Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy (DOE) Office of Environmental Management (EM).

Disclaimer:

This work was prepared under an agreement with and funded by the U.S. Government. Neither the U. S. Government or its employees, nor any of its contractors, subcontractors or their employees, makes any express or implied:

1) warranty or assumes any legal liability for the accuracy, completeness, or for the use or results of such use of any information, product, or process disclosed; or
2) representation that such use or results of such use would not infringe privately owned rights; or
3) endorsement or recommendation of any specifically identified commercial product, process, or service.

Any views and opinions of authors expressed in this work do not necessarily state or reflect those of the United States Government, or its contractors, or subcontractors.

SRNS-STI-2008-00100

WEAR TESTING OF STAINLESS STEELS IN HYDROGEN (U)

P. S. Lam
T. M. Adams

Savannah River National Laboratory
Materials Science & Technology Directorate

Publication Date: September 2008

[redacted]

Savannah River Nuclear Services
Savannah River Site
Aiken, SC 29808

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy. Distribution authorized to the Department of Energy only; other requests shall be approved by the cognizant DOE Departmental Element.

DISCLAIMER

This work was prepared under an agreement with and funded by the U.S. Government. Neither the U. S. Government or its employees, nor any of its contractors, subcontractors or their employees, makes any express or implied:
1. warranty or assumes any legal liability for the accuracy, completeness, or for the use or results of such use of any information, product, or process disclosed; or 2. representation that such use or results of such use would not infringe privately owned rights; or 3. endorsement or recommendation of any specifically identified commercial product, process, or service. Any views and opinions of authors expressed in this work do not necessarily state or reflect those of the United States Government, or its contractors, or subcontractors.

DOCUMENT: SRNS-STI-2008-00100
TITLE: Wear Testing of Stainless Steels in Hydrogen (U)

APPROVALS

[redacted] Date: 9/18/2008

Poh-Sang Lam, Author
Materials Compatibility & Welding Technology Group
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 9/18/08

Thad M. Adams, Author
Materials Compatibility & Welding Technology Group
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 9-18-2008

Robert L. Sindelar, Technical Review
SRNL-MATERIALS SCIENCE & TECHNOLOGY

[redacted] Date: 9/18/08

Natraj C. Iyer, Director
SRNL-MATERIALS SCIENCE & TECHNOLOGY

SRNS-STI-2008-00100

Table of Contents

List of Tables

List of Figures

EXECUTIVE SUMMARY

A wear test system has been assembled to conduct ASTM G 99, "Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus," testing in air or in gaseous hydrogen up to 13.8 MPa (2000 psig) at room temperature. Two separate disk materials, 316L and AUM10 stainless steels; and two separate pin materials, 316L and A286, were selected for testing. The objective of the testing is to evaluate hydrogen effects on wear characteristics of these materials when used in the design and fabrication of high pressure hydrogen storage vessels and equipment in automotive applications.

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. A planimeter was used to quantify the material loss and reconfiguration in the wear region, and integration along the wear track (disks) or over the wear area (pins) was made to estimate the volume loss. For wear test conditions with a travel distance of nominally 500 m and a unidirectional disk linear speed at nominally 800 mm/sec, the test data indicate:

- Materials transfer and excrescence resulted from this metal-to-metal sliding system. Examination of the surface finish of the post-test specimens was made with optical microscopy, scanning electron microscopy (SEM), and profilometer tracing. The phenomenon is consistent with adhesive wear and galling characteristics of stainless steels.
- AUM10 disk material had a slightly higher wear rate than 316L disk material in air, and a significantly higher wear rate in hydrogen. This is attributed to the fact that AUM10 is relatively softer than 316L and A286 in terms of tensile properties and hardness measurements.
- AUM10 disk material had a significantly higher wear rate in hydrogen compared to air; no clear effect of hydrogen pressure (1000 vs. 2000 psig) was observed.
- 316L disk material and pin material had higher wear rates in hydrogen compared to air; no clear effect of hydrogen pressure (1000 vs. 2000 psig) was observed.

INTRODUCTION

Joint research between the Toyota Research Institute North America and the Savannah River National Laboratory (SRNL) is being 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.

Results from this initial study of selected materials at air and hydrogen test conditions provide input for material selection for hydrogen service. Expected improvement in wear resistance through use of surface coatings will be the subject of a follow-on experimental effort between Toyota Research Institute North America and SRNL.

