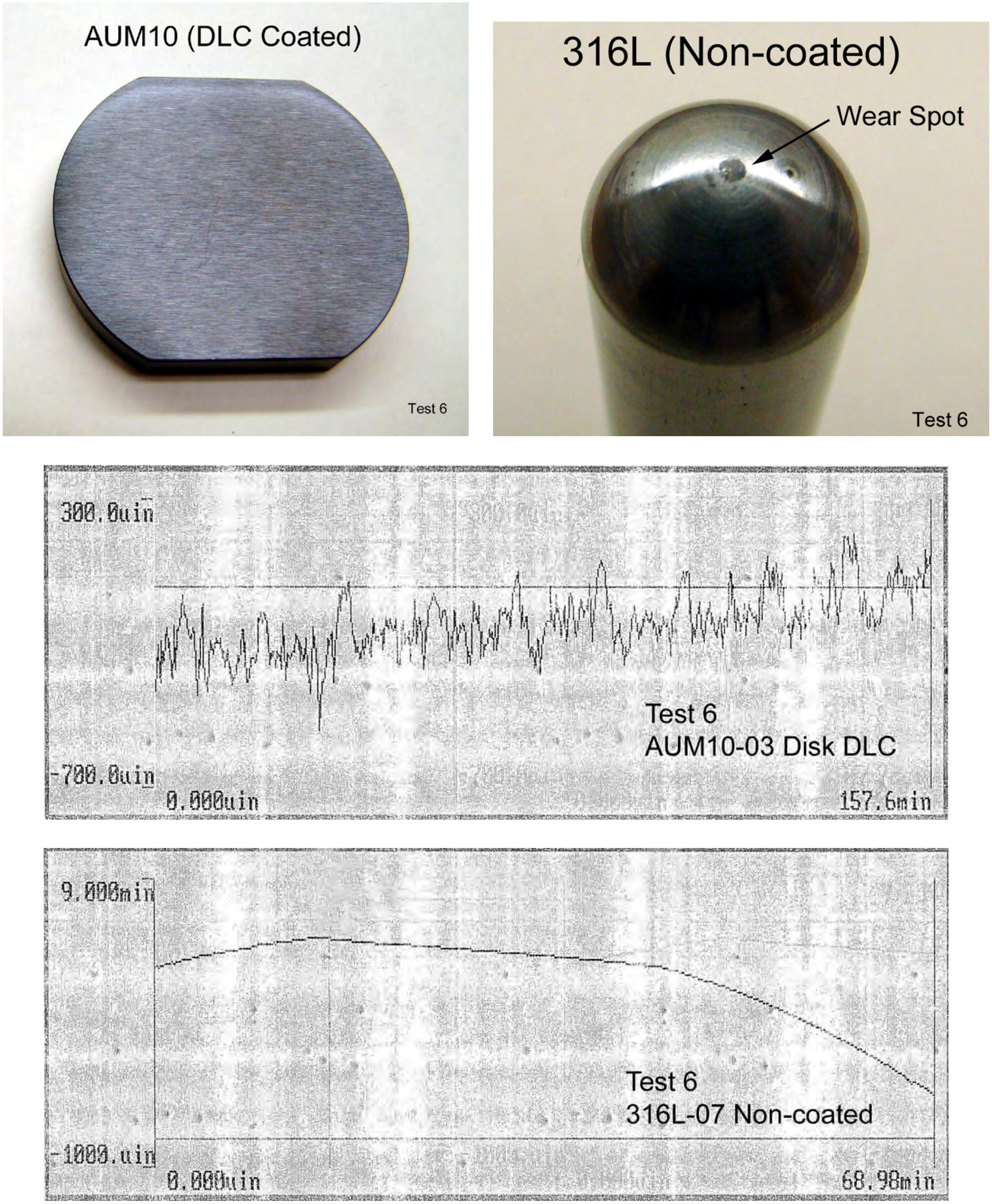

Figure 14. Post-Test Wear Surface Photographs and Profilometer Data for Test #6

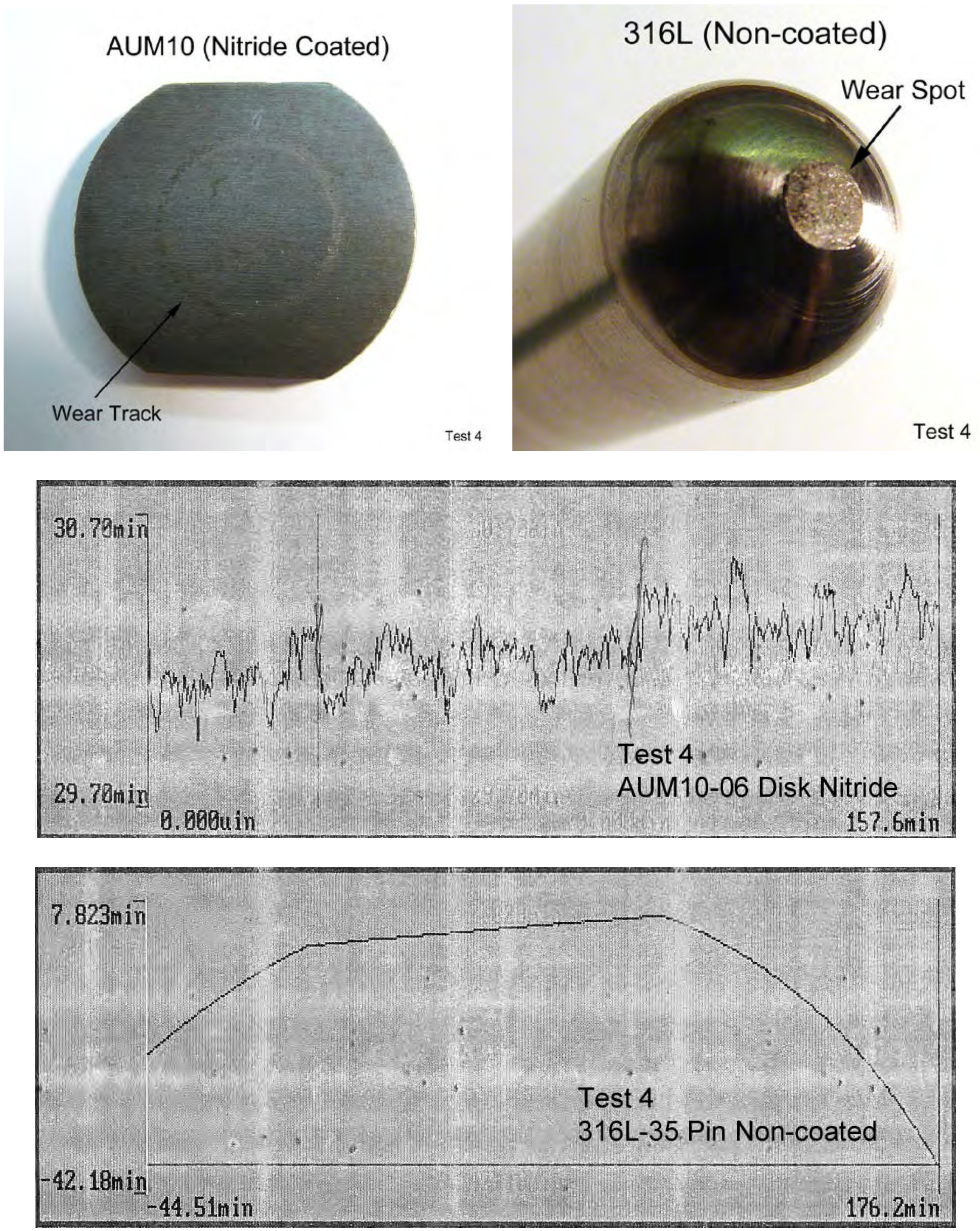

Figure 15. Post-Test Wear Surface Photographs and Profilometer Data for Test #4

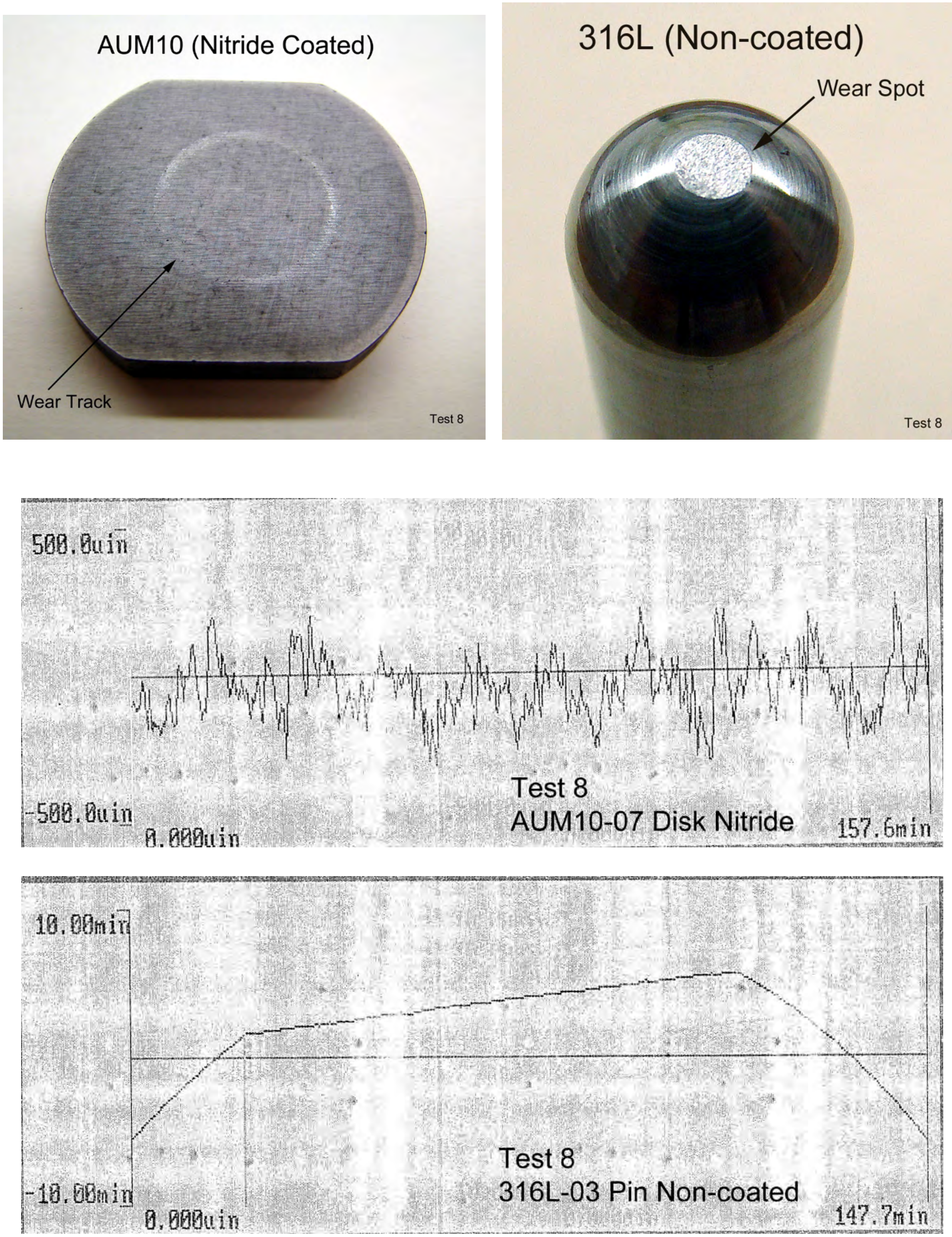

Figure 16. Post-Test Wear Surface Photographs and Profilometer Data for Test #8

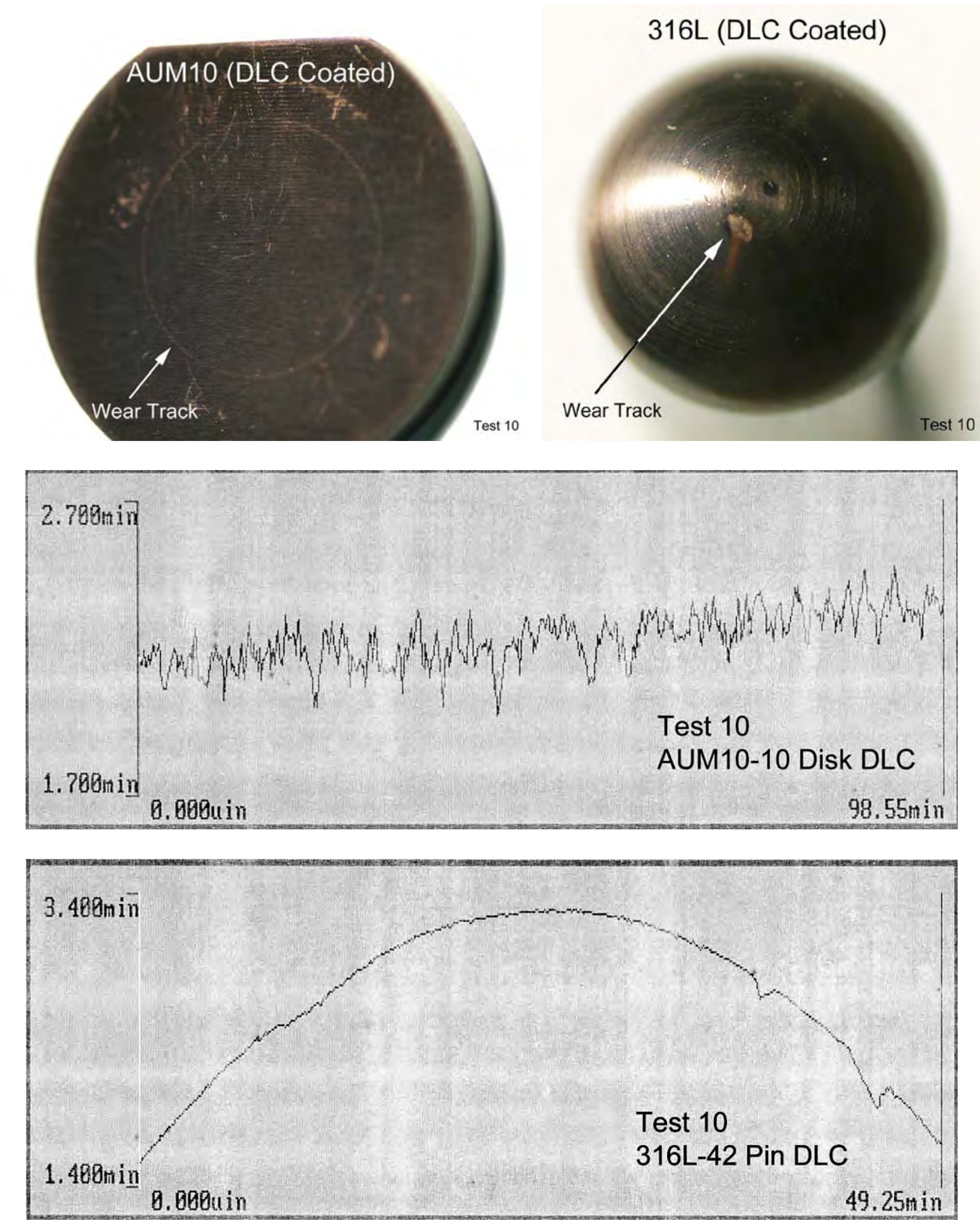

Figure 17. Post-Test Wear Surface Photographs and Profilometer Data for Test #10

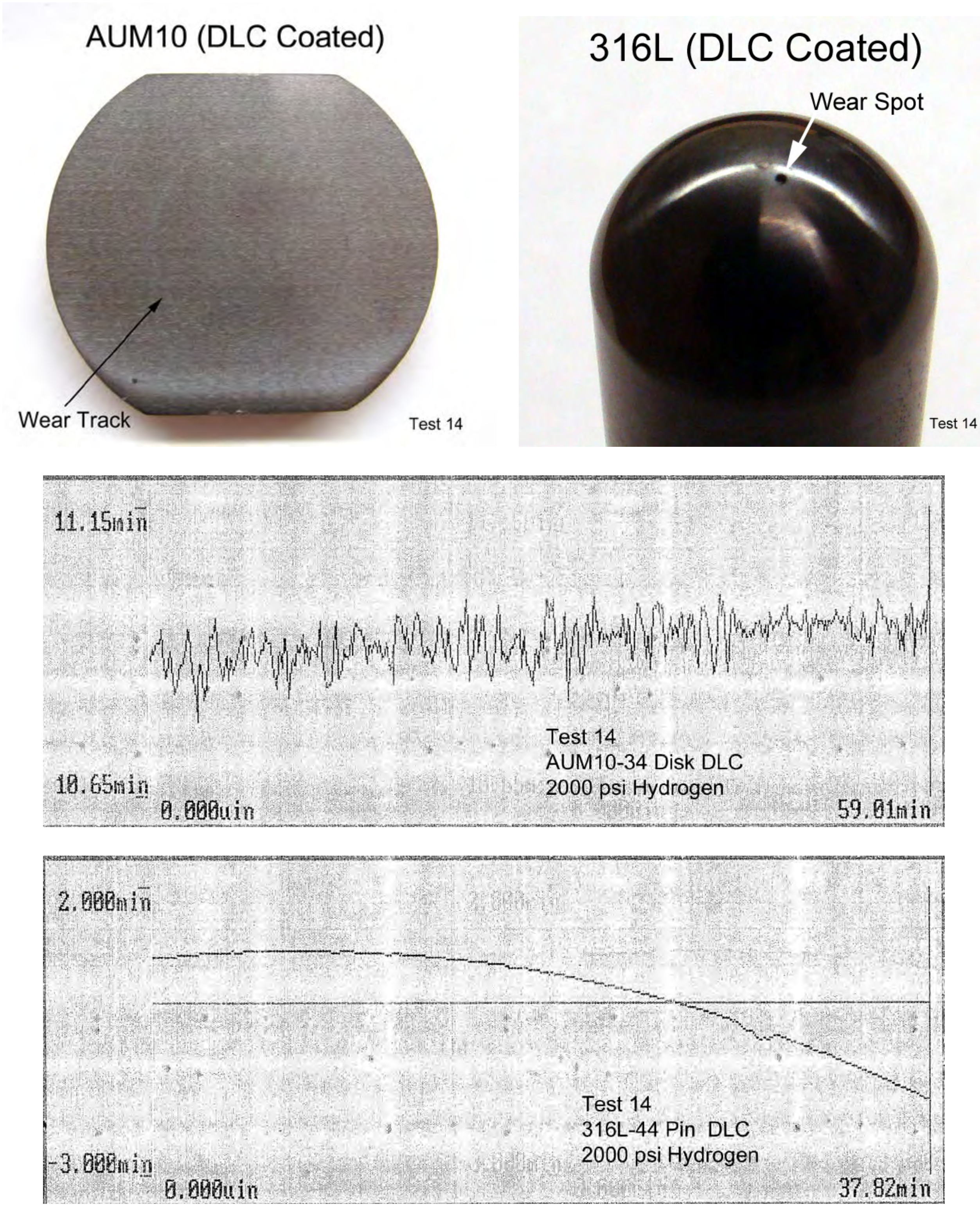

Figure 18. Post-Test Wear Surface Photographs and Profilometer Data for Test #14

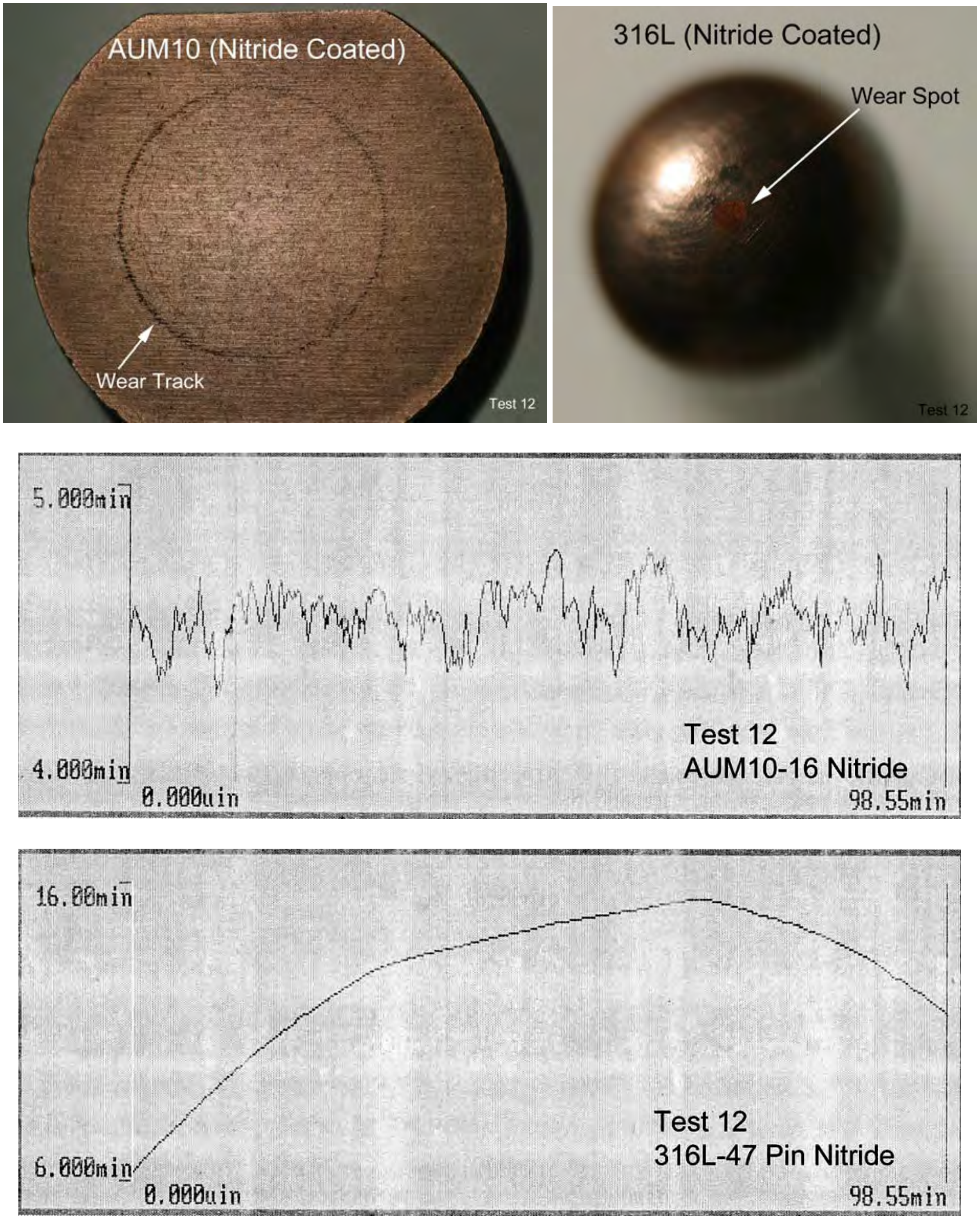

Figure 19. Post-Test Wear Surface Photographs and Profilometer Data for Test #12

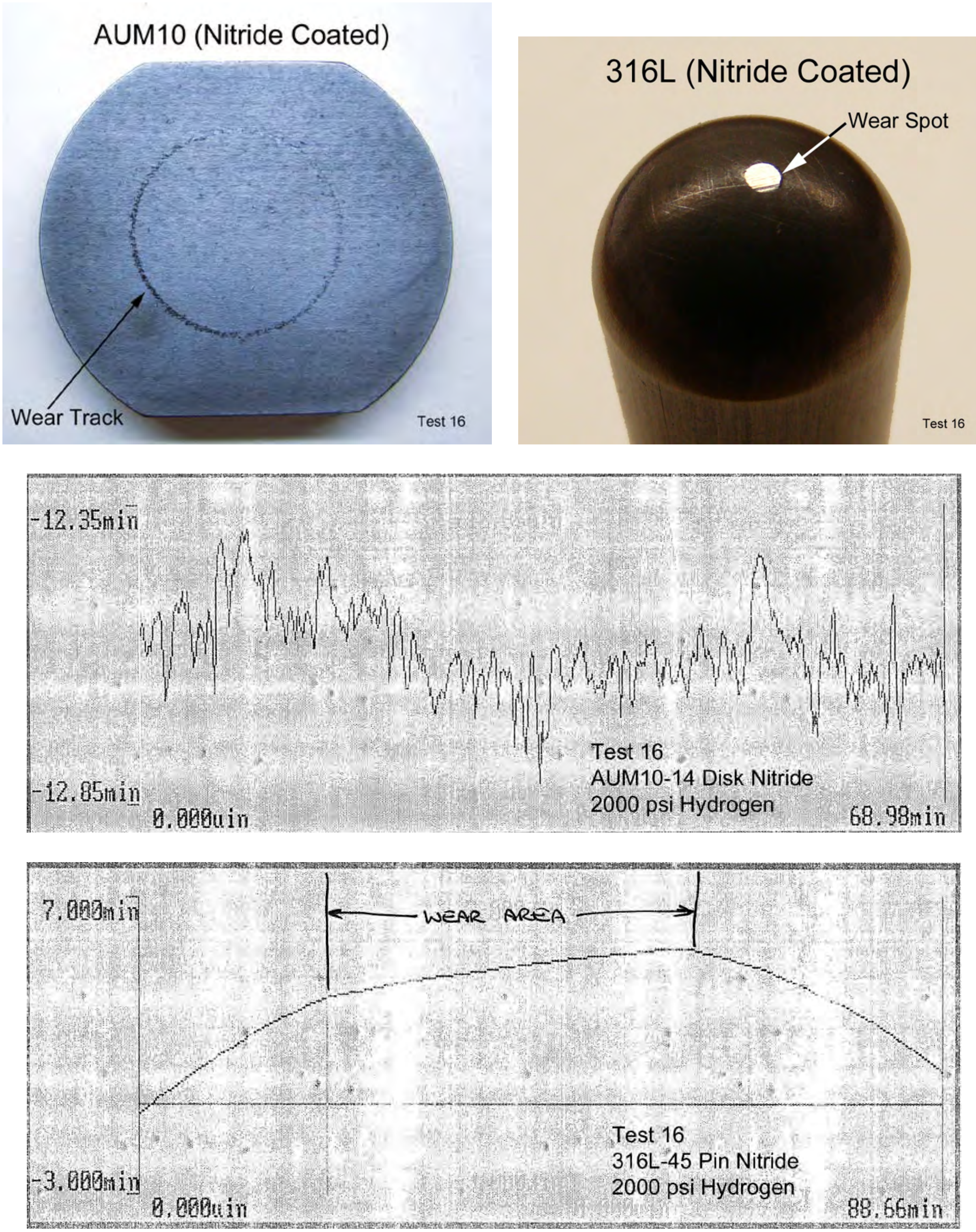

Figure 20. Post-Test Wear Surface Photographs and Profilometer Data for Test #16

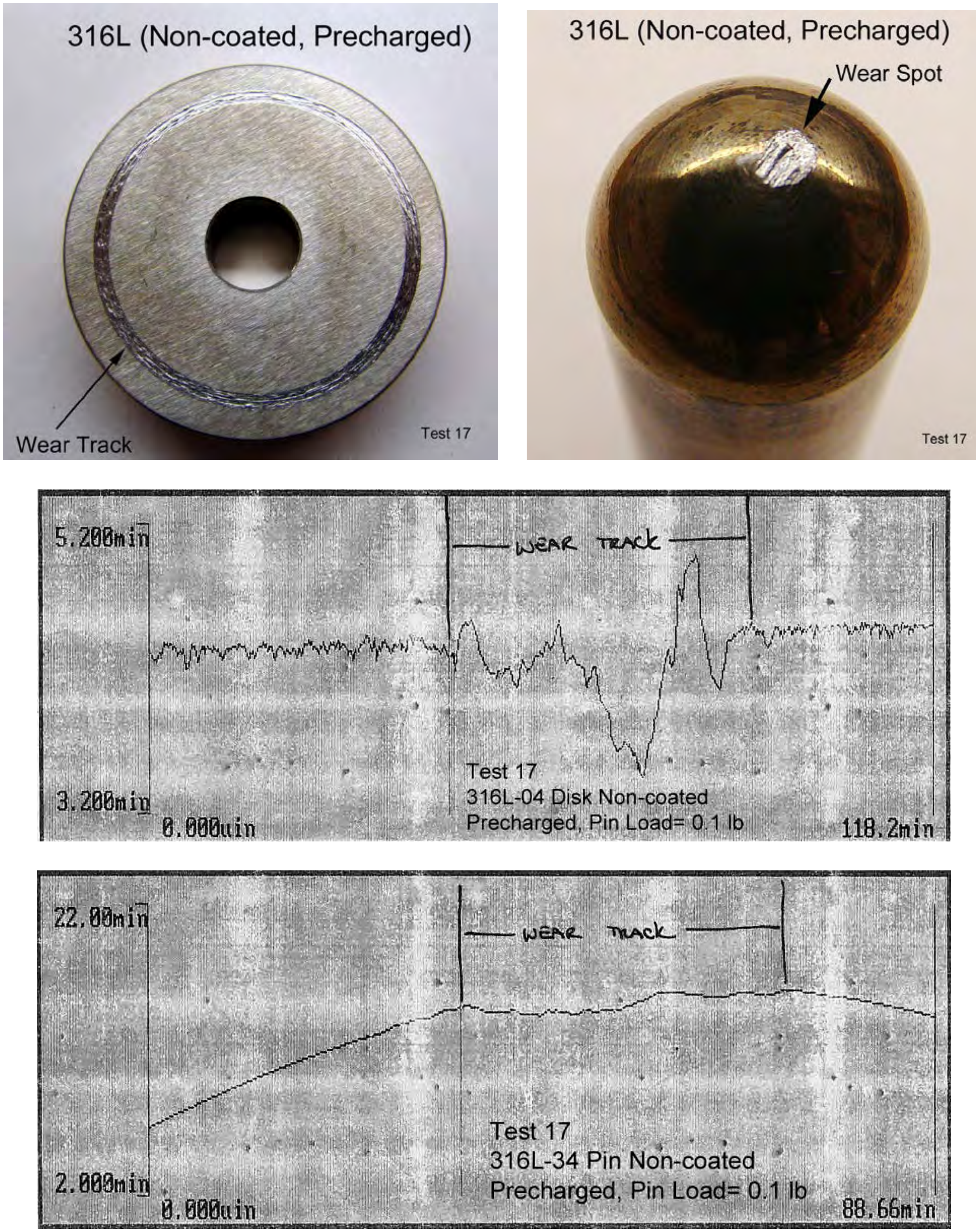

Figure 21. Post-Test Wear Surface Photographs and Profilometer Data for Test #17

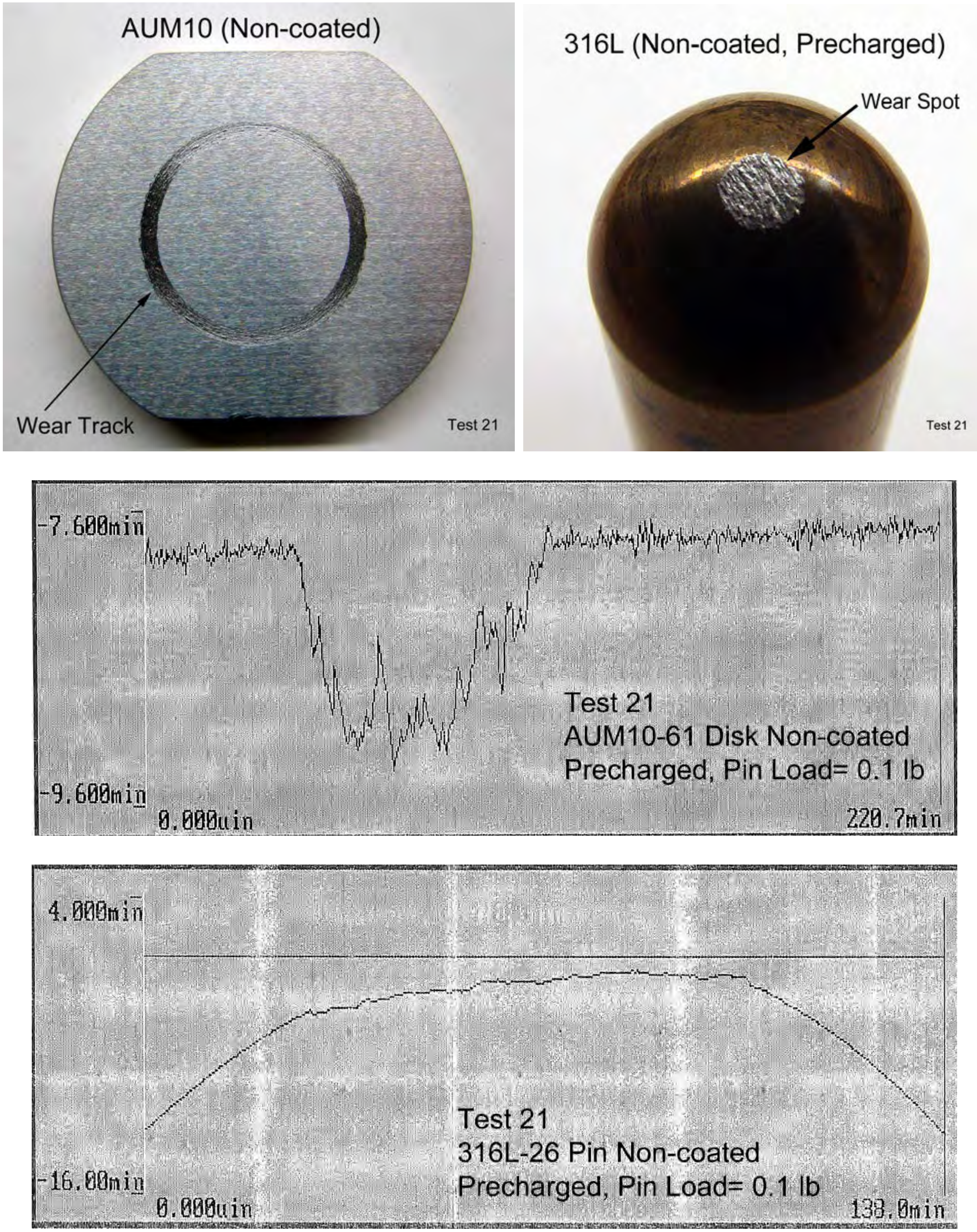

Figure 22. Post-Test Wear Surface Photographs and Profilometer Data for Test #21

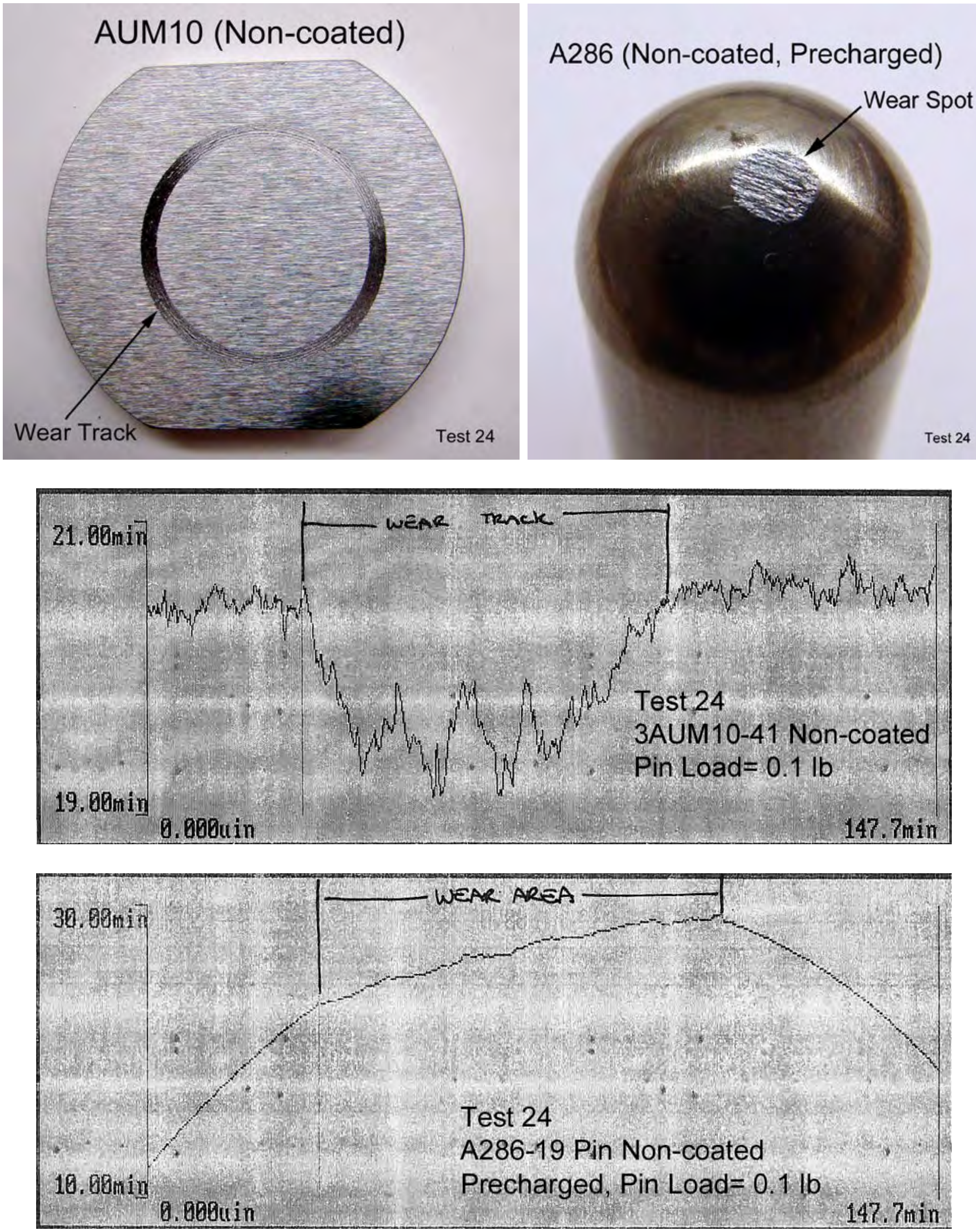

Figure 23. Post-Test Wear Surface Photographs and Profilometer Data for Test #24

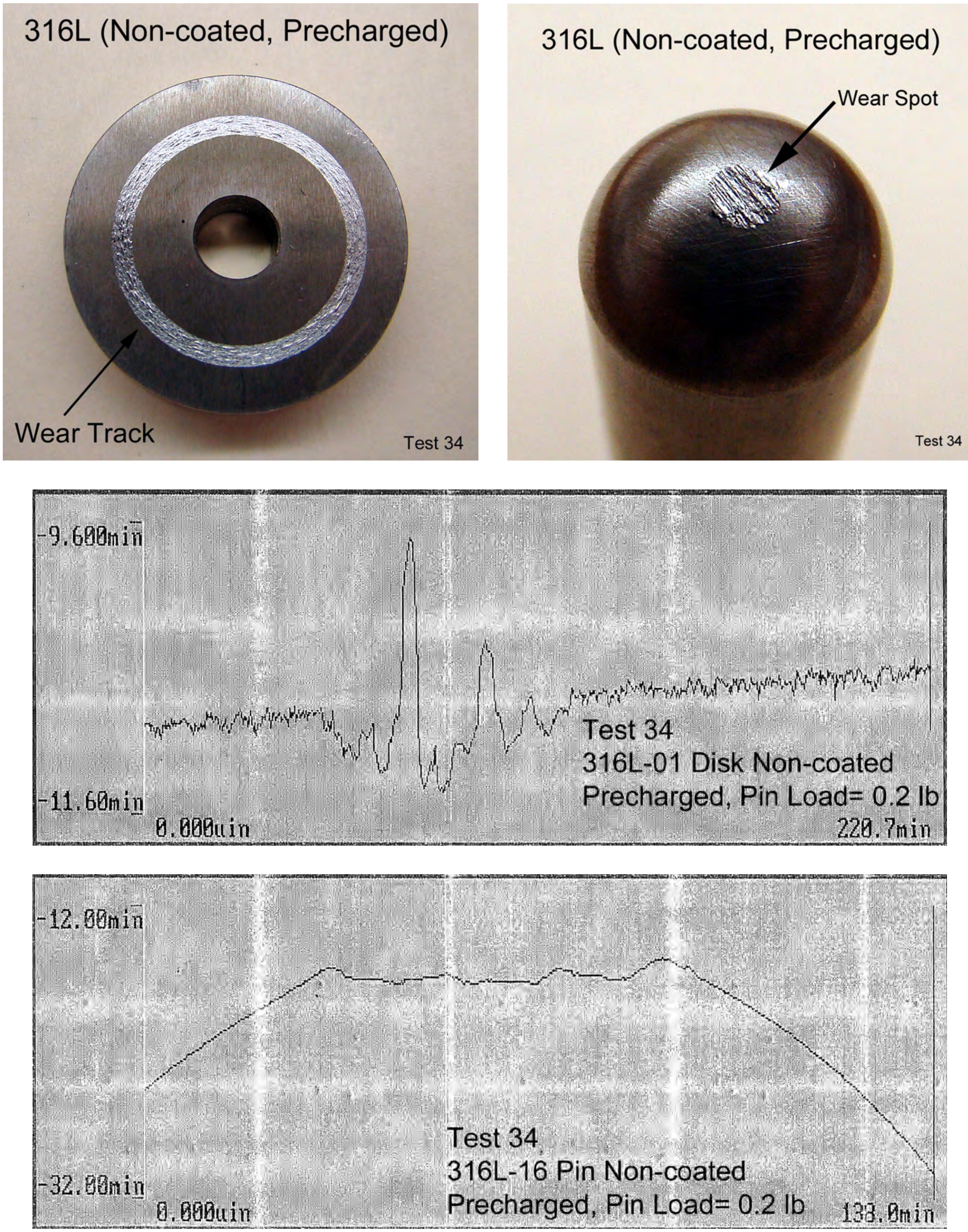

Figure 24. Post-Test Wear Surface Photographs and Profilometer Data for Test #34

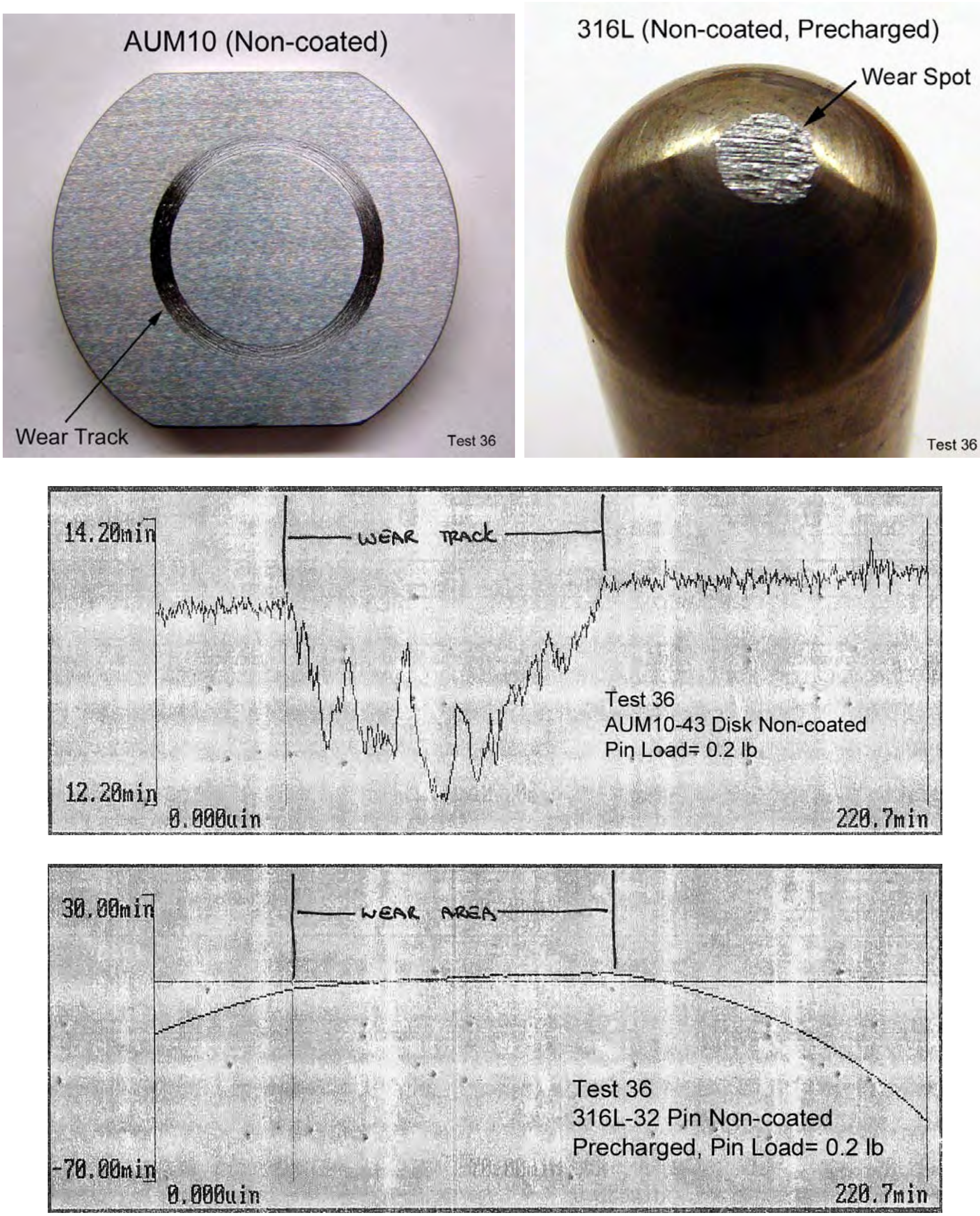

Figure 25. Post-Test Wear Surface Photographs and Profilometer Data for Test #36

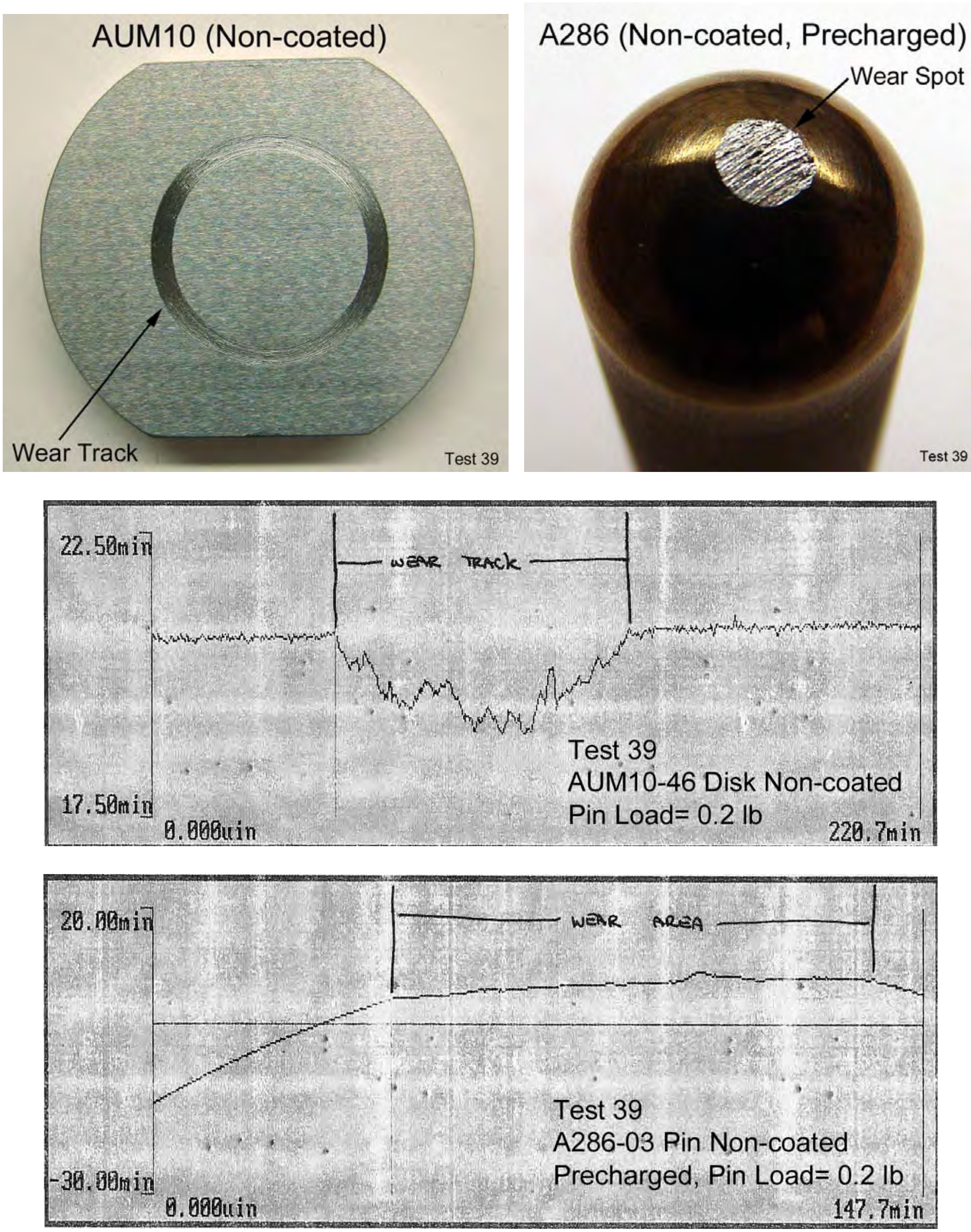

Figure 26. Post-Test Wear Surface Photographs and Profilometer Data for Test #39

8.2 SCANNING ELECTRON MICROSCOPY

Selected post-test samples were chosen for detailed characterization with scanning electron microscope (SEM). The wear tracks on nitride coated disks are similar for air and hydrogen tests when non-charged 316L pins were used (Figure 27-Figure 28). The wear spots on these pins appear to be smoother and unidirectional in the air test when Figure 29 - Figure 32 are compared. When the coated disks were tested with pre-charged 316L pins, Figure 33 shows a possible tearing in the DLC coating while the rough nitrided disk surface appears to be flattened (reduced roughness) by the pin (Figure 34). The wear patterns on the 316L pins are similar in Figure 35 and Figure 36; only the wear spot is much larger when it was tested with the nitride coated disk. Figure 37-Figure 40 show the wear details of DLC and nitride coated disks tested with pre-charged A286 pins in hydrogen. The wear track on the DLC coated disk is smoother but shows possible tearing. The nitrided disk shows that wear took place mainly on the ridges of the surface finish. The wear spot on the A286 pin in Figure 40 is not smooth but shows fracturing/chipping. It is possibly caused by the higher hardness of A286 (compared to 316L) and the inherent nature of the surface of the nitrided disk. Figure 41 and Figure 42 are the wear tracks on the DLC and nitrided coated disks and the pre-charged 316L pins with increasing load (0.2 lb). The test environment was 2000 psig hydrogen. Similar features can be seen earlier in Figure 33-Figure 34. The corresponding wear spots on pre-charged 316L pins are shown in Figure 43 and Figure 44, which can be compared with Figure 35and Figure 36 when the pin load was 0.1 lb.