WEAR TEST EQUIPMENT AND SPECIMEN DESIGNS

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 a high pressure hydrogen environment. A pressure vessel made of Super Alloy HASTELLOY® C276 with an outside diameter of 12.7 cm (5 in.), thickness of 3.81 cm (1.5 in.), and internal cavity height of 17.78 cm (7 in.) was adapted for the test equipment. An assembly of a rotating spindle to attach the disk, and a pin to provide a contact force was designed and fabricated to fit inside the pressure vessel.

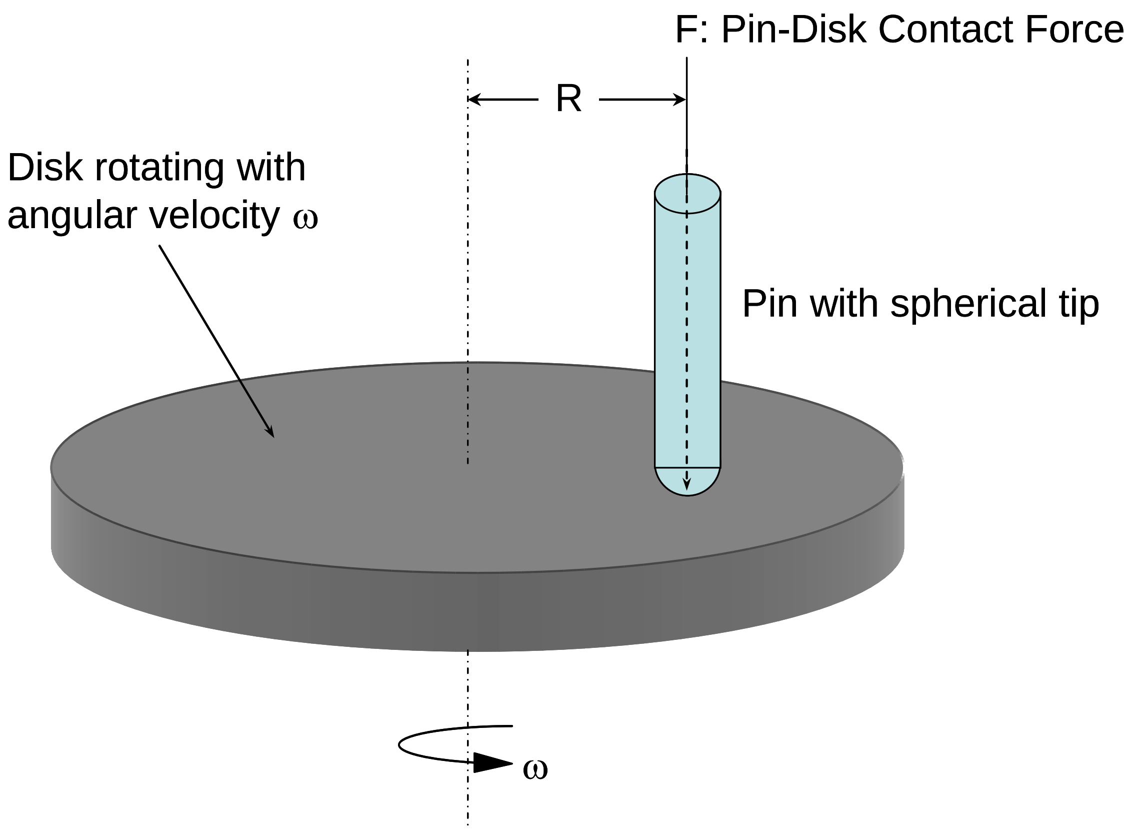


Figure 1 Schematic of disk-pin wear test system (R is the wear track radius).

Figure 1 shows the schematic diagram of the wear test arrangement 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 ($RPM = \frac{\omega}{2\pi} \times 60$) as

$$v = \omega R = \frac{\pi R \times RPM}{30}$$

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 D). 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.