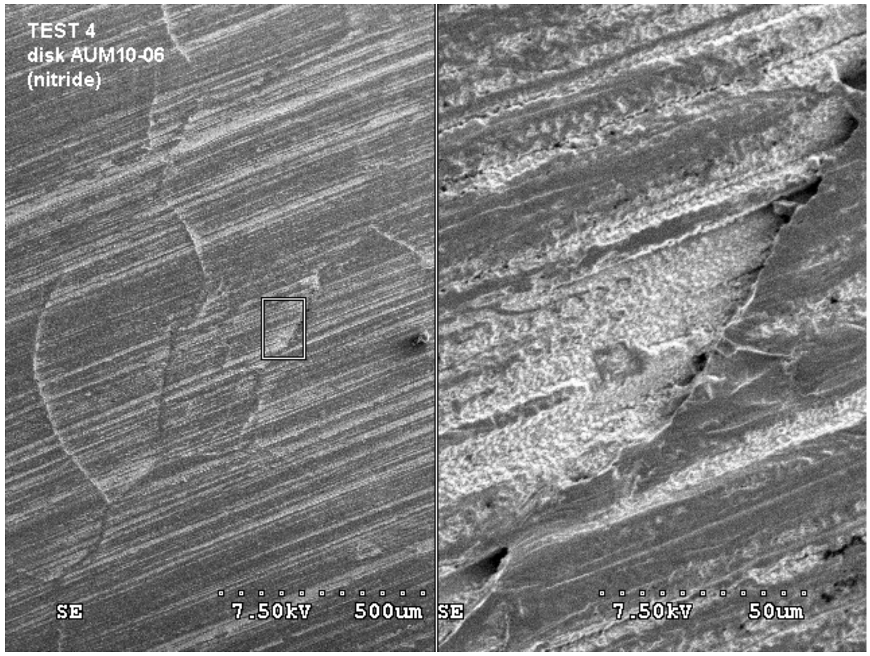

Figure 27. Wear track on nitride coated disk tested in air using non-charged 316L pin loaded with 0.1 lb.

Figure 28. Wear track on nitride coated disk tested in hydrogen using non-charged 316L pin loaded with 0.1 lb.

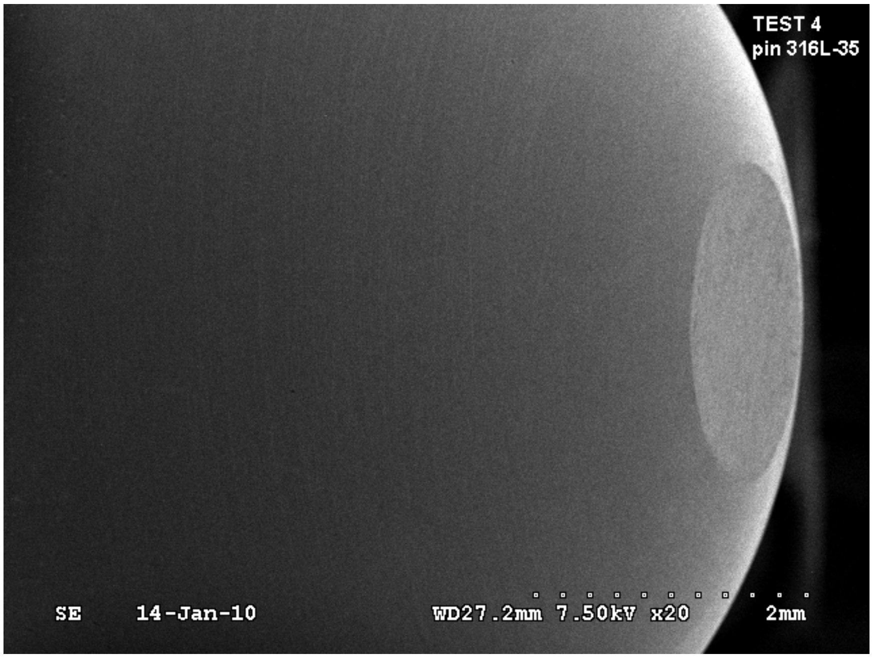

Figure 29. Wear spot on non-charged 316L pin loaded with 0.1 lb and tested in air with nitride coated disk.

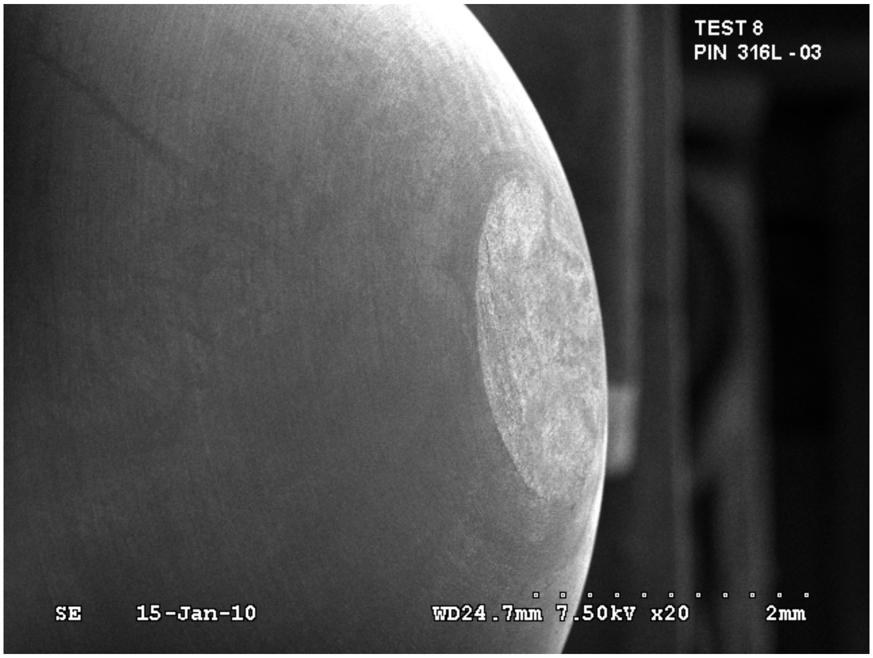

Figure 30. Wear spot on non-charged 316L pin loaded with 0.1 lb and tested in hydrogen with nitride coated disk.

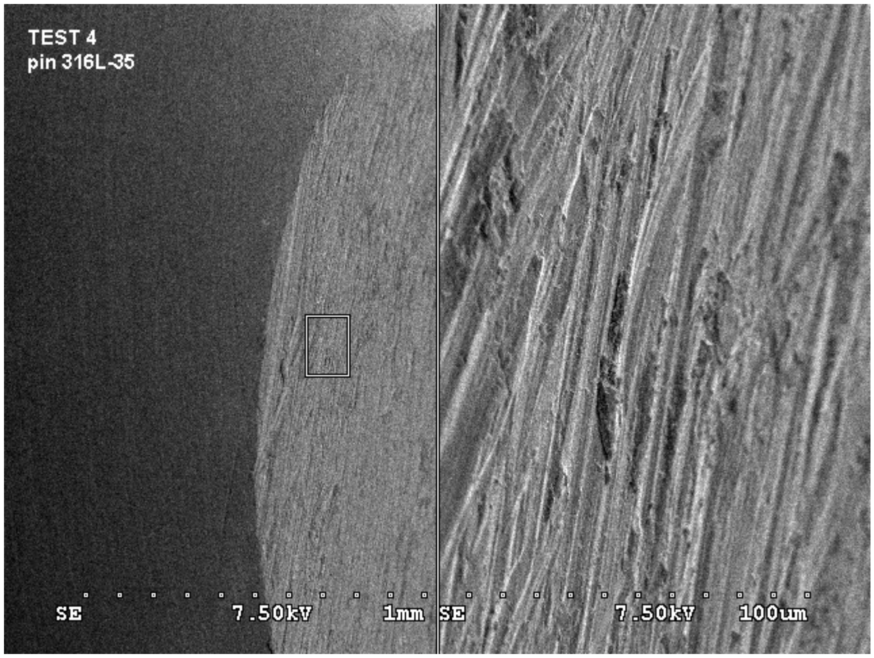

Figure 31. Wear spot details on non-charged 316L pin loaded with 0.1 lb and tested in air with nitride coated disk.

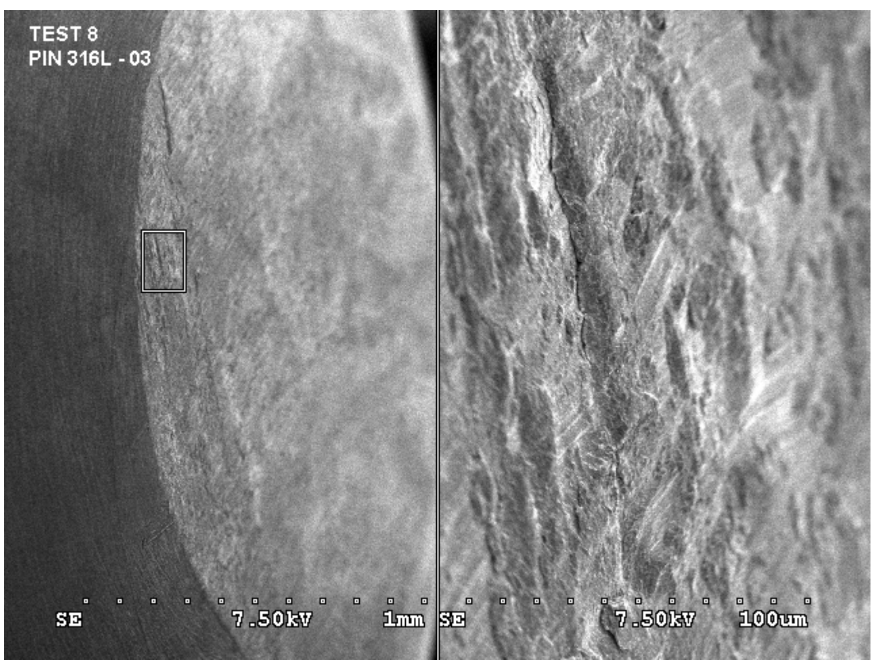

Figure 32. Wear spot details on non-charged 316L pin loaded with 0.1 lb and tested in hydrogen with nitride coated disk.

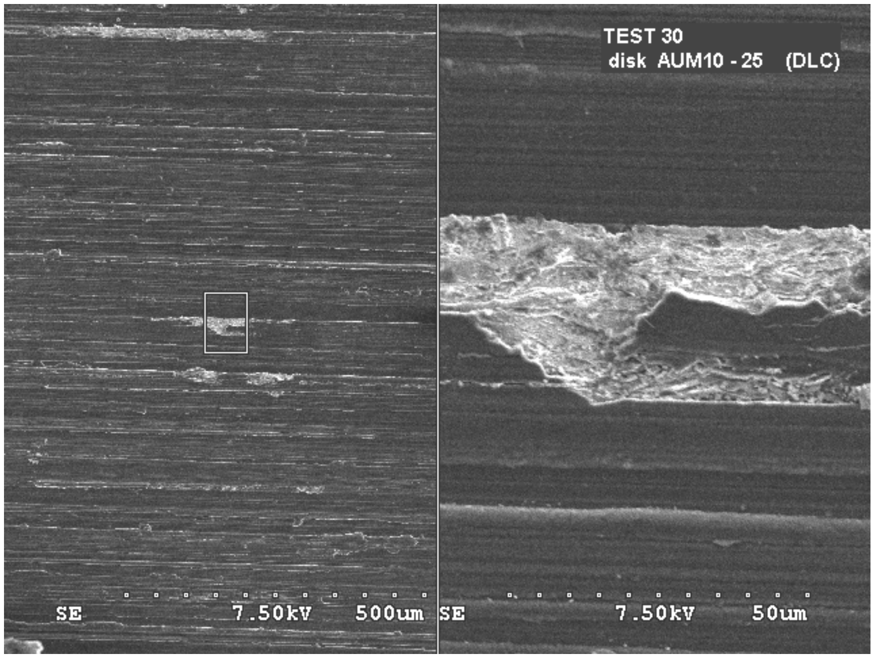

Figure 33. Wear track on DLC coated disk tested in hydrogen using pre-charged 316L pin loaded with 0.1 lb.

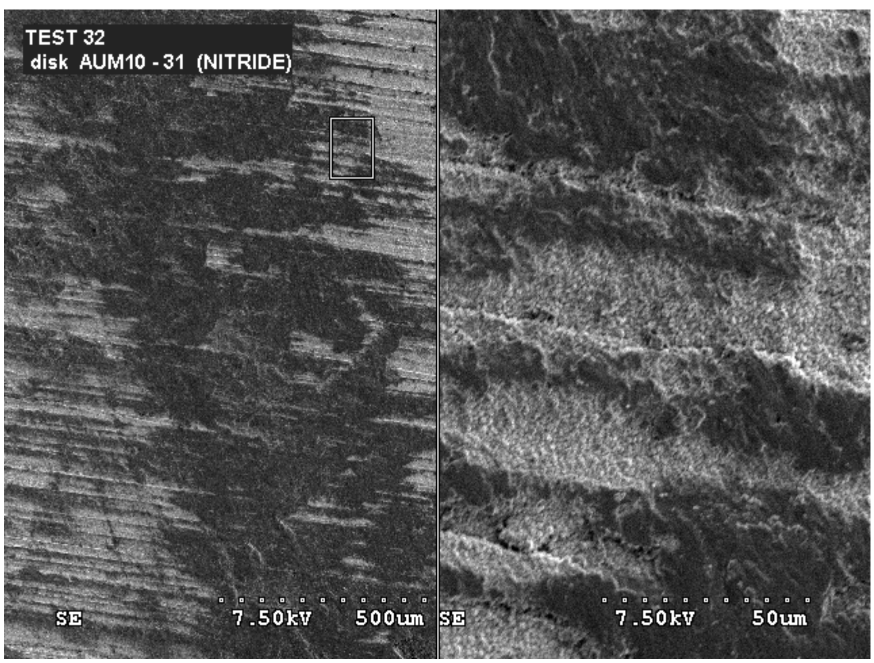

Figure 34. Wear track on nitride coated disk tested in hydrogen using pre-charged 316L pin loaded with 0.1 lb.

Figure 35. Wear spot on pre-charged 316L pin loaded with 0.1 lb and tested in hydrogen with DLC coated disk.

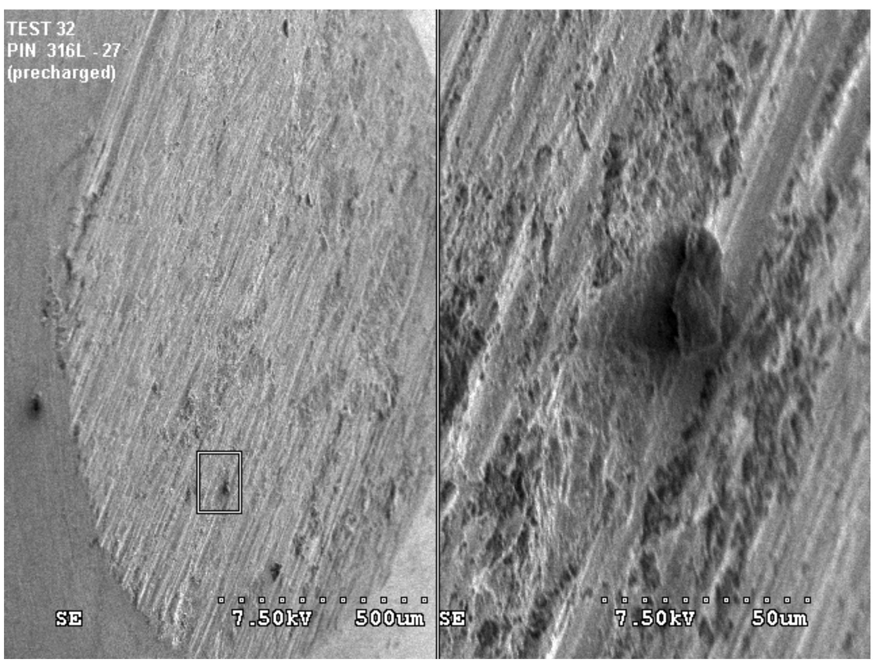

Figure 36. Wear spot on pre-charged 316L pin loaded with 0.1 lb and tested in hydrogen with nitride coated disk.

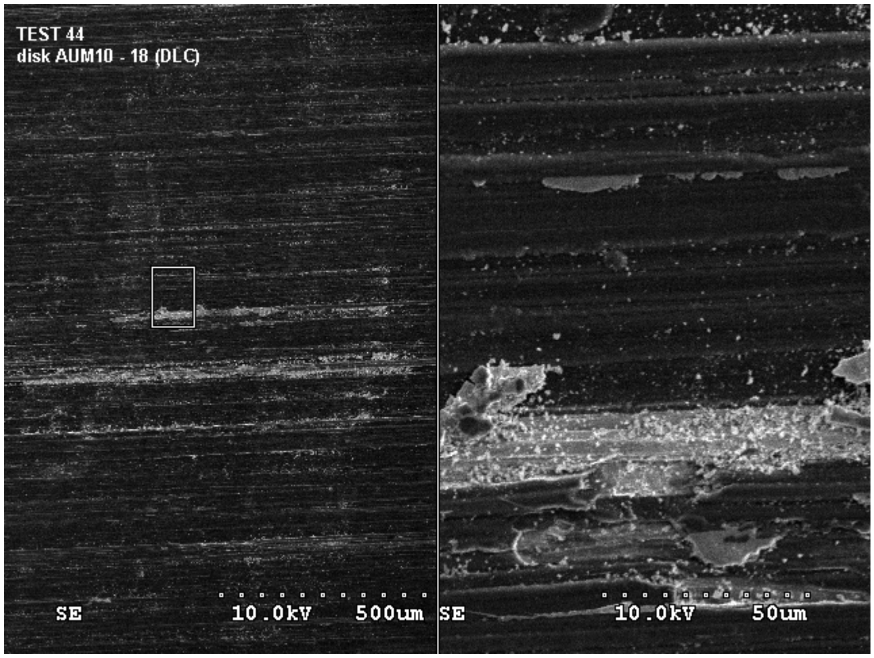

Figure 37. Wear track on DLC coated disk tested in hydrogen using pre-charged A286 pin loaded with 0.2 lb.

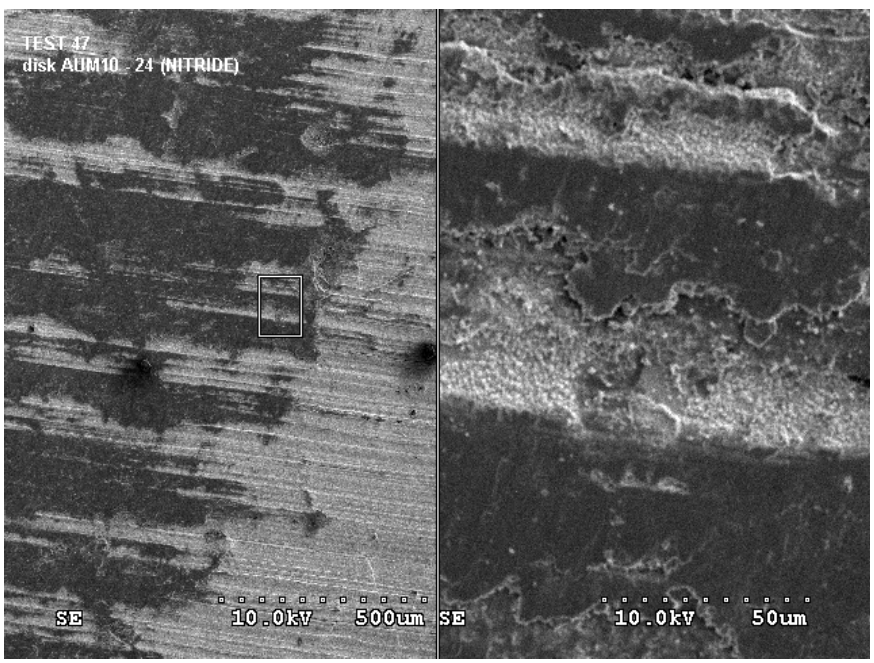

Figure 38. Wear track on Nitride coated disk tested in hydrogen using pre-charged A286 pin loaded with 0.2 lb.

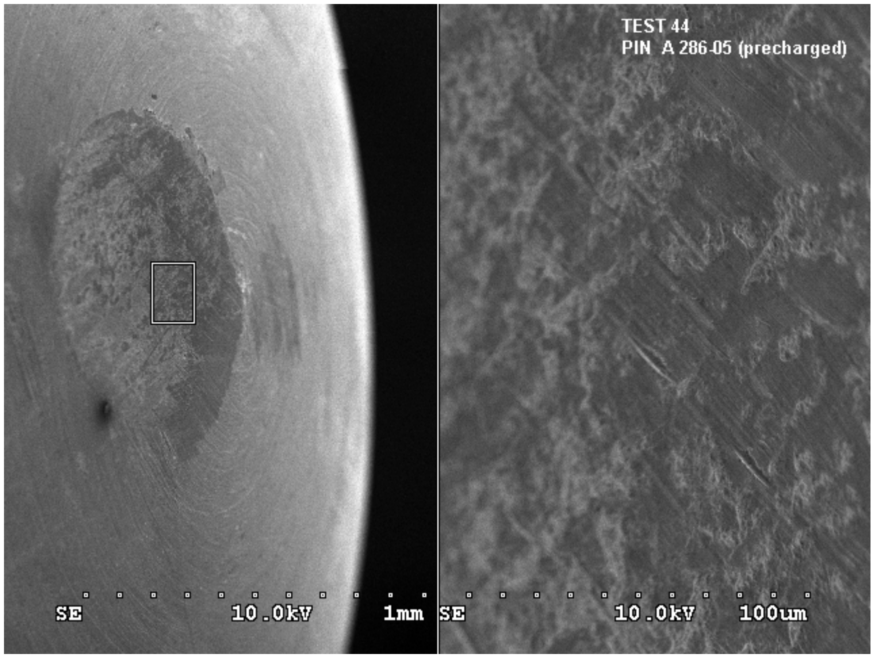

Figure 39. Wear spot on pre-charged A286 pin loaded with 0.2 lb and tested in hydrogen with DLC coated disk.

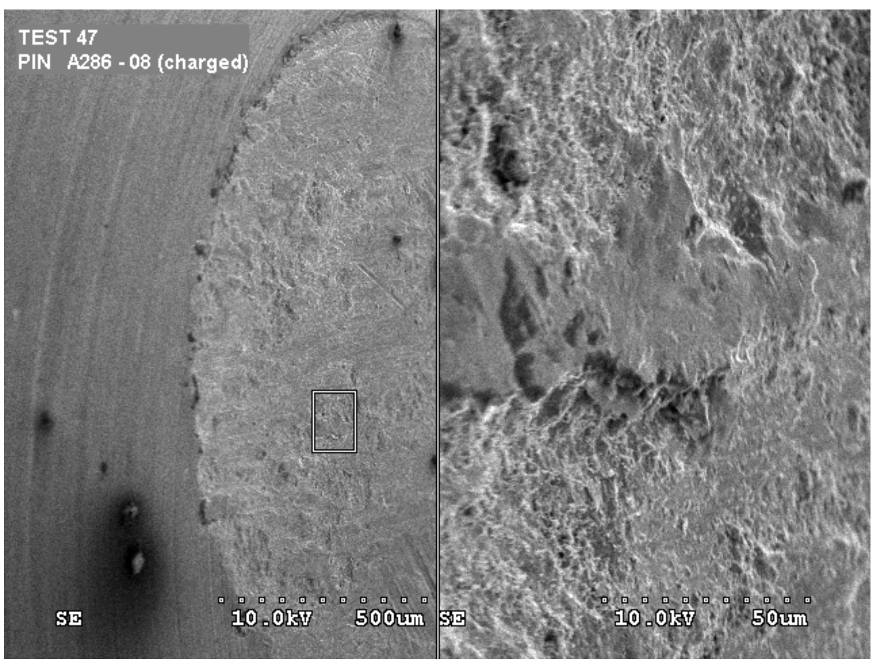

Figure 40. Wear spot on pre-charged A286 pin loaded with 0.2 lb and tested in hydrogen with nitride coated disk.

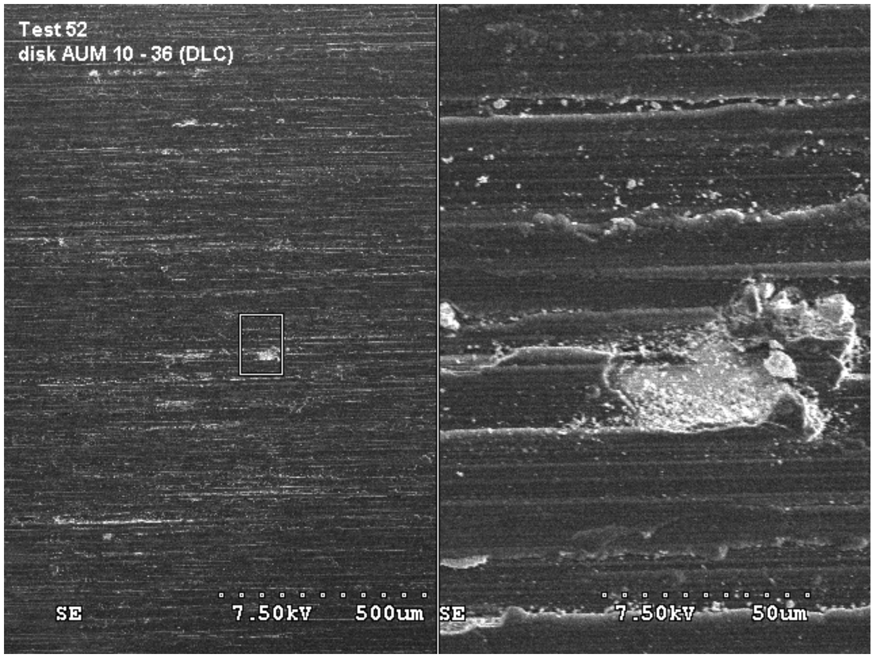

Figure 41. Wear track on DLC coated disk tested in hydrogen using pre-charged 316L pin loaded with 0.2 lb.

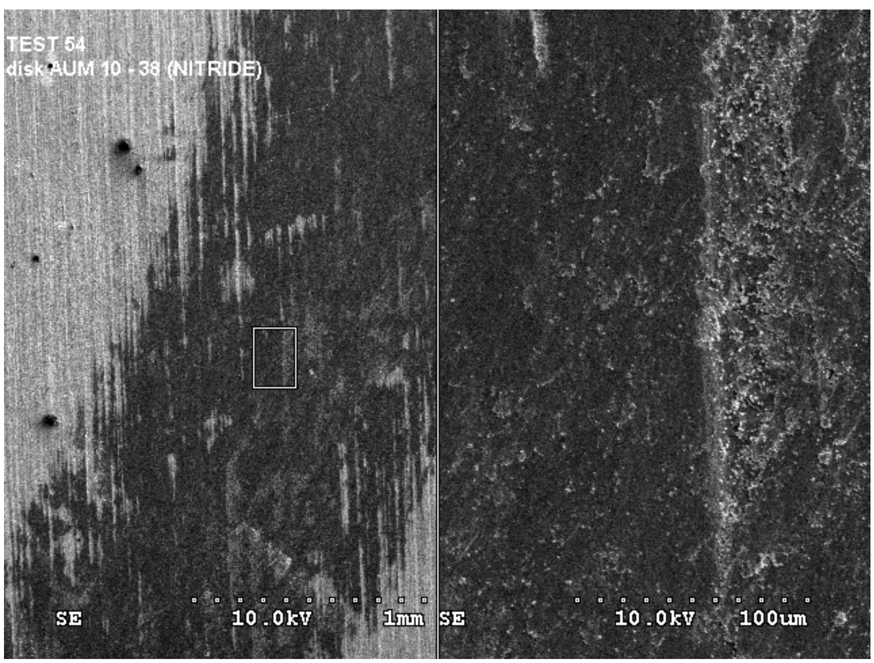

Figure 42. Wear track on nitride coated disk tested in hydrogen using pre-charged 316L pin loaded with 0.2 lb.

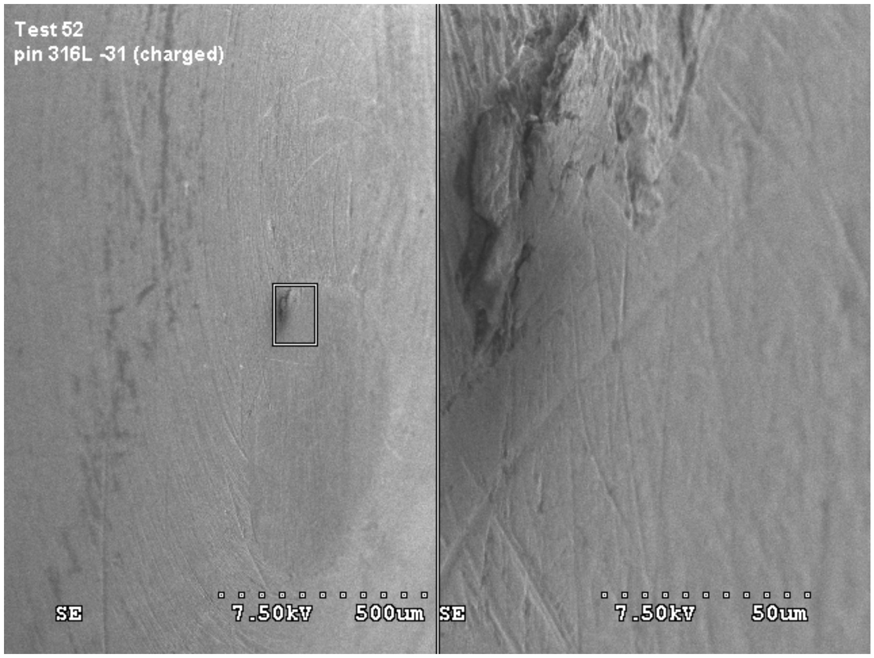

Figure 43. Wear spot on pre-charged 316L pin loaded with 0.2 lb and tested in hydrogen with DLC coated disk.

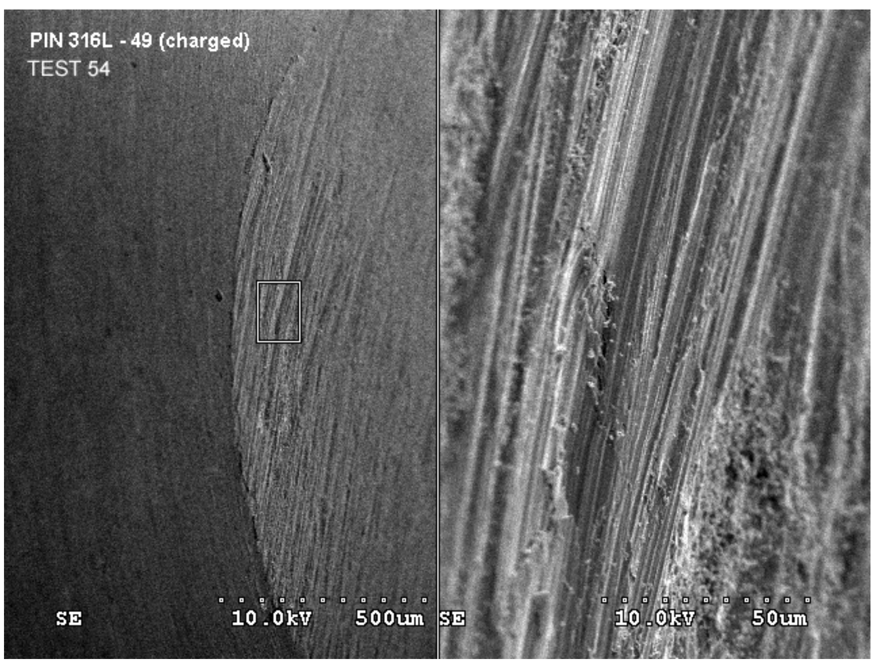

Figure 44. Wear spot on pre-charged 316L pin loaded with 0.2 lb and tested in hydrogen with nitride coated disk.

9.0 RESULTS

9.1 WEIGHT CHANGE

As discussed in a previous section, the weight change of the samples was obtained by weighing the sample with a four-place balance before and after the test. The weight changes and wear area measurements are shown in Table 5-Table 10 for the disks and for the pins. The results are shown graphically in Figure 45. From the weigh change results displayed in Figure 45 the following general conclusions can be made:

1. Wear for disk-pin combinations in which both are coated either with nitride or DLC tested in air and 2000 psig hydrogen shows minimal wear.
2. Wear for disk-pin combinations involving coated disk-non-coated pin combinations displays increased wear for the nitride coated disk cases and not the DLC, but also shows no sensitivity to environment—air vs. hydrogen.
3. For uncoated disk-pin test combination pre-charged with hydrogen and then tested in 2000 psig hydrogen, a small increase in wear is documented in comparison to similar previously tested samples in Phase I of this study
4. Samples with coated disk (nitride and DLC) tested with non-coated pre-charged pins tested at both 0.1lbs and 0.2 lbs show no significant difference between air and hydrogen environments and sample loading for tested disk-pin combinations.

Table 5. Test Results for Non-charged Samples (Disks)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Track Finish (μ–inch)	Inside Track Finish (μ–inch)	Averaged Track Diameter (inch)	Track width (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)
1	DLC AUM10	316L	Air	82.4	82.4	1.0175	0.0355	-0.00040	-0.11428
2	DLC AUM10	316L	Air	57.5	57.5	1.0965	0.0355	0	0
3	Nitride AUM10	316L	Air	33.5	29.5	0.974	0.078	0.00072	0.10285
4	Nitride AUM10	316L	Air	58.9	55.3	0.941	0.074	0.00222	0.31714
5	DLC AUM10	316L	Hydrogen 2000 psig	not measured	not measured	not measured	not measured	0.00030	0.08571
6	DLC AUM10	316L	Hydrogen 2000 psig	58.9	not measured.	not measured	not measured	0.00018	0.05142
7	Nitride AUM10	316L	Hydrogen 2000 psig	64	73.4	0.862	0.058	-0.00010	-0.01428
8	Nitride AUM10	316L	Hydrogen 2000 psig	86	67.4	0.8425	0.0335	-0.00006	-0.00857
9	DLC AUM10	DLC 316L	Air	55.5	not measured.	1.0845	0.0135	-0.00130	-0.37142
10	DLC AUM10	DLC 316L	Air	43.8	not measured	1.008	0.01	0.00070	0.2
11	Nitride AUM10	Nitride 316L	Air	49.5	not measured	1.022	0.023	0.00076	0.10858
12	Nitride AUM10	Nitride 316L	Air	47.8	not measured	1.0275	0.0215	0.00046	0.06571
13	DLC AUM10	DLC 316L	Hydrogen 2000 psig	32	25	1.1425	0.0175	0.00026	0.07428
14	DLC AUM10	DLC 316L	Hydrogen 2000 psig	23	23	1.08	0.015	-0.00038	-0.10857
15	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	39	23	1.0535	0.0245	0.00068	0.09714
16	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	32	32	0.9255	0.0275	0.00102	0.14571

Note: The negative value under Weight Loss or Volume Loss indicates that the sample gained weight or volume after testing. This may be caused by material transfer or measurement imprecision.

Table 6. Test Results for Non-charged Samples (Pins)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Wear Finish (μ–inch)	Inside Wear Finish (μ–inch)	Averaged Wear Spot Dia. (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)	Calculated Volume Loss (mm^3)
1	DLC AUM10	316L	Air	8.75	3.96	0.04	0.00004	0.005013	0.01102
2	DLC AUM10	316L	Air	5.4	8.6	0.035	-0.00090	-0.11278	0.00646
3	Nitride AUM10	316L	Air	3.4	17.6	0.104	0.00390	0.48872	0.51534
4	Nitride AUM10	316L	Air	4.44	21.38	0.0985	0.00266	0.33333	0.41351
5	DLC AUM10	316L	Hydrogen 2000 psig	5.89	5.12	0.03	0.00000	0	0.00348
6	DLC AUM10	316L	Hydrogen 2000 psig	9.8	4.3	0.0325	-0.00004	-0.00501	0.00480
7	Nitride AUM10	316L	Hydrogen 2000 psig	2.3	28.2	0.084	0.00166	0.20802	0.21727
8	Nitride AUM10	316L	Hydrogen 2000 psig	2.5	17.9	0.0925	0.00278	0.34837	0.32068
9	DLC AUM10	DLC 316L	Air	9.38	not measured	0.0155	-0.00160	-0.45714	0.00025
10	DLC AUM10	DLC 316L	Air	10.6	3.7	0.0165	0.00020	0.057143	0.00032
11	Nitride AUM10	Nitride 316L	Air	11.7	2.9	0.041	0.00006	0.00857	0.01217
12	Nitride AUM10	Nitride 316L	Air	12	6	0.0361	0.00002	0.00286	0.00730
13	DLC AUM10	DLC 316L	Hydrogen 2000 psig	5.7	not measured	0.015	-0.00002	-0.00571	0.00022
14	DLC AUM10	DLC 316L	Hydrogen 2000 psig	6	6	0.013	0.00008	0.02286	0.00012
15	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	8	7	0.037	0.00098	0.14	0.00807
16	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	11.5	3.8	0.0415	-0.00020	-0.02857	0.01278

Table 7. Test Results for Pre-charged Samples (Disks)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Track Finish (μ–inch)	Inside Track Finish (μ–inch)	Averaged Track Diameter (inch)	Track width (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)
17	316L	316L	Hydrogen 2000 psig	20	59	0.962	0.054	0.00314	0.39348
18	316L	316L	Hydrogen 2000 psig	19.7	180	0.8435	0.0635	0.00296	0.37092
19	316L	316L	Hydrogen 2000 psig	22	90	1.0205	0.0675	0.00334	0.41854
20	AUM10	316L	Hydrogen 2000 psig	26.2	39.8	0.8385	0.0175	0.00182	0.22807
21	AUM10	316L	Hydrogen 2000 psig	31	131.1	0.9105	0.0695	0.02058	2.57895
22	AUM10	316L	Hydrogen 2000 psig	21	132	1.032	0.103	0.03600	4.51128
23	AUM10	A286	Hydrogen 2000 psig	21	49	1.0195	0.0295	0.00010	0.01253
24	AUM10	A286	Hydrogen 2000 psig	44	76	1.0165	0.0745	0.01830	2.29323
25	AUM10	A286	Hydrogen 2000 psig	29.4	138.3	0.9955	0.0745	0.00028	0.03508
26	DLC AUM10	316L	Air	not measured	not measured	not measured	not measured	-0.00004	-0.01143
27	DLC AUM10	316L	Air	not measured	not measured	not measured	not measured	0.00014	0.04
28	Nitride AUM10	316L	Air	32.2	21.7	0.9985	0.0505	0.00092	0.13143
29	Nitride AUM10	316L	Air	76.3	60.9	1.023	0.06	0.00016	0.02286
30	DLC AUM10	316L	Hydrogen 2000 psig	43	43	1.003	0.028	-0.00004	-0.01143
31	DLC AUM10	316L	Hydrogen 2000 psig	65	65	0.9745	0.1565	-0.00004	-0.01143
32	Nitride AUM10	316L	Hydrogen 2000 psig	31	23	0.9775	0.0595	0.00082	0.11714
33	Nitride AUM10	316L	Hydrogen 2000 psig	37	15	0.9435	0.0515	0.00024	0.03429

Table 8. Test Results for Pre-charged Samples (Pins)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Wear Finish (μ–inch)	Inside Wear Finish (μ–inch)	Averaged Wear Spot Dia. (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)	Calculated Volume Loss (mm^3)
17	316L	316L	Hydrogen 2000 psig	4	71	0.0575	0.00002	0.002506	0.04727
18	316L	316L	Hydrogen 2000 psig	3.6	53.6	0.068	0.00212	0.265664	0.09276
19	316L	316L	Hydrogen 2000 psig	5	117	0.074	0.00018	0.022556	0.13035
20	AUM10	316L	Hydrogen 2000 psig	5.9	103.8	0.034	0.00034	0.042607	0.00575
21	AUM10	316L	Hydrogen 2000 psig	3.8	58.6	0.0825	0.00066	0.082707	0.20204
22	AUM10	316L	Hydrogen 2000 psig	5	70	0.099	0.00274	0.343358	0.42208
23	AUM10	A286	Hydrogen 2000 psig	13	82	0.036	0.00006	0.007519	0.00723
24	AUM10	A286	Hydrogen 2000 psig	4.5	52.6	0.0765	0.00084	0.105263	0.14902
25	AUM10	A286	Hydrogen 2000 psig	5.1	75.9	0.082	0.00008	0.010025	0.19714
26	DLC AUM10	316L	Air	23.3	12.5	0.038	-0.00006	-0.00752	0.00898
27	DLC AUM10	316L	Air	5.18	11.34	0.038	0.00000	0	0.00898
28	Nitride AUM10	316L	Air	5.18	13.7	0.1035	0.00372	0.466165	0.50537
29	Nitride AUM10	316L	Air	4.97	13.7	0.1065	0.00408	0.511278	0.56746
30	DLC AUM10	316L	Hydrogen 2000 psig	8	6	0.0295	-0.00006	-0.00752	0.00326
31	DLC AUM10	316L	Hydrogen 2000 psig	8	22	0.0935	0.00038	0.047619	0.33496
32	Nitride AUM10	316L	Hydrogen 2000 psig	4	48	0.0695	0.00056	0.070175	0.10127
33	Nitride AUM10	316L	Hydrogen 2000 psig	4	23	0.0635	0.00048	0.06015	0.07044

Table 9. Test Results for Pre-charged Samples (Disks)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 91 g or 0.2 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Track Finish (μ–inch)	Inside Track Finish (μ–inch)	Averaged Track Diameter (inch)	Track width (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)
34	316L	316L	Hydrogen 2000 psig	25.9	307.9	0.808	0.073	0.00380	0.47619
35	316L	316L	Hydrogen 2000 psig	21.7	59.8	0.817	0.076	0.00396	0.49624
36	AUM10	316L	Hydrogen 2000 psig	32	182	0.9665	0.0985	0.02774	3.47619
37	AUM10	316L	Hydrogen 2000 psig	27	96	0.9765	0.0915	0.02456	3.07769
38	AUM10	A286	Hydrogen 2000 psig	28	176	0.9615	0.1015	0.04106	5.14536
39	AUM10	A286	Hydrogen 2000 psig	33	138	0.9195	0.0895	0.02822	3.53634
40	DLC AUM10	A286	Air	not measured	not measured	not measured	not measured	-0.00016	-0.04571
41	DLC AUM10	A286	Air	not measured	not measured	not measured	not measured	-0.00004	-0.01143
42	Nitride AUM10	A286	Air	59.1	40.8	0.985	0.059	0.00208	0.29714
43	Nitride AUM10	A286	Air	24	26	0.9665	0.0695	0.00084	0.12
44	DLC AUM10	A286	Hydrogen 2000 psig	45	45	1.0215	0.0295	-0.00016	-0.04571
45	DLC AUM10	A286	Hydrogen 2000 psig	35	35	1.04	0.015	-0.00012	-0.03428
46	Nitride AUM10	A286	Hydrogen 2000 psig	35	23	0.943	0.046	0.00210	0.3
47	Nitride AUM10	A286	Hydrogen 2000 psig	57	42	0.984	0.043	0.00006	0.00857
48	DLC AUM10	316L	Air	29.5	28.5	0.978	0.026	0.00026	0.07429
49	DLC AUM10	316L	Air	not measured	not measured	not measured	not measured	-0.00006	-0.01714
50	Nitride AUM10	316L	Air	83.8	74.6	1.0005	0.0875	-0.00028	-0.04
51	Nitride AUM10	316L	Air	101.2	65.1	1.0205	0.0695	0.00042	0.06
52	DLC AUM10	316L	Hydrogen 2000 psig	28	28	1.1055	0.0285	-0.00006	-0.01714
53	DLC AUM10	316L	Hydrogen 2000 psig	21	21	1.024	0.025	-0.00022	-0.06286
54	Nitride AUM10	316L	Hydrogen 2000 psig	30	17	0.992	0.064	0.00054	0.07714
55	Nitride AUM10	316L	Hydrogen 2000 psig	53	46	0.971	0.083	0	6.3E-18

Table 10. Test Results for Pre-charged Samples (Pins)

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 91 g or 0.2 lb)

Test No.	Disk Material	Pin Material	Test Environ.	Outside Wear Finish (μ–inch)	Inside Wear Finish (μ–inch)	Averaged Wear Spot Dia. (inch)	Weight Loss (gram)	Estimated Volume Loss (mm^3)	Calculated Volume Loss (mm^3)
34	316L	316L	Hydrogen 2000 psig	9.1	76.2	0.0805	0.00088	0.110276	0.18300
35	316L	316L	Hydrogen 2000 psig	8.7	68.1	0.0805	0.00074	0.092732	0.18300
36	AUM10	316L	Hydrogen 2000 psig	8	116	0.094	0.00192	0.240602	0.34223
37	AUM10	316L	Hydrogen 2000 psig	3	101	0.0885	0.00310	0.388471	0.26822
38	AUM10	A286	Hydrogen 2000 psig	5	123	0.097	0.00146	0.182957	0.38861
39	AUM10	A286	Hydrogen 2000 psig	5	70	0.0925	0.00174	0.218045	0.32067
40	DLC AUM10	A286	Air	10.4	13.6	0.0545	0.00004	0.005013	0.03812
41	DLC AUM10	A286	Air	10.5	2.6	0.042	-0.00088	-0.11028	0.01341
42	Nitride AUM10	A286	Air	7.2	9.3	0.119	0.00252	0.315789	0.89095
43	Nitride AUM10	A286	Air	6	14	0.11	0.00536	0.671679	0.64706
44	DLC AUM10	A286	Hydrogen 2000 psig	6	7	0.0385	0.00092	0.115288	0.00946
45	DLC AUM10	A286	Hydrogen 2000 psig	4	5	0.033	-0.00042	-0.05263	0.00510
46	Nitride AUM10	A286	Hydrogen 2000 psig	7	25	0.083	0.00148	0.185464	0.20702
47	Nitride AUM10	A286	Hydrogen 2000 psig	8	33	0.067	0.00360	0.451128	0.08739
48	DLC AUM10	316L	Air	19.99	4.01	0.0315	0.00006	0.007519	0.00423
49	DLC AUM10	316L	Air	9.1	11.3	0.03	-0.00004	-0.00501	0.00348
50	Nitride AUM10	316L	Air	13.8	8.3	0.1085	0.00482	0.60401	0.61197
51	Nitride AUM10	316L	Air	6.3	19.1	0.112	0.00692	0.867168	0.69620
52	DLC AUM10	316L	Hydrogen 2000 psig	6	3	0.0295	-0.00010	-0.01253	0.00326
53	DLC AUM10	316L	Hydrogen 2000 psig	10	4	0.028	-0.00010	-0.01253	0.00264
54	Nitride AUM10	316L	Hydrogen 2000 psig	5	32	0.071	0.00040	0.050125	0.11035
55	Nitride AUM10	316L	Hydrogen 2000 psig	4	20	0.0935	0.00268	0.33584	0.33492

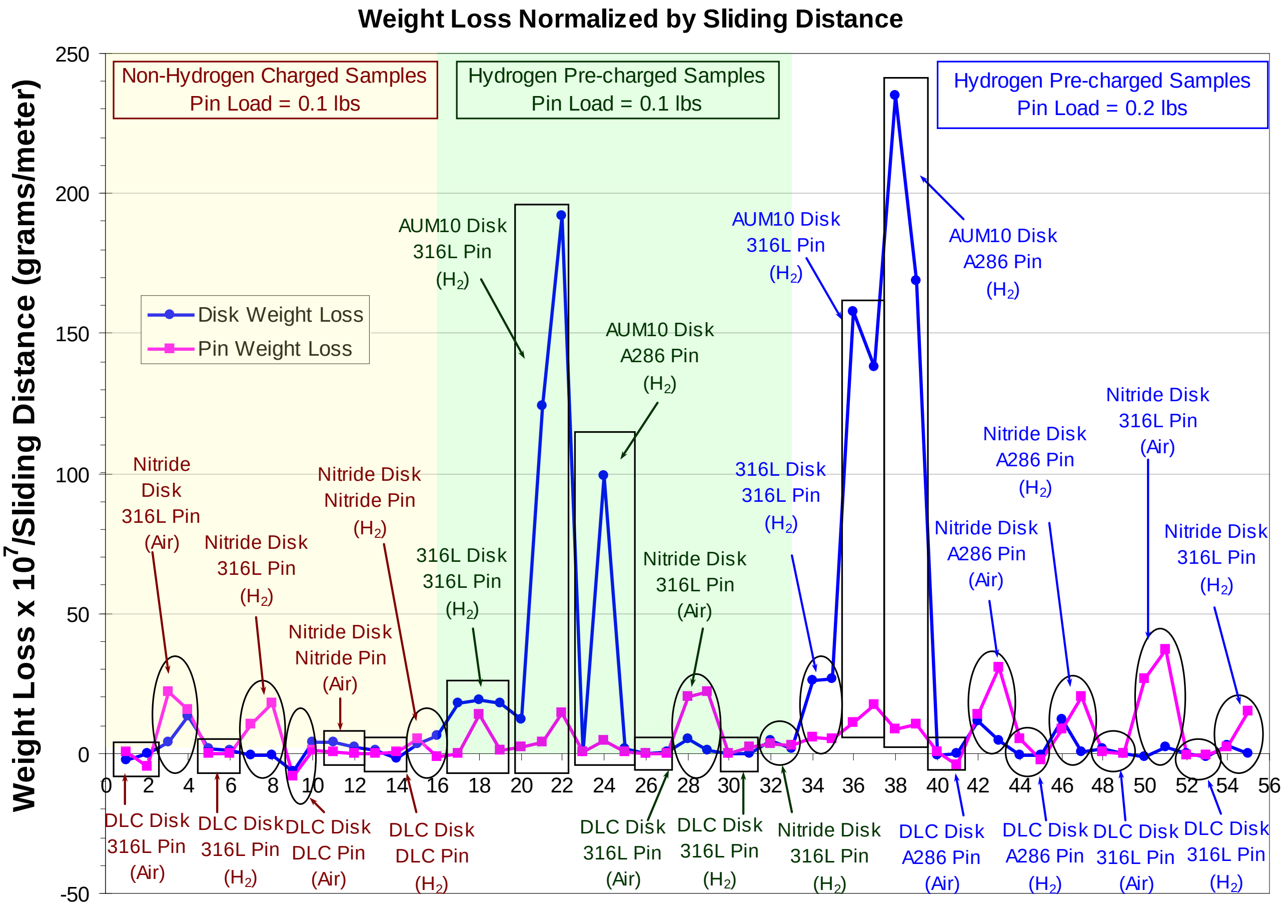

Figure 45. Disk weight change (loss) after 2000 m of travel distance and under a pin load of 45.4 g (0.1 lb) or 91 g (0.2lb)—non-pre-charged, pre-charged, non-coated, and coated.

9.2 WEAR COEFFICIENT (Kw)

A wear coefficient was calculated based on the Archard Equation [5-8] for each test where the volume loss took place by the wear. This coefficient is the proportionality between the wear rate (volume loss per unit sliding distance) and the ratio of the external load to the flow pressure of the material. Mathematically, it can be regarded as the probability of any material surface junctions leading to transferred fragments [5]. The majority of the wear coefficients based on the SRNL test data are within the range of those for the stainless steels as reported in the literature, on the order of 0.01 [5].

A wear equation was proposed by Holm in 1946 [6] and later was derived analytically by Archard in 1953 [7,8] as

$$W=kL/3p,$$

where W is the wear rate (volume loss per unit sliding distance), L is the external loading acting on the flat plate, p is the flow pressure of the metal (the Brinell Hardness can be used as an approximation), the "3" in the denominator is a shape factor for the assumed circular junctions and hemispheric fragments or debris (for a square junctions and cubical fragment, the factor would be 1), and k is the probability of any material surface junctions leading to transferred fragments [5].

The above Archard Equation is rearranged to incorporate the test data for calculation the wear coefficient K_w, in which the shape factor has been absorbed:

$$K_w = \frac{\text{Hardness (kg/mm}^2\text{)} \times \text{(Wear Volume per unit Sliding Distance, mm}^2\text{)}}{\text{Total Normal Load (kg)}}$$

Typical density of 7.98 g/cc was used in estimating the wear volume for the stainless steels (316L, A285, and AUM10). For the DLC coating, the pure diamond density 3.5 g/cc [9] was used in the Archard equation for DLC-coated samples. Because its hardness is from HV 1000 to 3500 [3], which exceeds the Brinell hardness scale HB 739 (at HV 832) [10], a value of 1000 was used in the Archard equation for DLC coating by extrapolating from charts provided in the literature [11].

The maximum density of the nitriding steels is 7.7g/cc (typical stainless steel is 7.98 g/cc) [12]. Therefore, a density of 7 g/cc was used for the nitride coating in the analysis for K_w. Because nitriding is a thermo-chemical diffusion process and its properties depend on the substrate material, the hardness of the nitriding steel in general increases with the chromium content in the steel. The surface hardness of 17% Cr stainless steel was used (Note that the chromium contents in the materials investigated in this report are 16.7, 14.0, and 12.5% for, respectively, 316L pins, A286 pins, and AUM10 disks). The surface hardness value is HV 1050 [3], which quickly drops to HV 200 at 0.2 mm (0.008 inch.) below the surface, typical for the stainless steels.

The wear coefficients for the test samples are listed in Table 11-Table 13 below, and is shown graphically in Figure 46. Many of the tests resulted in $K_w<0.001$, which may be consistent with the observation by Rabinowicz (Table 6.1 of Ref. 5), in which he reported that $k= 21\times10^{-3}$ (equivalently, $Kw=7\times10^{-3}$) for stainless steels. Rabinowicz also reported that the values of k above 0.1 are very rare in his 172 data points, with most of them are in between 10^{-4} and 10^{-2} (Figure 6.15 in Ref. 5) on non-lubricated surfaces for metals and non-metals.

Table 11. K_w for Non-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test Number	Disk Material	Pin Material	Test Environ.	K_w (Disk)	K_w (Pin)
1	DLC AUM10	316L	Air	-0.00136	0.00001
2	DLC AUM10	316L	Air	0.00000	-0.00026
3	Nitride AUM10	316L	Air	0.00094	0.00129
4	Nitride AUM10	316L	Air	0.00301	0.00091
5	DLC AUM10	316L	Hydrogen 2000 psig	0.00094	0.00000
6	DLC AUM10	316L	Hydrogen 2000 psig	0.00056	-0.00001
7	Nitride AUM10	316L	Hydrogen 2000 psig	-0.00015	0.00062
8	Nitride AUM10	316L	Hydrogen 2000 psig	-0.00009	0.00106
9	DLC AUM10	DLC 316L	Air	-0.00414	-0.00510
10	DLC AUM10	DLC 316L	Air	0.00240	0.00069
11	Nitride AUM10	Nitride 316L	Air	0.00095	0.00007
12	Nitride AUM10	Nitride 316L	Air	0.00057	0.00002
13	DLC AUM10	DLC 316L	Hydrogen 2000 psig	0.00079	-0.00006
14	DLC AUM10	DLC 316L	Hydrogen 2000 psig	-0.00122	0.00026
15	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	0.00082	0.00119
16	Nitride AUM10	Nitride 316L	Hydrogen 2000 psig	0.00141	-0.00028

Note: The negative values of K_w are associated with negative wear volume in the previous section

Table 12. K_w for Pre-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 45.4 g or 0.1 lb)

Test Number	Disk Material	Pin Material	Test Environ.	K_w (Disk)	K_w (Pin)
17	316L	316L	Hydrogen 2000 psig	0.00091	0.00001
18	316L	316L	Hydrogen 2000 psig	0.00098	0.00081
19	316L	316L	Hydrogen 2000 psig	0.00092	0.00006
20	AUM10	316L	Hydrogen 2000 psig	0.00057	0.00013
21	AUM10	316L	Hydrogen 2000 psig	0.00596	0.00023
22	AUM10	316L	Hydrogen 2000 psig	0.00920	0.00085
23	AUM10	A286	Hydrogen 2000 psig	0.00003	0.00003
24	AUM10	A286	Hydrogen 2000 psig	0.00475	0.00040
25	AUM10	A286	Hydrogen 2000 psig	0.00007	0.00004
26	DLC AUM10	316L	Air	-0.00012	-0.00002
27	DLC AUM10	316L	Air	0.00044	0.00000
28	Nitride AUM10	316L	Air	0.00118	0.00120
29	Nitride AUM10	316L	Air	0.00020	0.00128
30	DLC AUM10	316L	Hydrogen 2000 psig	-0.00014	-0.00002
31	DLC AUM10	316L	Hydrogen 2000 psig	-0.00014	0.00013
32	Nitride AUM10	316L	Hydrogen 2000 psig	0.00107	0.00018
33	Nitride AUM10	316L	Hydrogen 2000 psig	0.00032	0.00016

Note: The negative values of K_w are associated with negative wear volume in the previous section

Table 13. K_w for Pre-charged Samples

(Sliding Distance: 2000 m, Speed: 800 mm/s, Pin Load: 91 g or 0.2 lb)

Test Number	Disk Material	Pin Material	Test Environ.	K_w (Disk)	K_w (Pin)
34	316L	316L	Hydrogen 2000 psig	0.00066	0.00017
35	316L	316L	Hydrogen 2000 psig	0.00068	0.00015
36	AUM10	316L	Hydrogen 2000 psig	0.00378	0.00032
37	AUM10	316L	Hydrogen 2000 psig	0.00331	0.00051
38	AUM10	A286	Hydrogen 2000 psig	0.00563	0.00037
39	AUM10	A286	Hydrogen 2000 psig	0.00404	0.00046
40	DLC AUM10	A286	Air	-0.00025	0.00001
41	DLC AUM10	A286	Air	-0.00006	-0.00019
42	Nitride AUM10	A286	Air	0.00135	0.00062
43	Nitride AUM10	A286	Air	0.00055	0.00135
44	DLC AUM10	A286	Hydrogen 2000 psig	-0.00027	0.00022
45	DLC AUM10	A286	Hydrogen 2000 psig	-0.00020	-0.00010
46	Nitride AUM10	A286	Hydrogen 2000 psig	0.00142	0.00038
47	Nitride AUM10	A286	Hydrogen 2000 psig	0.00004	0.00089
48	DLC AUM10	316L	Air	0.00046	0.00001
49	DLC AUM10	316L	Air	-0.00009	-0.00001
50	Nitride AUM10	316L	Air	-0.00018	0.00077
51	Nitride AUM10	316L	Air	0.00026	0.00109
52	DLC AUM10	316L	Hydrogen 2000 psig	-0.00009	-0.00001
53	DLC AUM10	316L	Hydrogen 2000 psig	-0.00037	-0.00002
54	Nitride AUM10	316L	Hydrogen 2000 psig	0.00035	0.00006
55	Nitride AUM10	316L	Hydrogen 2000 psig	0.00000	0.00044

Note: The negative values of K_w are associated with negative wear volume in the previous section

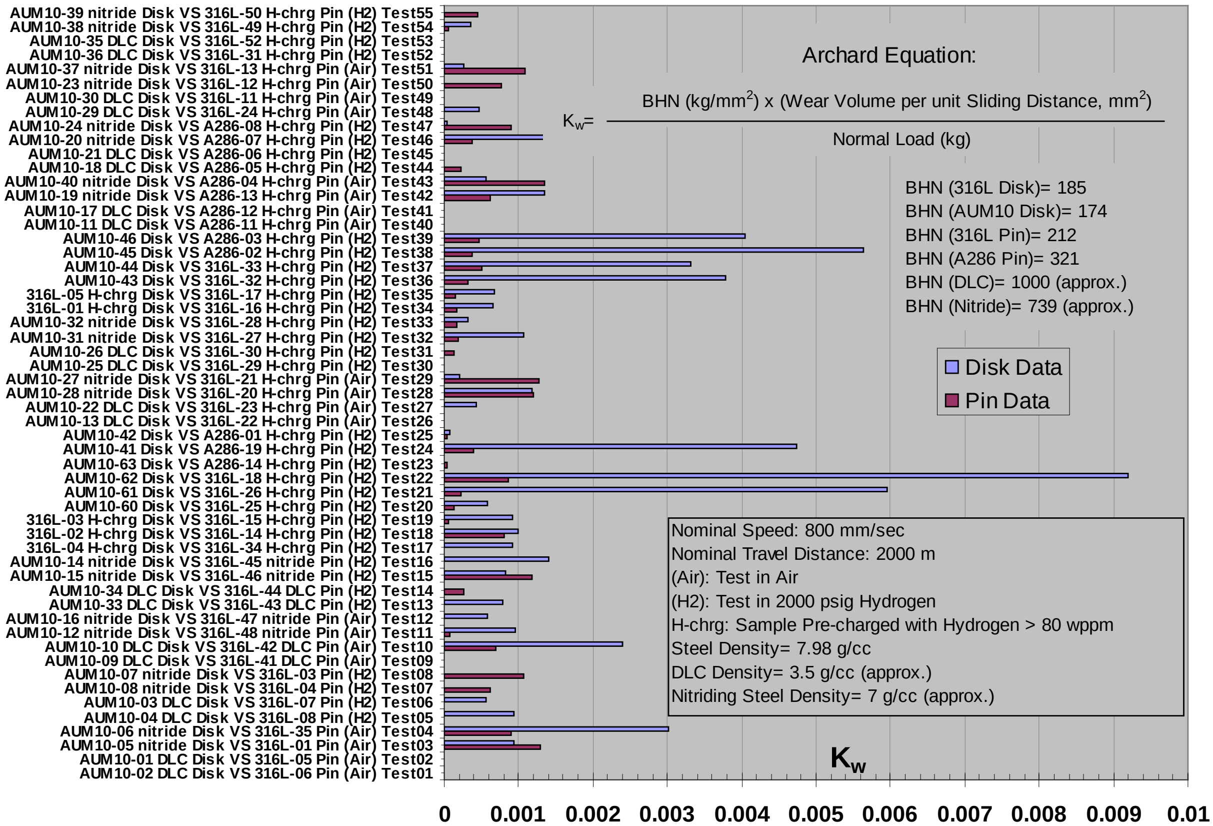

Figure 46. The wear coefficients calculated for all wear test cases.

Examination of the wear coefficient data displayed in Figure 46 indicates that consistent with the previous Phase I wear testing study AUM10 disk material exhibits more wear in comparison to the 316L disk material in the uncoated disk-uncoated pin condition for samples tested in hydrogen in the pre-charged condition and at both 0.1 and 0.2 lb loads. Additional observations from the wear coefficient data are as follows:

1. Samples tested with nitride coated disk display highest pin wear—this can be attributed to the high hardness and increased surface roughness associated with the nitride coatings.

2. There is minimal influence associated with hydrogen pre-charge and increasing load on K_w.

3. Samples involving the DLC coating typically display the lowest K_w value which is consistent both with visual surface examination and wear track measurements.

10.0 CONCLUSIONS

Based on the data collected for a travel distance of 2000 m and loads of both 45.4 g and 91 g, the tribological effects of the stainless disks (316L and AUM10) and the pins (316L and A286) in the pre-charged or coated conditions are not significant. Consistent with Phase I test results, the Phase II results do show a tendency for somewhat higher wear of non-coated materials sliding against each other in a gaseous hydrogen environment. Results for coated samples either nitride or DLC show that the coatings reduce the overall sample wear for samples tested in both air and hydrogen. It should be noted that for test conducted with nitride coated disks and non-coated pins, that increased wear was seen on the pins when compared to similar samples tested with DLC coated disks. This increased pin wear is most likely due to the increased roughening of the disk surface associated with the nitride coating application process.

Testing conducted in Phase II which was aimed at helping understand the previously collected results in Phase I; several critical questions were addressed: 1) does increasing the wear distance increase wear and aid weight change measurement sensitivity, 2) will pre-charging in hydrogen exacerbate the effect of gaseous hydrogen on surface wear, 3) will increased load increase the wear in hydrogen, and 4) can surface coatings reduce wear in both air and hydrogen.

Results from Phase II testing indicate that increasing the load from 45g to 91g (0.1 to 0.2 lb) does show some increase in wear. Additionally, increased test load also shows a trend of increasing wear for nitride coated samples. The increased load, however, does not appear to influence the wear behavior of DLC coated materials. Analysis of the test data also indicates that pre-charging with hydrogen has a slight effect for uncoated samples but shows essentially no effect for coated samples.

The major result from Phase II testing is the significant impact of surface coatings on wear. Both surface coating materials—nitride or DLC—reduce wear in air and in hydrogen (compared to non-coated disks), and they performed equally well in resisting wear. However, as previously mentioned, the non-coated materials (pins) tested against nitride coated materials (disks) exhibited more wear than the non-coated materials tested against DLC coated materials resulting from the inherent nature of the surface due to nitriding. From the Phase II test results, it may be concluded that DLC coating appears to be the most versatile coatings for reducing wear.

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Customer:
Washington Savannah River Co
Building 723-A
Aiken, SC 29808

Ship To Address:
Washington Savannah River Co
Operations Receiving 731-1N
Aiken, SC 29808

Customer Order: 7P5896

Item No.: 3

PN: NONE

Dimensions: 2.000 IN DIA X 27.1250 INCHES

Alloy/Grade: STAINLESS STEEL 316 COND A

Specification/Grade: QQ-S-763 REV F

No. Of Boxes	*No of Pieces*	*Length*	*Weight*	*Packing Slip No.*	*Heat No.*	*Lot No.*
1	1	27.1250 INCHES	24.0 LBS	59849	415377	426500950

MILL TEST REPORT ATTACHED X

MATERIAL HAS NOT BEEN EXPOSED TO MERCURY WHILE IN DIVERSIFIED METALS INC. FACILITY.

This is to certify that the material covered by this report and shipped on the above order has been inspected in accordance with, and has been found to meet the applicable requirements described herewith, involving any specifications forming a part of this description.

We certify that the Chemical Analysis and Physical Test Results applying on the above order number are correct and true.

QUALITY APPROVAL:

[redacted]

Sharon Brown
Quality Control Administrator

Date: November 29, 2007

Mill Cert. – REV 2. – 2/27/2007

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Conferma ordine nr: EI04007851

Produttore: **STABILIMENTO DI BOLZANO**

Ordine nr: 12779/STOCK (1)

Marchio di Fabbrica:

Oggetto Prove: Polished Annealed Peeled

Tipo di Elaborazione: E+AOD

Punzone del Collaudatore: SC

Specifiche:

FIRST METALS 2003 316/316L A
ASME (1) SA182 2001 S31600/03 (0)
ASME (1) SA479 2001 S31600/03 (3)
ASTM A193 2004C B8M
ASTM A276 2004 S31600/03
ASTM A370 2003A .
MIL-S-862 B/1 316
AMS-QQ-S-763 98 316/316L
(0) SEC.II PT.A 2001 EDITION ADD.2002
(1) SEC.II PT.A 2001 EDITION ADD.2002
(3) SEC.II PT.A 2001 EDITION ADD.2002

AMS 5648 K S31600
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ASME (1) SA484 2001 .
ASTM A194 99 8M
ASTM A314 97 S31600/03
ASTM A473 99 S31600/03
NACE MR0175 2002 S31600/03
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AMS 5653 F S31603
ASME (1) SA320 2001 B8M (2)
ASTM A182 2002 S31600/03 (4)
ASTM A262 2002A .
ASTM A320 2004 B8M
ASTM A479 2004 S31600/03
QQ-S-763 F 316/316L

(0) Chemical analisys only and mechanical properties.
(2) SEC.II PT.A 2001 EDITION ADD.2002
(4) Chemical analysis only.

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DATE 1/6/06
CAROL RALPH
Q.C. MANAGER

Qualità: S31603

Marca: MVAPML MAXIVAL

Punzonatura: S31603

Pos. nr.	Oggetto	Dimensioni - in	Tolleranza	Lunghezza - Ft	Colata	Pezzi	Peso - LB	Lotto nr.
0180	Round	2,0000	A484	12 / 13	415377		4.113	426500950

Sono state soddisfatte tutte le condizioni richieste
The material has been furnished in accordance with the requirements

Controllo antimescolanza: OK
Antimixing testing performed: OK

Controllo visivo e dimensionale: soddisfa le esigenze:
Visual inspection and dimensional check:satisfactory

TEST	Provetta/ mm	°F	Posiz. Saggio	Snervamento Rp 0,2% k.s.i.	Snervamento	Resistanza Rm k.s.i.	Allungamento	E 4d %	Strizione	RA %	Resilienza			Durezza HB		
Valori richiesti 1		min max		30 ✓	-	75 115 ✓	-	40 ✓	-	50 ✓	-			140 223		
A	12,50	68	L	39		86		66		73				185		

1) L=longitudinale/lengs, C=conversale/cper, T=Tangenziale/tangential

Grain size for ASTM E112 : 5

Analisi chimica

Chemische Zusammensetzung/Chemical Analysis/Analyse chimique

Colata Heat	C %	Si %	Mn %	Cr %	Mo %	Cu %	Ni %	P %	S %	N %					
min - max	0,030	- 1,00	1,25 2,00	16,50 18,00	2,00 3,00	- 1,00	10,00 14,00	- 0,040	0,020 0,030	- 0,100	- -	- -	- -	- -	- -
415377	0,018	0,70	1,57	17,11	2,01	0,42	10,23	0,028	0,026	0,078					

Produced without class I-II Ozone depleting substances.
Solution heat treated free from continuous carbide network.
Annealing temperature: 1960° F for 2,50h/H2O.
✓ Micro and macro etch test: OK
Reduction ratio > 4 : 1
✓ Intergranular corrosion test per ASTM A262,02, pract. A&E:ok

Melted and manufactured in Italy No welding or weld repair Material free from Mercury or radio-activity contamination ✓

The Quality Management System is Certified acc. Pressure Equipment Directive [97/23/EC] Annex 1,s.,4.3 by TUEV and LLOYD'S

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P.O. # 7P5896
ITEM# 3

Bolzano, 15/11/05	Il collaudatore di stabilimento / der Werkssachverständige / Works inspector / L'agent d'usine R.Cristel [redacted]	Pagina - 1 di 1

A
V
Valbruna Group

Valbruna Stainless, Inc.

31 Iron Horse Road
Oakland, NJ 07436
Tel. (201) 337-1233
Fax (201) 337-0833
njsales@valbruna.com

TEST CERTIFICATE

BUYER : Diversified Metals
BUYERS P.O. No 42239

11/10/2005
VALBRUNA No: 12779

GRADE	SIZE / SHAPE	DESCRIPTION AND SPECIFICATION		QTY (LBS)
S31603	ROUND 2.000"	FIRST METALS 2003 316/316L ASME(1)SA182 2001 S31600/03 (1) ASME (1) SA479 2001 S31600/03 (3) ASTM A193 2004C B8M ASTM A276 2004 S311600/03 ASTM A370 2003A ML-S-862 B/1 316	AMS-QS-763 98 316/316L (o) SEC.11PT A 2001 EDITION ADD 2002 (1) SEC.11PT A 2001 EDITION ADD 2002 (2) SEC.11PT A 2001 EDITION ADD 2002	1,000

CHEMICAL ANALYSIS

*Chemical analysis only

HEAT NUMBER	C	Mn	P	S	Si	Ni	Cr
415377							

Mo	Cu	Ti		Co		Cb+Ta	Sn	N

MECHANICAL PROPERTIES

TENSILE STRENGTH (KSI)	YIELD STRENGTH (KSI)	ELONG %	RED.OF AREA %	HARDNESS			AS SHIPPED HARDNESS
				BRINELL	ROCKWELL "B"	ROCKWELL "C"	

OTHER TEST(S) AND / OR REQUIREMENTS

AMS 5648 K S31600
ASME (1) SA193 2001 B8M(1)
ASME(1) SA484 2001
ASTM A194 99 8M
ASTM A314 97 S31600/03
ASTM A479 99 S31600/03
NACE MR0175 2002 S31600/03
QQ-S-763 E/1 316/316L

AMS 5653 FS31603
ASME (1) SA320 2001 B8M (2)
ASTM A182 2002 S31600/03 (4)
ASTM A262 2002A
ASTMA320 2004 B8M
ASTM A479 2004S31600/03
QQ-S-763 F 316316L

(1) Chemical analysis only and mechanical properties
(2) SEC 11PT A 2001 EDITION ADD 2002
(4) Chemical analysis only

NOTES

"Statement of Compliance"
"This material, is produced by Acciaierie Valbruna and transferred to Valbruna Stainless, Inc., is mercury free and satisfies the requirements of the related specifications and standards."

[redacted]

Timothy P. Cooney
Authorized Representative

APPENDIX B STAINLESS STEEL TYPE AUM10 (FOR DISKS)

No.301

AICHI STEEL

ハイクォリティスティール

軟磁性ステンレス鋼 AUMシリーズ

特　長

1. 優れた磁気特性　　磁束密度が高く、保磁力が小さい。
2. 大きい電気抵抗　　比抵抗が高く、交流特性が優れている。
3. 優れた耐食性　　優れた耐食性を有している。(AUM6を除く)
4. 豊富な品揃え　　用途、加工方法に応じて最適な鋼種選択ができる。

種　類

分類	特性 / 鋼種	磁束密度	保磁力	電気抵抗	引張強さ	耐食性	切削性	冷鍛性	溶接性	鋼種選定のポイント
切削用	AUM6	◎	◎	○	◎	×	◎	—	—	ステンレス鋼ではない。珪素鉄の電気抵抗、切削性を改善した鋼種。磁束密度が非常に高い。 電磁弁の可動鉄心に最適。
	AUM10	○	◎	◎	◎	○	—	—	◎	磁気特性、電気抵抗、溶接性に優れている。 油圧用電磁弁に幅広く使用。
	AUM11	○	◎	◎	◎	○	◎	—	—	AUM10の切削性を改善した鋼種。
冷鍛用	AUM12	○	◎	○	○	○	—	◎	◎	軟鋼並の冷間鍛造性を有し、しかも優れた磁気特性、耐食性を有する鋼種。
	AUM15	○	◎	○	○	○	◎	◎	—	冷間鍛造性と切削性を両立させた鋼種。耐食性、電磁特性も優れている。 量産タイプの電子制御燃料噴射装置に最適。
	AUM15H	○	◎	○	○	○	◎	◎	—	AUM15の冷鍛性を改善した鋼種。
	AUM25	○	◎	◎	○	○	◎	◎	—	動的磁気特性が特に優れている。耐食性、冷鍛性、切削性も優れている。 パルス駆動型電磁弁に最適。
耐食用	AUM20	○	◎	○	◎	◎	—	○	◎	SUS316並の優れた耐食性と優れた磁気特性を有する鋼種。

注) ◎：特に優れている　○：優れている　×：劣る

用　途

電磁弁、EFI（電子制御式燃料噴射装置）、スピードセンサ　など

AUMシリーズ

化学成分

分類	鋼種名	化学成分(%)							
		C+N	Si	Cr	Al	Pb	S	Ti	Mo
切削用	AUM6	0.02	2.2	3.6	添加	添加	調整	—	—
	AUM10	0.02	2.4	12.5	—	—	調整	添加	—
	AUM11	0.02	2.2	12.5	—	添加	調整	添加	—
冷鍛用	AUM12	0.02	0.2	12.0	—	—	—	—	—
	AUM15	0.02	0.7	12.0	添加	添加	調整	添加	—
	AUM15H	0.02	0.2	12.0	添加	添加	調整	添加	—
	AUM25	0.02	0.2	10.0	添加	添加	調整	—	—
耐食用	AUM20	0.02	0.2	19.0	—	—	—	—	添加

(1) 13％Crステンレス鋼をベース成分として低(C+N)化とAl、Ti等の添加により磁気特性、電気抵抗、耐食性、冷鍛性を改善しています。

(2) 高耐食性用途のために19％Cr鋼をベースとし、必要に応じてMoを添加することにより耐食性を改善しています。

(3) Pb、Sにより切削性を改善しています。

(4) AUM 6 は磁束密度を改善するためにCr量を3.6％にしています。

特　　性

1．電磁特性（代表特性値）

分類	特性 / 鋼種名	磁束密度(G)				保磁力	電気抵抗	透磁率
		B_1	B_2	B_{10}	B_{20}	Hc(Oe)	μΩ-cm	μmax
切削用	AUM6	4000	12000	14000	14500	1.0	72	4700
	AUM10	3000	11000	12000	12800	1.0	93	4200
	AUM11	3600	11000	12100	12900	1.0	90	4100
冷鍛用	AUM12	3300	11200	12900	14000	1.5	47	3500
	AUM15	3500	10800	11800	12900	1.0	72	4500
	AUM15H	5400	11000	12200	13200	1.0	60	5000
	AUM25	5400	10800	11700	12700	1.0	100	4900
耐食用	AUM20	6000	10500	11500	12000	1.0	53	5000
比較材	軟鉄(SIOC)	480	9000	13200	15500	1.8	15	1700
	SUS403	30	140	290	660	3.3	57	40

2．耐食性（耐海水性）

(1) AUM20はSUS316より耐食性が良好で、特に耐食性が要求される場合に最適です。

(2) AUM10からAUM25までは、13％Crステンレス鋼より耐食性が優れています。

愛　知　製　鋼　株　式　会　社

本社　愛知県東海市荒尾町ワノ割1番地　〒476　☎〈052〉604－1111（大代表）FAX.052－601－0301
東京支店　東京都千代田区大手町2丁目6番2号（日本ビル）　〒100　☎〈03〉3270－0854（代表）FAX.03－3245－0649
名古屋支店　名古屋市中村区名駅4丁目7番23号（豊田ビル）　〒450　☎〈052〉571－6493（代表）FAX.052－561－8432
大阪支店　大阪市中央区南船場4丁目3番11号（大阪豊田ビル）　〒542　☎〈06〉252－7373（代表）FAX.06－251－9497
広島営業所　広島市中区八丁堀11番28号（朝日広告ビル）　〒730　☎〈082〉228－0228（代表）FAX.082－227－5140
福岡営業所　福岡市博多区博多駅前2丁目11番16号（第2大西ビル）　〒812　☎〈092〉474－1690（代表）FAX.092－474－0558
米国駐在員事務所　771 Corporate Drive, Suite 460 Lexington, Kentucky 40503, -5444, U.S.A.　☎〈606〉223－7052　FAX.606－224－4736
工場　知多・刈谷・鍛造・東浦

1940611

特約店

2008年8月24日
愛知製鋼㈱
品質保証部
品質・技術サービス室
余語

軟磁性ステンレス鋼AUM10の機械的性質

熱処理　焼鈍 900℃×2Hr での機械的性質を下記に示します。

0. 2%耐力(N／mm2)	:	290以上（代表例 390）
引張強さ(N／mm2)	:	490以上（代表例 530）
伸び(%)	:	30以上（代表例 37）
絞り(%)	:	55以上（代表例 74）
硬さ(HRB)	:	83～95（代表例 88）

以上

APPENDIX C STAINLESS STEEL TYPE 316L (FOR PINS)

NAS

METALLURGICAL TEST REPORT

NORTH AMERICAN STAINLESS
6870 HIGHWAY 42 EAST
GHENT, KY 41045

6870 HIGHWAY 42 EAST

Certificate: 434100 4 Mail To: Ship To: Date: 10/23/2008 Page: 1

Customer: RICKARD METALS, INC. # 1493

SAVANNAH RIVER NL P.O. # 4R3679

Steel: 316L/316

Finish: CD

Your Order: NAS Order: IN 0052893 01 Corrosion: ASTM A262-02a PRACTICE E-

PRODUCT DESCRIPTION:
Round bar, annealed, cold drawn. ASTM-A-484-06B UNS S31600 UNS S31603, ASTM A276/04, ASTM A479/04, AMS 5648K, AMS 5653F, QQS-763F, EN 10204 3.1B ASME SA479/01, AMS QQS-763A

REMARKS:
Melted & Manufactured in the USA. Product complies w/ requirements of EU directive2002.95.EC.RoHS.Material Free from Mercury contamination. No weld repair. NAS certifies the analysis on certification is correct & the material meets specs stated.

Product Id	Skid #	Diameter	Size	Weight	-------Length------	Mark	Pieces	Commodity Code
BC1389 1		.3750		771	144.00	3	1	

CHEMICAL ANALYSIS CM(Country of Melt) ES(Spain) US(United States) ZA(South Africa) JP(Japan)

HEAT	CM	C	CB	CO	CR	CU	MN	MO	N	NI
4EE9	US	.0296	.0138	.3425	16.6747	.4985	1.4133	2.1839	.0390	11.0082
		P	S	SI	TI					
		.0309	.0242	.4226	.0053					

MECHANICAL PROPERTIES

Product Id,	loc	dir	HB No.	.2 YS KSI	UTS KSI	RA %	Elo-4D %	Oxalic P/F
BC1389 1	C	L	212.00	81.43	99.84	75.20	46.01	1.00

NAS hereby certifies that the analysis on this certification is correct and the material meets the specifications stated.

QC ENGINEER ERIC HESS 10/23/2008

Rcu. 10.24-08

APPENDIX D STAINLESS STEEL TYPE A286 (FOR PINS)

CERTIFICATE OF TESTS **ABNAHMEPRUEFZEUGNIS** **CERTIFICAT DE CONTROLE**

CERT SERIAL# 000661755

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

- THE RECORDING OF FALSE, FICTICIOUS OR FRAUDULENT STATEMENTS OR ENTRIES ON THIS DOCUMENT MAY BE PUNISHED AS A FELONY UNDER FEDERAL STATUTES INCLUDING FEDERAL LAW, TITLE 18, CHAPTER 47.
- THE VALUES AND OTHER TECHNICAL DATA REPRESENT THE RESULTS OF ANALYSES AND TESTS MADE ON SAMPLES COLLECTED FROM THE TOTAL LOT. ORIGINAL DATA RECORDS CAN BE TRACED BY REFERENCE TO THE CARPENTER ORDER NUMBER.
- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
- THIS DOCUMENT SHALL NOT BE REPRODUCED, EXCEPT IN FULL, WITHOUT THE WRITTEN CONSENT OF CARPENTER TECHNOLOGY CORPORATION.

555513-3

08/30/08

CUSTOMER / BESTELLER / CLIENT
RICKARD METALS, INC. # 1493

SELLER / VERKÄUFER / VENDEUR PAGE 1 OF 2
SAVANNAH RIVER NL P.O. # 4R3679

CUSTOMER ORDER NO. / BESTELL-NR. / Nº DE COMMANDE	CARPENTER NO. / WERKS-NR. / Nº DE REFERENCE INTERNE	DATE / DATUM / DATE	WEIGHT / GEWICHT / POIDS
	W94868	08/30/08	1888.000

HEAT NUMBER / SCHMELZE-NR. / Nº DE COULEE : 555513

PRODUCT DESCRIPTION: CONSUMET A286 SOLUTION ANNEALED AGED GROUND

SPECIFICATION: ASTM-A638-00(2004) GRADE 660, TYPE 2
ASTM-A453-04 GRADE 660 CLASS B (REPORT GRAIN AS SHIPPED)
AMS 5732 REV J (09/ /06)
GE S-400 (10/31/07)
GE S-1000 (01/02/08)
FAIRCHILD MS 314 "CLASS A" REV 4 (01/17/03)
DFARS 1998 EDITION

SIZE 0.375000 IN. (9.53 MM) RD BAR INGOT 3

PRIMARY HEAT CHEMISTRY (WT%): (TEST METHOD IS SHOWN IN PARENTHESIS)

C (OES) 0.04	MN (XRF) 0.40	SI (XRF) 0.13	P (OES) 0.021	S (OES) 0.001	CR (XRF) 14.04
NI (XRF) 24.27	MO (XRF) 1.18	CU (XRF) 0.24	CO (XRF) 0.35	AL (OES) 0.17	TI (OES) 2.18
V (XRF) 0.26	B (OES) 0.007				

GEAG SUPPLIER CODE 21100 / CARPENTER

THE CHEMICAL ANALYSIS OF THIS HEAT HAS BEEN PERFORMED BY THE CARPENTER SPECIALTY ALLOYS CHEMICAL LABORATORY, (CODE NUMBER PRI 100004), WHICH WAS ACCREDITED TO THE ISO/IEC 17025.

MILL HEAT TREATMENT:

	SOLUTION ANNEAL	AGE
TYPE	SOLUTION ANNEAL	AGE
TEMP	1800F (982C)	1328F (720C)
TIME (BATCH FURNACE)	1.00 HOURS	16.00 HOURS
QUENCH	WATER	AIR

HARDNESS AS SHIPPED, HRC - 34 (MIDRADIUS)

3/8 RD

CONTINUED ON NEXT PAGE

CERTIFICATE OF TESTS **ABNAHMEPRUEFZEUGNIS** **CERTIFICAT DE CONTROLE**

CERT SERIAL# 000661755

CARPENTER

Carpenter Technology Corporation
101 West Bern Street, Reading, Pa. 19601
Tel: (610) 208-2000 (800) 338-4592

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- MATERIAL IS MANUFACTURED FREE FROM MERCURY, RADIUM, ALPHA AND GAMMA SOURCE CONTAMINATION.
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08/30/08

CUSTOMER / BESTELLER / CLIENT: RICKARD METALS, INC. # 1493

SELLER / VERKÄUFER / VENDEUR: SAVANNAH RIVER NL P.O. # 4R3679

PAGE 2 OF 2

CUSTOMER ORDER NO. / BESTELL-NR. / N° DE COMMANDE	CARPENTER NO. / WERKS-NR. / N° DE REFERENCE INTERNE	DATE/DATUM/DATE	WEIGHT/GEWICHT/POIDS
	W94868	08/30/08	1888.000

HEAT NUMBER / SCHMELZE-NR. / N° DE COULEE: 555513

YIELD STRENGTH, (0.20 %) KSI(MPA)	134.0	(924)
TENSILE STRENGTH, KSI(MPA)	168.0	(1158)
ELONGATION IN 1.53", %	23.0	
REDUCTION OF AREA, %	39.0	

GRAIN SIZE PER ASTM E112: 9 (KALLINGS)

COMBINATION STRESS RUPTURE

TEST TEMP	1200 F	(649 C)
STRESS, KSI(MPA)	56.0	(386)
ELONGATION %	31.3	
HOURS	149.2	

AFTER MINIMUM TIME UNDER SPECIFIED STRESS, THE STRESS RUPTURE TEST WAS OVERLOADED IN INCREMENTS AS FOLLOWS:

TOTAL HOURS	STRESS KSI(MPA)
103	61.0(421)
111	66.0(455)
119	71.0(490)
127	76.0(524)
135	81.0(558)
143	86.0(593)

COMBINATION STRESS RUPTURE

TEST TEMP	1200 F	(649 C)
STRESS, KSI(MPA)	70.0	(483)
ELONGATION %	27.8	
HOURS	82.2	

AFTER MINIMUM TIME UNDER SPECIFIED STRESS, THE STRESS RUPTURE TEST WAS OVERLOADED IN INCREMENTS AS FOLLOWS:

TOTAL HOURS	STRESS KSI(MPA)
55	75.0(517)
66	80.0(552)
79	85.0(586)

MATERIAL PRODUCED ON THIS ORDER WAS MELTED AND MANUFACTURED IN THE U.S.A. MATERIAL HAS BEEN MELTED IN USA OR QUALIFYING COUNTRY TO DFARS REQUIREMENTS 252.225-7014 WITH ALTERNATE 1 FOR QUALIFYING COUNTRY 225.872.1. CARPENTER'S QUALITY MANAGEMENT SYSTEM WAS REGISTERED AS OF SEPTEMBER 2, 2004 TO THE REQUIREMENTS OF ISO 9001:2000 APPROVAL CERTIFICATE 07-0869 BY PERFORMANCE REVIEW INSTITUTE. CERTIFICATE OF TEST IS PREPARED IN ACCORDANCE WITH PARAGRAPH 3.1 OF EN 10204 (DIN 50049). WE HEREBY CERTIFY THAT THE ABOVE TEST DATA ARE IN ACCORDANCE WITH THE PURCHASE ORDER AND SPECIFICATION REQUIREMENTS.

MICHELE L. HEFFNER
MET RELEASE/REQUIREMENTS ANALYST
CARPENTER TECHNOLOGY CORPORATION

[redacted]

APPENDIX E CERTIFICATE OF RESEARCH GRADE HYDROGEN

AIR LIQUIDE

CERTIFICATE OF BATCH/LOT ANALYSIS

Certification Of Batch/Lot #: 348LAP7698A

Product: Hydrogen **Grade: Research**

Customer:	WSRC	**Test Cylinder #:**	K-9017
Date of Certification:	1/3/2008	**Item Number:**	
P.O. Number:	KO84592	**Valve:**	350
Document Number:	27606650	**Cylinder Size:**	44

ANALYSIS REPORT

Major Component	Specification	Purity
Hydrogen Research	99.9995%	>99.9995%

Impurities	Specification	Actual Analysis
Moisture	<1 ppm	0.1 PPM
Oxygen	<1 ppm	0.1 PPM
Total Hydrocarbons	<0.2 ppm	N/D
Carbon Dioxide	<1 ppm	N/D
Carbon Monoxide	<1 ppm	N/D
Nitrogen	<1 ppm	N/D

Notes: SERIAL NUMBERS:
H-73268 , W-402637 , H-87986 , H-2434889 , 14869 , H-2087368 , 55961 , H-875341 , T210623 , T241253 , AF-9053 , H1098996 , T240371 , K118929 , 39771 , 250-032814 , 84-16414 , 998 , T-146554 , K133399 , K-071920 , 250-278966 , K161980 , 250-721261 , K-78020 , K-128664 , T-180699 , K-9017 , K-127508

Certified By: [redacted]
Name

Cure date: 12/14/07
Exp date : 12/14/12

Air Liquide America, L.P. 11426 Fairmont Pkwy LaPorte, TX 77571-6000
Phone: 281-474-8400

ICSC-CYL-0307-W Revision: 2 Effective Date:

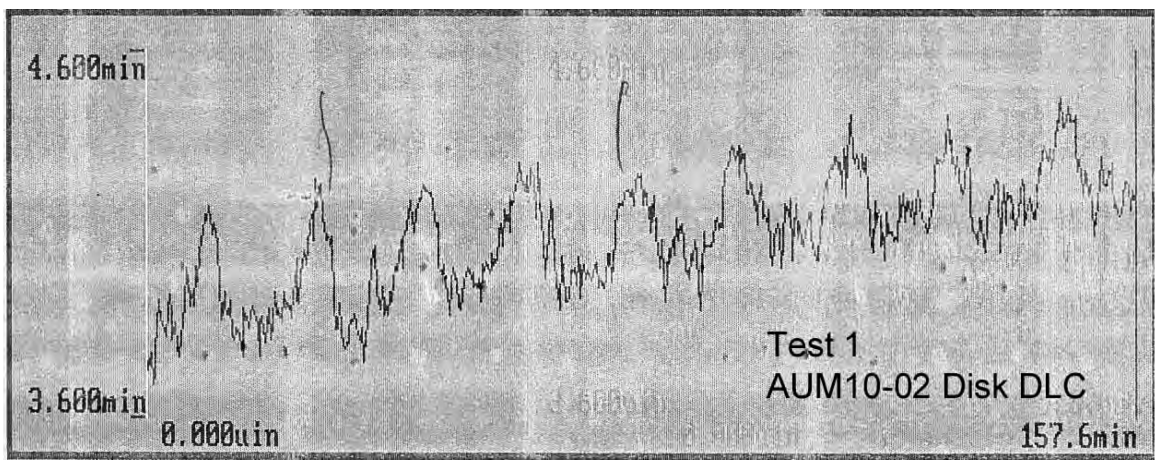
10/14/2009 09:05 FAX 8036528137 001/001

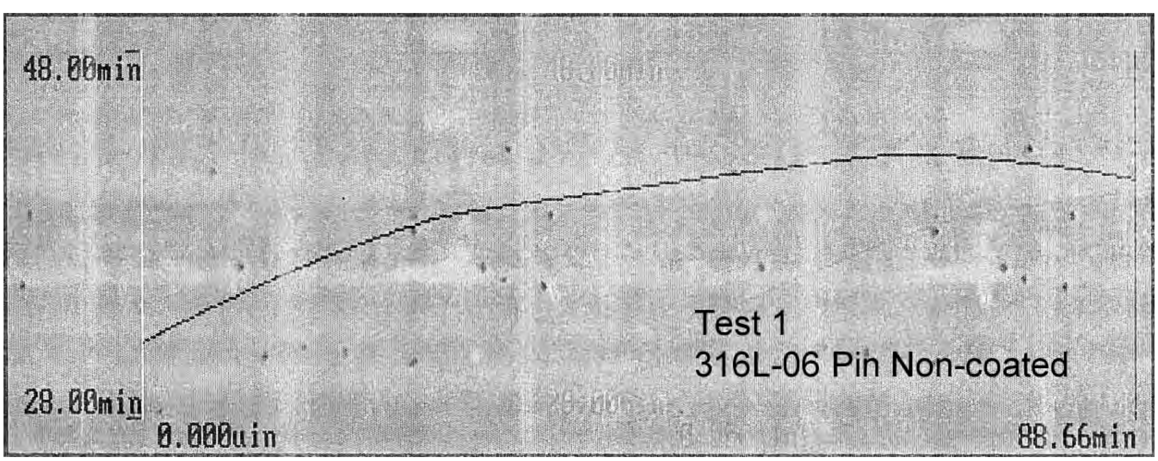
APPENDIX F POST-TEST SAMPLE PHOTOGRAPHS AND CONTACT PROFILOMETER SCANS

Test 1


AUM10 (DLC Coated)
Wear Track
Test 1


316L (Non-coated)
Wear Spot
Test 1

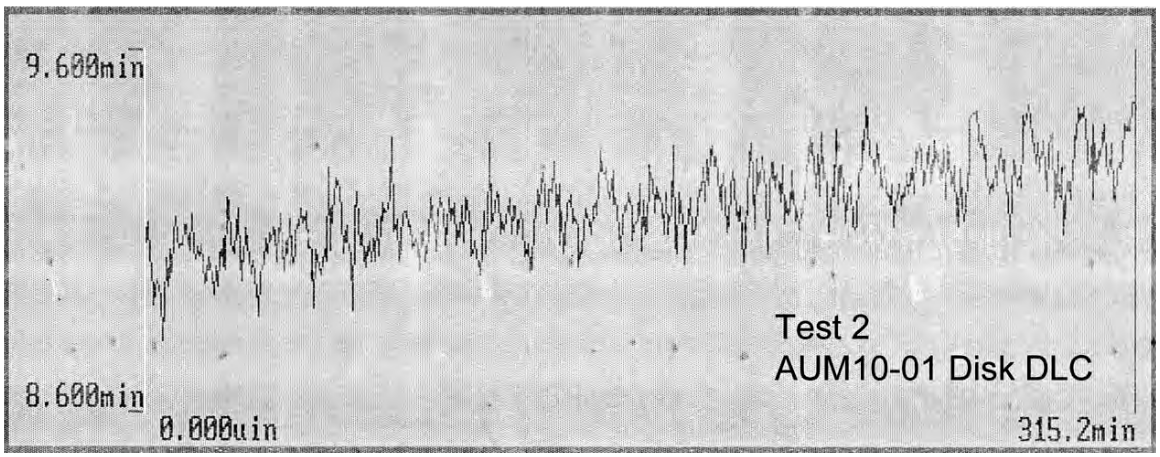

4.600min
3.600min
0.000uin
157.6min
Test 1
AUM10-02 Disk DLC

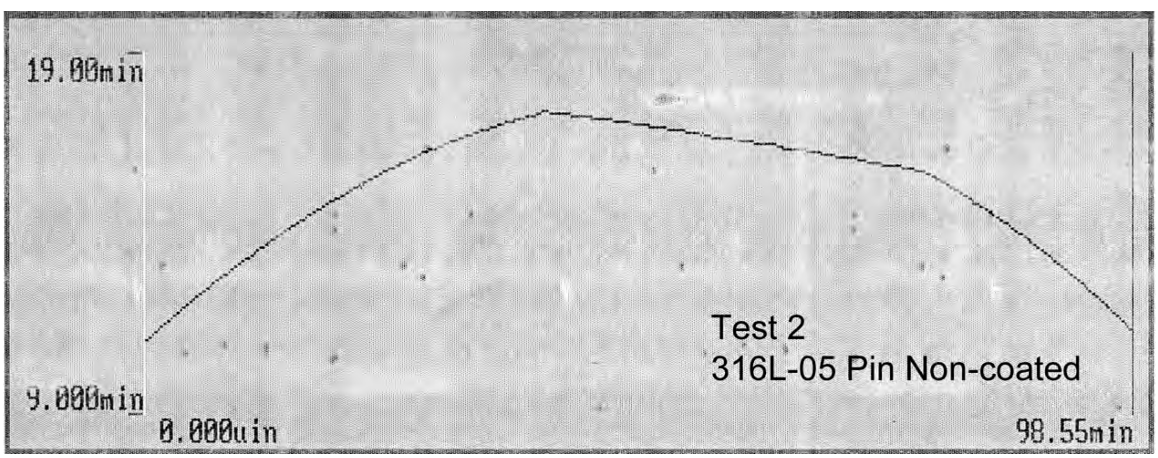

48.00min
28.00min
0.000uin
88.66min
Test 1
316L-06 Pin Non-coated

Test 2


AUM10 (DLC-Coated)
Wear Track
Test 2

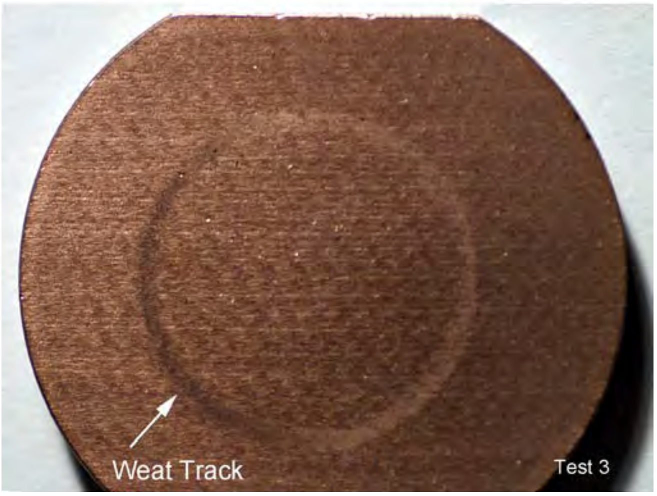

316L (Uncoated)
Wear Spot
Test 2

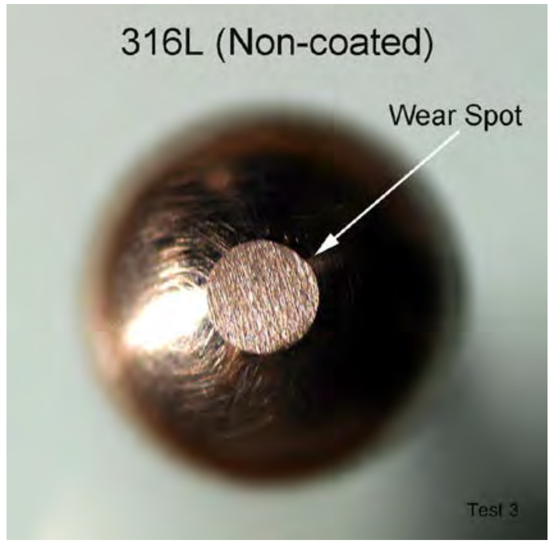

9.600min
8.600min
0.000uin
315.2min
Test 2
AUM10-01 Disk DLC

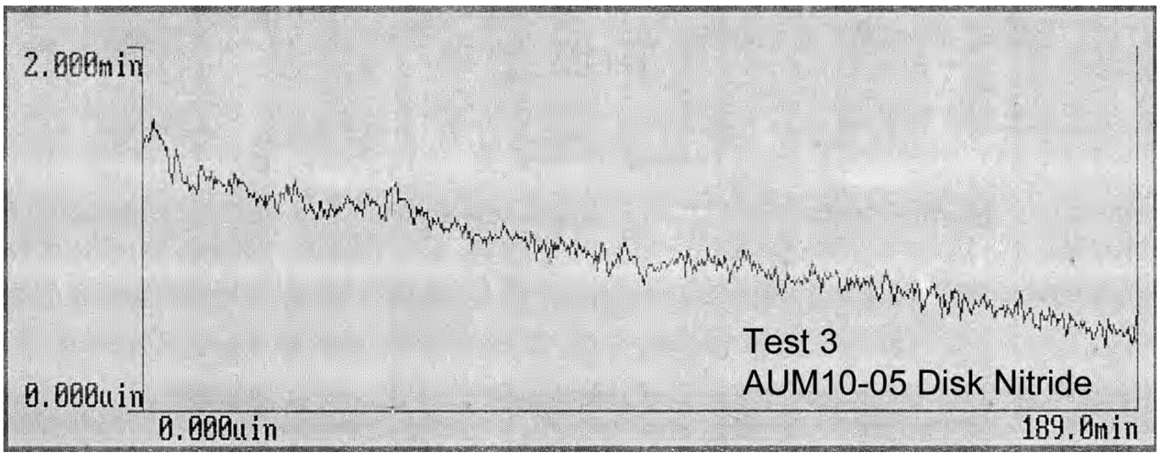

19.00min
9.000min
0.000uin
98.55min
Test 2
316L-05 Pin Non-coated

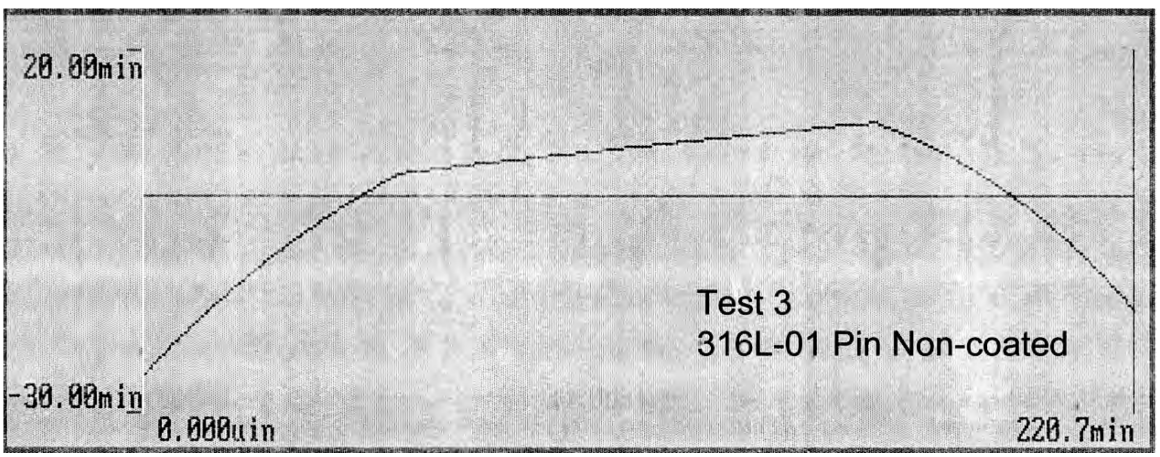
Test 3

AUM10 (Nitride Coated)

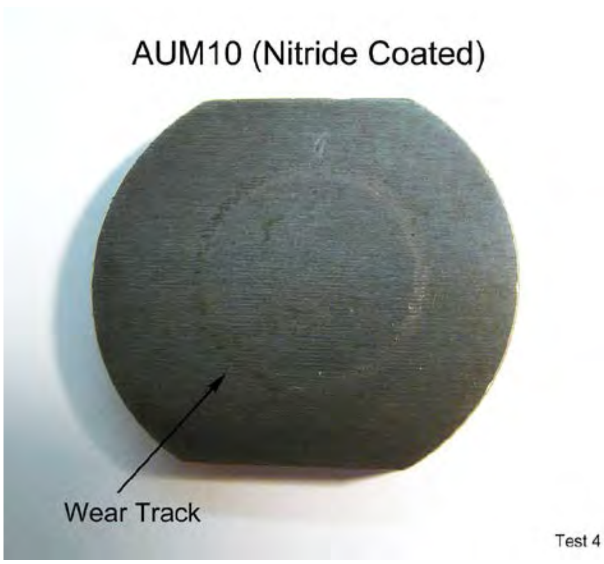


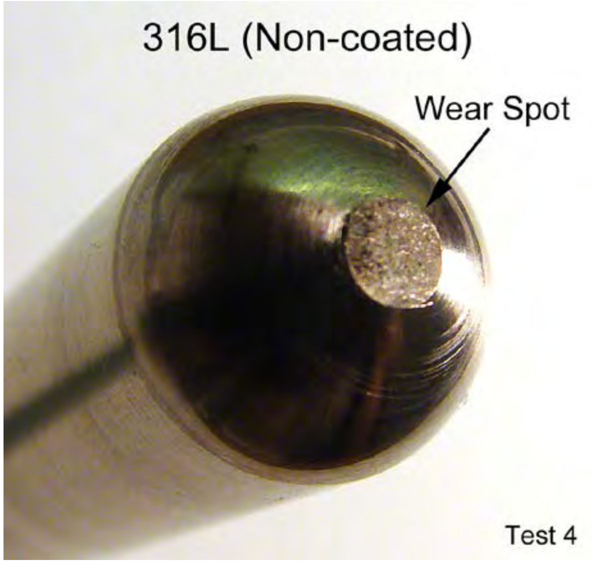


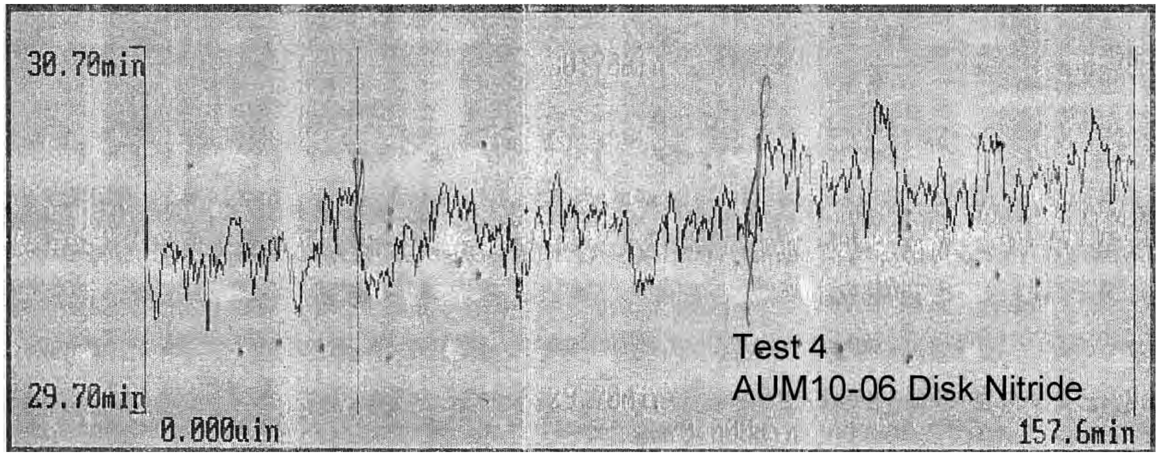


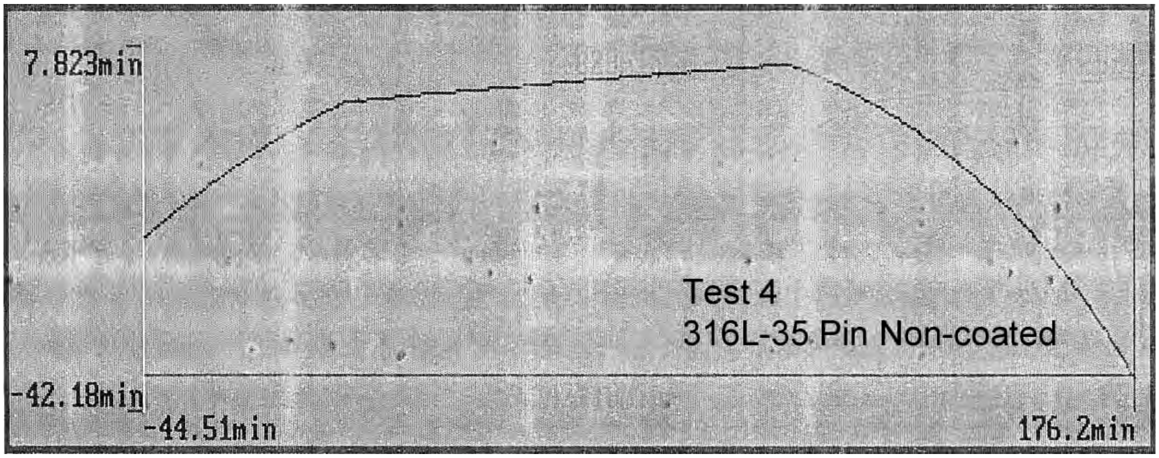


Test 4

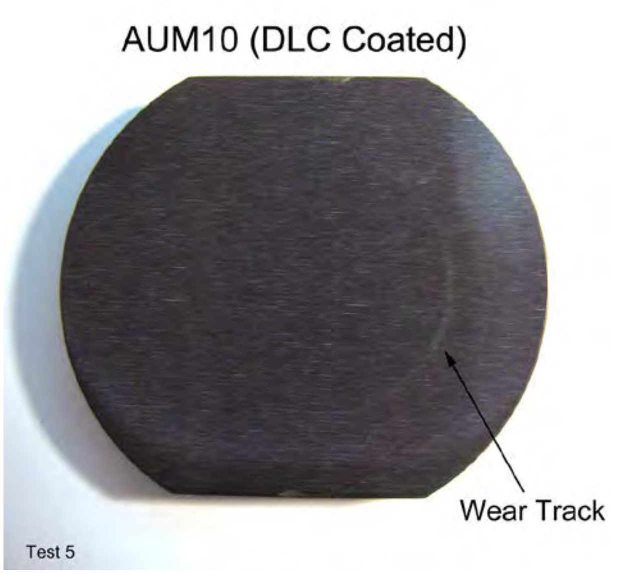

AUM10 (Nitride Coated)
Wear Track
Test 4


316L (Non-coated)
Wear Spot
Test 4

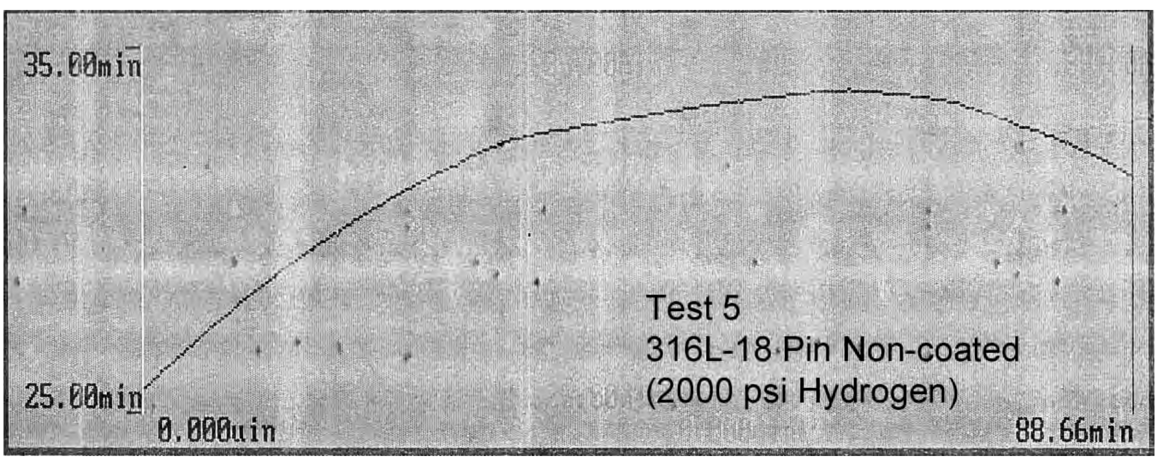

30.70min
29.70min
0.000uin
157.6min
Test 4
AUM10-06 Disk Nitride


7.823min
-42.18min
-44.51min
176.2min
Test 4
316L-35 Pin Non-coated

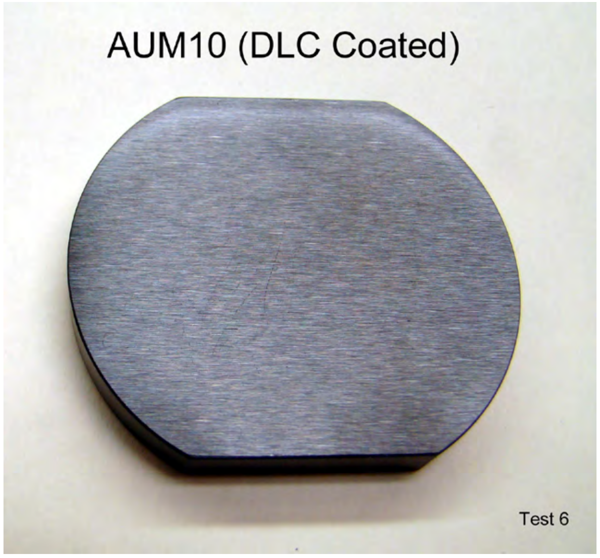
Test 5



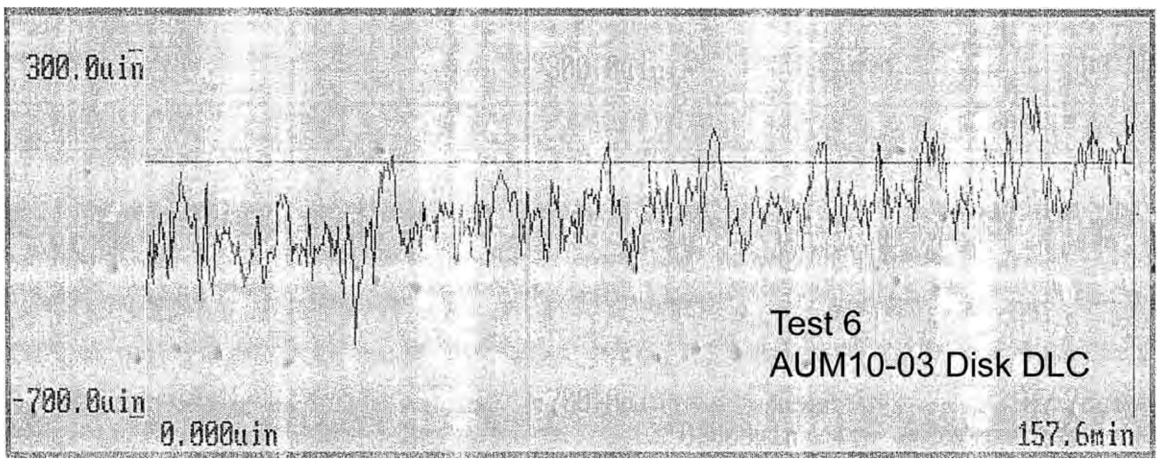
(Wear track on disk was not measurable.)