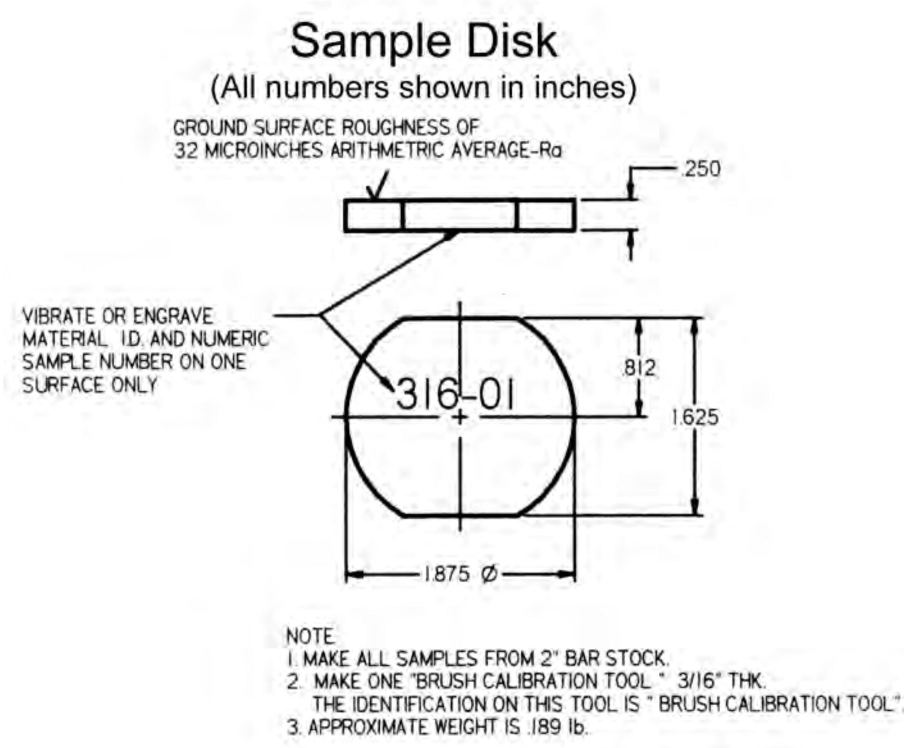


Figure 2 Wear sample disk design and dimensions.

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 6.985 cm (2-3/4 in.) long with a spherical tip on one end and is threaded on the other (Fig. 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. Typical as-finished sample disk and pin can be seen in Figure 4.

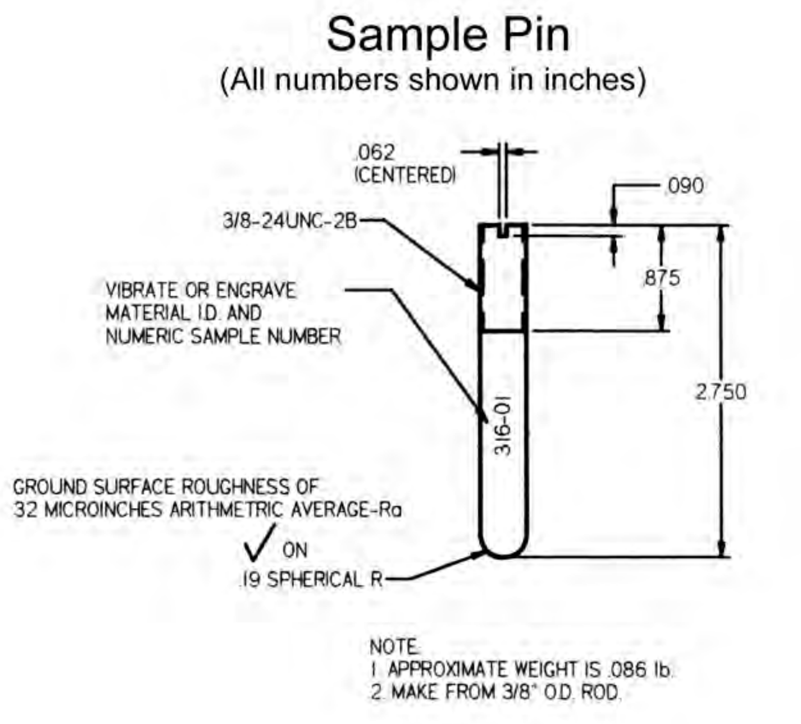


Figure 3 Wear sample pin design and dimensions.