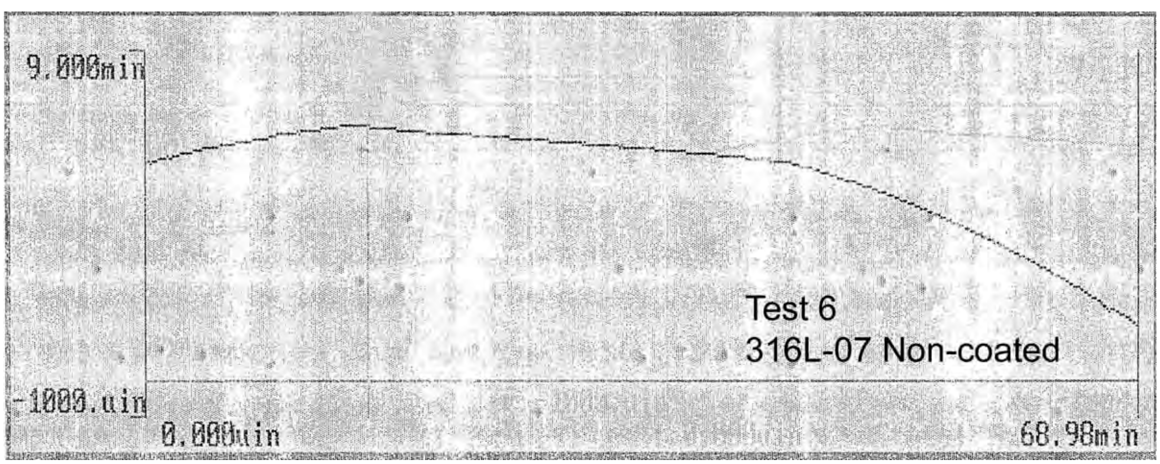


Test 6

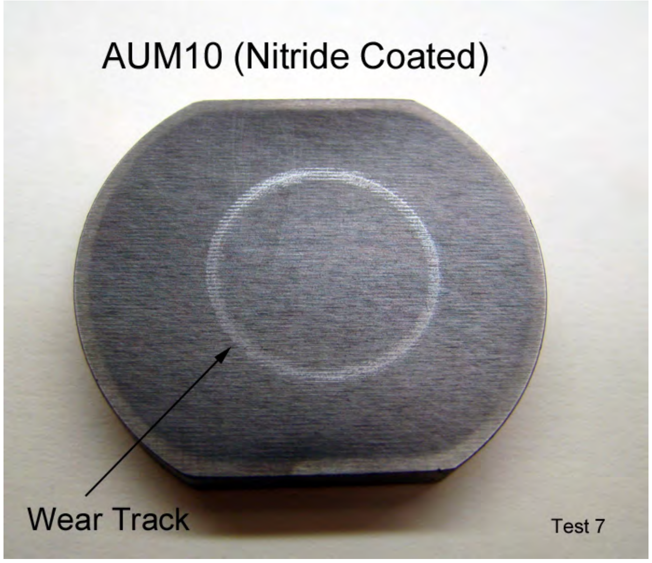

AUM10 (DLC Coated)
Test 6

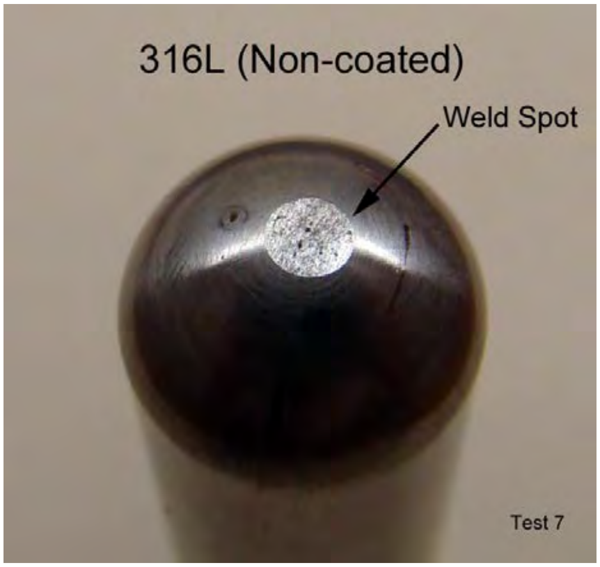

316L (Non-coated)
Wear Spot
Test 6

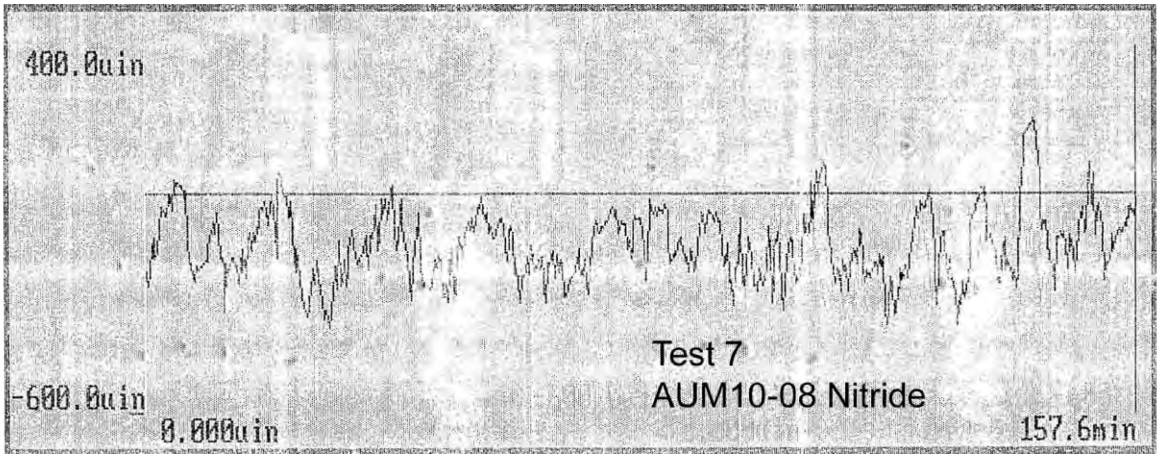

300.0uin
-700.0uin
0.000uin
157.6min
Test 6
AUM10-03 Disk DLC

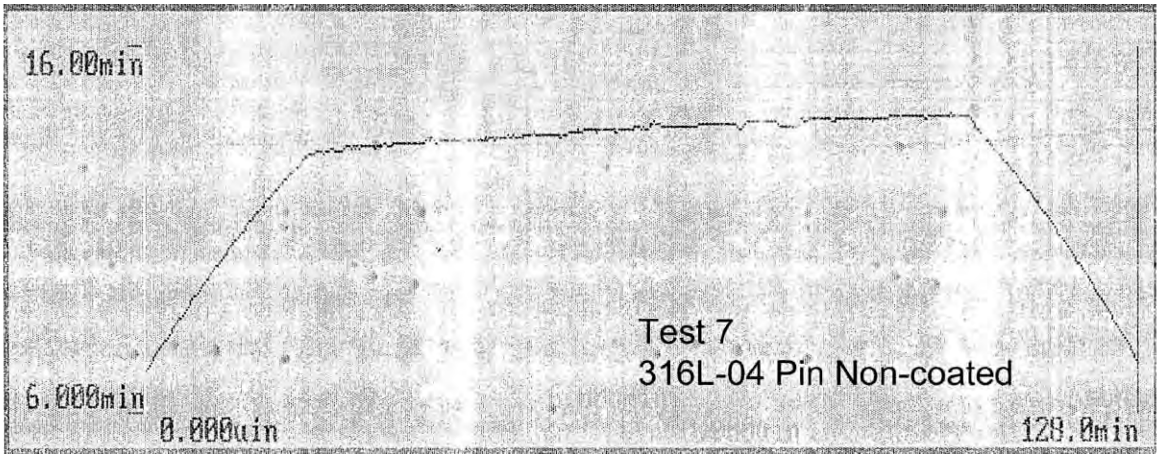

9.000min
-1000.uin
0.000uin
68.98min
Test 6
316L-07 Non-coated

Test 7

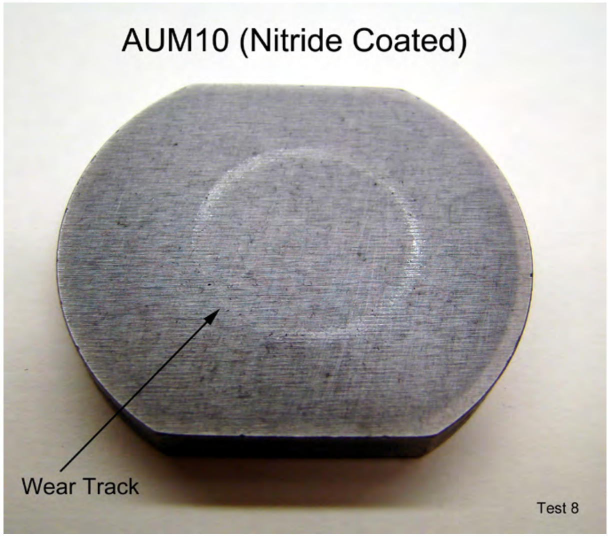

AUM10 (Nitride Coated)
Wear Track
Test 7


316L (Non-coated)
Weld Spot
Test 7

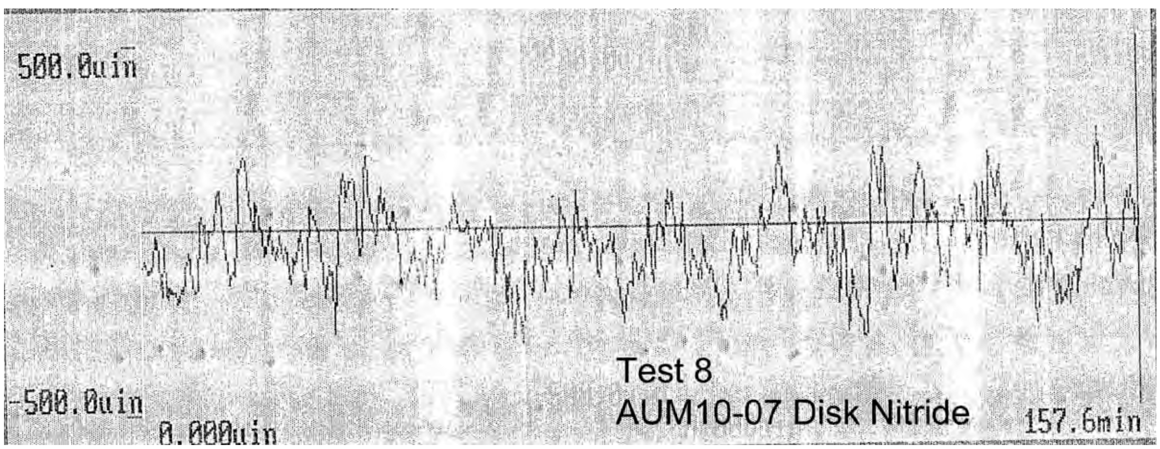

400.0uin
-600.0uin
0.000uin
157.6min
Test 7
AUM10-08 Nitride

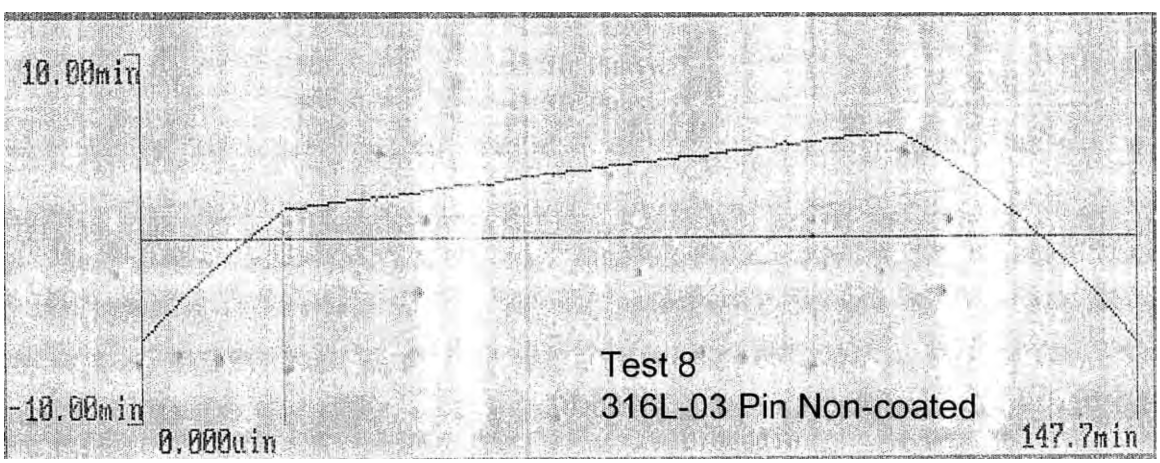

16.00min
6.000min
0.000uin
128.0min
Test 7
316L-04 Pin Non-coated

Test 8

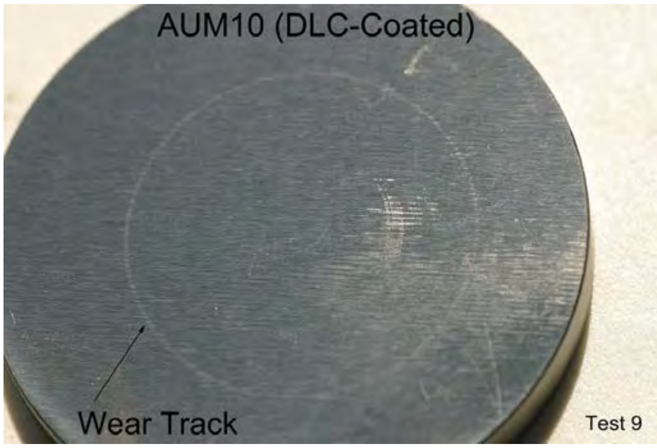

AUM10 (Nitride Coated)
Wear Track
Test 8


316L (Non-coated)
Wear Spot
Test 8

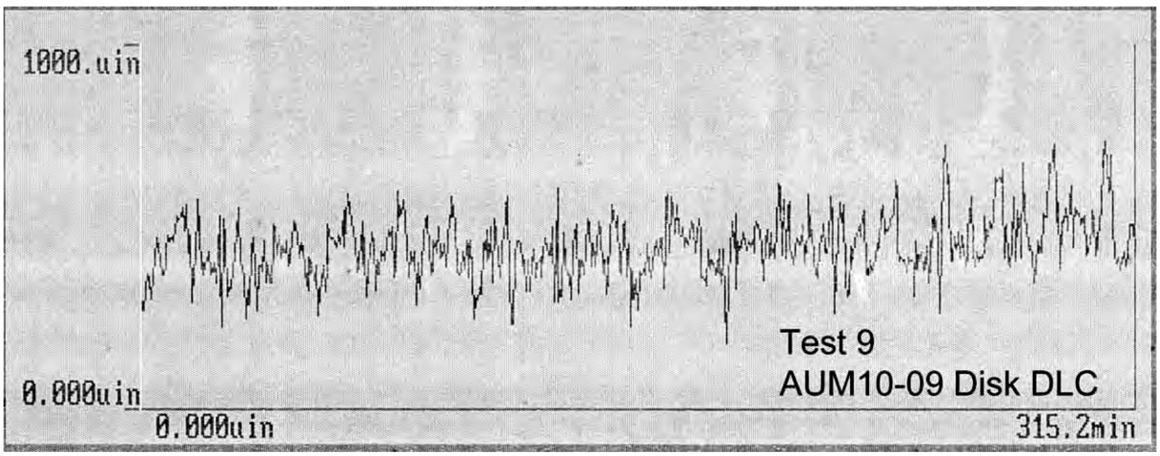

500.0uin
-500.0uin
0.000uin
Test 8
AUM10-07 Disk Nitride
157.6min

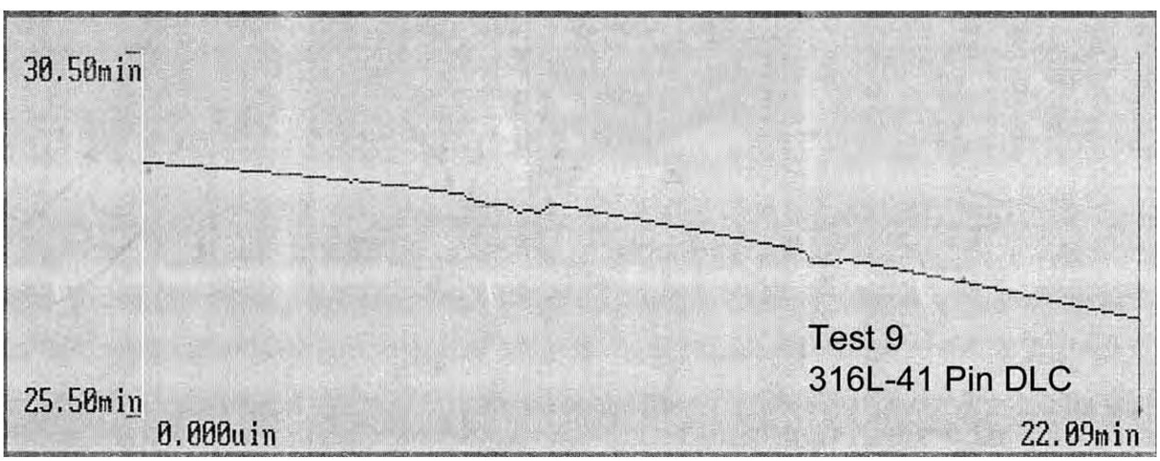

10.00min
-10.00min
0.000uin
Test 8
316L-03 Pin Non-coated
147.7min

Test 9

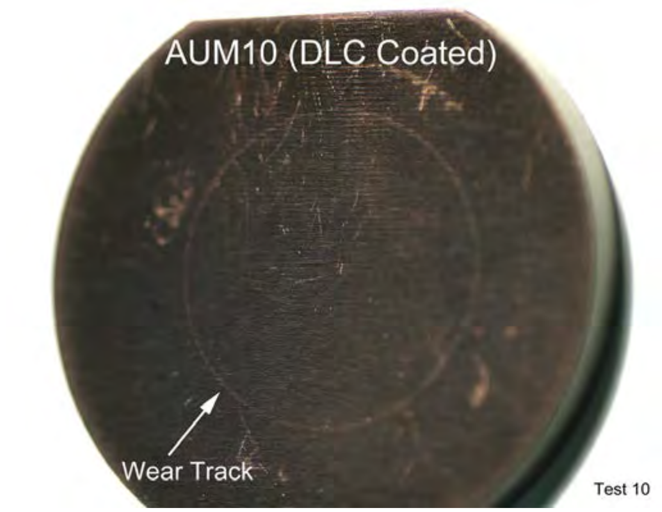

AUM10 (DLC-Coated)
Wear Track
Test 9

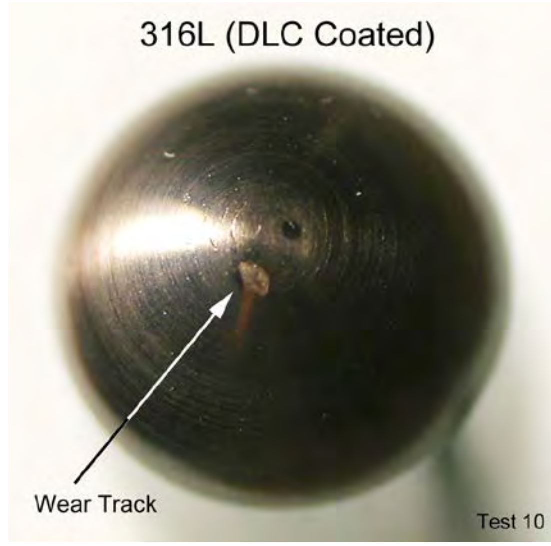

316L (DLC-Coated)
Wear Spot
Test 9

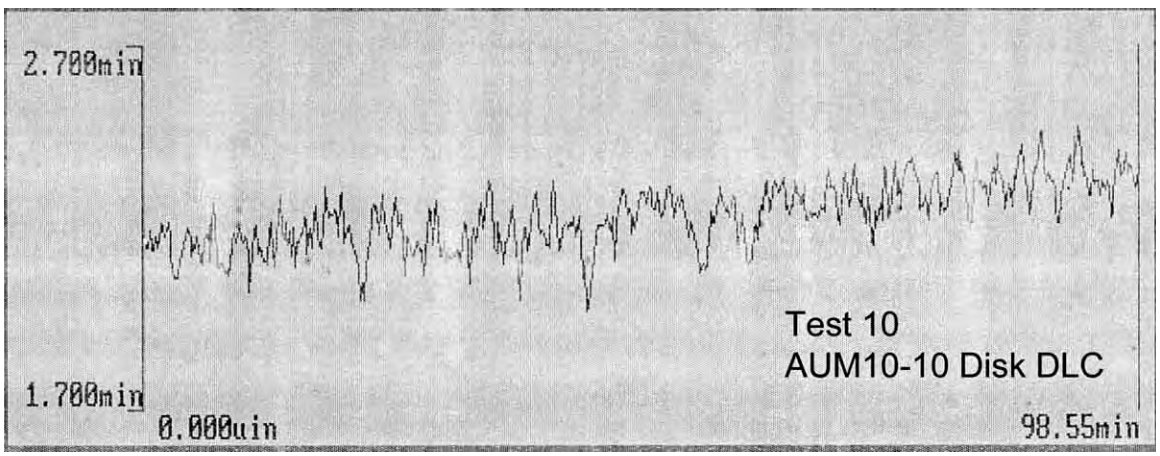

1000.uin
0.000uin
0.000uin
315.2min
Test 9
AUM10-09 Disk DLC

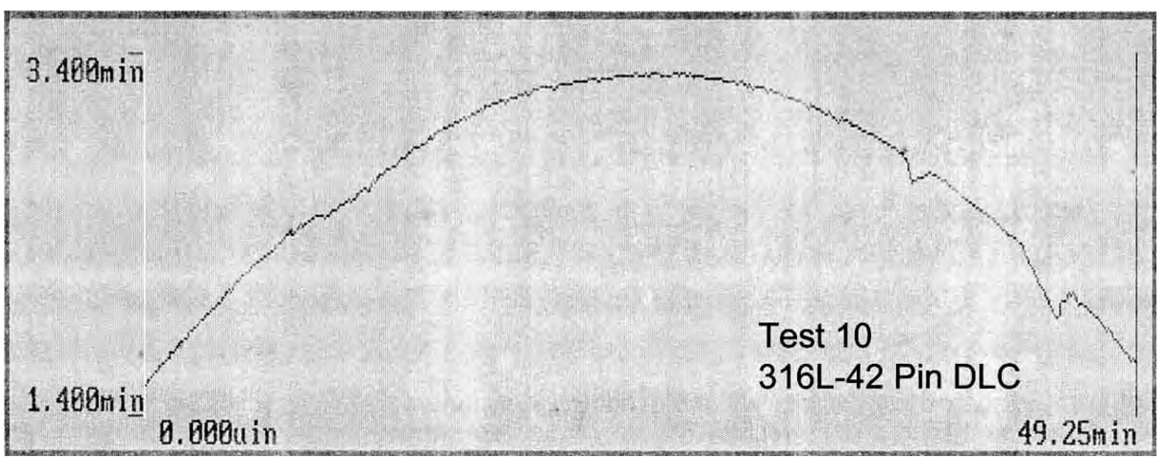

30.50min
25.50min
0.000uin
22.09min
Test 9
316L-41 Pin DLC

Test 10

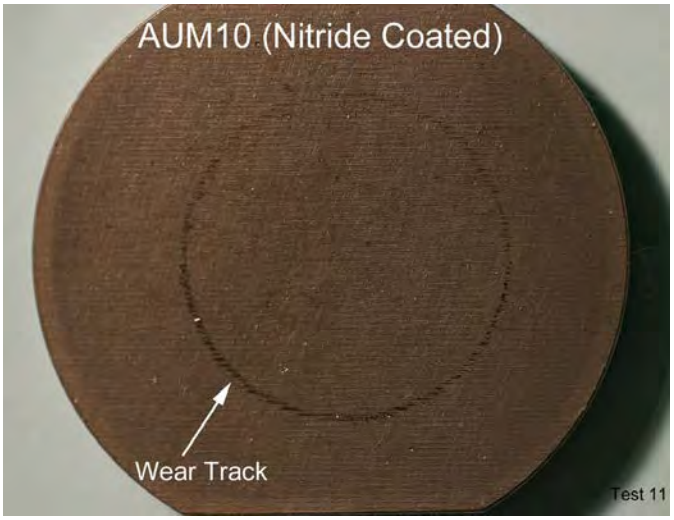

AUM10 (DLC Coated)
Wear Track
Test 10

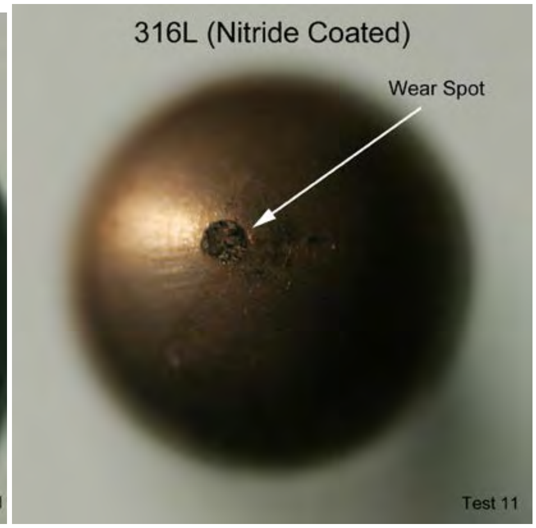

316L (DLC Coated)
Wear Track
Test 10

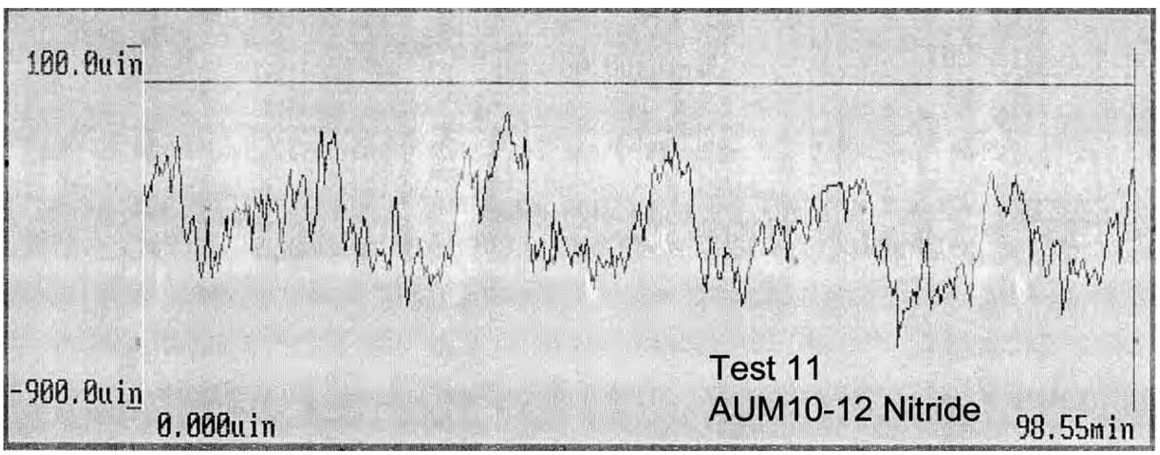

2.700min
1.700min
0.000uin
98.55min
Test 10
AUM10-10 Disk DLC

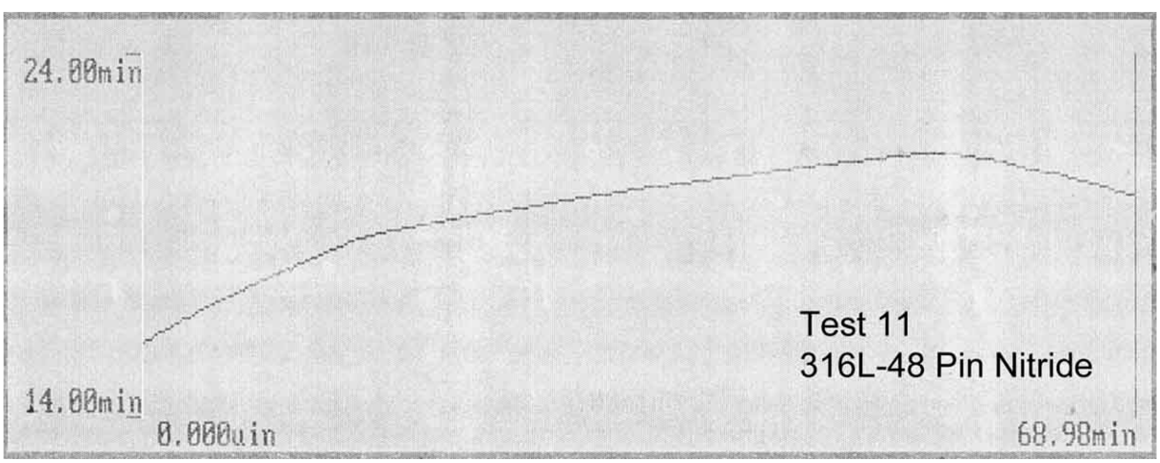

3.400min
1.400min
0.000uin
49.25min
Test 10
316L-42 Pin DLC

Test 11

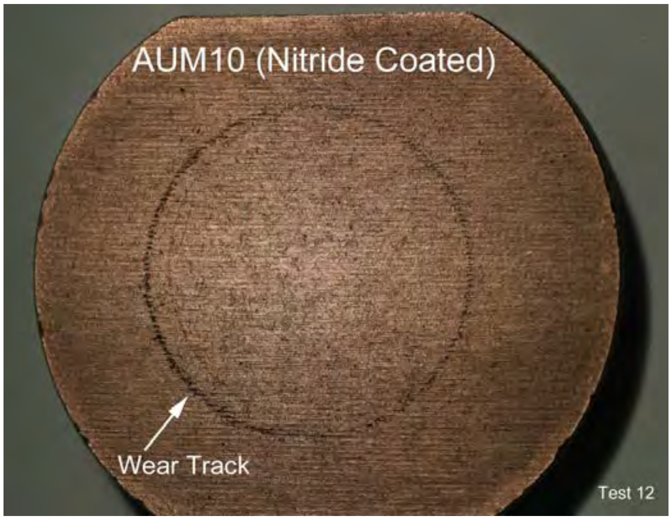

AUM10 (Nitride Coated)
Wear Track
Test 11


316L (Nitride Coated)
Wear Spot
Test 11

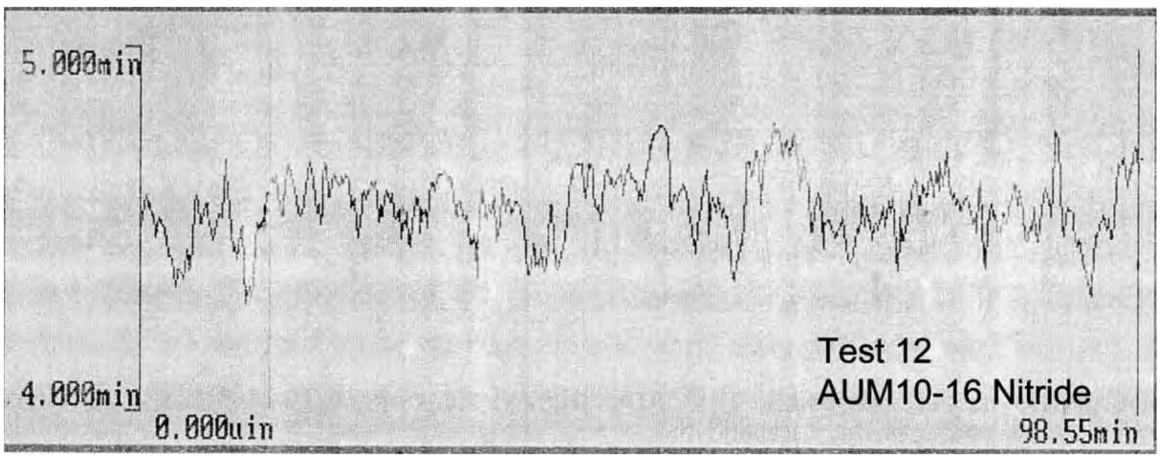

100.0uin
-900.0uin
0.000uin
Test 11
AUM10-12 Nitride
98.55min

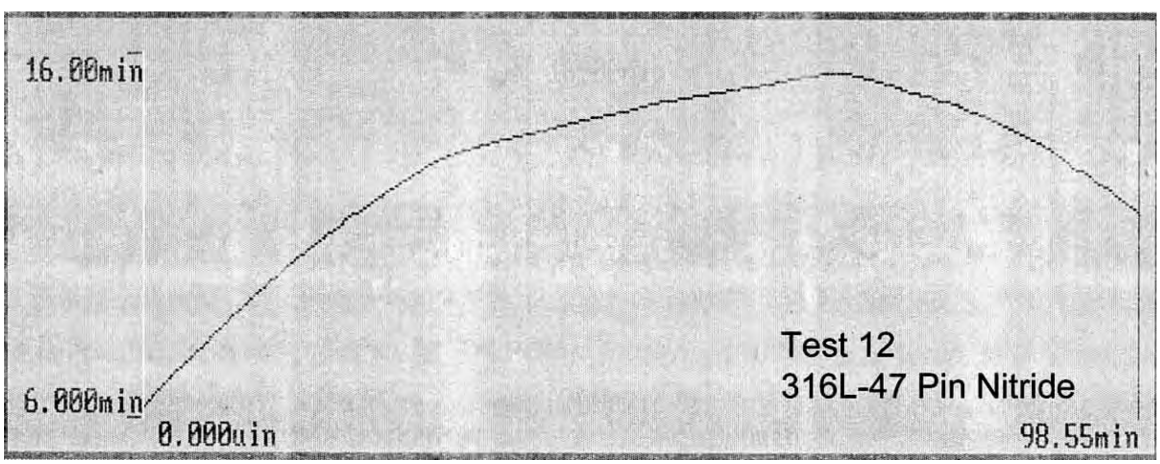

24.00min
14.00min
0.000uin
Test 11
316L-48 Pin Nitride
68.98min

Test 12

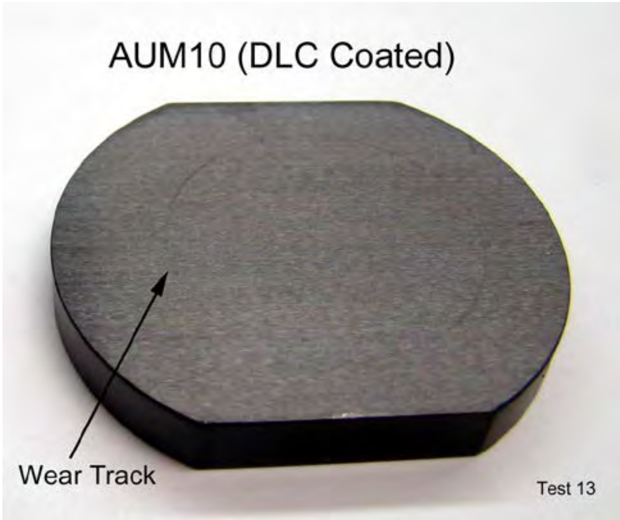

AUM10 (Nitride Coated)
Wear Track
Test 12


316L (Nitride Coated)
Wear Spot
Test 12

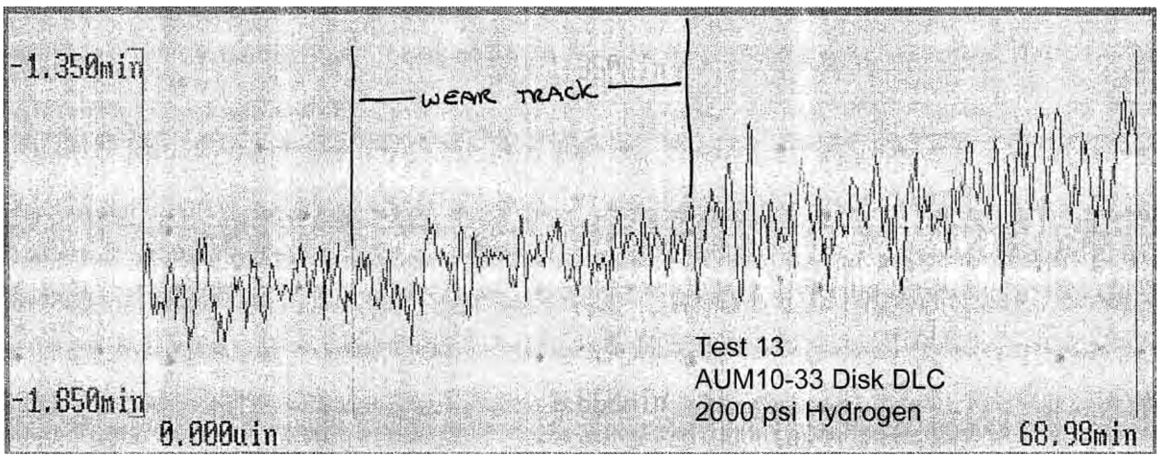

5.000min
4.000min
0.000uin
Test 12
AUM10-16 Nitride
98.55min

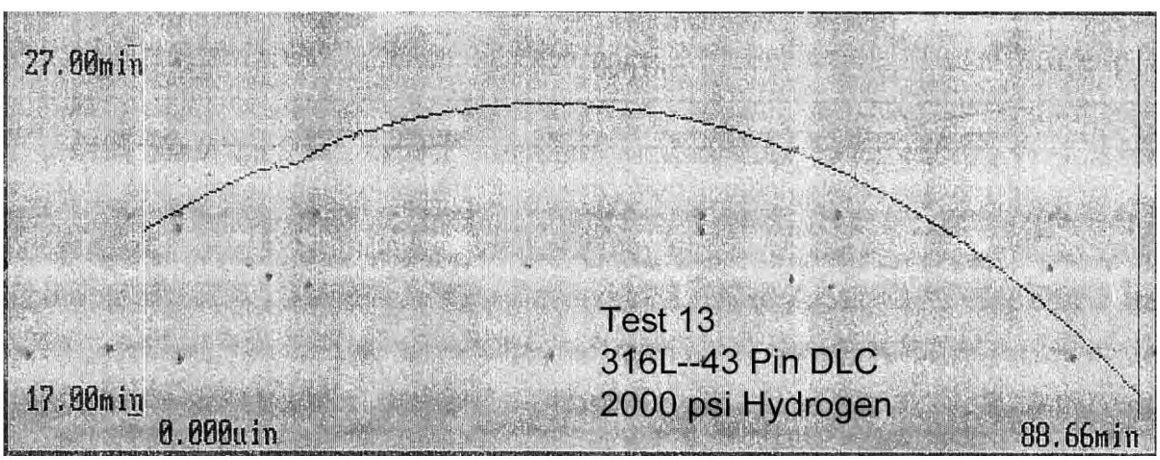

16.00min
6.000min
0.000uin
Test 12
316L-47 Pin Nitride
98.55min

Test 13

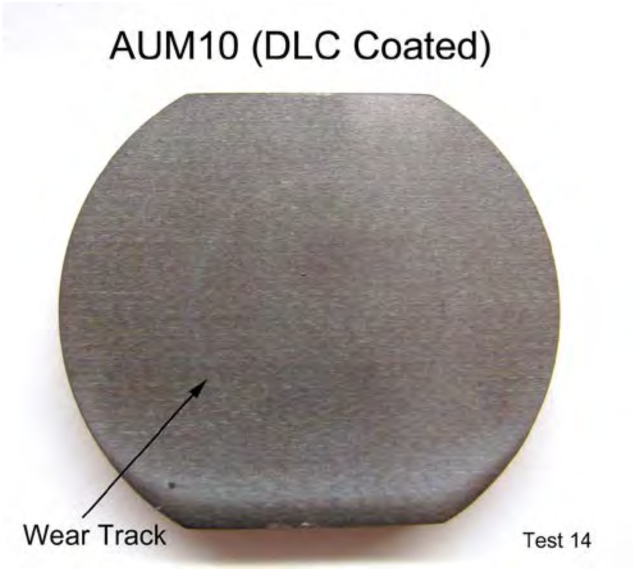

AUM10 (DLC Coated)
Wear Track
Test 13


316L (DLC Coated)
Wear Spot
Test 13

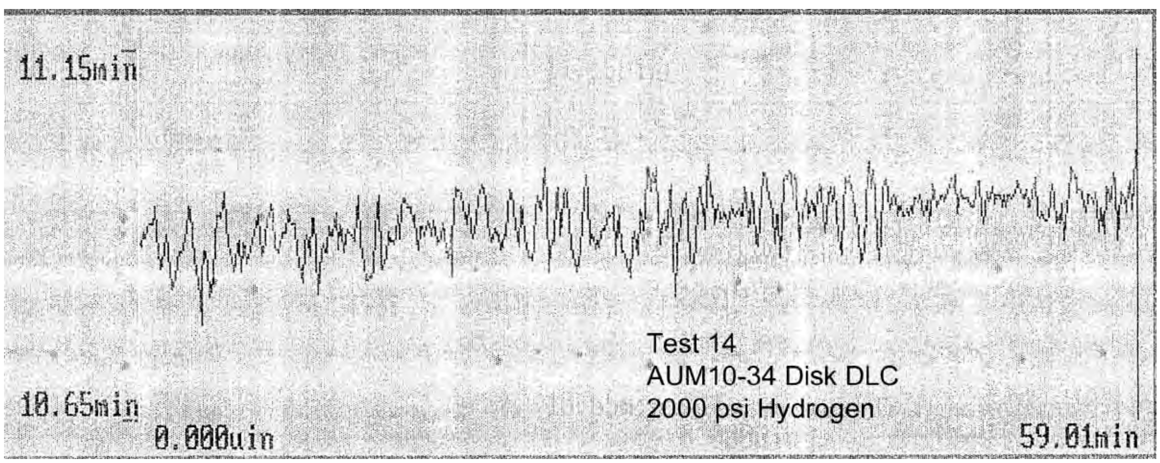

-1.350min
WEAR TRACK
-1.850min
0.000uin
Test 13
AUM10-33 Disk DLC
2000 psi Hydrogen
68.98min

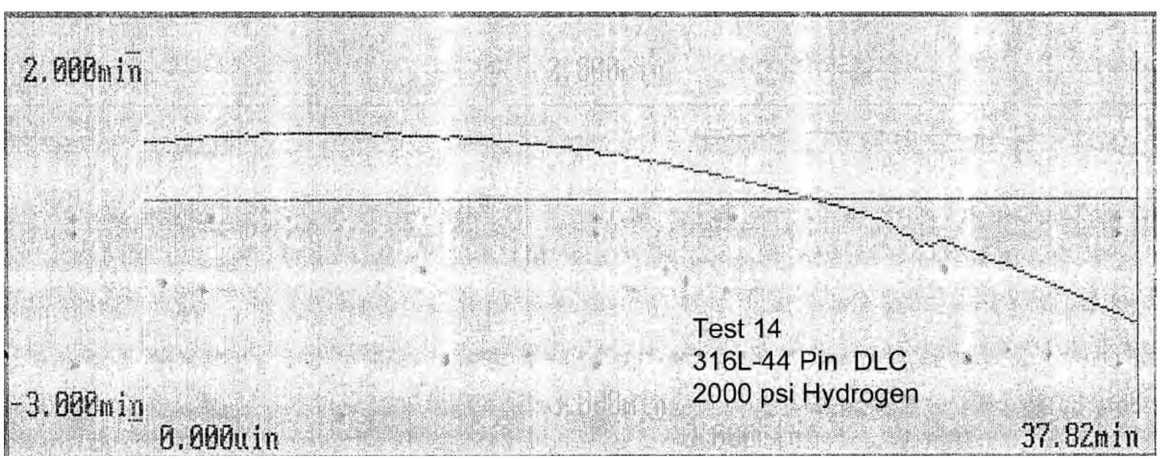

27.00min
17.00min
0.000uin
Test 13
316L--43 Pin DLC
2000 psi Hydrogen
88.66min

Test 14

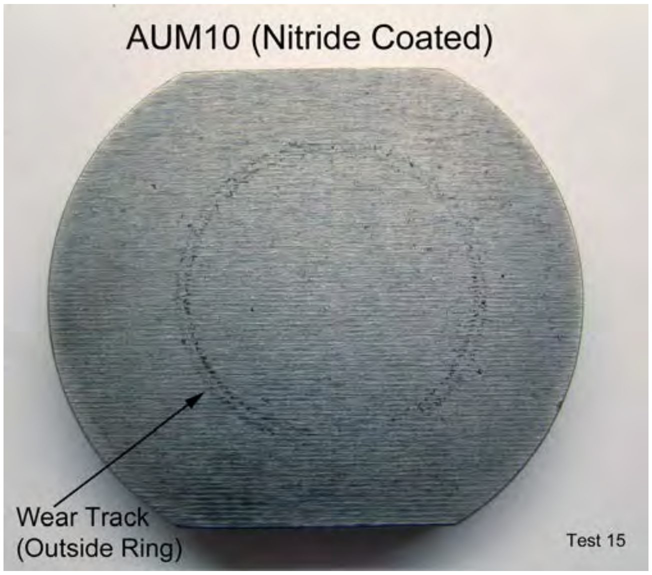

AUM10 (DLC Coated)
Wear Track
Test 14


316L (DLC Coated)
Wear Spot
Test 14

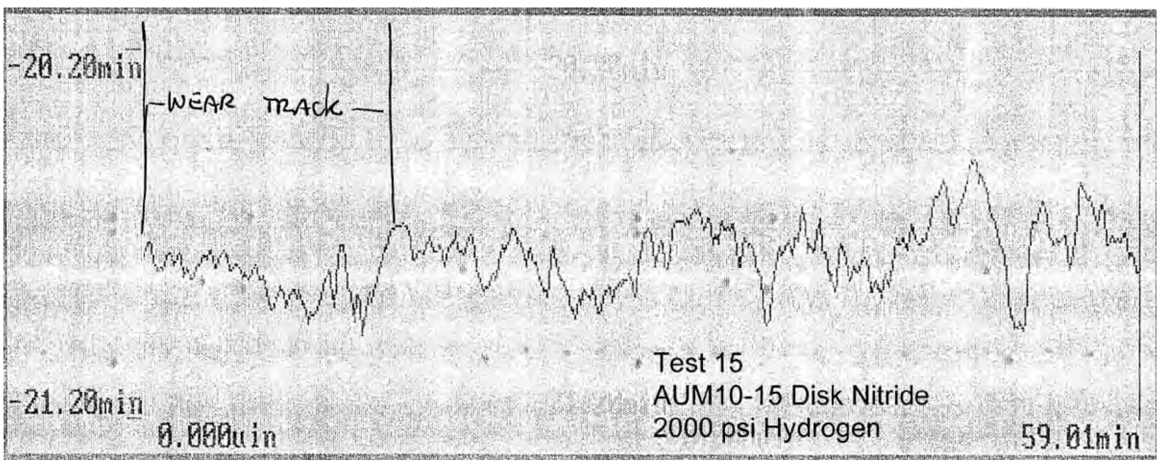

11.15min
10.65min
0.000uin
59.01min
Test 14
AUM10-34 Disk DLC
2000 psi Hydrogen

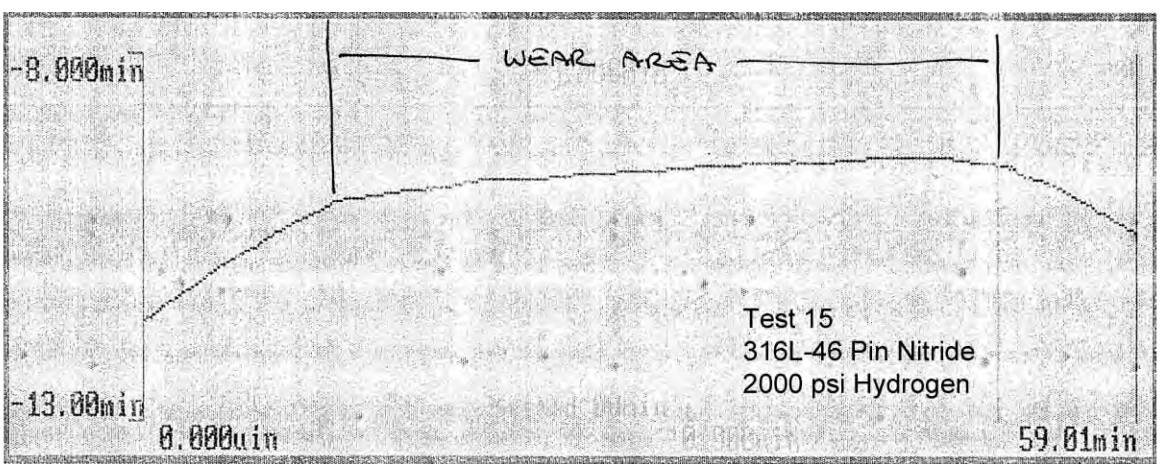

2.000min
-3.000min
0.000uin
37.82min
Test 14
316L-44 Pin DLC
2000 psi Hydrogen

Test 15

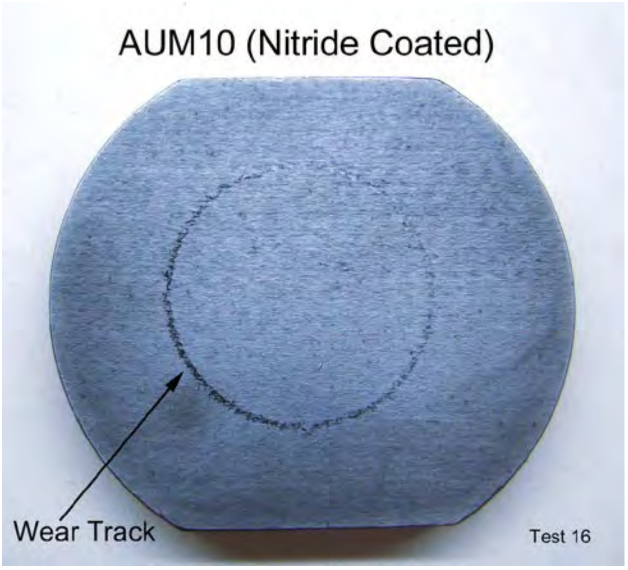

AUM10 (Nitride Coated)
Wear Track
(Outside Ring)
Test 15

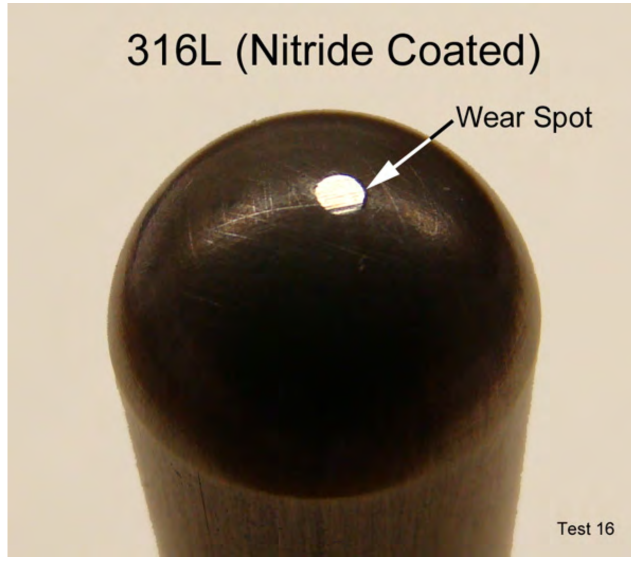

316L (Nitride Coated)
Wear Spot
Test 15

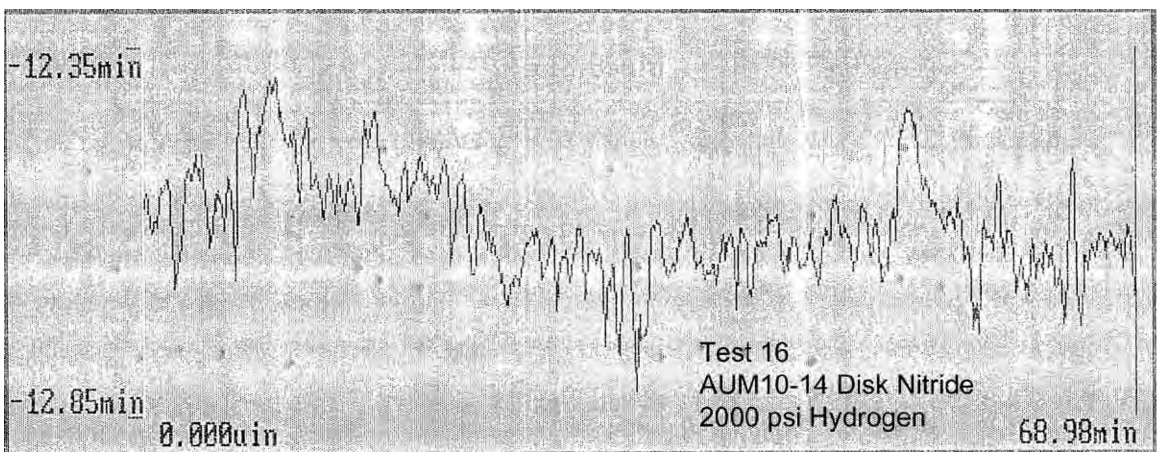

-20.20min
WEAR TRACK
-21.20min
0.000uin
Test 15
AUM10-15 Disk Nitride
2000 psi Hydrogen
59.01min

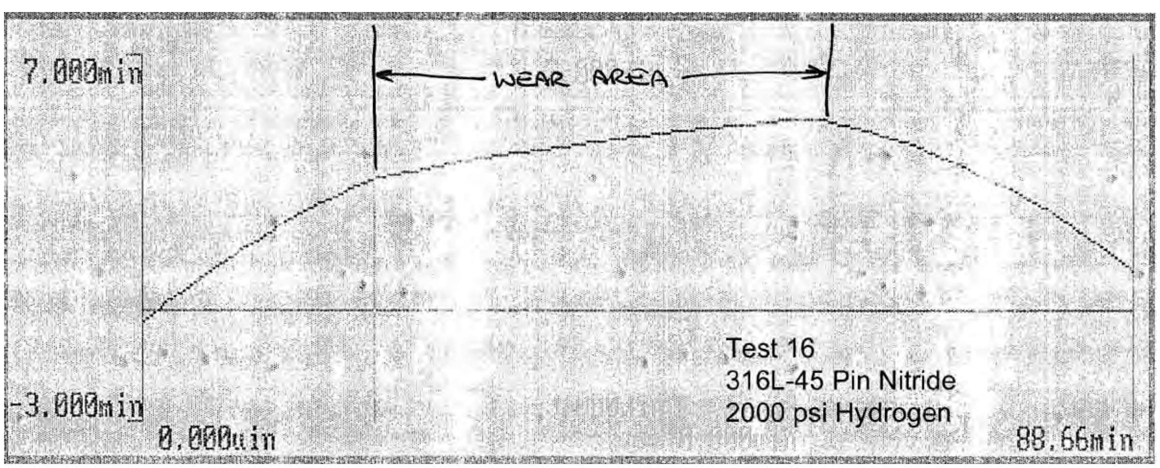

-8.000min
WEAR AREA
-13.00min
0.000uin
Test 15
316L-46 Pin Nitride
2000 psi Hydrogen
59.01min

Test 16


AUM10 (Nitride Coated)
Wear Track
Test 16


316L (Nitride Coated)
Wear Spot
Test 16

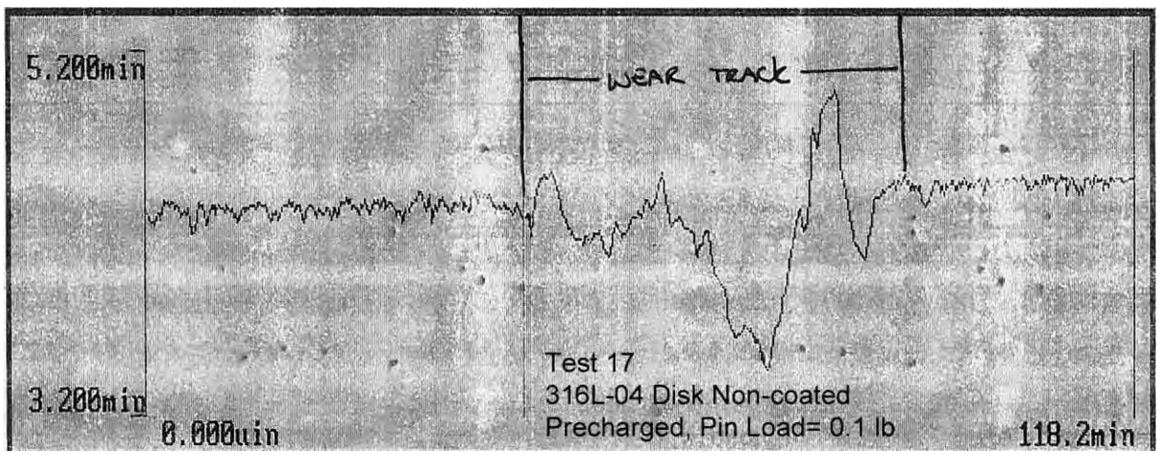

-12.35min
-12.85min
0.000uin
Test 16
AUM10-14 Disk Nitride
2000 psi Hydrogen
68.98min

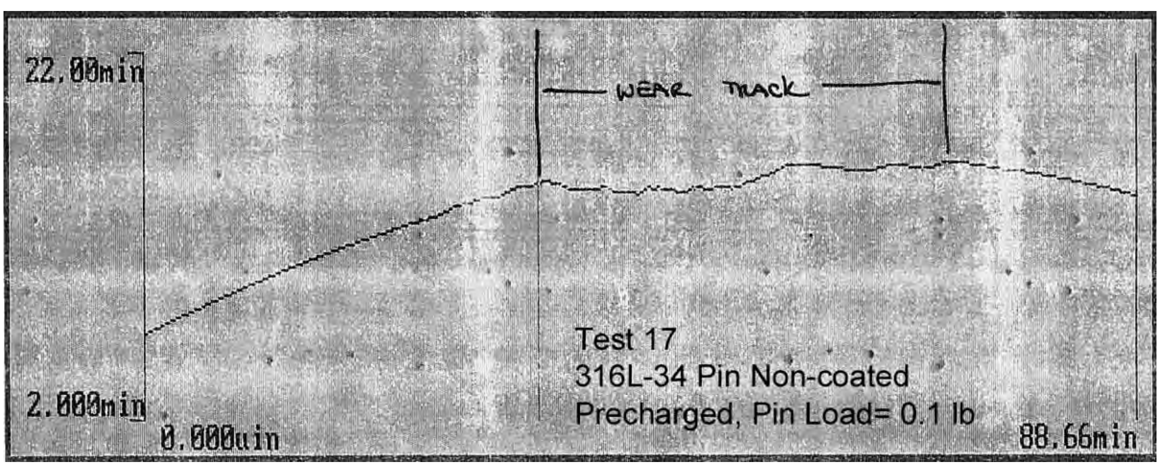

7.000min
WEAR AREA
-3.000min
0.000uin
Test 16
316L-45 Pin Nitride
2000 psi Hydrogen
88.66min

Test 17


316L (Non-coated, Precharged)
Wear Track
Test 17


316L (Non-coated, Precharged)
Wear Spot
Test 17

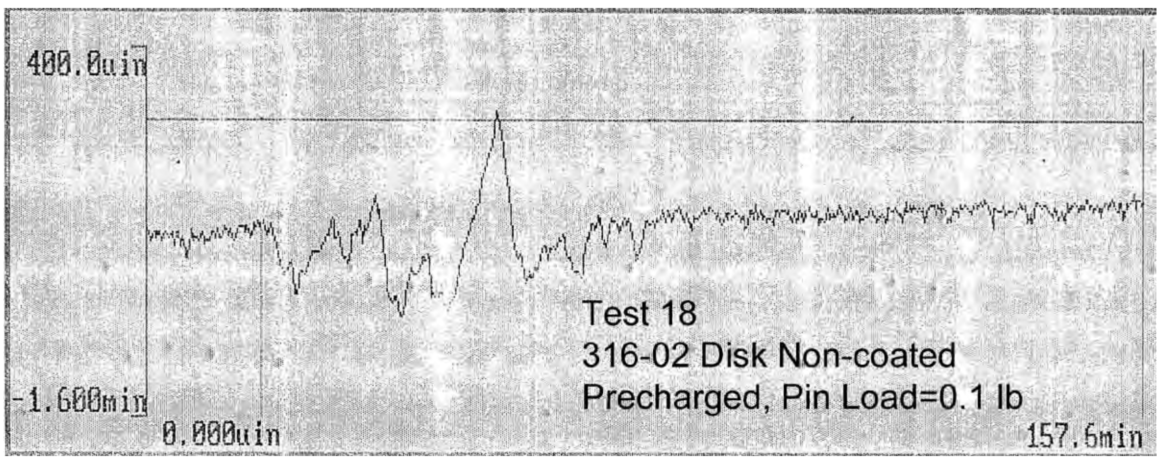

5.200min
3.200min
0.000uin
118.2min
WEAR TRACK
Test 17
316L-04 Disk Non-coated
Precharged, Pin Load= 0.1 lb

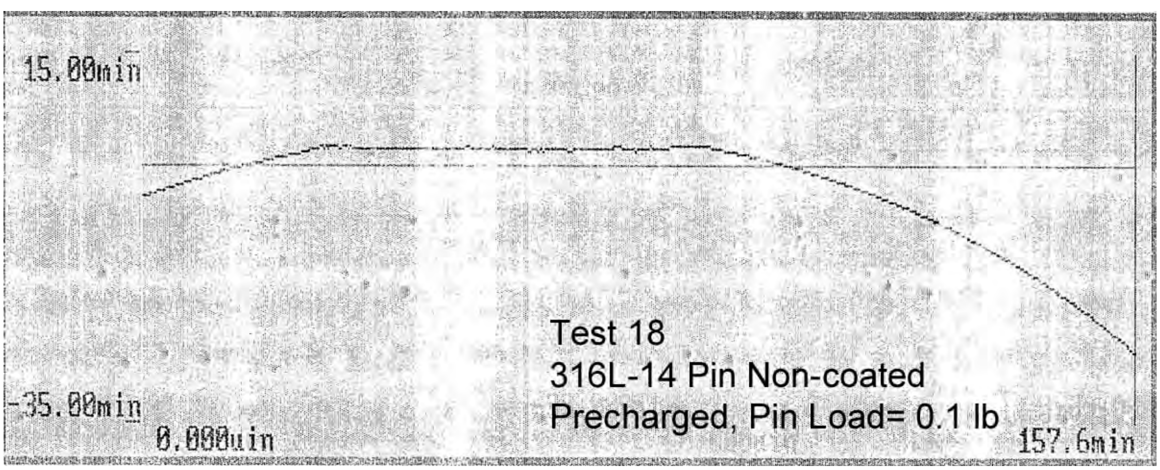

22.00min
2.000min
0.000uin
88.66min
WEAR TRACK
Test 17
316L-34 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 18


316L (Non-coated, Precharged)
Wear Track
Test 18


316L (Non-coated, Precharged)
Wear Spot
Test 18

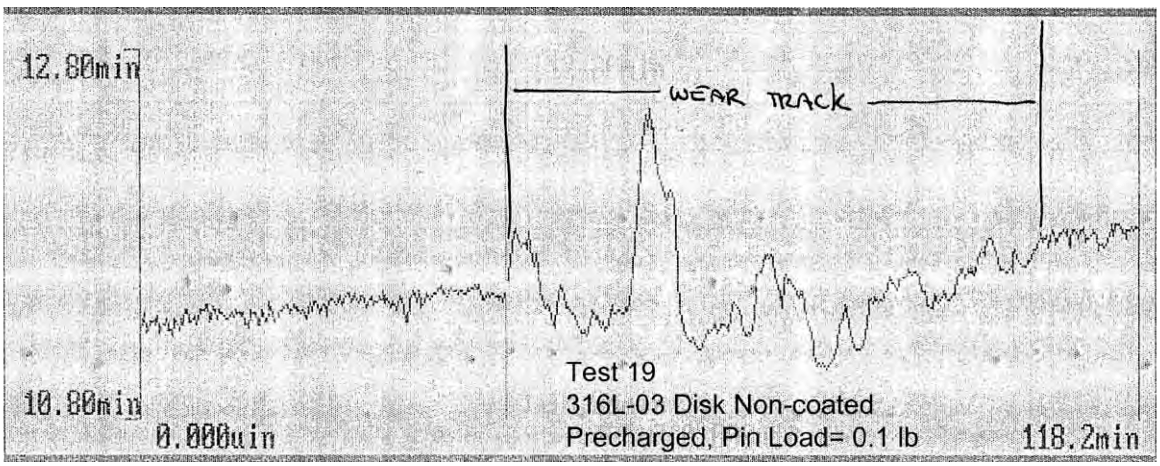

400.0uin
-1.600min
0.000uin
157.6min
Test 18
316-02 Disk Non-coated
Precharged, Pin Load=0.1 lb

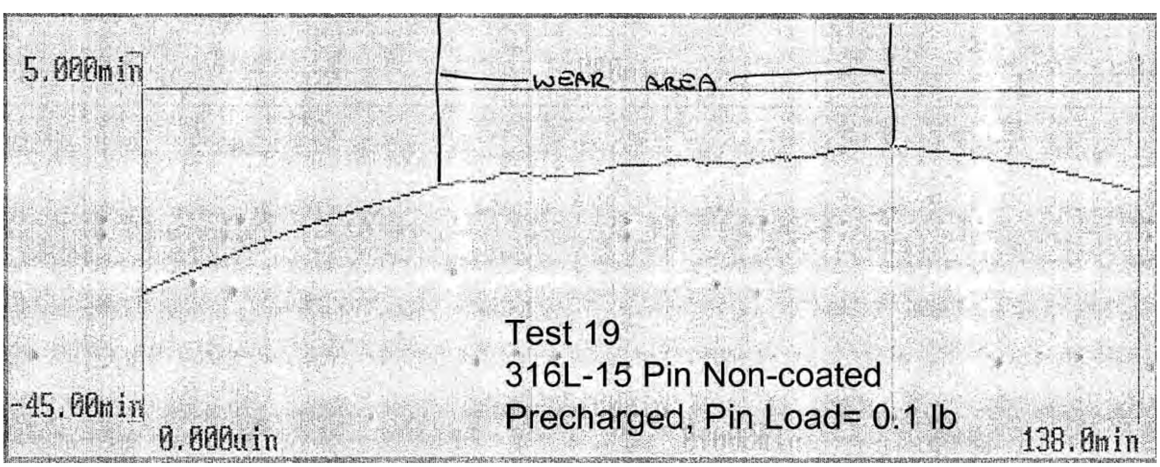

15.00min
-35.00min
0.000uin
157.6min
Test 18
316L-14 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 19

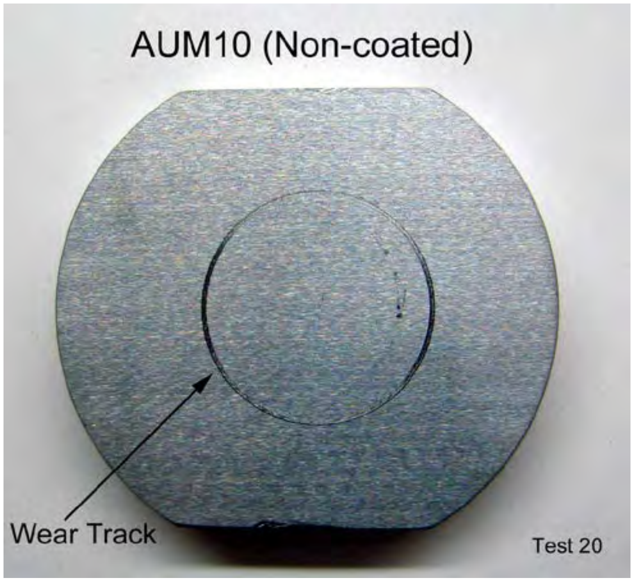

316L (Non-coated, Precharged)
Wear Track
Test 19


316L (Non-coated, Precharged)
Wear Spot
Test 19

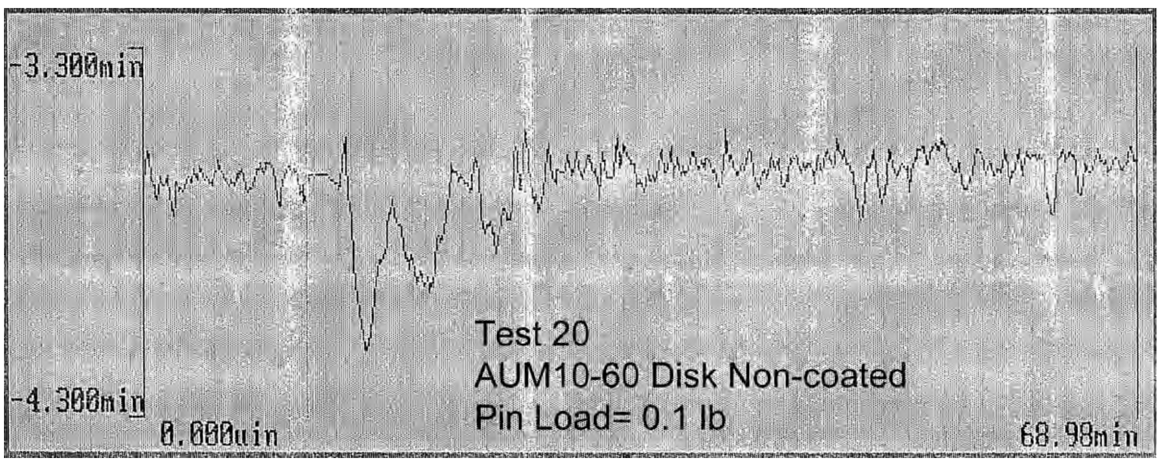

12.80min
WEAR TRACK
10.80min
0.000uin
Test 19
316L-03 Disk Non-coated
Precharged, Pin Load= 0.1 lb
118.2min

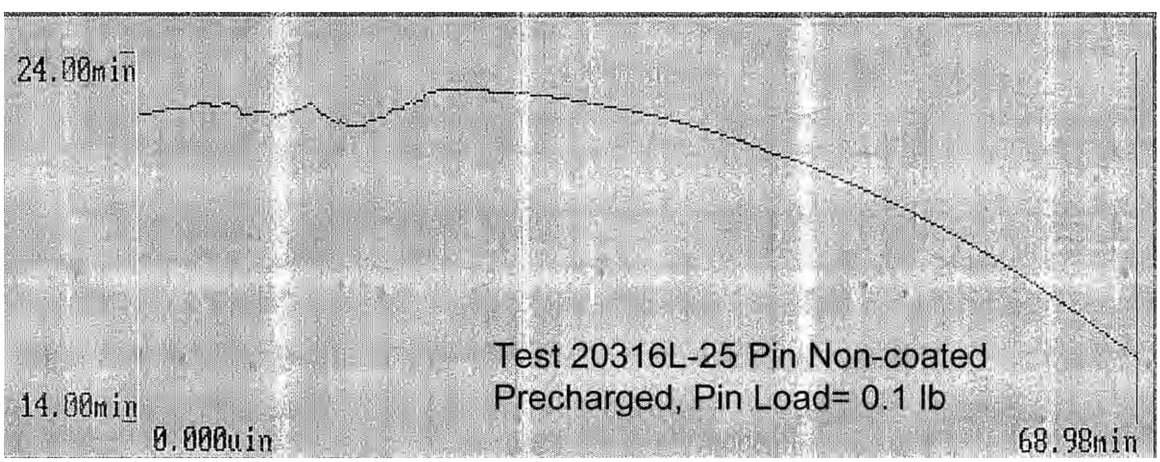

5.000min
WEAR AREA
-45.00min
0.000uin
Test 19
316L-15 Pin Non-coated
Precharged, Pin Load= 0.1 lb
138.0min

Test 20

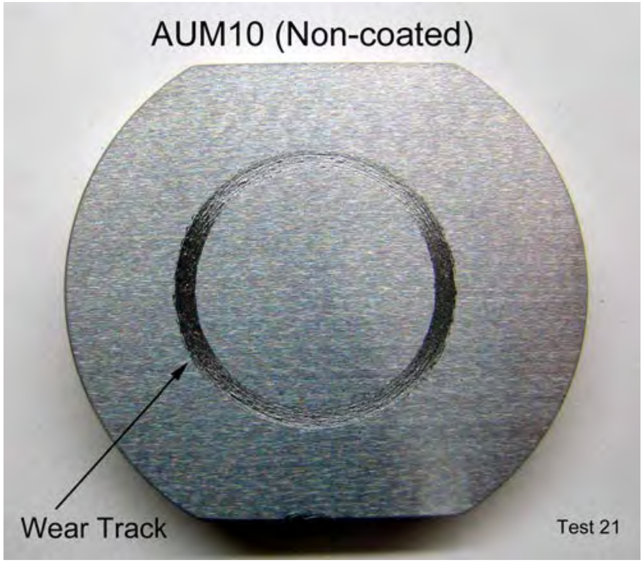

AUM10 (Non-coated)
Wear Track
Test 20


316L (Non-coated, Precharged)
Wear Spot
Test 20

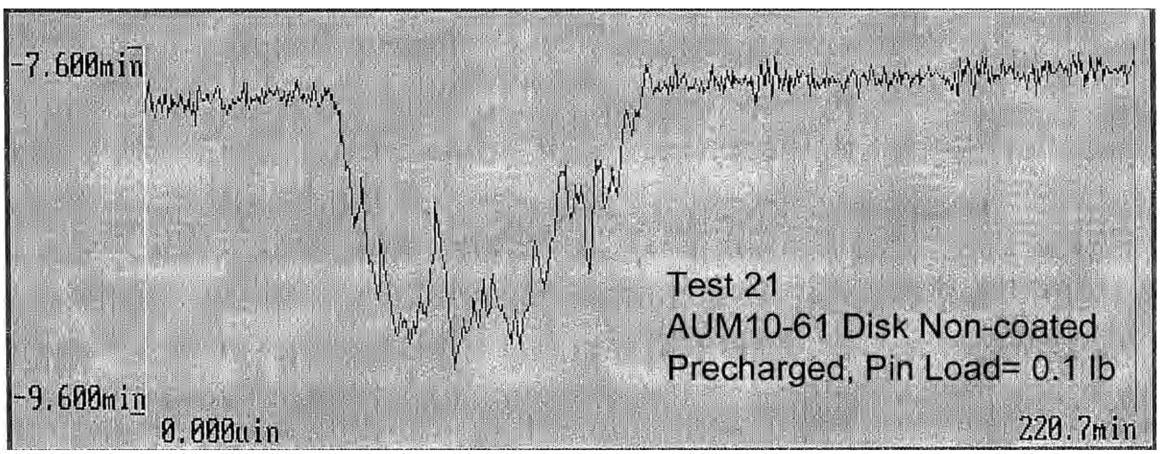

-3.300min
-4.300min
0.000uin
68.98min
Test 20
AUM10-60 Disk Non-coated
Pin Load= 0.1 lb

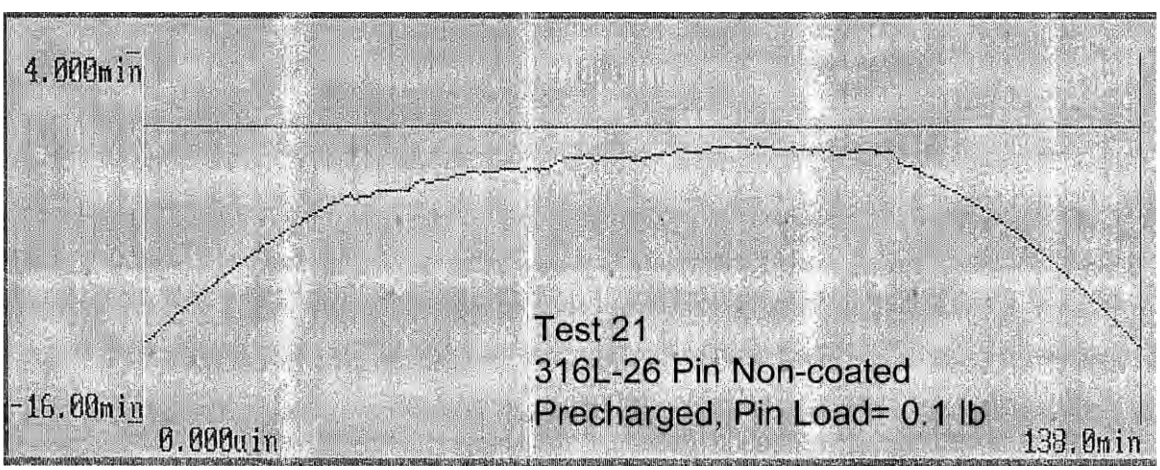

24.00min
14.00min
0.000uin
68.98min
Test 20316L-25 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 21

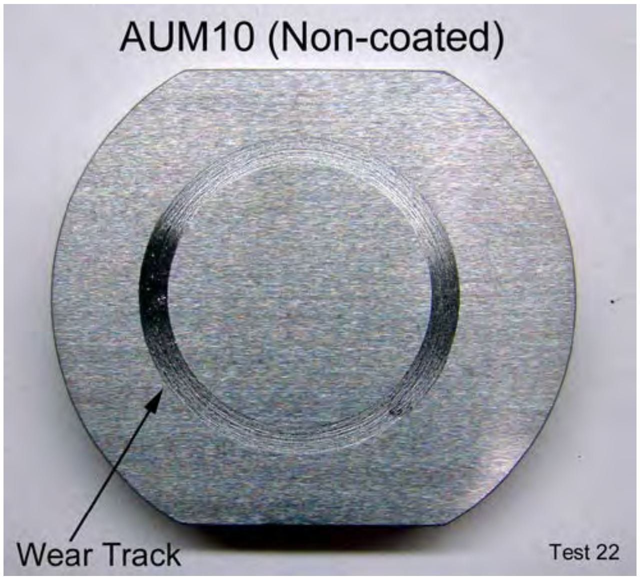

AUM10 (Non-coated)
Wear Track
Test 21


316L (Non-coated, Precharged)
Wear Spot
Test 21

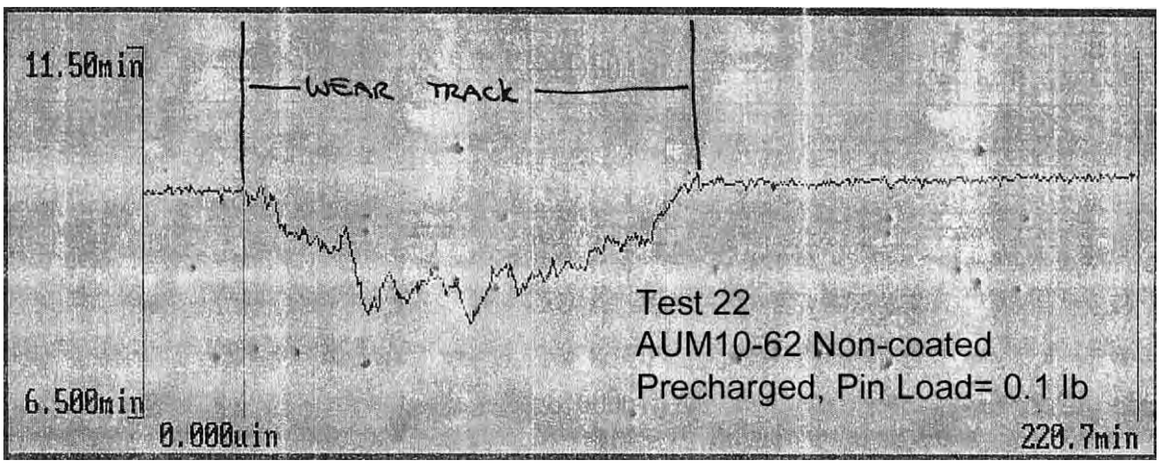

-7.600min
-9.600min
0.000uin
220.7min
Test 21
AUM10-61 Disk Non-coated
Precharged, Pin Load= 0.1 lb

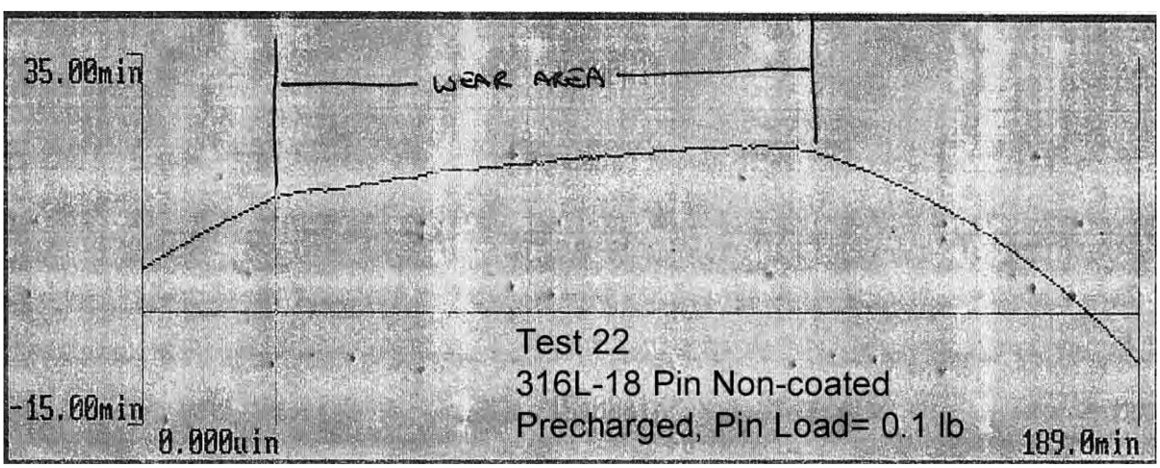

4.000min
-16.00min
0.000uin
138.0min
Test 21
316L-26 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 22

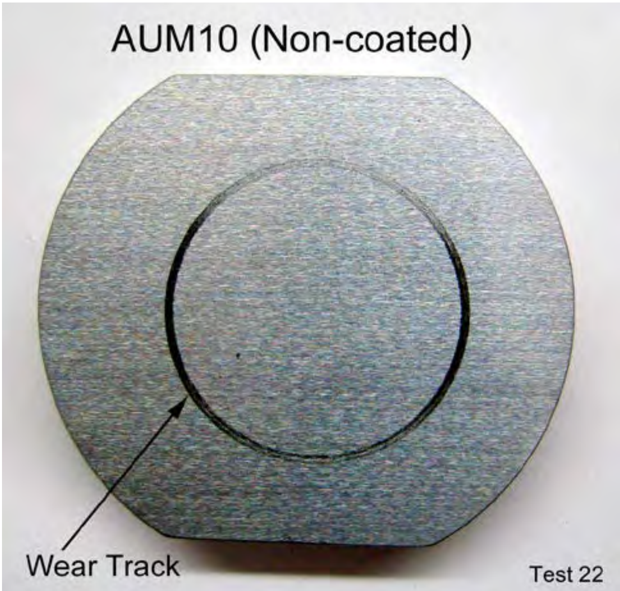

AUM10 (Non-coated)
Wear Track
Test 22


316L (Non-coated, Precharged)
Wear Spot
Test 22

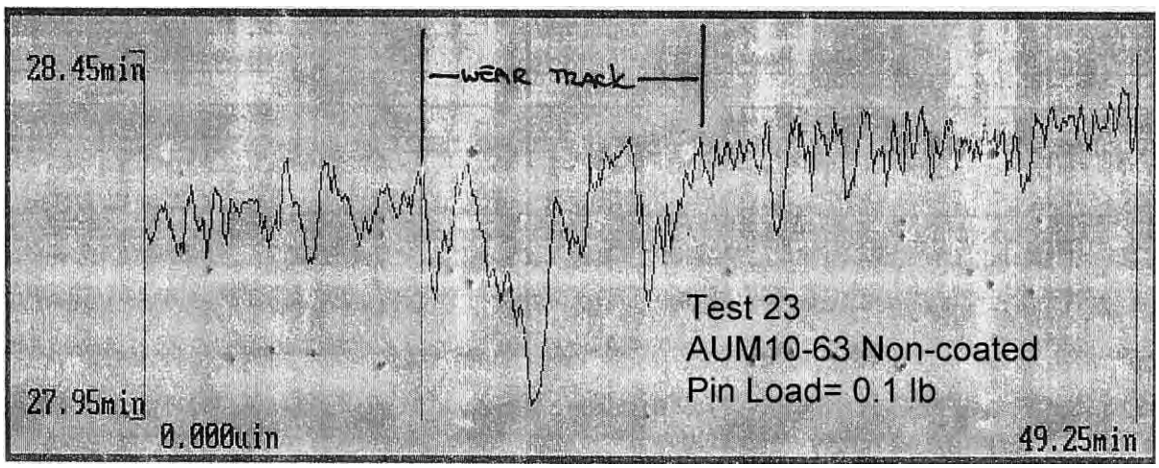

11.50min
WEAR TRACK
6.500min
0.000uin
220.7min
Test 22
AUM10-62 Non-coated
Precharged, Pin Load= 0.1 lb

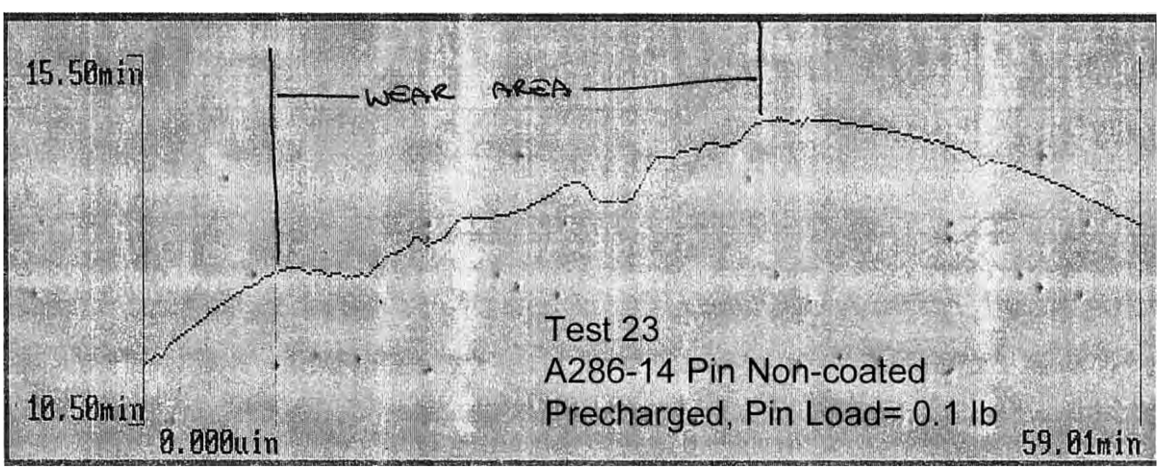

35.00min
WEAR AREA
-15.00min
0.000uin
189.0min
Test 22
316L-18 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 23


AUM10 (Non-coated)
Wear Track
Test 22


A286 (Non-coated, Precharged)
Wear Spot
Test 23

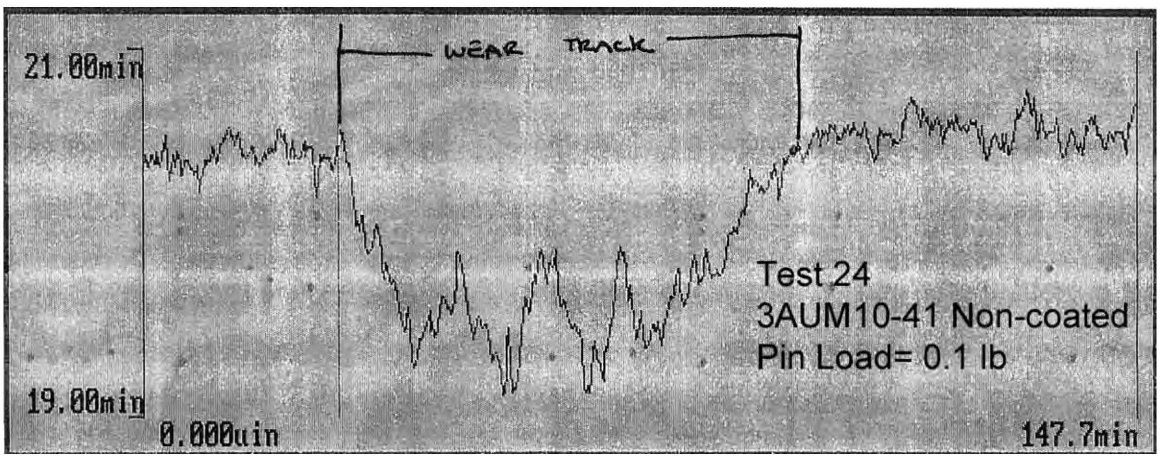

28.45min
27.95min
0.000uin
49.25min
WEAR TRACK
Test 23
AUM10-63 Non-coated
Pin Load= 0.1 lb

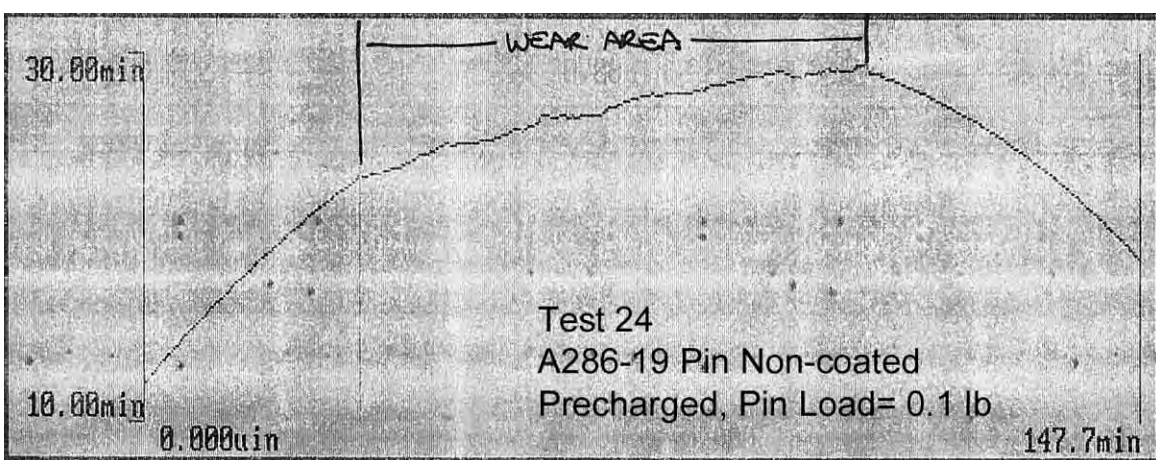

15.50min
10.50min
0.000uin
59.01min
WEAR AREA
Test 23
A286-14 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 24

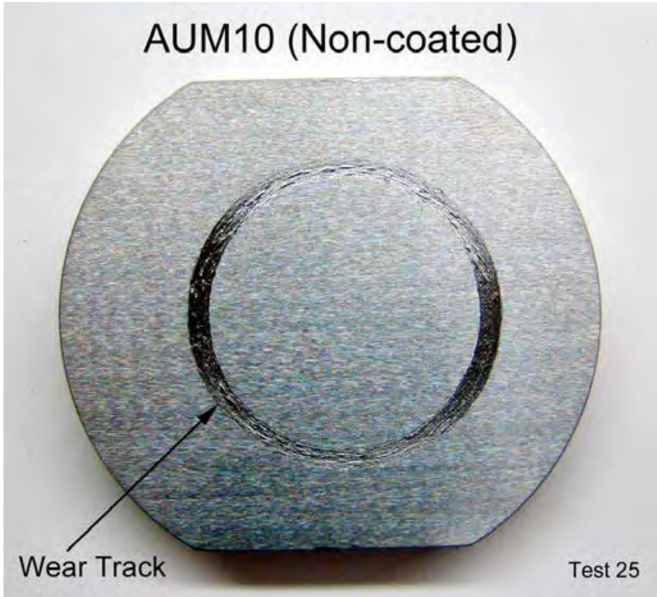

AUM10 (Non-coated)
Wear Track
Test 24


A286 (Non-coated, Precharged)
Wear Spot
Test 24

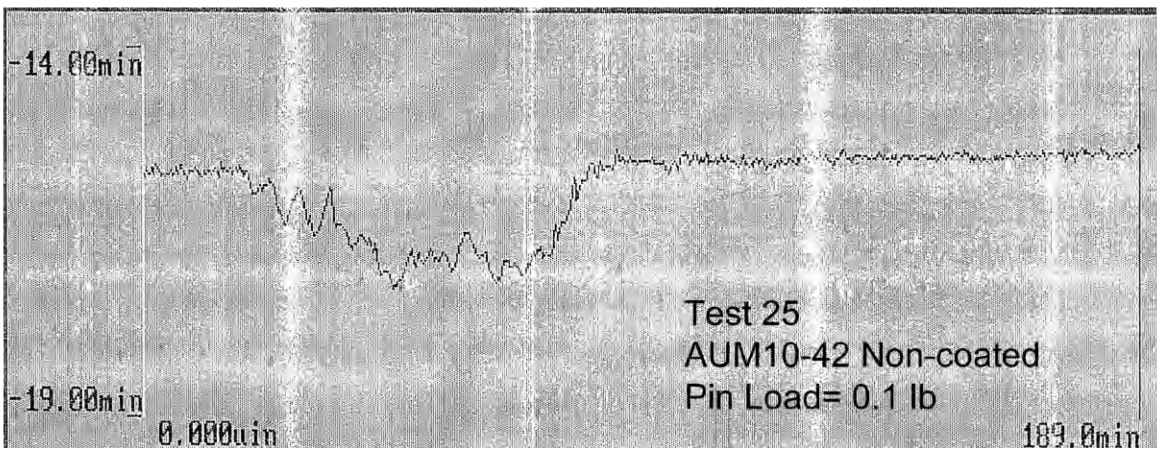

WEAR TRACK
21.00min
19.00min
0.000uin
147.7min
Test 24
3AUM10-41 Non-coated
Pin Load= 0.1 lb

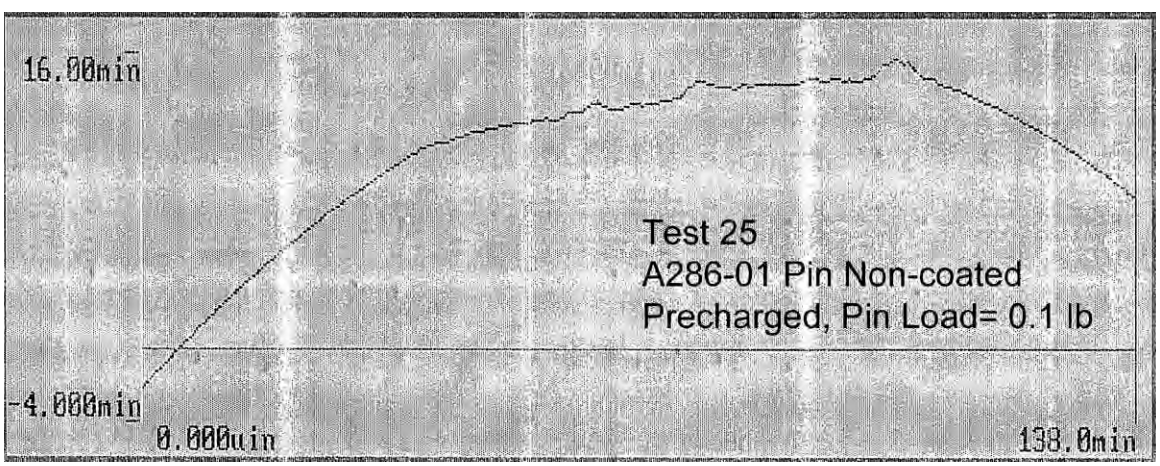

WEAR AREA
30.00min
10.00min
0.000uin
147.7min
Test 24
A286-19 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 25

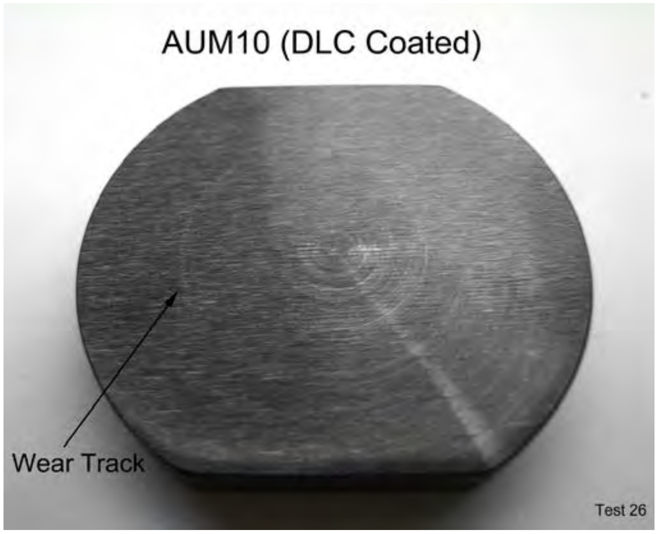

AUM10 (Non-coated)
Wear Track
Test 25


A286 (Non-coated)
Wear Spot
Test 25

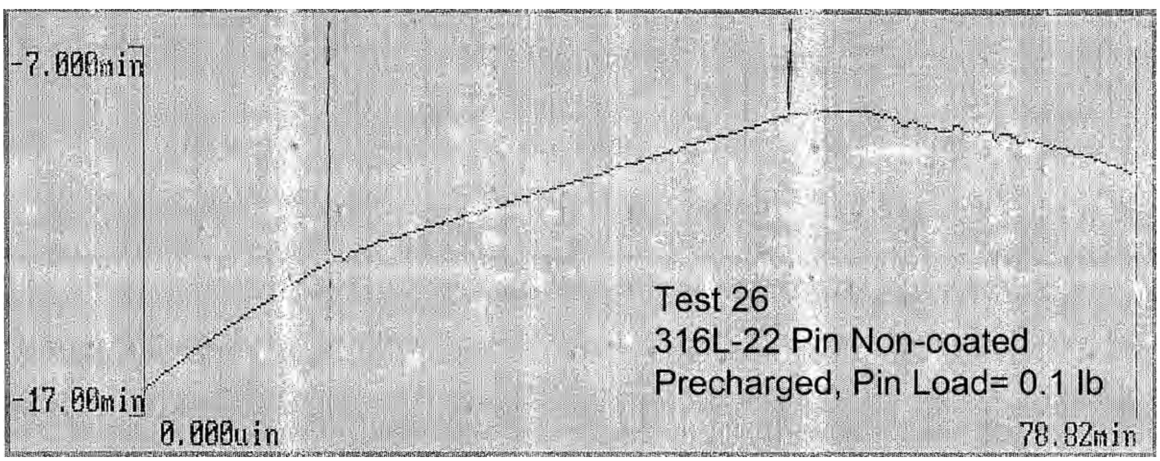

-14.00min
-19.00min
0.000uin
189.0min
Test 25
AUM10-42 Non-coated
Pin Load= 0.1 lb


16.00min
-4.000min
0.000uin
138.0min
Test 25
A286-01 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 26

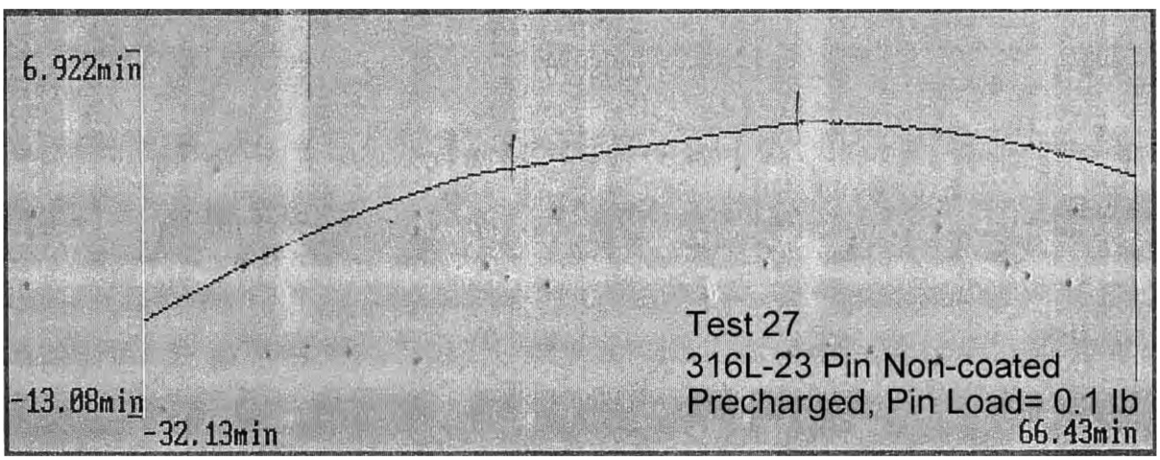


(Wear track on disk was not measurable.)

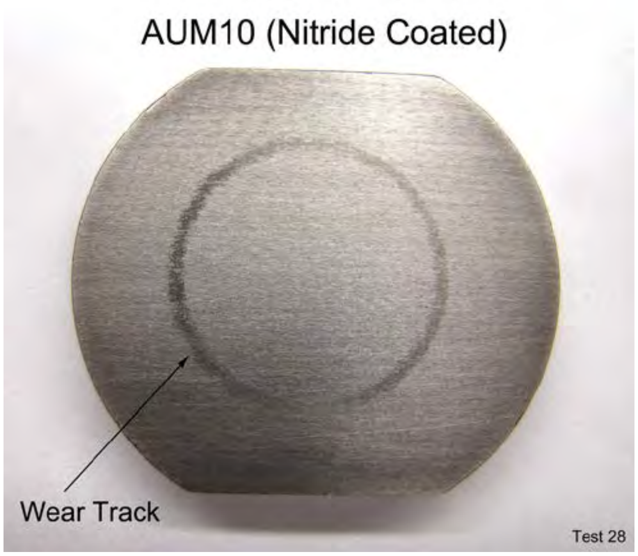


Test 27

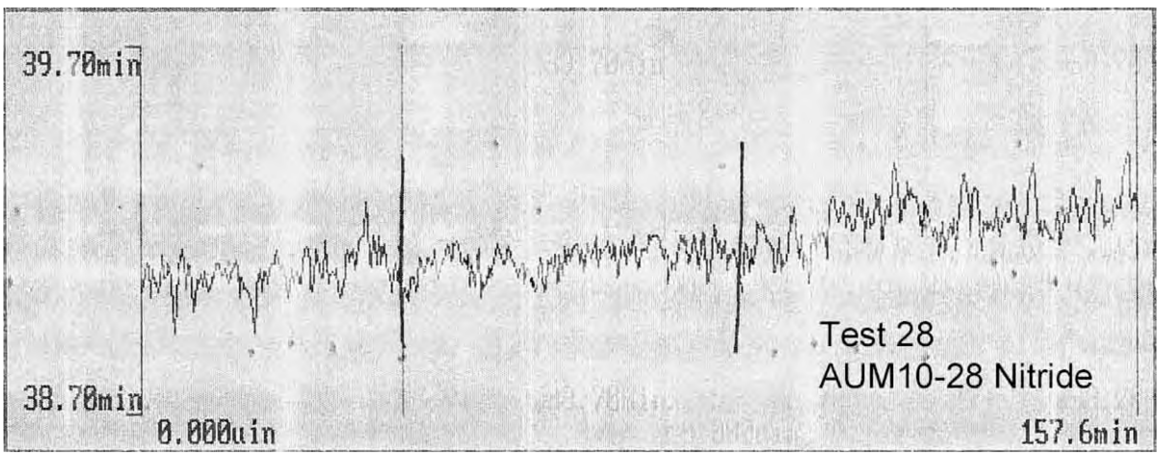
(Wear track on disk was not measurable.)

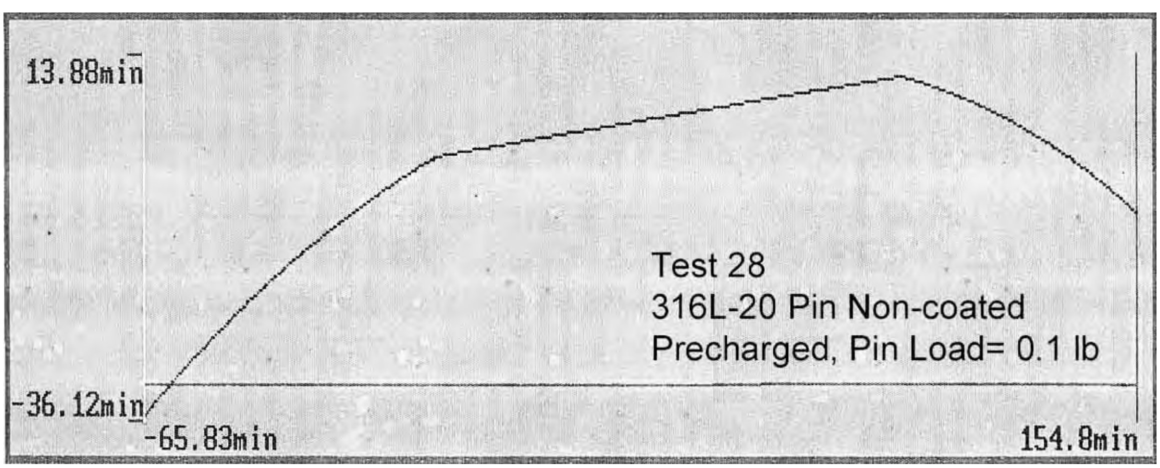


Test 28


AUM10 (Nitride Coated)
Wear Track
Test 28


316L (Non-coated, Precharged)
Wear Spot
Test 28

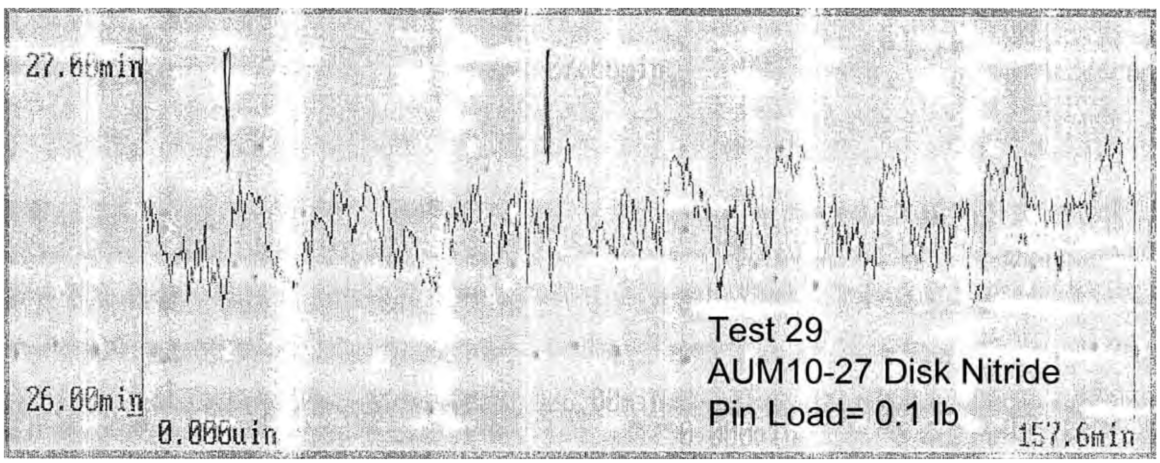

39.70min
38.70min
0.000uin
157.6min
Test 28
AUM10-28 Nitride

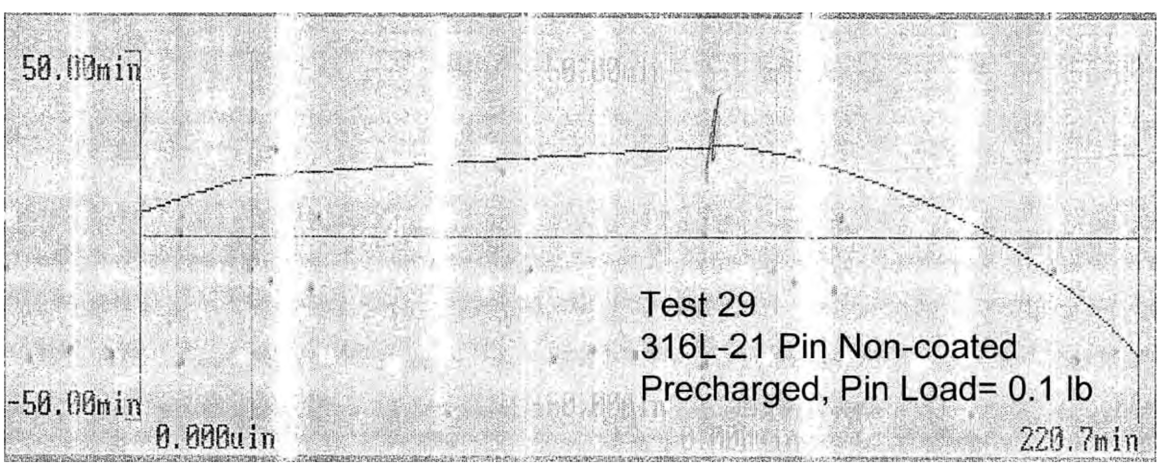

13.88min
-36.12min
-65.83min
154.8min
Test 28
316L-20 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 29


AUM10 (Nitride Coated)
Wear Track
Test 29


316L (Non-coated, Precharged)
Wear Spot
Test 29

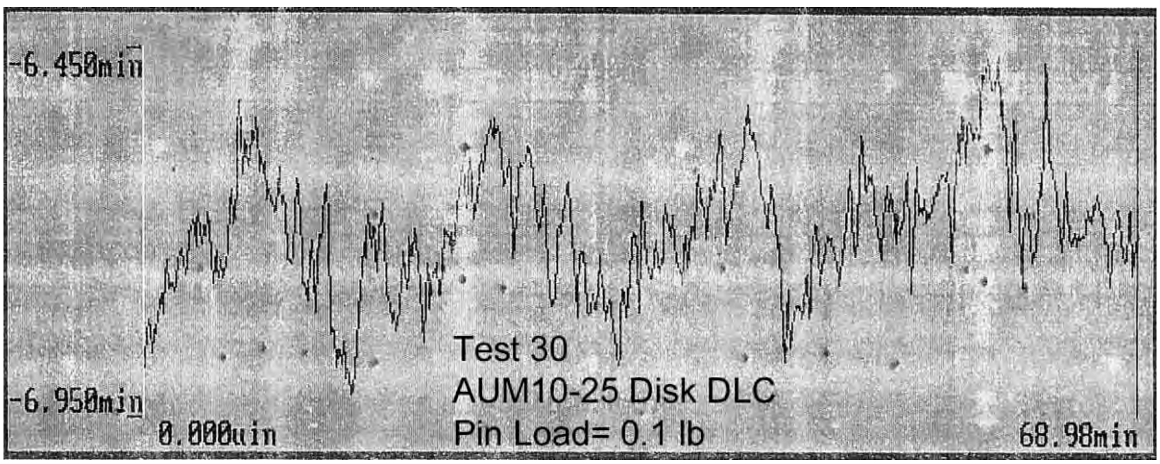

27.00min
26.00min
0.000uin
157.6min
Test 29
AUM10-27 Disk Nitride
Pin Load= 0.1 lb

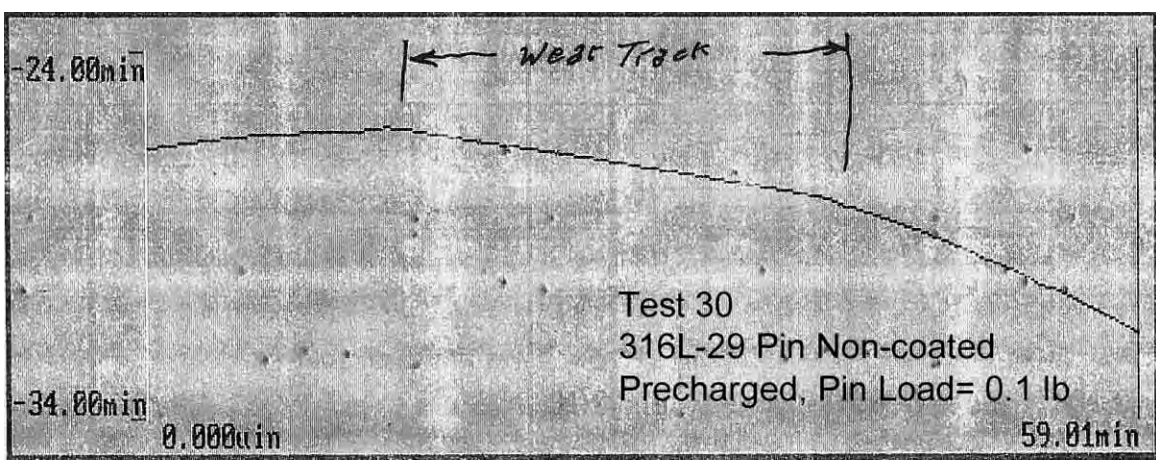

50.00min
-50.00min
0.000uin
220.7min
Test 29
316L-21 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 30


AUM10 (DLC-Coated)
Unidentifiable Wear Track
Test 30


316L (Non-coated, Precharged)
Wear Spot
Test 30

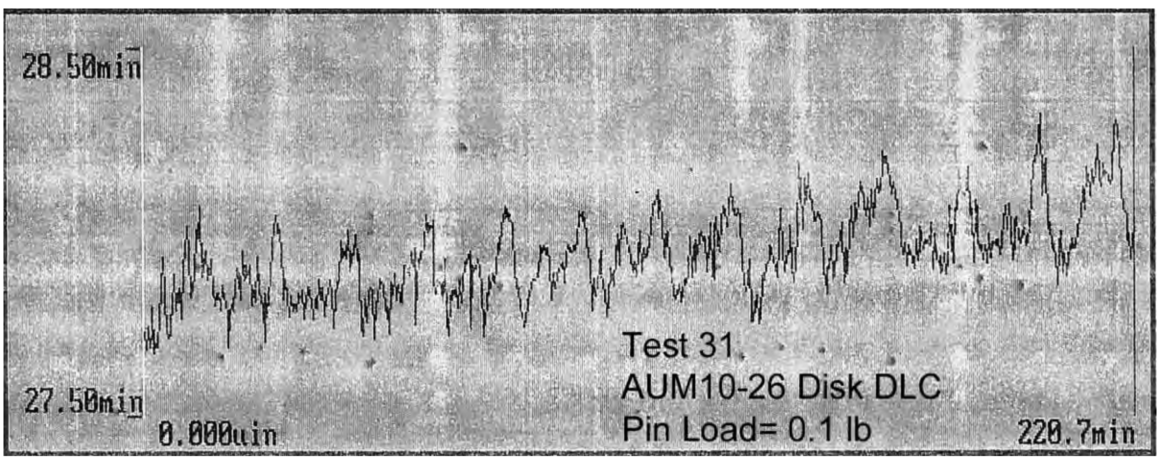

-6.450min
-6.950min
0.000uin
68.98min
Test 30
AUM10-25 Disk DLC
Pin Load= 0.1 lb

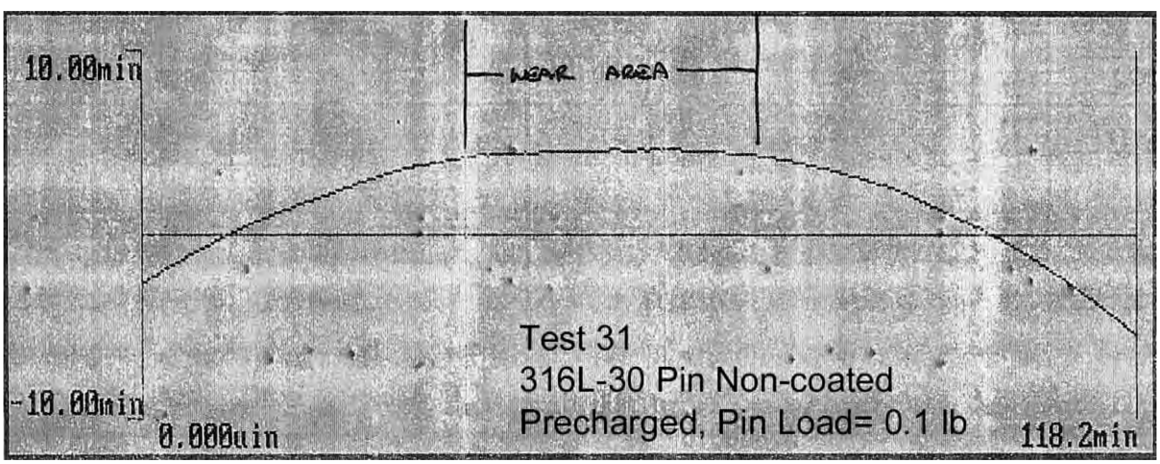

-24.00min
-34.00min
0.000uin
59.01min
Wear Track
Test 30
316L-29 Pin Non-coated
Precharged, Pin Load= 0.1 lb

Test 31


AUM10 (DLC-Coated)
Unidentifiable Wear Track
Test 31


316L (Non-coated, Precharged)
Wear Spot
Test 31

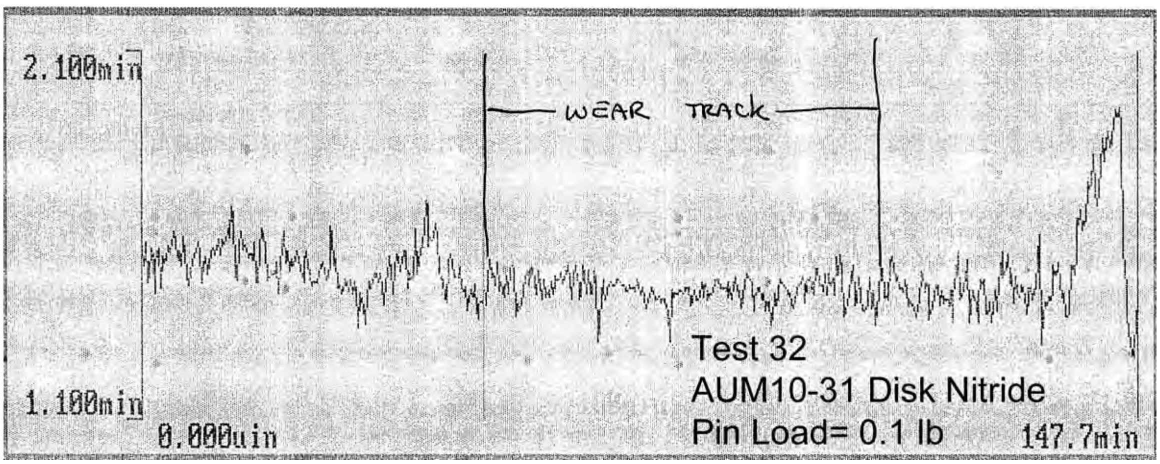

28.50min
27.50min
0.000uin
Test 31
AUM10-26 Disk DLC
Pin Load= 0.1 lb
220.7min

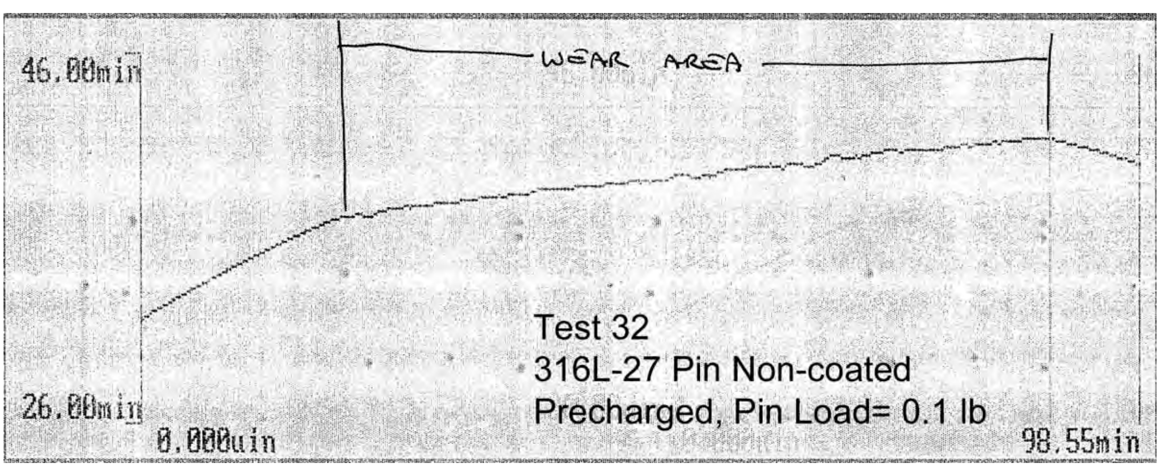

10.00min
WEAR AREA
-10.00min
0.000uin
Test 31
316L-30 Pin Non-coated
Precharged, Pin Load= 0.1 lb
118.2min

Test 32

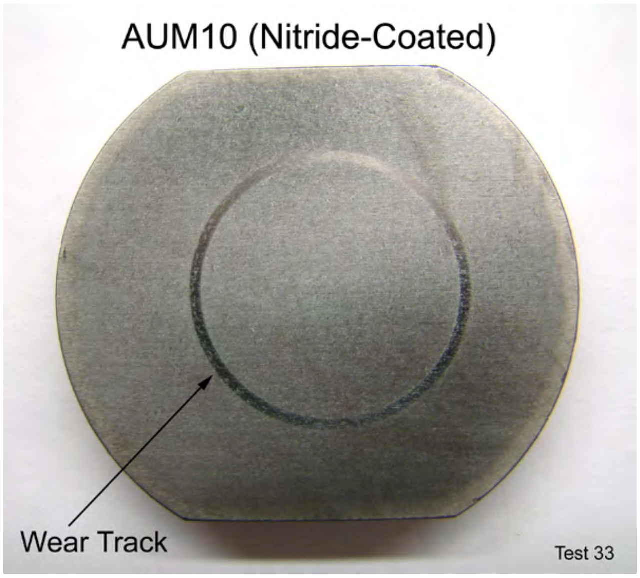

AUM10 (Nitride-Coated)
Wear Track
Test 32


316L (Non-coated, Precharged)
Wear Spot
Test 32

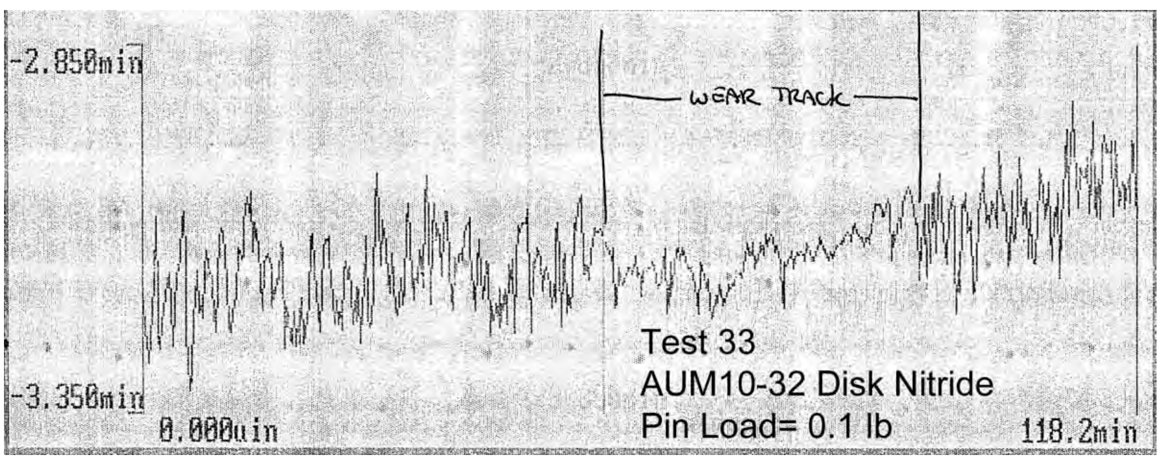

2.100min
WEAR TRACK
Test 32
AUM10-31 Disk Nitride
Pin Load= 0.1 lb
1.100min
0.000uin
147.7min

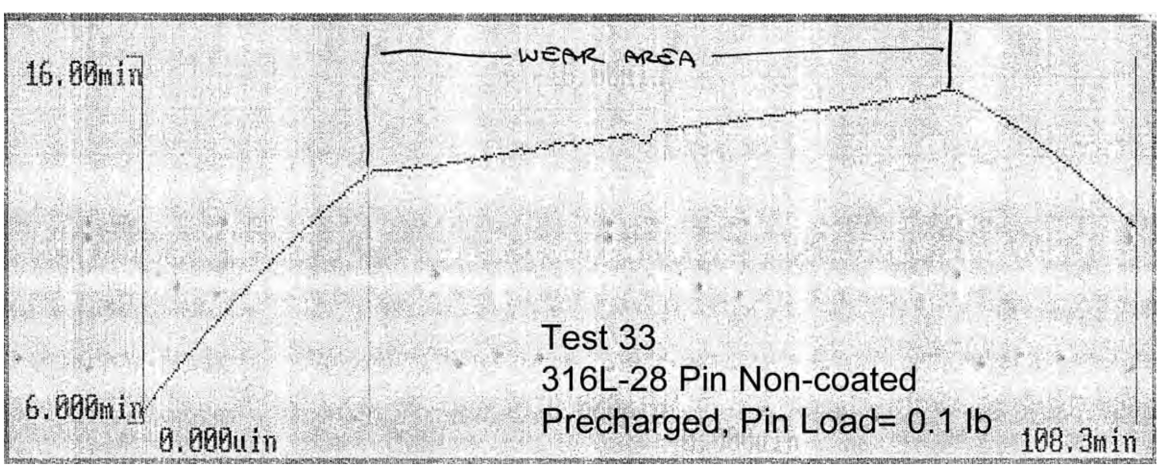

46.00min
WEAR AREA
Test 32
316L-27 Pin Non-coated
Precharged, Pin Load= 0.1 lb
26.00min
0.000uin
98.55min

Test 33


AUM10 (Nitride-Coated)
Wear Track
Test 33

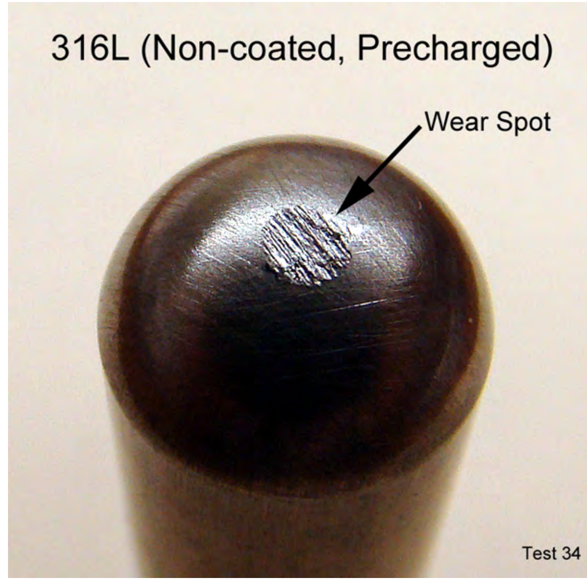

316L (Non-coated, Precharged)
Wear Spot
Test 33

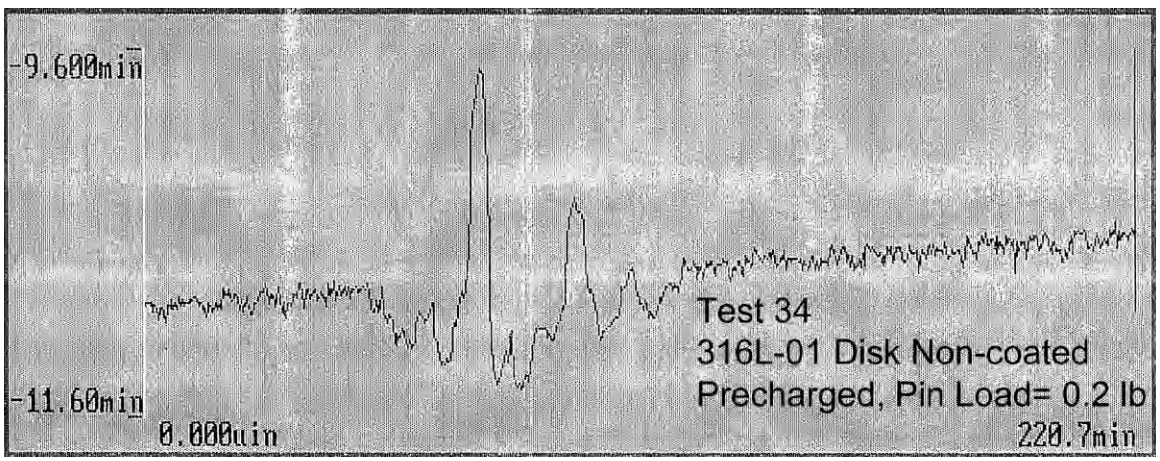

-2.850min
WEAR TRACK
Test 33
AUM10-32 Disk Nitride
Pin Load= 0.1 lb
-3.350min
0.000uin
118.2min