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)	316L Pin (Appendix B)	A286 Pin (Appendix C)	AUM10 Disk (Appendix D)
Bar Stock Diameter cm (in.)	5.08 (2)	9.525 (3/8)	9.525 (3/8)	5.486[1] (2.16)
0.2% Yield Stress MPa (ksi)	269 (39)	607 (88)	1027 (149)	57[2]
UTS MPa (ksi)	593 (86)	717 (104)	1241 (180)	77[2]
Elongation (%)	66	41	18	37[2]
RA (%)	73	74	44	74[2]
Hardness	HB 185	HB 207	HB 335	HV 183[1] (3mm below surface) HV 186[1] (D/4) HV 183[1] (D/2) HRB 88[2]

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 D for the information sheets from Aichi Steel Co. (Japan) [7].
The heat treatment is 900 °C x 2 Hr which is different from that in Note 1.
HRB 88 is equivalent to HB 175.

TEST PROCEDURE AND EQUIPMENT DESCRIPTION

The sample disks and pins were cleaned in an ultrasonic cleaner, handled without any type of surface contamination, wrapped in tissue, and stored in a plastic bag prior to testing.

The overall layout of the wear test facility can be seen in Figure 5, with the wear test system and its components shown in Figure 6. The threaded end of the pin (Fig. 4) is screwed into a threaded hole in one end of a first class lever (Fig. 7). 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. The movable weight is adjusted until the force of the pin on the balance is exactly 45.4 g (0.1 lb).

The pin-holding assembly is then mounted over the sample disk (Figs. 7 and 8) with the load preset to 45.4 g (0.1 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. Thus, the initial (pre-wear) contact point between the disk and the pin remains on a spherical surface as recommended by ASTM G 99-05.

Figure 9 displays the wear system with the pressure vessel lowered to enclose the disk-pin test mechanism for wear 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%. 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 (Fig. 6). The rotational speed is measured by a non-contact laser tachometer connected to a computer which records speed vs. time during each test.

Figure 5 Test facility: Wear test system (left) and hydrogen gas supply cylinder (right).