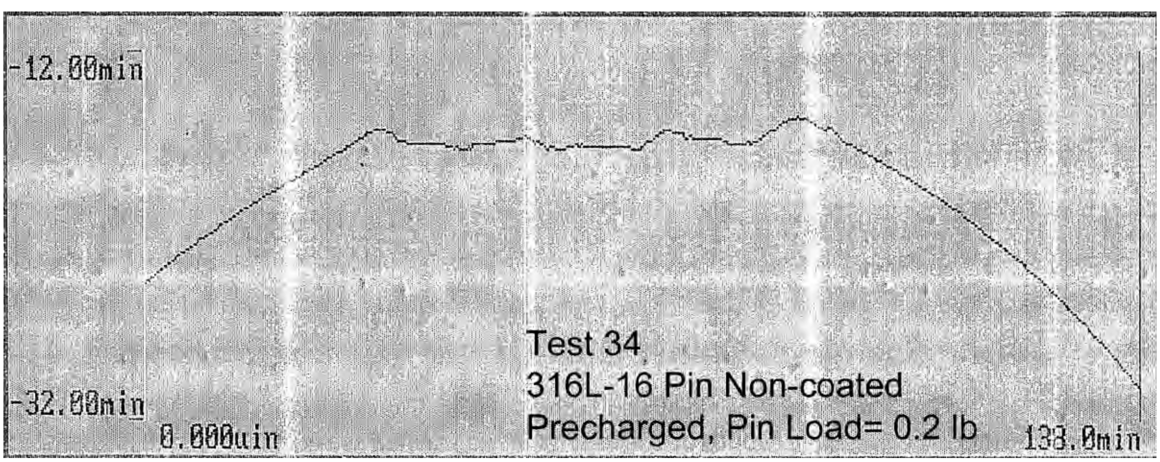

16.00min
WEAR AREA
Test 33
316L-28 Pin Non-coated
Precharged, Pin Load= 0.1 lb
6.000min
0.000uin
108.3min

Test 34


316L (Non-coated, Precharged)
Wear Track
Test 34

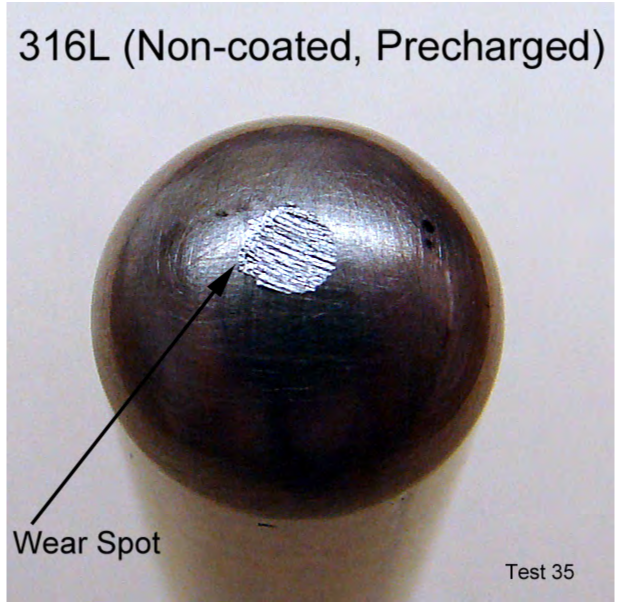

316L (Non-coated, Precharged)
Wear Spot
Test 34

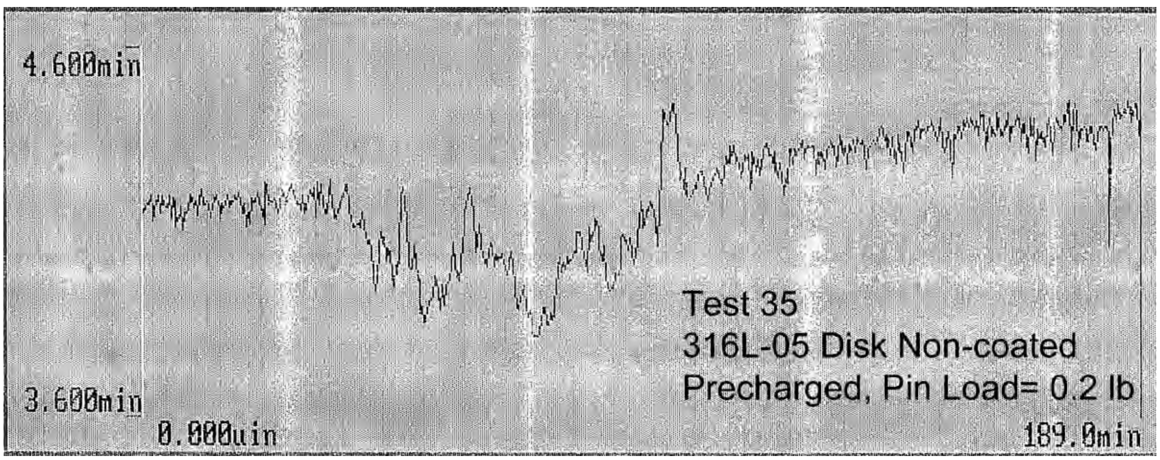

-9.600min
-11.60min
0.000uin
220.7min
Test 34
316L-01 Disk Non-coated
Precharged, Pin Load= 0.2 lb

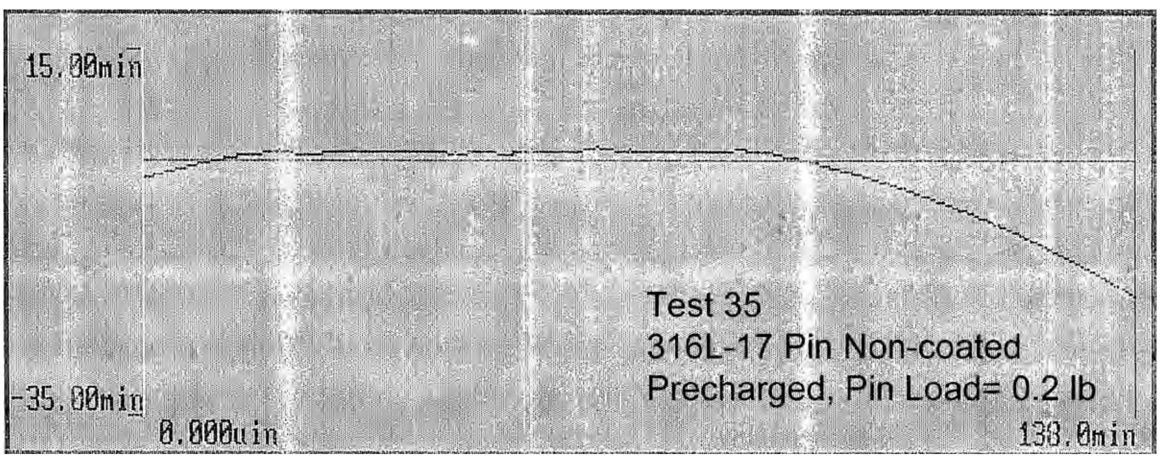

-12.00min
-32.00min
0.000uin
133.0min
Test 34
316L-16 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 35

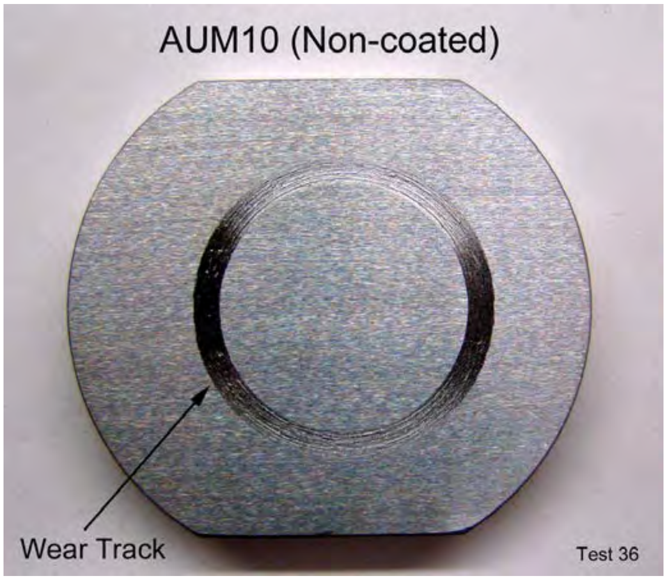

316L (Non-coated, Precharged)
Wear Track
Test 35


316L (Non-coated, Precharged)
Wear Spot
Test 35

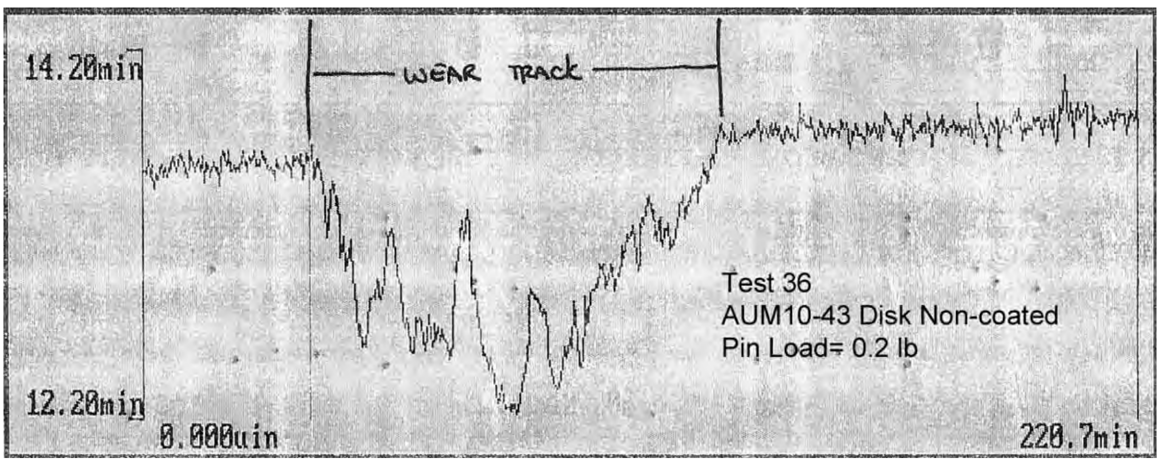

4.600min
3.600min
0.000uin
189.0min
Test 35
316L-05 Disk Non-coated
Precharged, Pin Load= 0.2 lb

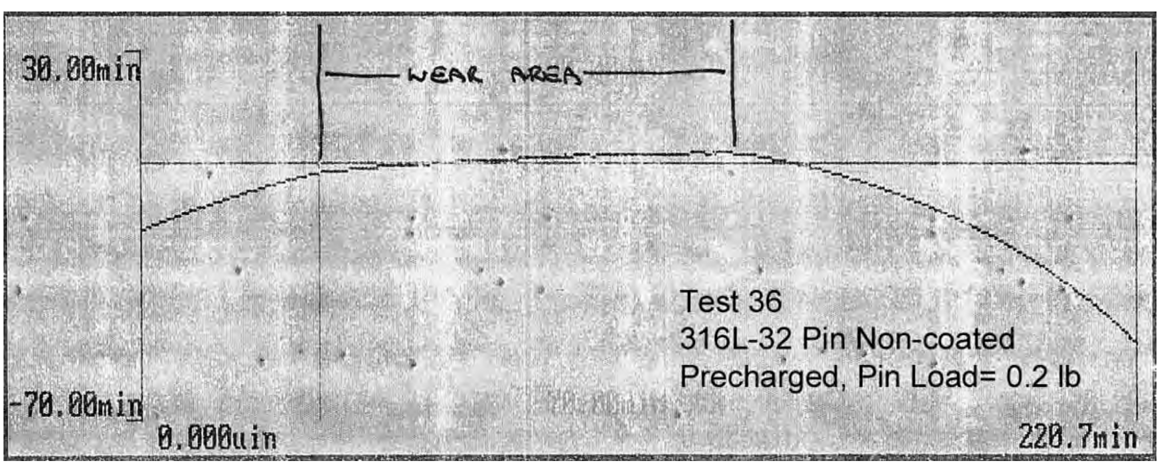

15.00min
-35.00min
0.000uin
138.0min
Test 35
316L-17 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 36


AUM10 (Non-coated)
Wear Track
Test 36


316L (Non-coated, Precharged)
Wear Spot
Test 36

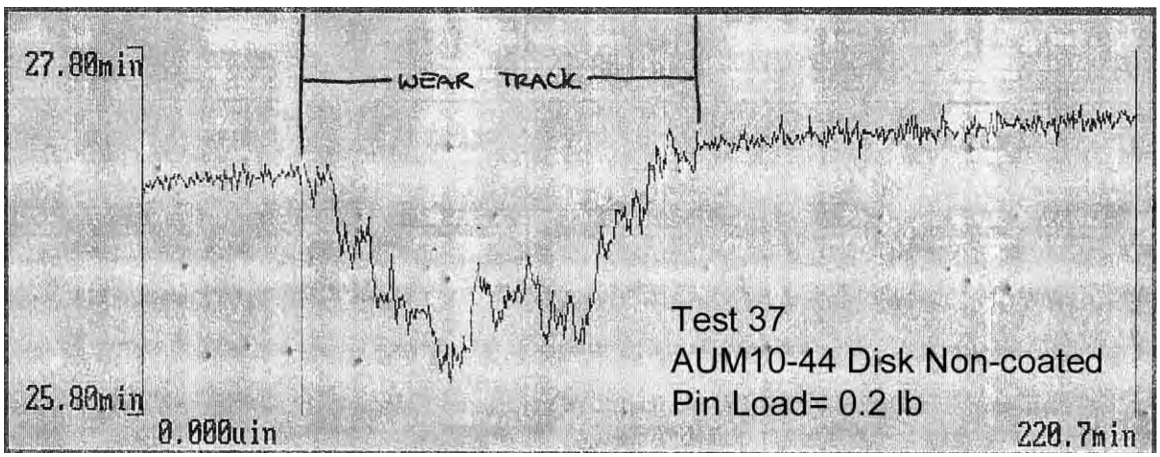

14.20min
12.20min
0.000uin
220.7min
WEAR TRACK
Test 36
AUM10-43 Disk Non-coated
Pin Load= 0.2 lb

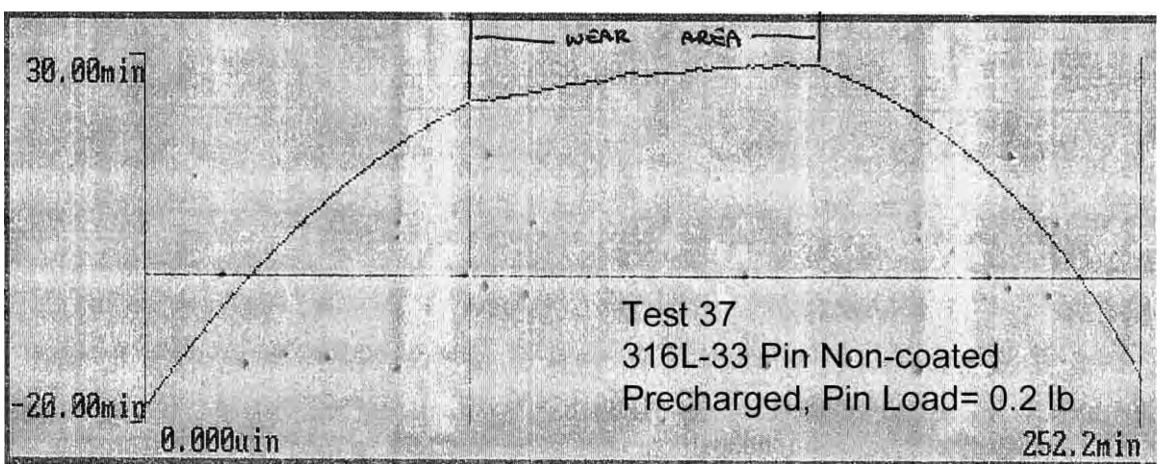

30.00min
-70.00min
0.000uin
220.7min
WEAR AREA
Test 36
316L-32 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 37

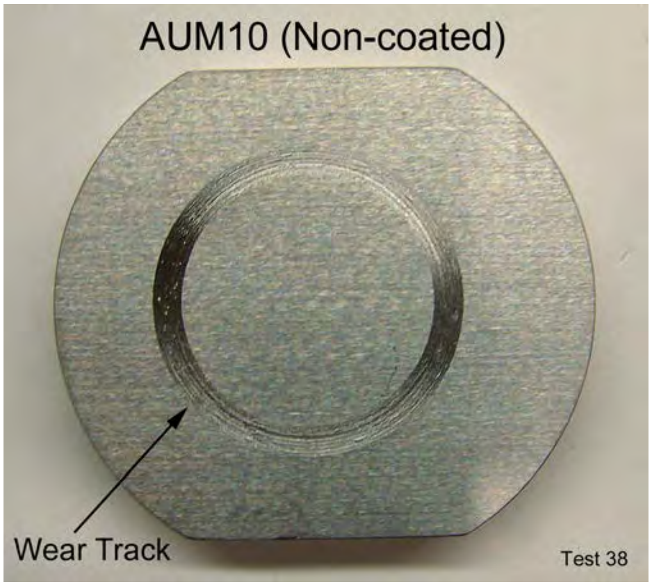

AUM10 (Non-coated)
Wear Track
Test 36


316L (Non-coated, Precharged)
Wear Spot
Test 37

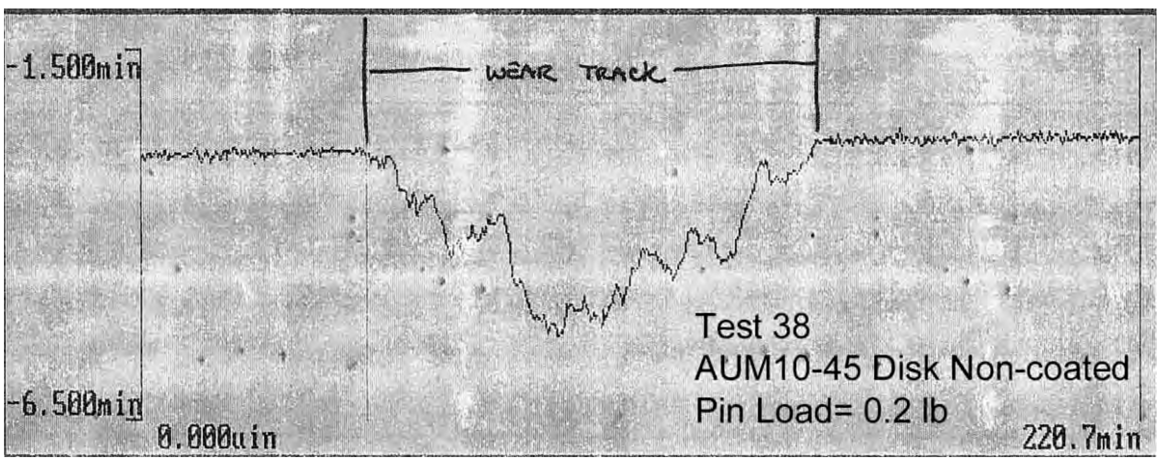

27.80min
25.80min
0.000uin
220.7min
WEAR TRACK
Test 37
AUM10-44 Disk Non-coated
Pin Load= 0.2 lb

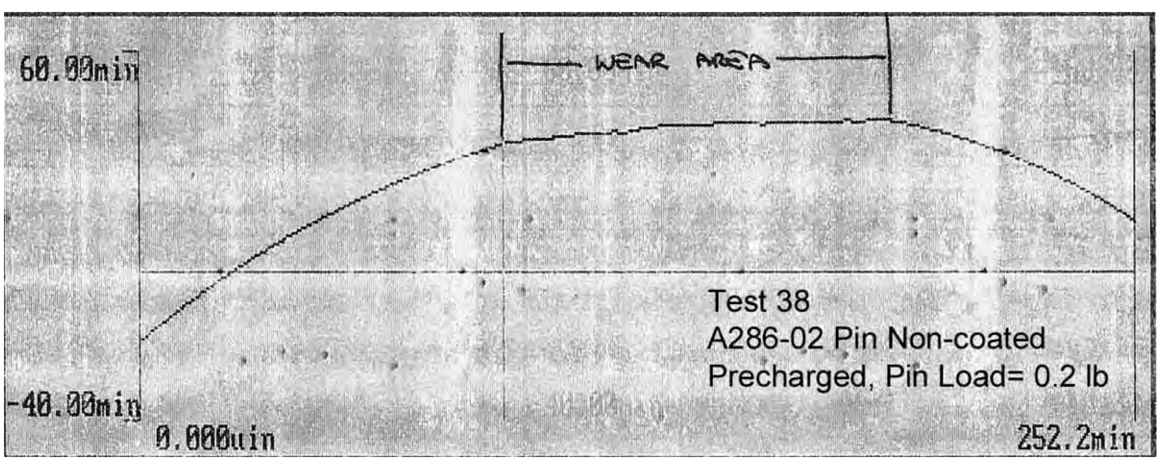

30.00min
-20.00min
0.000uin
252.2min
WEAR AREA
Test 37
316L-33 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 38


AUM10 (Non-coated)
Wear Track
Test 38


A286 (Non-coated, Precharged)
Wear Spot
Test 38

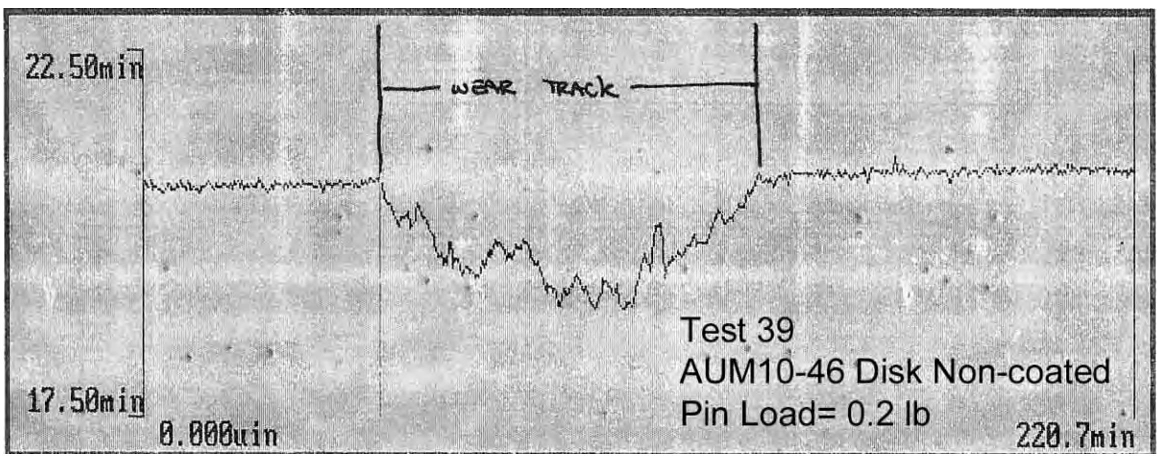

-1.500min
WEAR TRACK
-6.500min
0.000uin
220.7min
Test 38
AUM10-45 Disk Non-coated
Pin Load= 0.2 lb

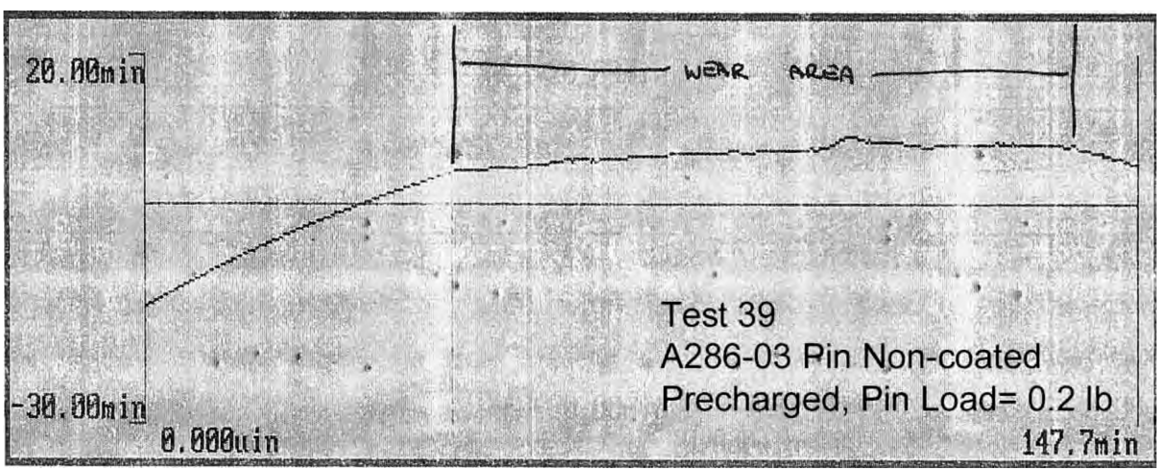

60.00min
WEAR AREA
-40.00min
0.000uin
252.2min
Test 38
A286-02 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 39


AUM10 (Non-coated)
Wear Track
Test 39

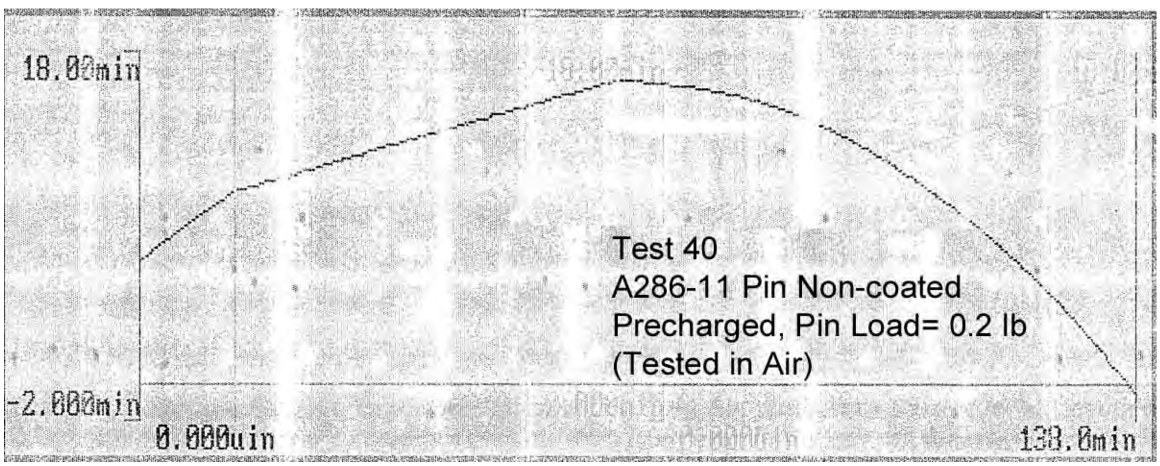

A286 (Non-coated, Precharged)
Wear Spot
Test 39


22.50min
WEAR TRACK
Test 39
AUM10-46 Disk Non-coated
Pin Load= 0.2 lb
17.50min
0.000uin
220.7min

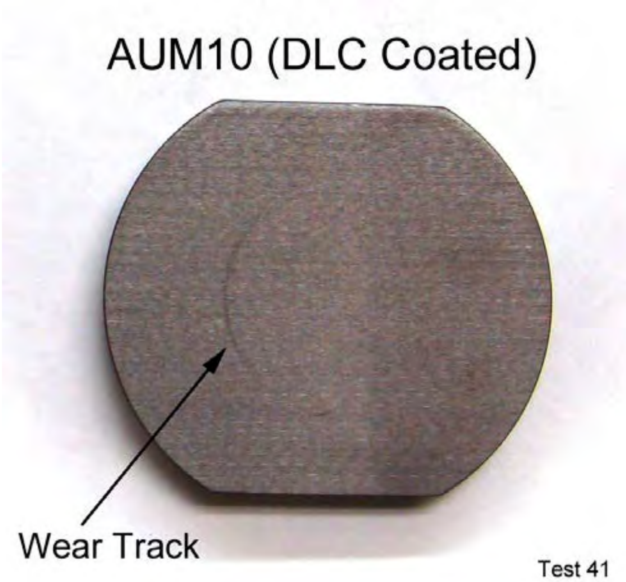

20.00min
WEAR AREA
Test 39
A286-03 Pin Non-coated
Precharged, Pin Load= 0.2 lb
-30.00min
0.000uin
147.7min

Test 40

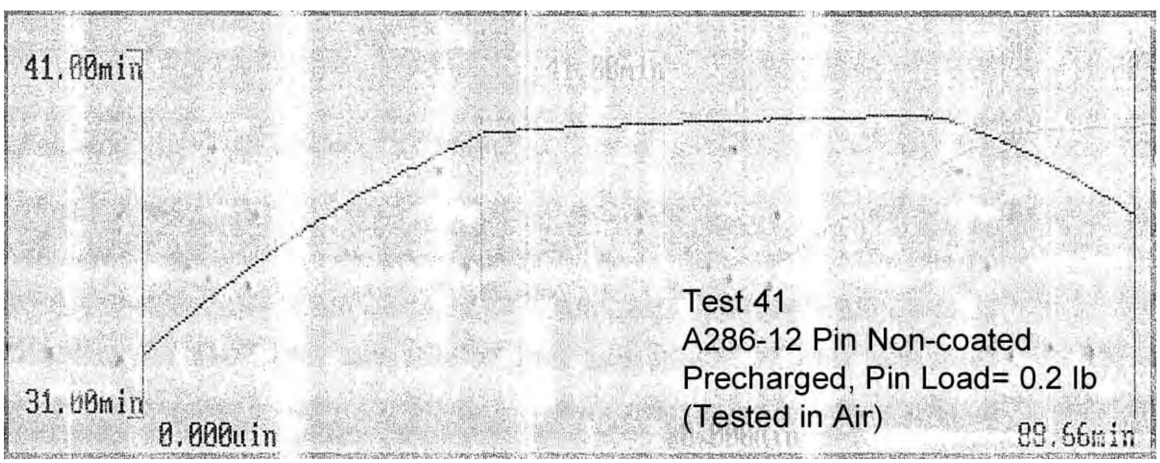
(Wear track on disk was not measurable.)



Test 41



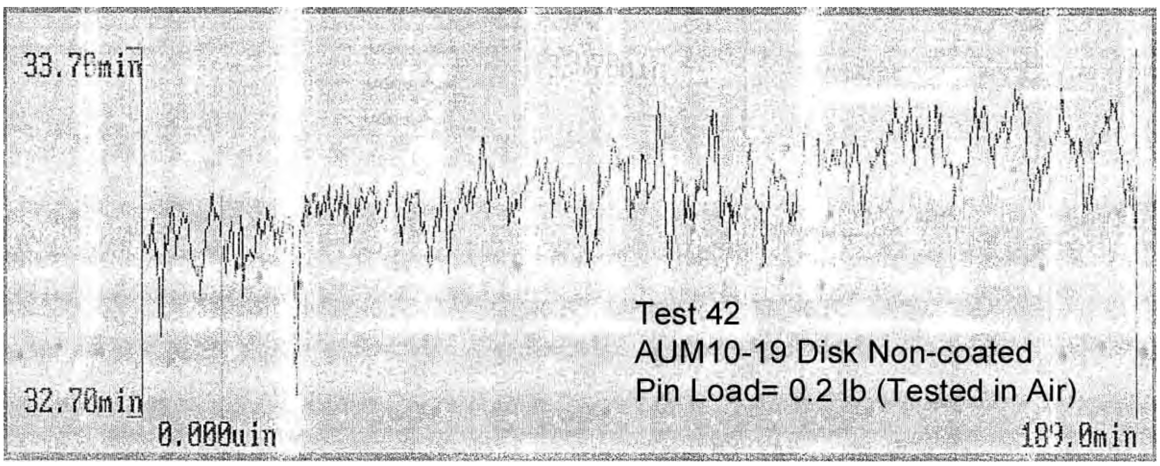
(Wear track on disk was not measurable.)

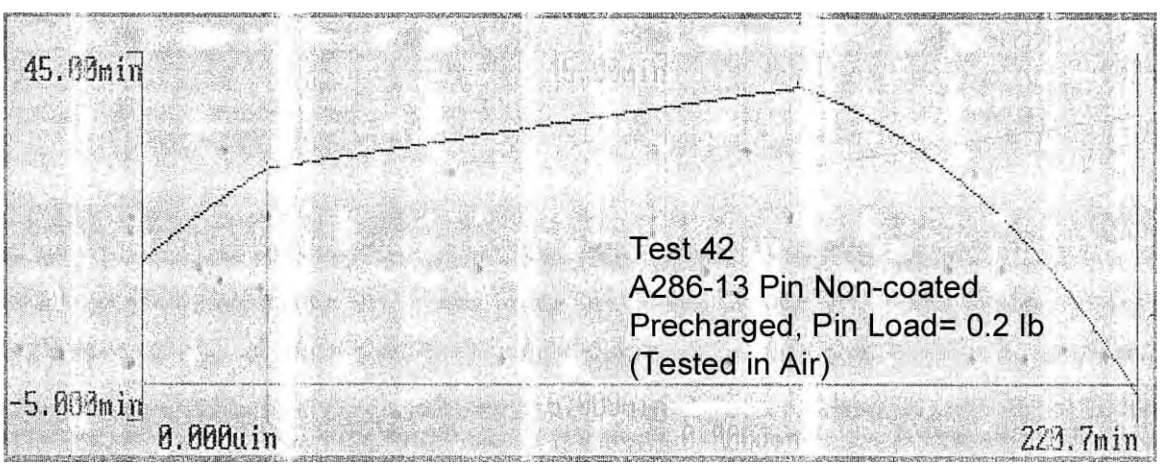


Test 42

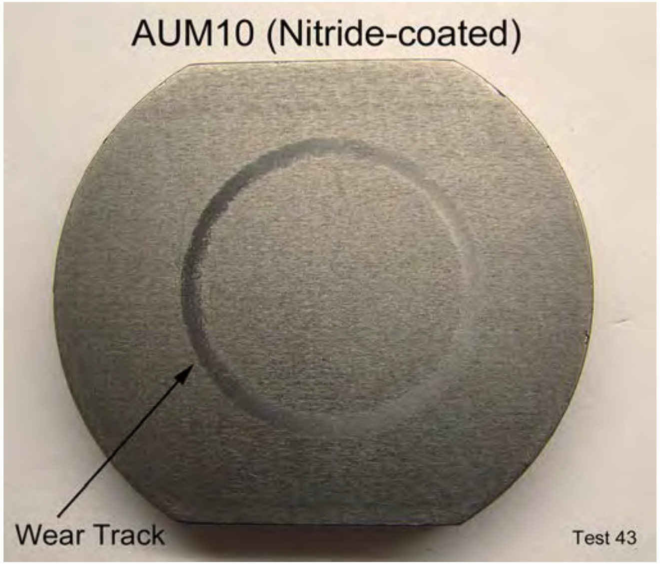

AUM10 (Nitride Coated)
Wear Track
Test 42


A286 (Non-coated, Precharged)
Pin Load = 0.2 lb
Wear Spot
Test 42

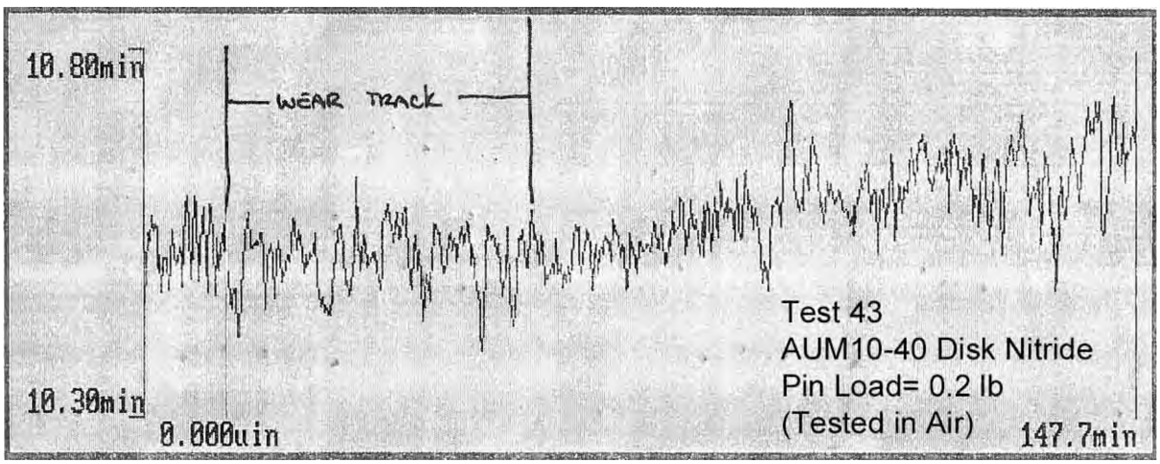

33.70min
32.70min
0.000uin
189.0min
Test 42
AUM10-19 Disk Non-coated
Pin Load= 0.2 lb (Tested in Air)

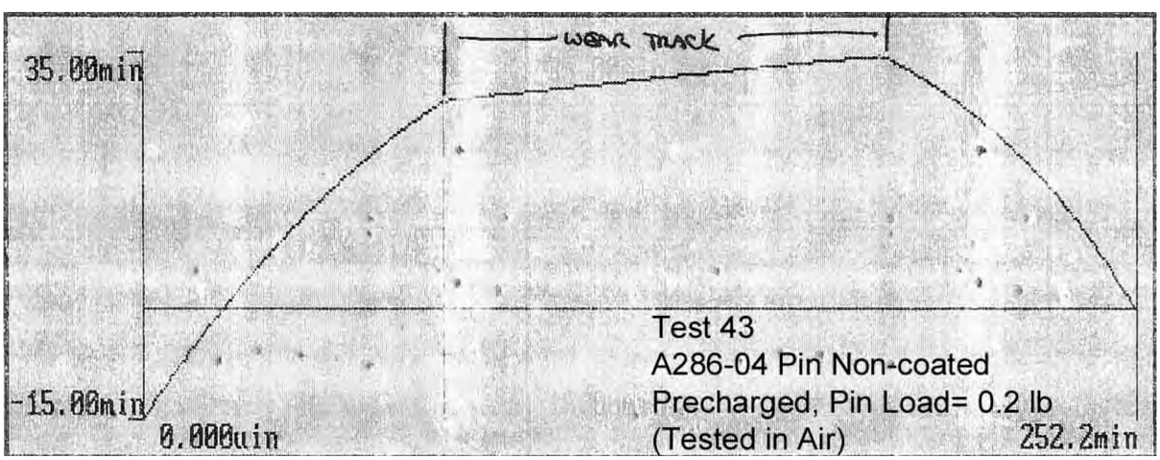

45.00min
-5.000min
0.000uin
223.7min
Test 42
A286-13 Pin Non-coated
Precharged, Pin Load= 0.2 lb
(Tested in Air)

Test 43


AUM10 (Nitride-coated)
Wear Track
Test 43


A286 (Non-coated, Precharged)
Wear Spot
Test 43

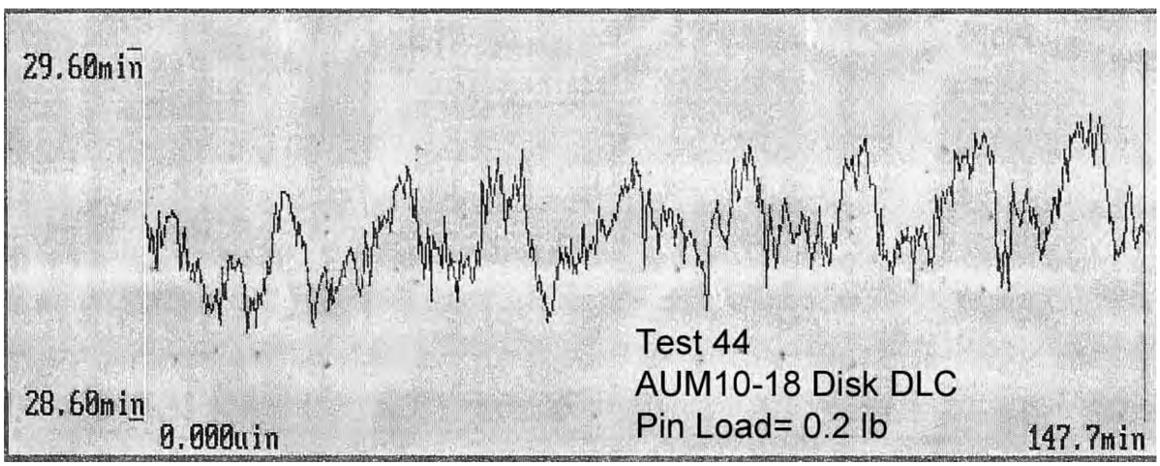

10.80min
WEAR TRACK
10.30min
0.000uin
Test 43
AUM10-40 Disk Nitride
Pin Load= 0.2 lb
(Tested in Air)
147.7min

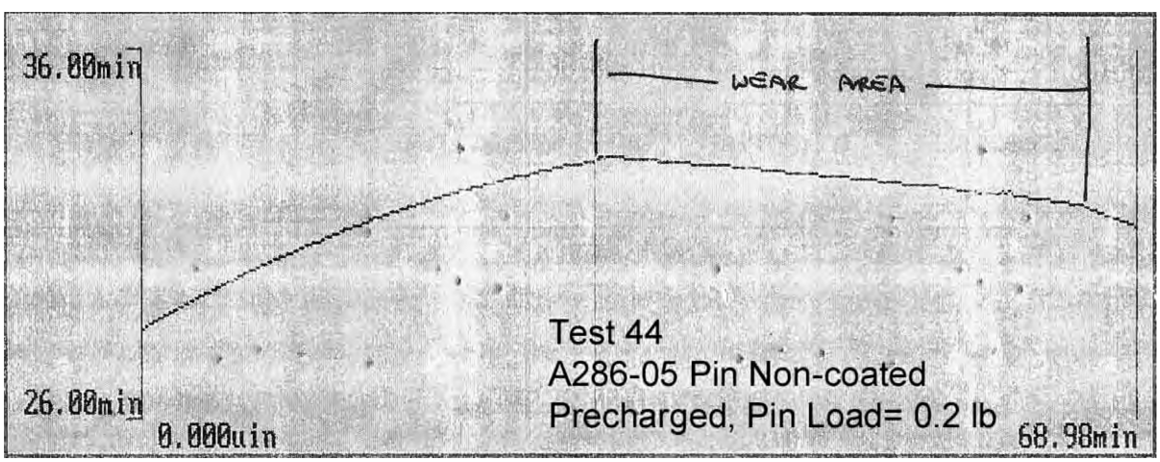

35.00min
WEAR TRACK
-15.00min
0.000uin
Test 43
A286-04 Pin Non-coated
Precharged, Pin Load= 0.2 lb
(Tested in Air)
252.2min

Test 44

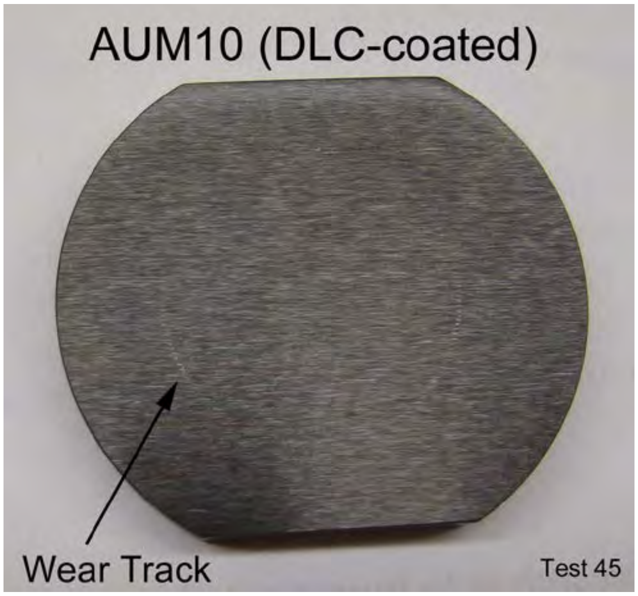

AUM10 (DLC-coated)
Wear Track
Test 44


A286 (Non-coated, Precharged)
Wear Spot
Test 44

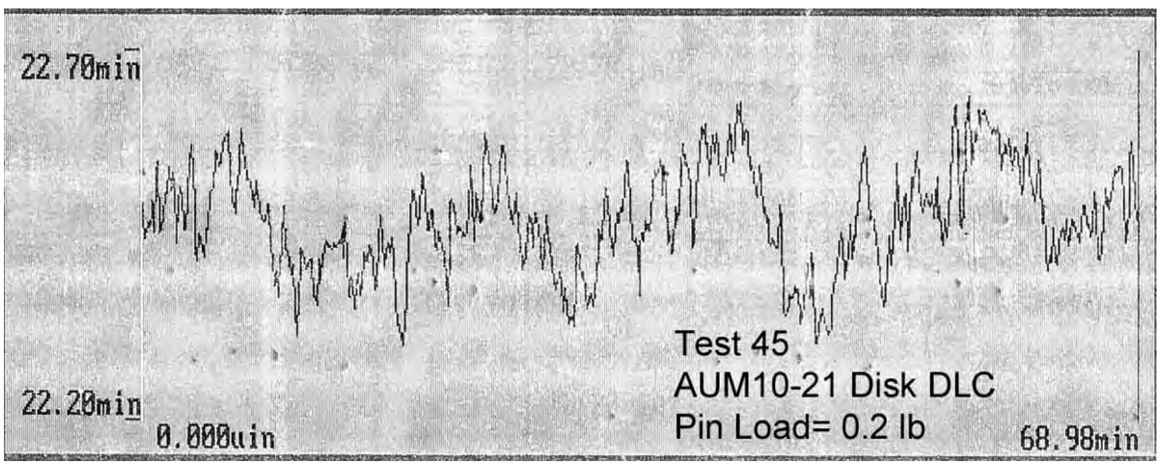

29.60min
28.60min
0.000uin
Test 44
AUM10-18 Disk DLC
Pin Load= 0.2 lb
147.7min

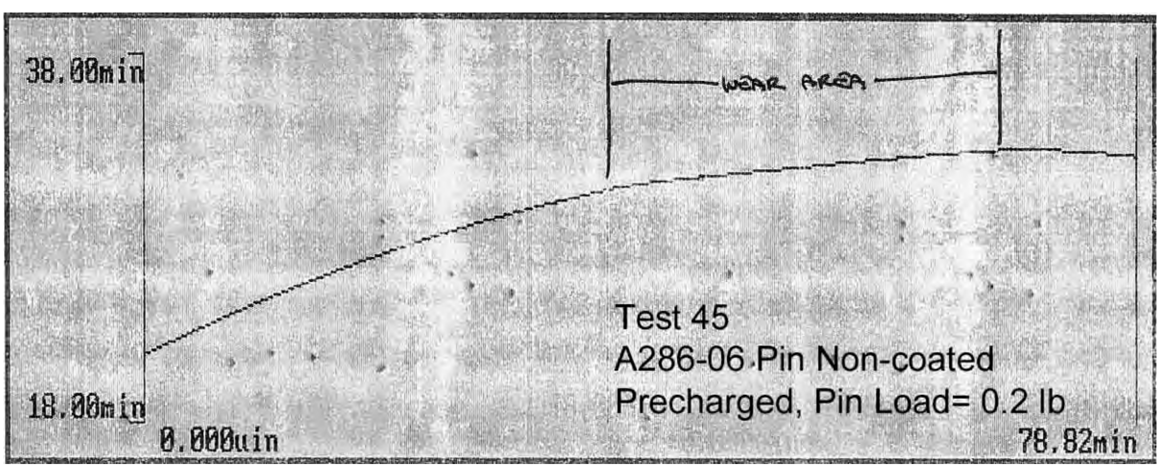

36.00min
WEAR AREA
26.00min
0.000uin
Test 44
A286-05 Pin Non-coated
Precharged, Pin Load= 0.2 lb
68.98min