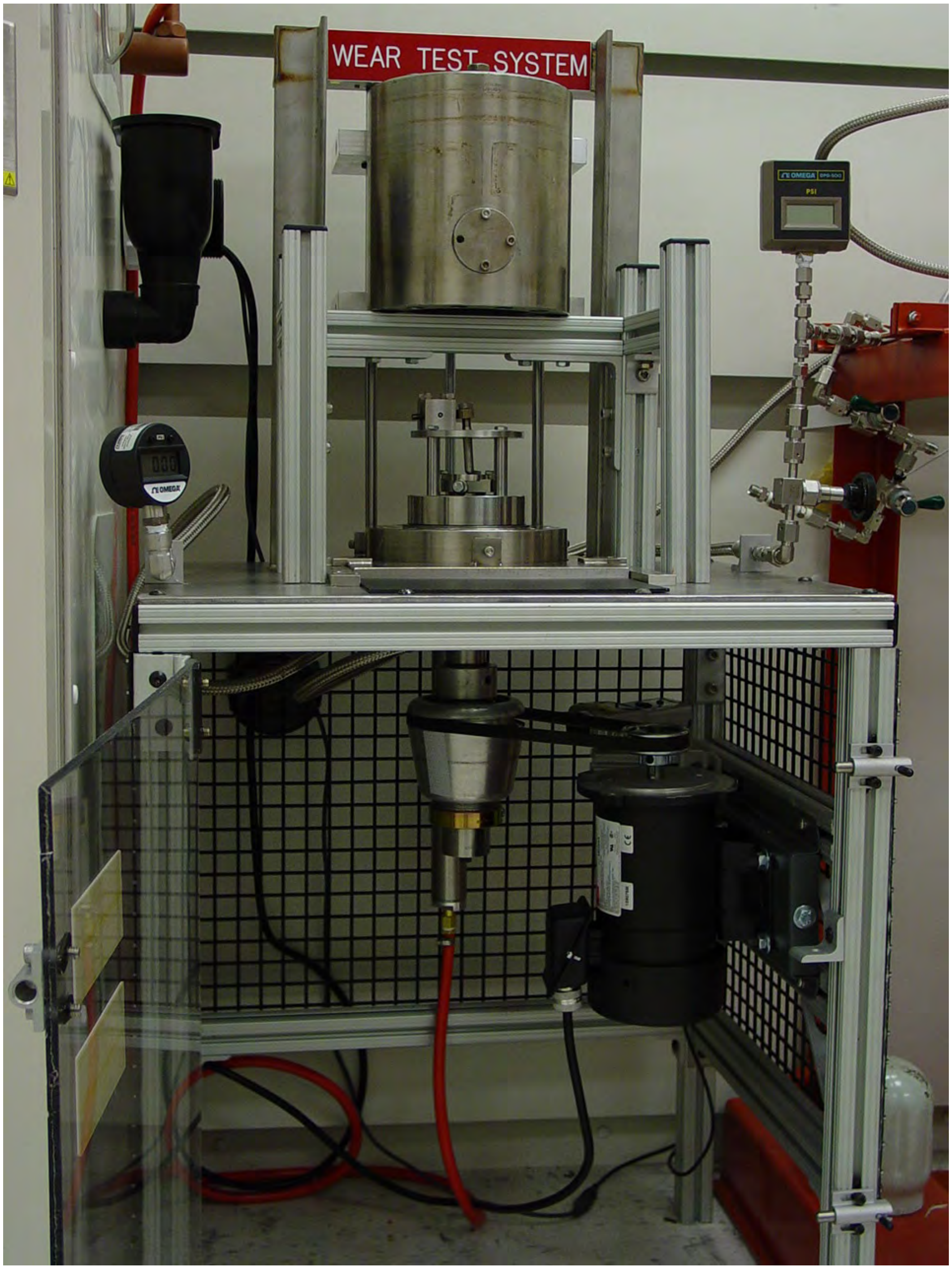


Figure 6 Wear test system from top to bottom: pressure vessel enclosure for providing hydrogen test environment (to be lowered when testing), disk-pin holding assembly (samples are mounted), and Magnedrive® with a V-belt connected to a DC motor. A non-contact laser tachometer is visible above the motor and behind the V-belt.

Figure 7 Sample disk on a rotating platform and the sample pin mounted in a fixed position.

Figure 8 Sample pin in contact with the disk.

Figure 9 Pressure vessel lowered to enclose the wear test mechanism ready for testing in gaseous hydrogen.

WEAR MEASUREMENT

After the samples are run in the test apparatus with a specified speed and travel distance (nominally 500 m) under the load of 45.4 g (0.1 lb), the wear track on the disk and the wear area on the pin are photographed through an optical microscope (e.g., Figs. 10 and 12). The wear surface morphology is obtained with a contact profilometer. A diamond tip stylus is moved in a straight line from an undisturbed area, across the wear region, and ending in the undisturbed area on the other side. A typical trace of the surface profile can be seen in Figures 11 and 13. From the trace on the chart, the wear width can 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 and become roughened. The wear width obtained by profilometer can be confirmed by that measured using a microscope.

The output of the profilometer can be analyzed using a planimeter as an alternative to estimate the weight change due to wear. The area between the line representing original surface and the profilometer trace would represent the material that is displaced by wear. This area can be integrated along the wear track on the disk ($2\pi R$ in Fig. 1), or along the wear area on the pin (assuming an elliptic patch in this report), to obtain the volume loss (or gain, if additional material is transferred to this surface) due to wear. By using a typical mass density of the stainless steel (i.e., 7.98 g/cc), the weight loss (or gain) can be estimated.

The individual disk and pin samples were weighed with a five-place balance to determine weight changes by direct measurement. AS discussed, estimation of the disk weight change from profilometer traces was performed. These results, together with the surface examination by means of optical microscopy and/or SEM, provide characterization of the wear region.

Table 2 lists the test matrix of the present study, including the test parameters and the test completion dates. Note that the actual disk speed and the actual total travel distance 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 did not coincide with the design distance of R= 2.54 cm (1 in.).

Table 2 Test matrix with completion dates

Test No.	Disk Material	Pin Material	Ambient. Gas	Ambient Pressure (psig)	Disk Speed (mm/sec)	Travel Distance (m)	Pin Load (lb)	Test Date Year 2008
1	316L	316L	Air	0	704	450	0.1	5-May
3	316L	316L	Air	0	808	520	0.1	15-Apr
2	316L	316L	Air	0	86	445	0.1	8-May
21	316L	316L	Air	0	98	488	0.1	28-Apr
9	316L	316L	Hydrogen	1000	688	423	0.1	0-Jan
11	316L	316L	Hydrogen	1000	712	445	0.1	29-May
12	316L	316L	Hydrogen	1000	92	463	0.1	17-Jun
13	316L	316L	Hydrogen	1000	91	453	0.1	18-Jun
20	316L	316L	Hydrogen	2000	808	496	0.1	9-Jun
22	316L	316L	Hydrogen	2000	764	469	0.1	10-Jun
23	316L	316L	Hydrogen	2000	94	471	0.1	23-Jun
24	316L	316L	Hydrogen	2000	97	487	0.1	24-Jun
4	316L	A286	Air	0	696	485	0.1	7-May
6	316L	A286	Air	0	776	500	0.1	17-Apr
14	316L	A286	Hydrogen	1000	696	435	0.1	30-May
15	316L	A286	Hydrogen	1000	752	470	0.1	2-Jun
25	316L	A286	Hydrogen	2000	814	501	0.1	11-Jun
26	316L	A286	Hydrogen	2000	816	501	0.1	16-Jun
5	AUM10	316L	Air	0	688	470	0.1	7-May
8	AUM10	316L	Air	0	792	510	0.1	14-Apr
16	AUM10	316L	Hydrogen	1000	819	511	0.1	3-Jun
17	AUM10	316L	Hydrogen	1000	785	490	0.1	4-Jun
27	AUM10	316L	Hydrogen	2000	803	494	0.1	16-Jun
28	AUM10	316L	Hydrogen	2000	847	523	0.1	18-Jun
7	AUM10	A286	Air	0	696	475	0.1	7-May
10	AUM10	A286	Air	0	776	500	0.1	15-Apr
18	AUM10	A286	Hydrogen	1000	712	445	0.1	28-May
19	AUM10	A286	Hydrogen	1000	819	503	0.1	5-Jun
29	AUM10	A286	Hydrogen	2000	869	535	0.1	18-Jun
30	AUM10	A286	Hydrogen	2000	807	496	0.1	20-Jun

POST-TEST WEAR CHARACTERIZATION

The post-wear testing surface conditions for selected disk and pin samples are displayed in this section. These tests were conducted in air (Table 3) and in 13.8 MPa (2000 psi) hydrogen gas (Table 4). For all these tests, the nominal travel speed was 800 mm/sec and the nominal travel distance was 500 m. For each of these samples, the results from the optical microscope, profilometer, and scanning electronic microscope (SEM) are displayed (Figs. 10 to 53 for air testing; and Figs. 54 to 97 for hydrogen testing). Tables 3 and 4 provide a guide for these images:

Table 3 Selected Air tested surface characterization – Guide to figures 10 to 53

	Test No. 1 Disk-Pin: 316L-316L	Test No. 4 Disk-Pin: 316L-A286	Test No. 5 Disk-Pin: AUM10-316L	Test No. 7 Disk-Pin: AUM10-A286
Disk Wear Track Optical	Figure 10	Figure 21	Figure 32	Figure 43
Disk Wear Track Profilometer	Figure 11	Figure 22	Figure 33	Figure 44
Pin Wear Area Optical	Figure 12	Figure 23	Figure 35	Figure 45
Pin Wear Area Profilometer	Figure 13	Figure 24	Figure 35	Figure 46
Disk Wear Track SEM 60X	Figure 14	Figure 25	Figure 36	Figure 47
Disk Wear Track SEM Detailed	Figure 15	Figure 26	Figure 37	Figure 48
Disk Wear Track SEM 500X	Figure 16	Figure 27	Figure 38	Figure 49
Disk Wear Track SEM 1000X	Figure 17	Figure 28	Figure 39	Figure 50
Pin Wear Area SEM 20X	Figure 18	Figure 29	Figure 40	Figure 51
Pin Wear Area SEM 60X	Figure 19	Figure 30	Figure 41	Figure 52
Pin Wear Area SEM Detailed	Figure 20	Figure 31	Figure 42	Figure 53

Table 4 Selected Hydrogen (13.8 MPa or 2000 psi) tested surface characterization – Guide to Figures 54 to 97

	Test No. 22 Disk-Pin: 316L-316L	Test No. 25 Disk-Pin: 316L-A286	Test No. 27 Disk-Pin: AUM10-316L	Test No. 30 Disk-Pin: AUM10-A286
Disk Wear Track Optical	Figure 54	Figure 65	Figure 76	Figure 87
Disk Wear Track Profilometer	Figure 55	Figure 66	Figure 773	Figure 88
Pin Wear Area Optical	Figure 56	Figure 67	Figure 78	Figure 89
Pin Wear Area Profilometer	Figure 57	Figure 68	Figure 79	Figure 90
Disk Wear Track SEM 60X	Figure 58	Figure 69	Figure 80	Figure 91
Disk Wear Track SEM Detailed	Figure 59	Figure 70	Figure 81	Figure 92
Disk Wear Track SEM 500X	Figure 60	Figure 71	Figure 82	Figure 93
Disk Wear Track SEM 1000X	Figure 61	Figure 72	Figure 83	Figure 94
Pin Wear Area SEM 20X	Figure 62	Figure 73	Figure 84	Figure 95
Pin Wear Area SEM 60X	Figure 63	Figure 74	Figure 85	Figure 96
Pin Wear Area SEM Detailed	Figure 64	Figure 75	Figure 86	Figure 97