Test 45


AUM10 (DLC-coated)
Wear Track
Test 45

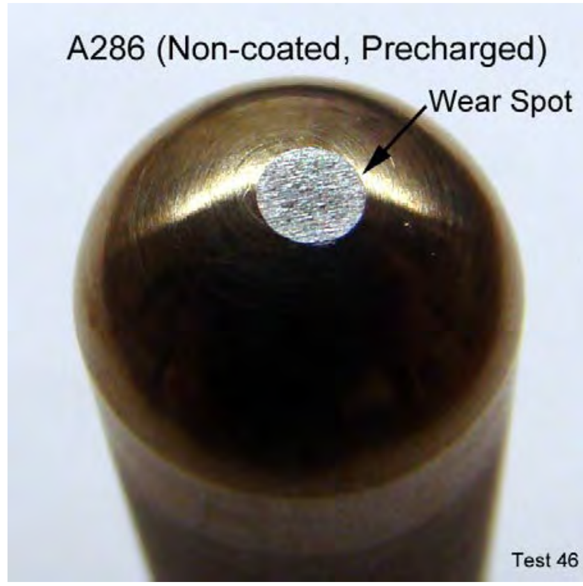

A286 (Non-coated, Precharged)
Wear Spot
Test 45

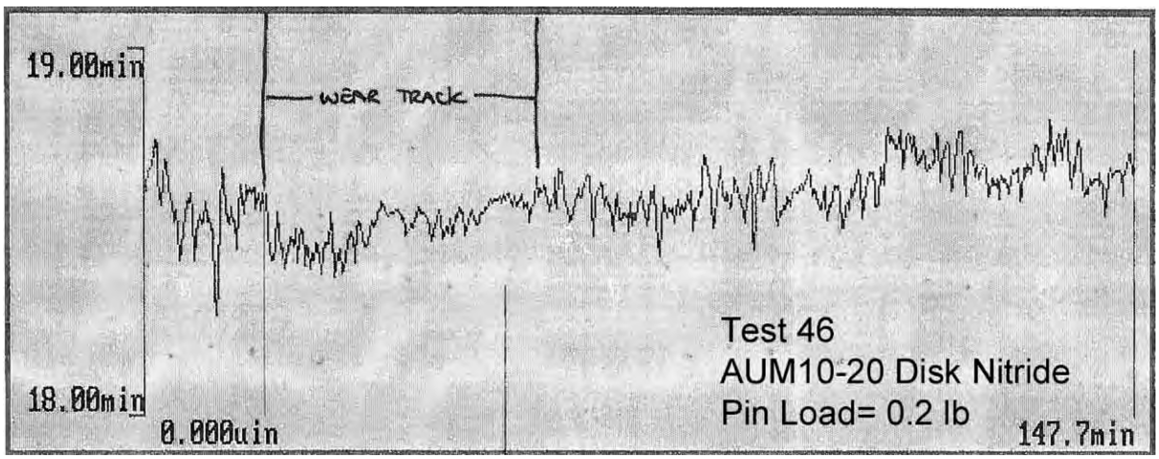

22.70min
22.20min
0.000uin
68.98min
Test 45
AUM10-21 Disk DLC
Pin Load= 0.2 lb

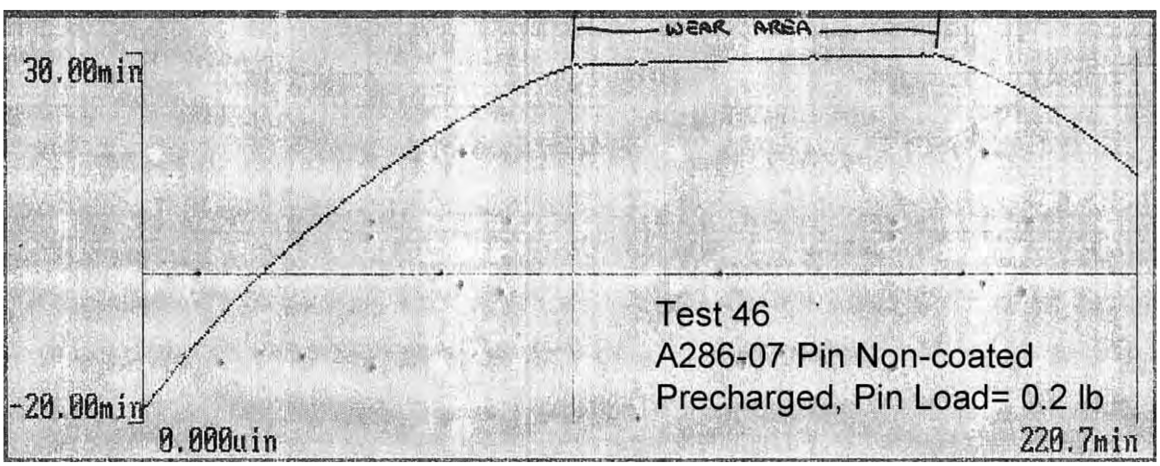

38.00min
18.00min
0.000uin
78.82min
WEAR AREA
Test 45
A286-06 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 46

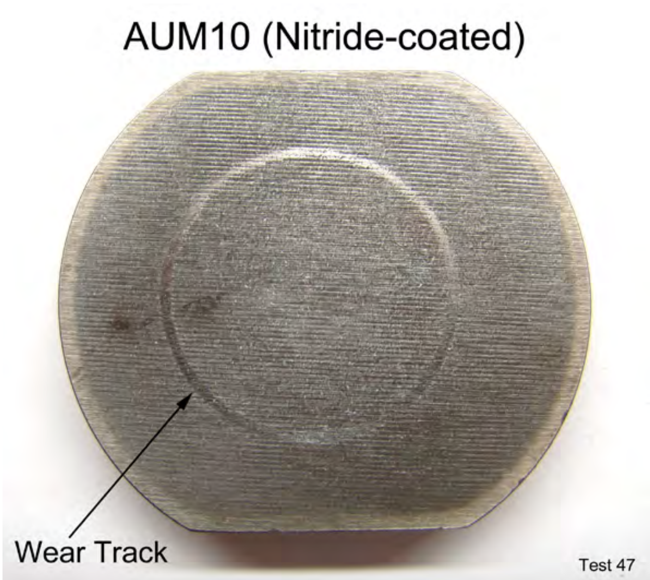

AUM10 (Nitride-coated)
Wear Track
Test 46


A286 (Non-coated, Precharged)
Wear Spot
Test 46

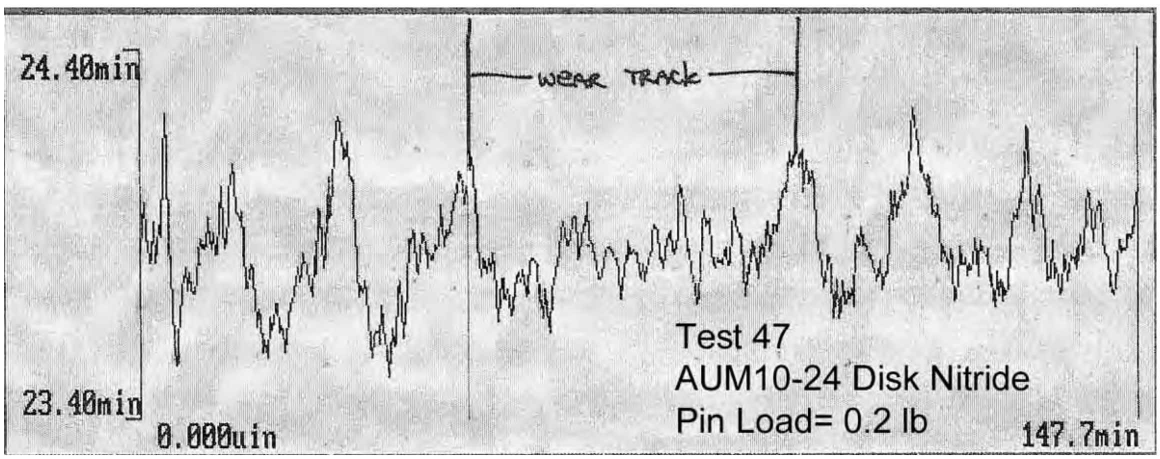

19.00min
WEAR TRACK
18.00min
0.000uin
Test 46
AUM10-20 Disk Nitride
Pin Load= 0.2 lb
147.7min

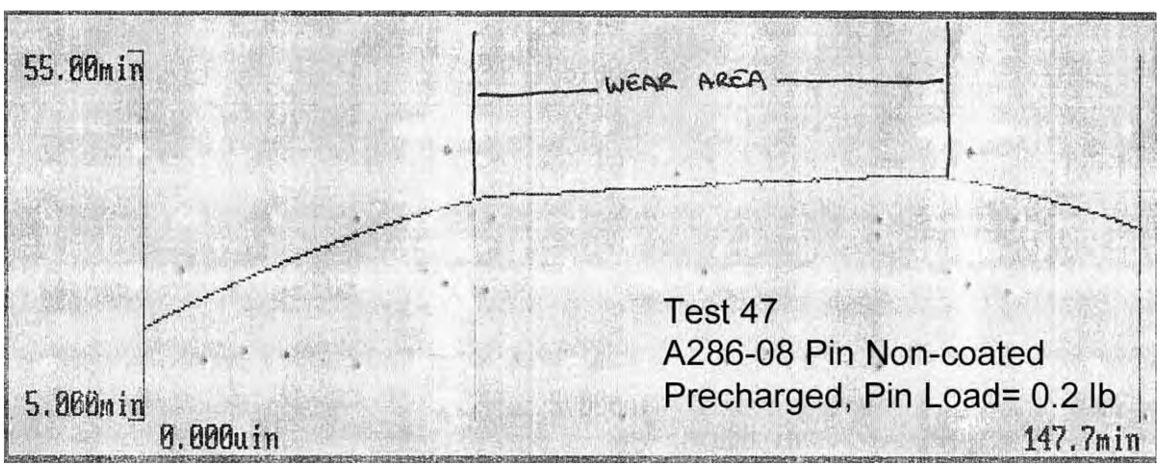

30.00min
WEAR AREA
-20.00min
0.000uin
Test 46
A286-07 Pin Non-coated
Precharged, Pin Load= 0.2 lb
220.7min

Test 47

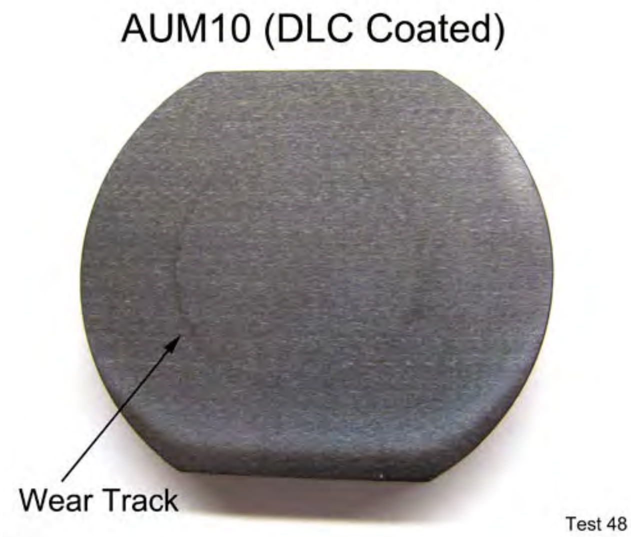

AUM10 (Nitride-coated)
Wear Track
Test 47


A286 (Non-coated, Precharged)
Wear Spot
Test 47

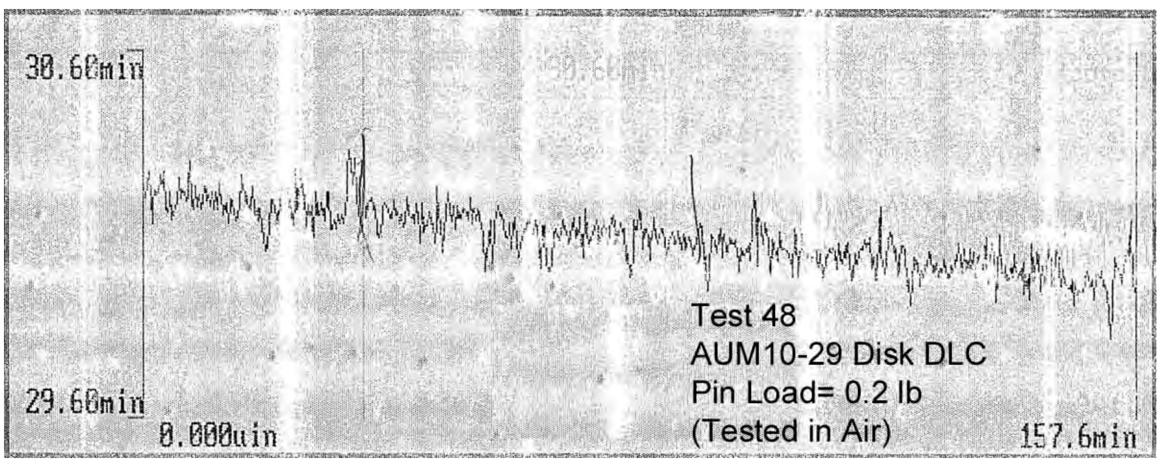

24.40min
WEAR TRACK
Test 47
AUM10-24 Disk Nitride
Pin Load= 0.2 lb
23.40min
0.000uin
147.7min

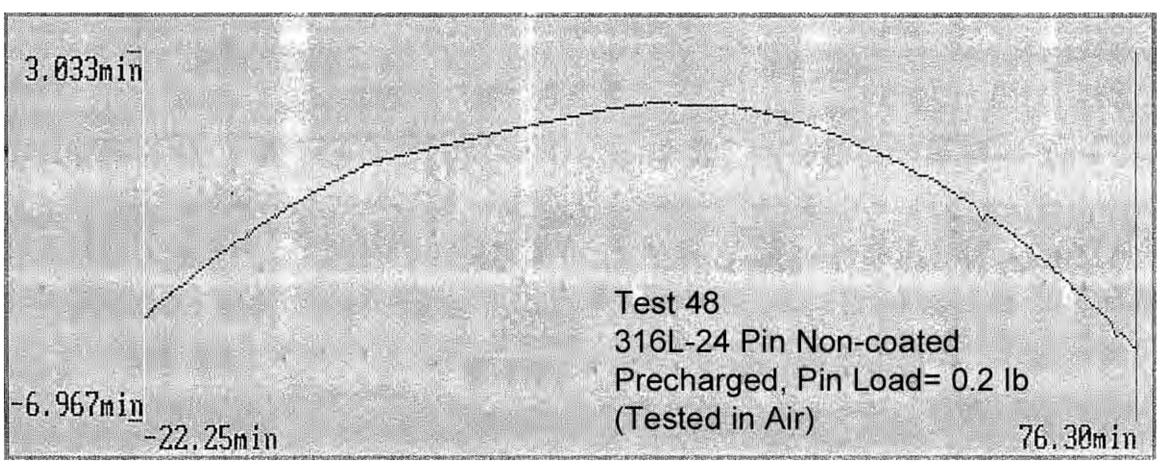

55.00min
WEAR AREA
Test 47
A286-08 Pin Non-coated
Precharged, Pin Load= 0.2 lb
5.000min
0.000uin
147.7min

Test 48

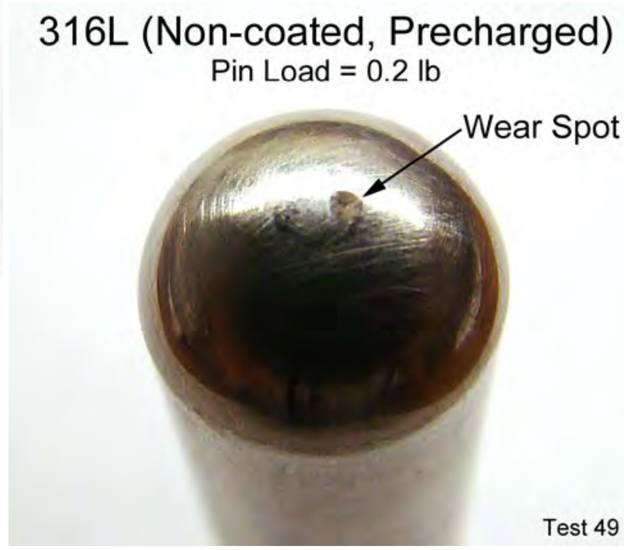

AUM10 (DLC Coated)
Wear Track
Test 48


316L (Non-coated, Precharged)
Pin Load = 0.2 lb
Wear Spot
Test 48

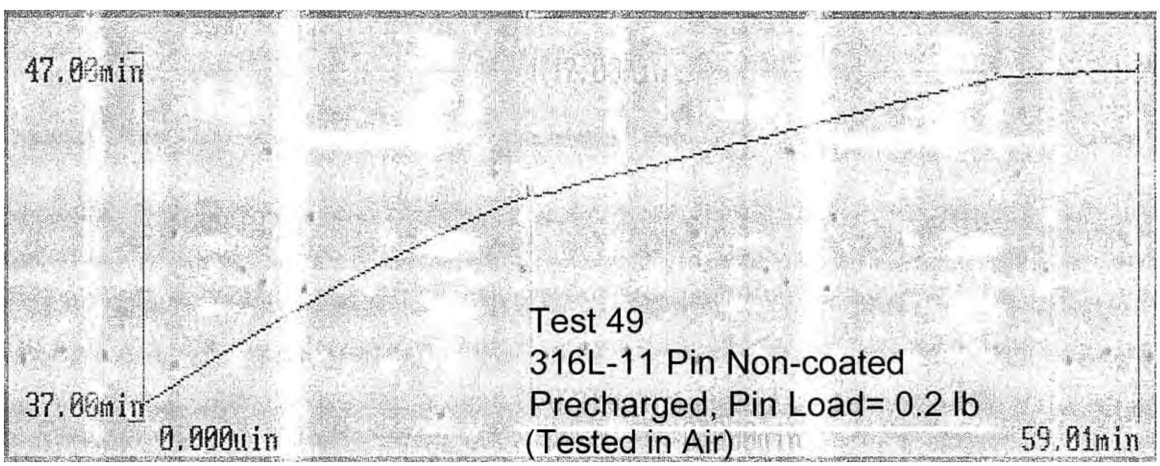

30.60min
29.60min
0.000uin
157.6min
Test 48
AUM10-29 Disk DLC
Pin Load= 0.2 lb
(Tested in Air)


3.033min
-6.967min
-22.25min
76.30min
Test 48
316L-24 Pin Non-coated
Precharged, Pin Load= 0.2 lb
(Tested in Air)

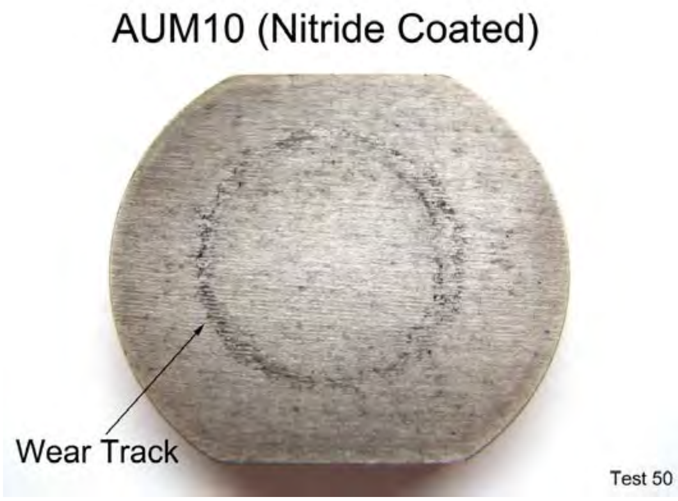
Test 49



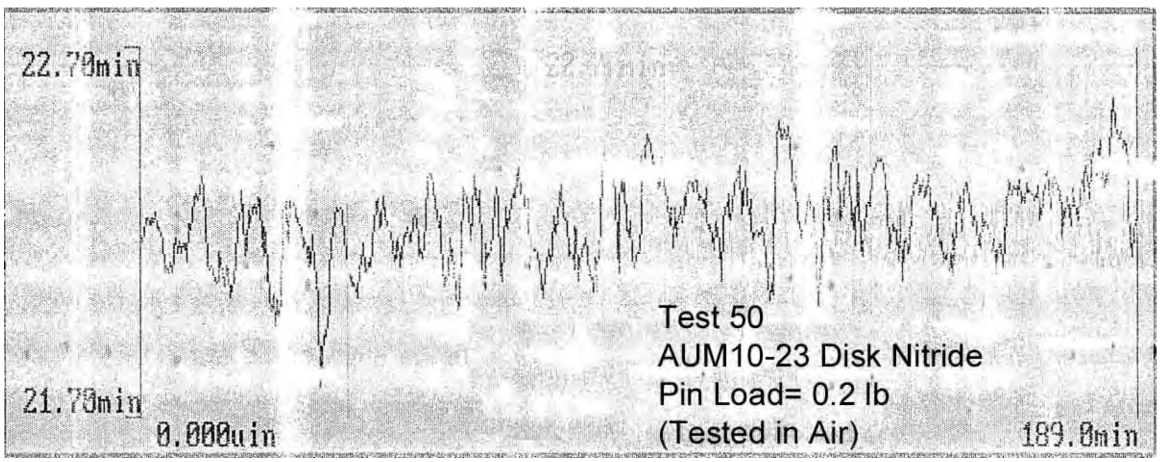
(Wear track on disk was not measurable.)

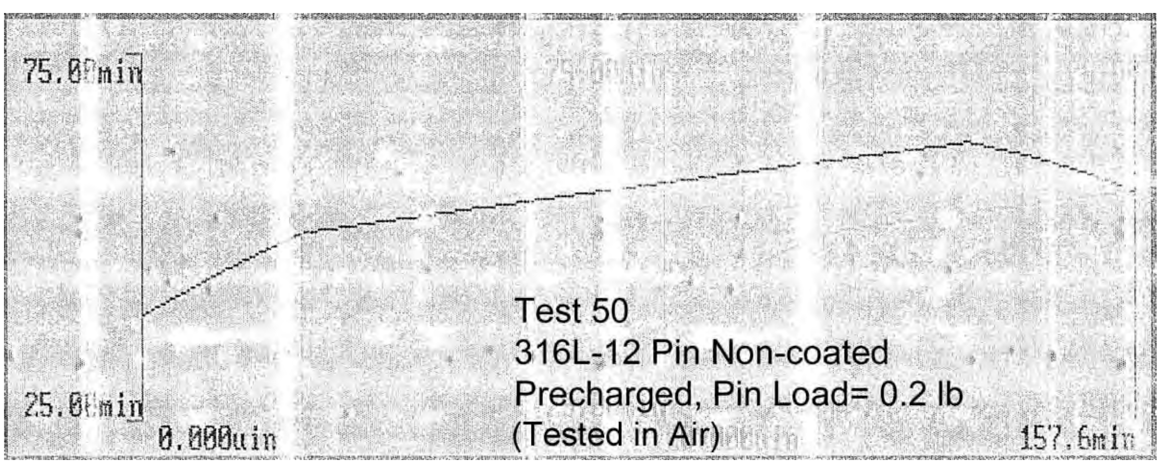


Test 50


AUM10 (Nitride Coated)
Wear Track
Test 50


316L (Non-coated, Precharged)
Pin Load = 0.2 lb
Wear Spot
Test 50

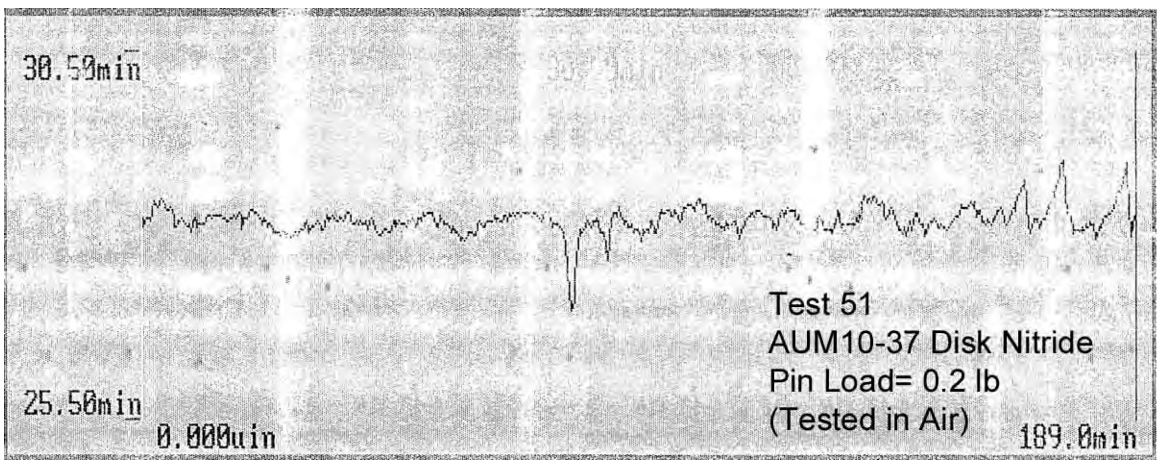

22.70min
21.70min
0.000uin
Test 50
AUM10-23 Disk Nitride
Pin Load= 0.2 lb
(Tested in Air)
189.0min

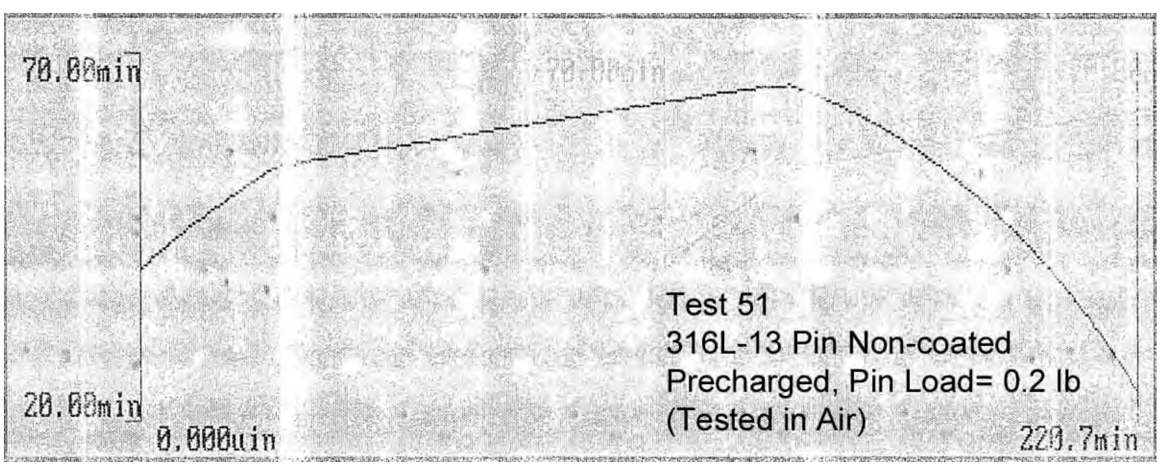

75.00min
25.00min
0.000uin
Test 50
316L-12 Pin Non-coated
Precharged, Pin Load= 0.2 lb
(Tested in Air)
157.6min

Test 51

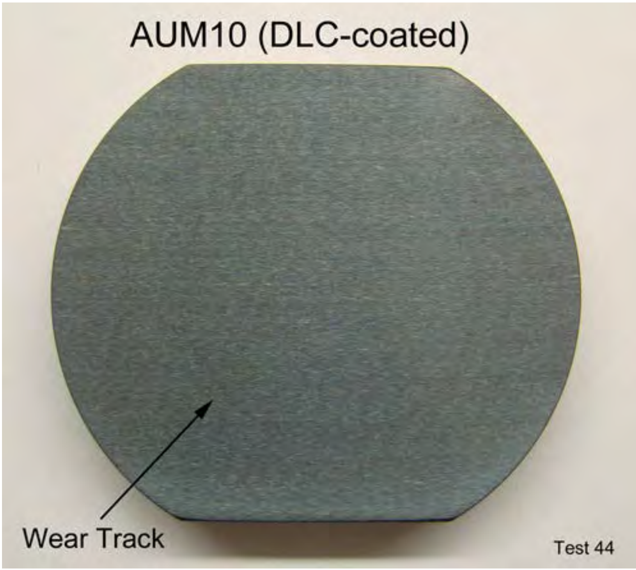

AUM10 (Nitride Coated)
Wear Track
Test 51

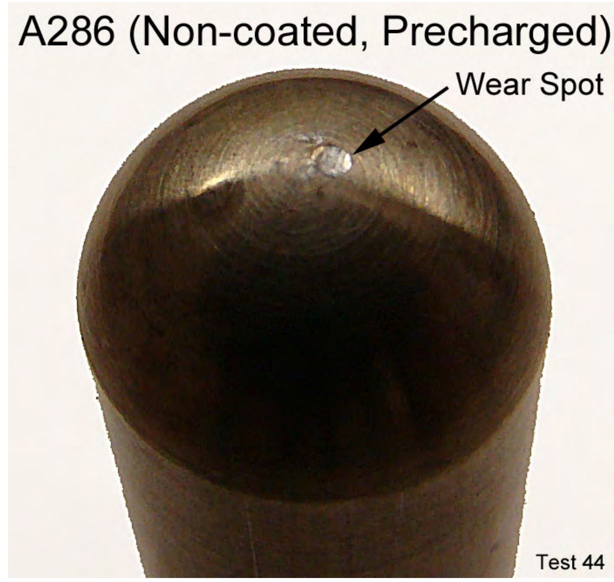

316L (Non-coated, Precharged)
Pin Load = 0.2 lb
Wear Spot
Test 51

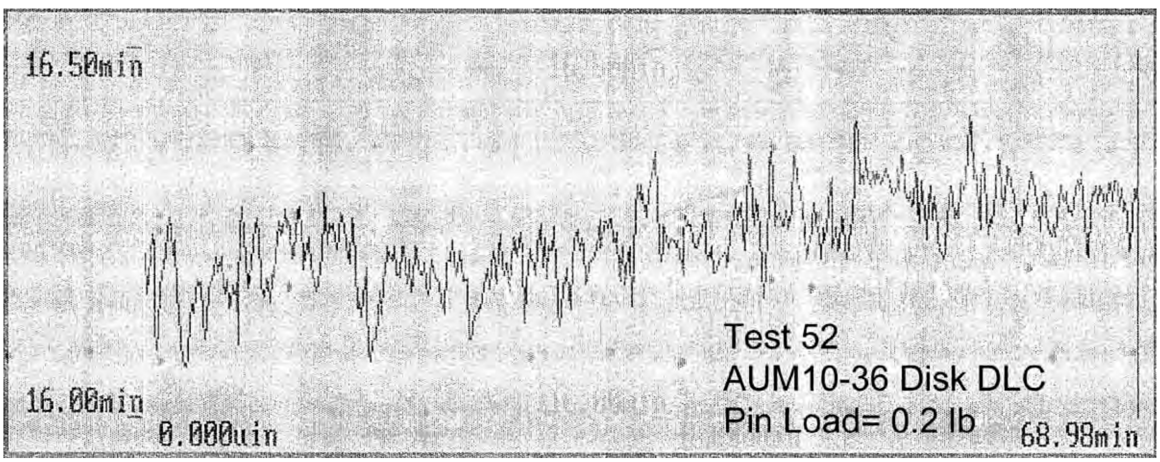

30.50min
25.50min
0.000uin
189.0min
Test 51
AUM10-37 Disk Nitride
Pin Load= 0.2 lb
(Tested in Air)

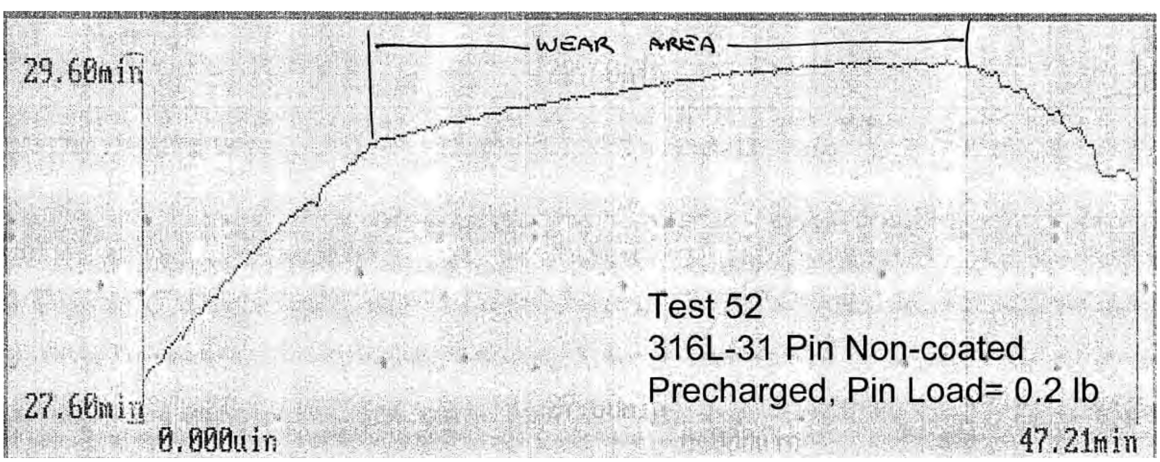

70.00min
20.00min
0.000uin
220.7min
Test 51
316L-13 Pin Non-coated
Precharged, Pin Load= 0.2 lb
(Tested in Air)

Test 52

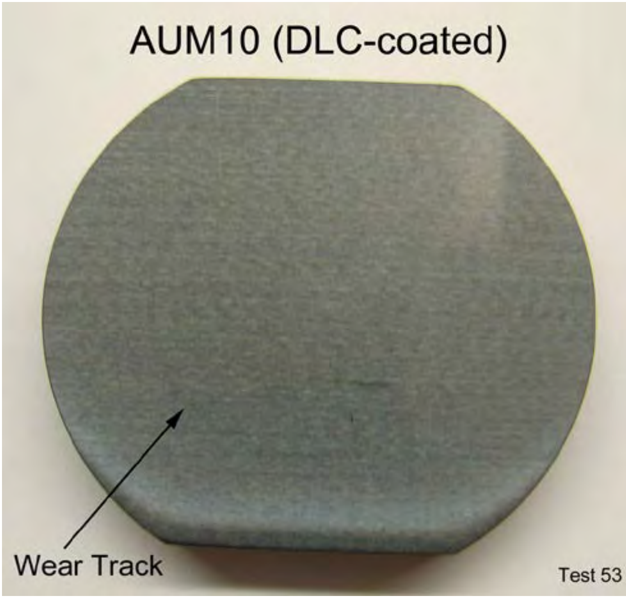

AUM10 (DLC-coated)
Wear Track
Test 44


A286 (Non-coated, Precharged)
Wear Spot
Test 44

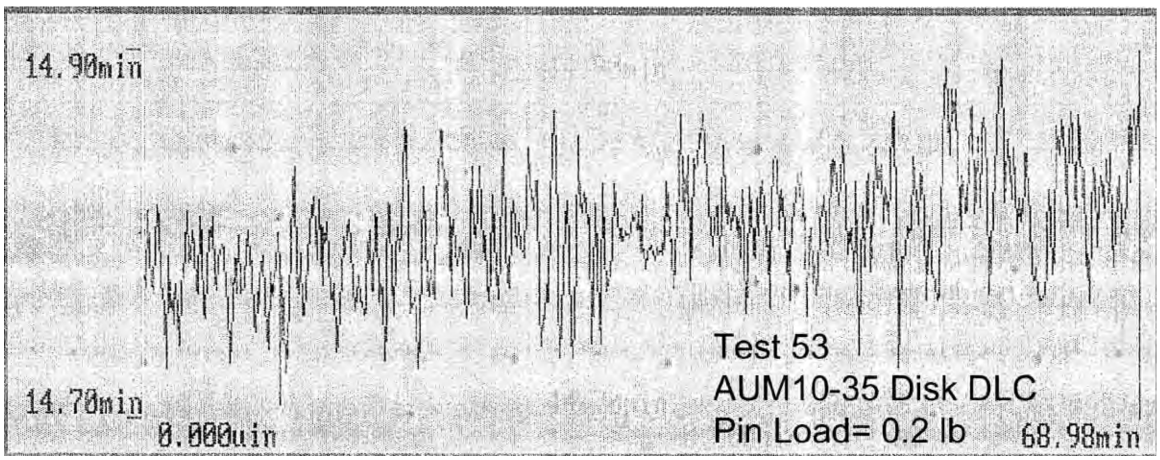

16.50min
16.00min
0.000uin
68.98min
Test 52
AUM10-36 Disk DLC
Pin Load= 0.2 lb

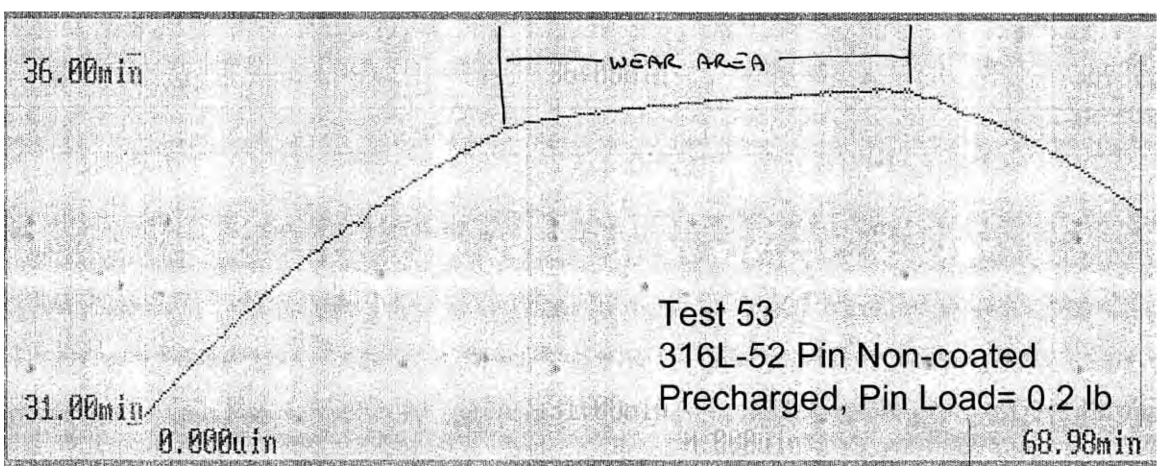

WEAR AREA
29.60min
27.60min
0.000uin
47.21min
Test 52
316L-31 Pin Non-coated
Precharged, Pin Load= 0.2 lb

Test 53

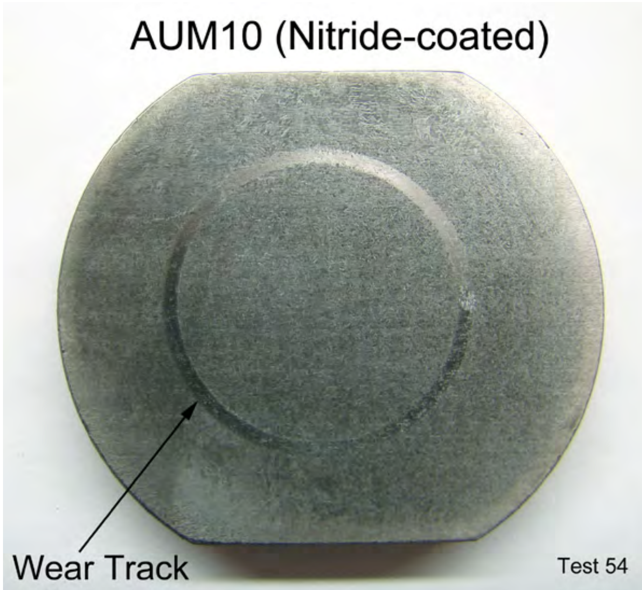

AUM10 (DLC-coated)
Wear Track
Test 53


316L (Non-coated, Precharged)
Wear Spot
Test 53

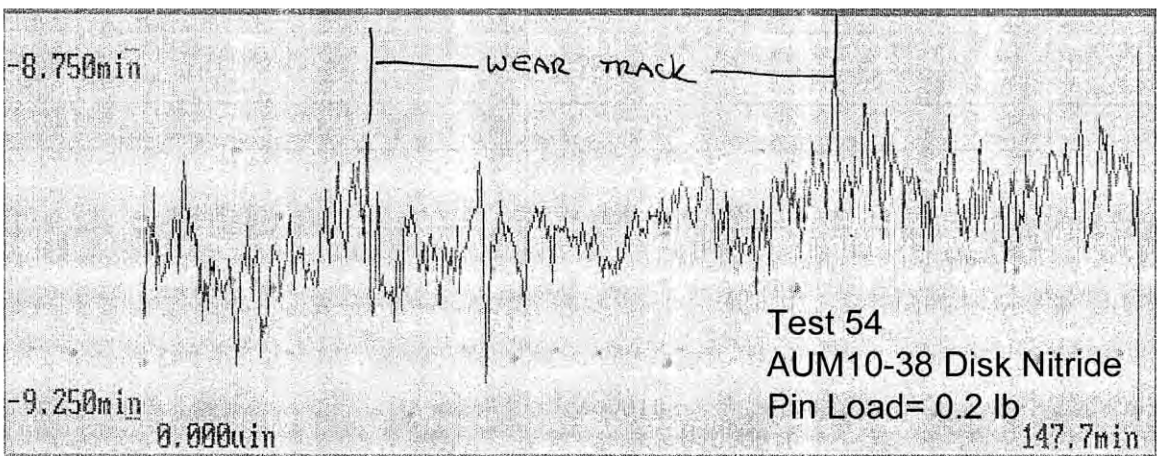

14.90min
14.70min
0.000uin
Test 53
AUM10-35 Disk DLC
Pin Load= 0.2 lb
68.98min

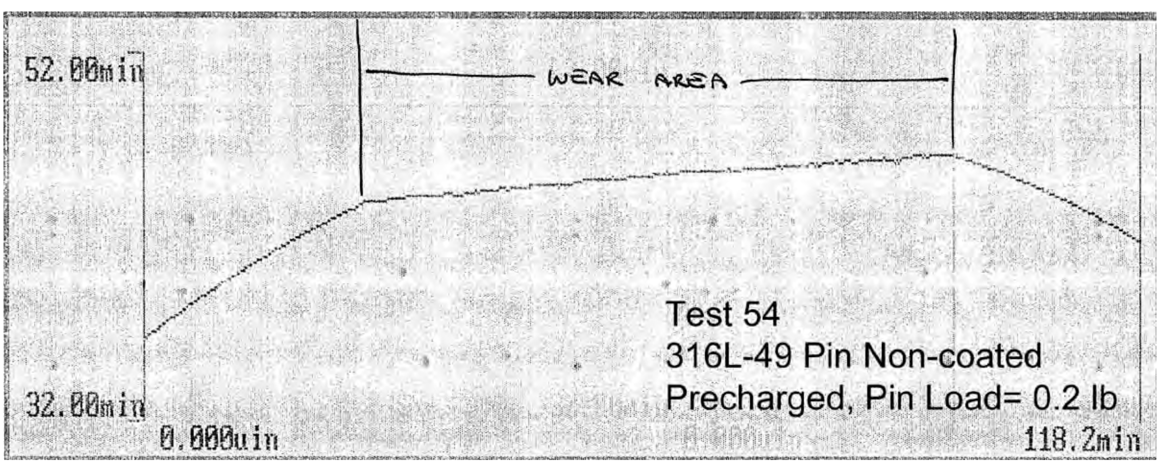

36.00min
WEAR AREA
31.00min
0.000uin
Test 53
316L-52 Pin Non-coated
Precharged, Pin Load= 0.2 lb
68.98min

Test 54

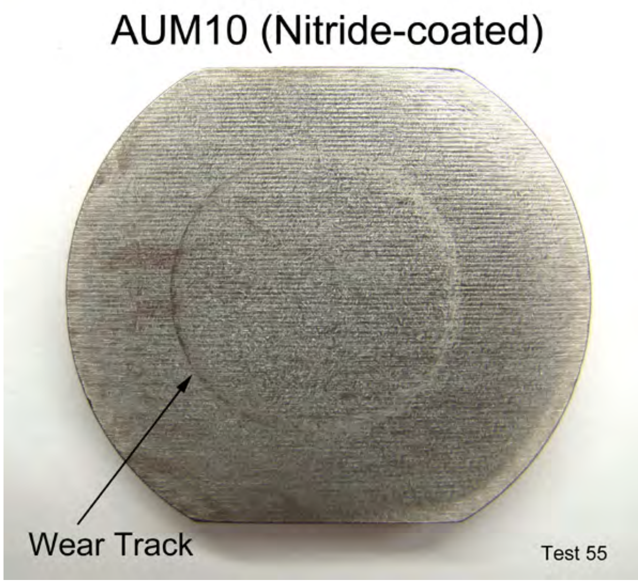

AUM10 (Nitride-coated)
Wear Track
Test 54


316L (Non-coated, Precharged)
Wear Spot
Test 54

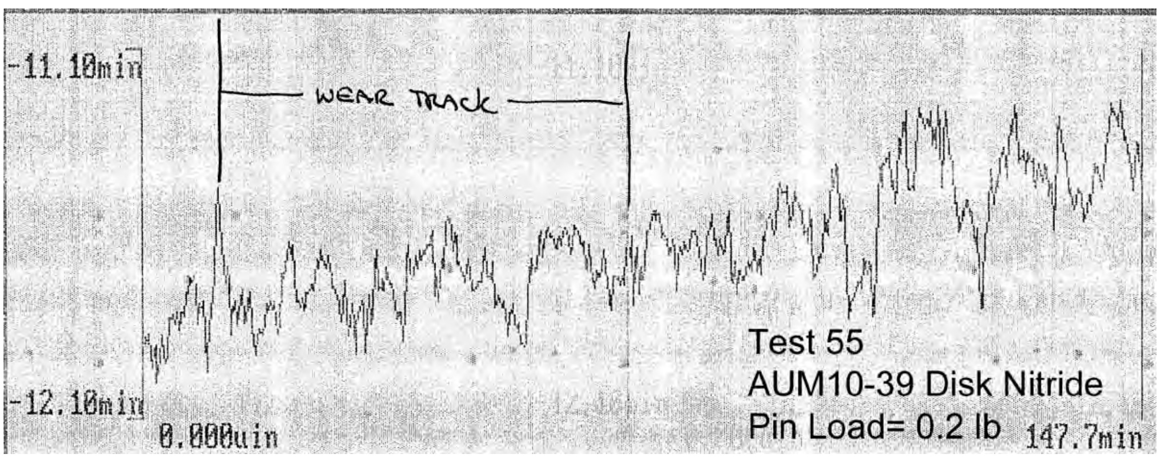

-8.750min
WEAR TRACK
Test 54
AUM10-38 Disk Nitride
Pin Load= 0.2 lb
-9.250min
0.000uin
147.7min

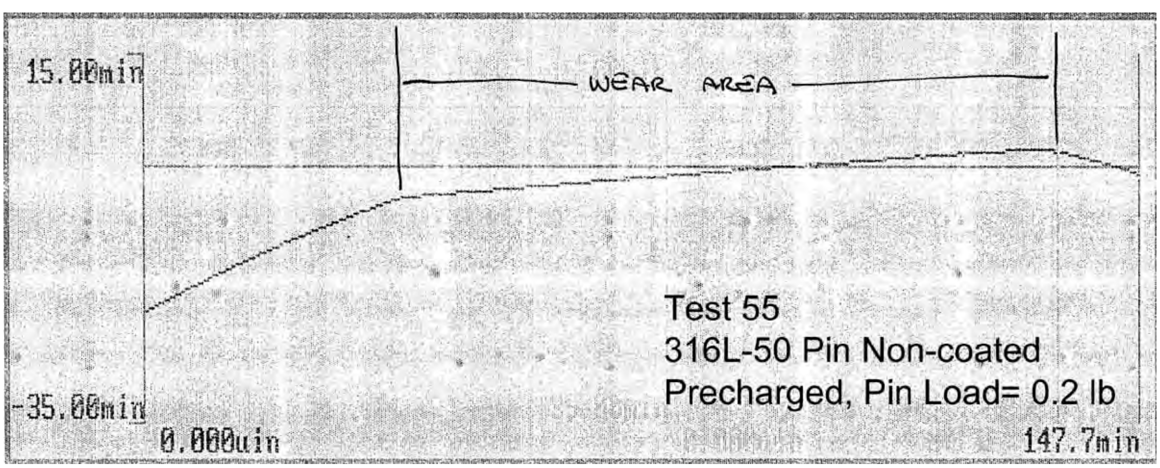

52.00min
WEAR AREA
Test 54
316L-49 Pin Non-coated
Precharged, Pin Load= 0.2 lb
32.00min
0.000uin
118.2min

Test 55


AUM10 (Nitride-coated)
Wear Track
Test 55


316L (Non-coated, Precharged)
Wear Spot
Test 55


-11.10min
-12.10min
0.000uin
147.7min
WEAR TRACK
Test 55
AUM10-39 Disk Nitride
Pin Load= 0.2 lb


15.00min
-35.00min
0.000uin
147.7min
WEAR AREA
Test 55
316L-50 Pin Non-coated
Precharged, Pin Load= 0.2 lb

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