All the wear surfaces exhibit typical adhesive wear and galling features that include indication of material transfer, plastic deformation, and excrescence resulting from metal-to-metal sliding, scoring and scuffing. The observation is consistent with the wear characteristics of stainless steels [1-3].

Air Test Surfaces

SEM images of the wear scar surfaces for disk and pin samples tested in air are displayed in Figures 10 to 53. Examination of the wear scar surface images for the 316L and AUM10 disk materials tested in air indicates the following: 1) for the 316L and AUM10 disk materials tests conducted using both a 316L and A286 pin materials, evidence of surface roughening and protrusion in addition to evidence of surface fragmentation is observed, 2) surface roughening, protrusion development and fragmentation in the wear scar area is increased for the 316L disk materials when tested with the A286 pin material compared to the 316L pin material, and 3) testing for the AUM10 disk materials with both the 316L and A286 pin materials displays moderate protrusion development and evidence of void formation and fragmentation.

Figure 10 Wear track on the disk under optical microscope (Test No. 1).

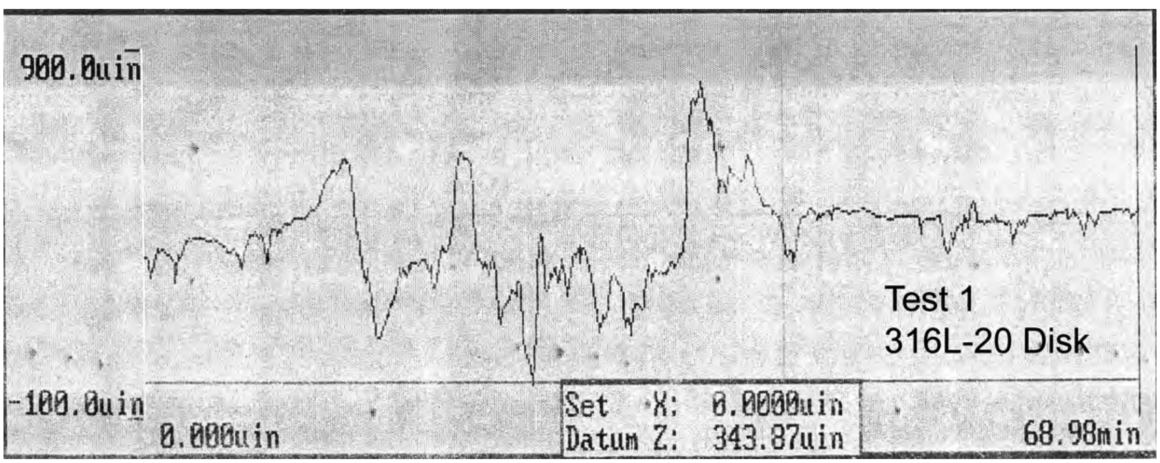


Figure 11 Profilometer trace and measurement across the wear track on the disk (Test No. 1).

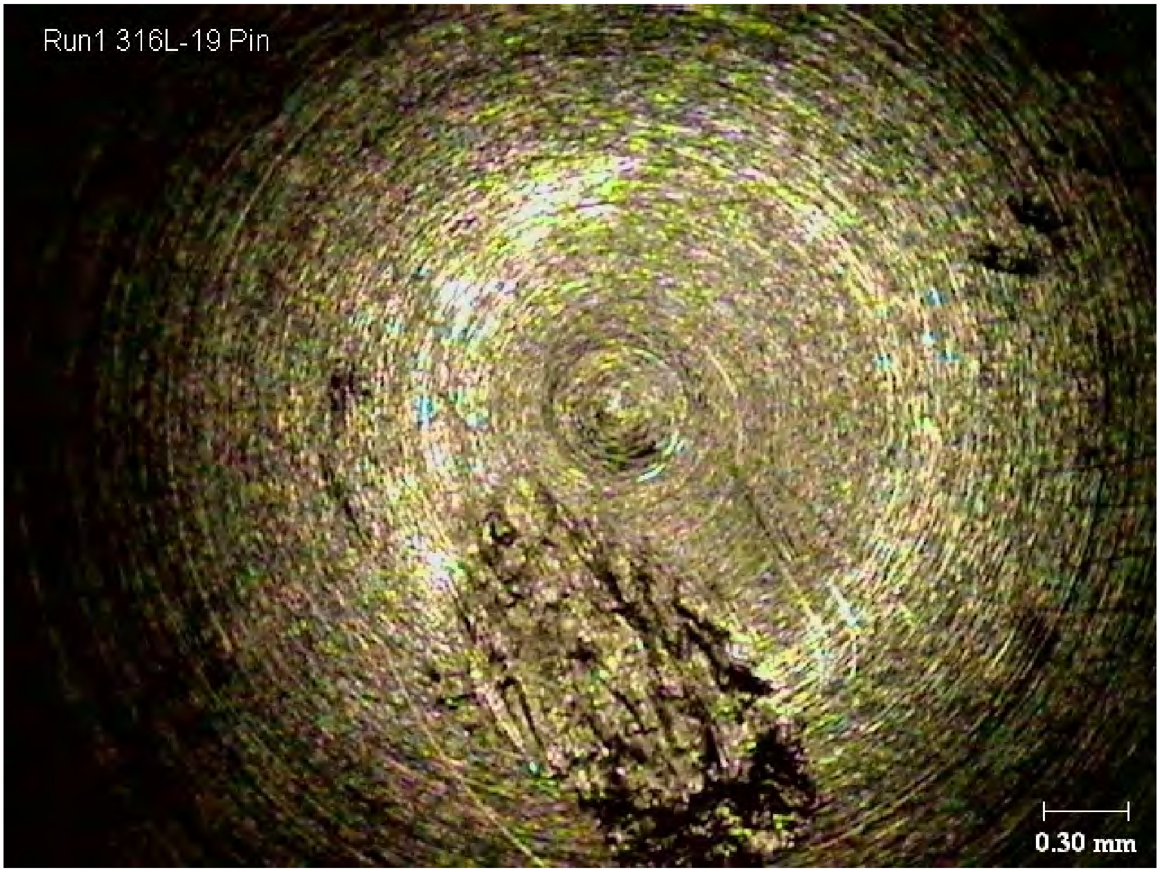


Figure 12 Wear area on the spherical surface of the pin under optical microscope (Test No. 1).

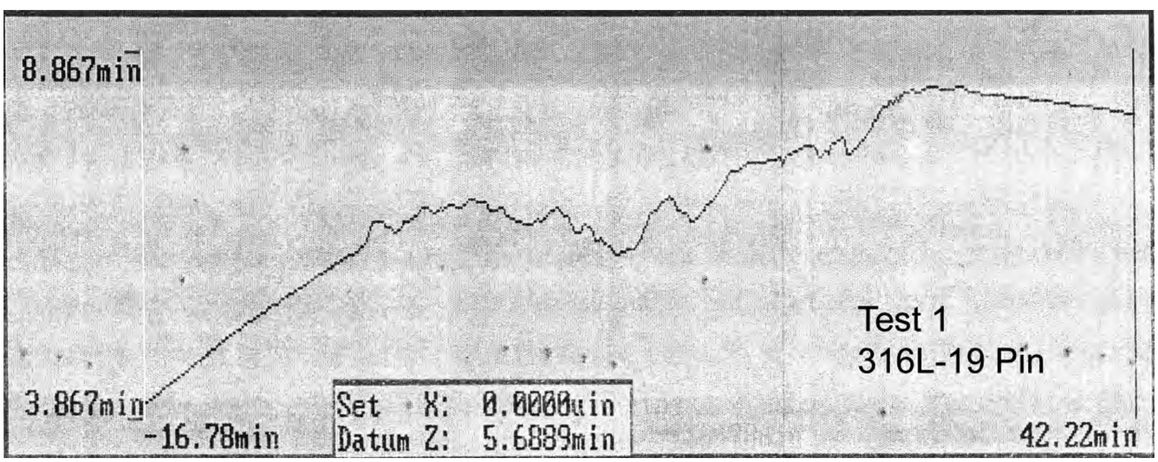


Figure 13 Profilometer trace and measurement across the wear area on the pin (Test No. 1).

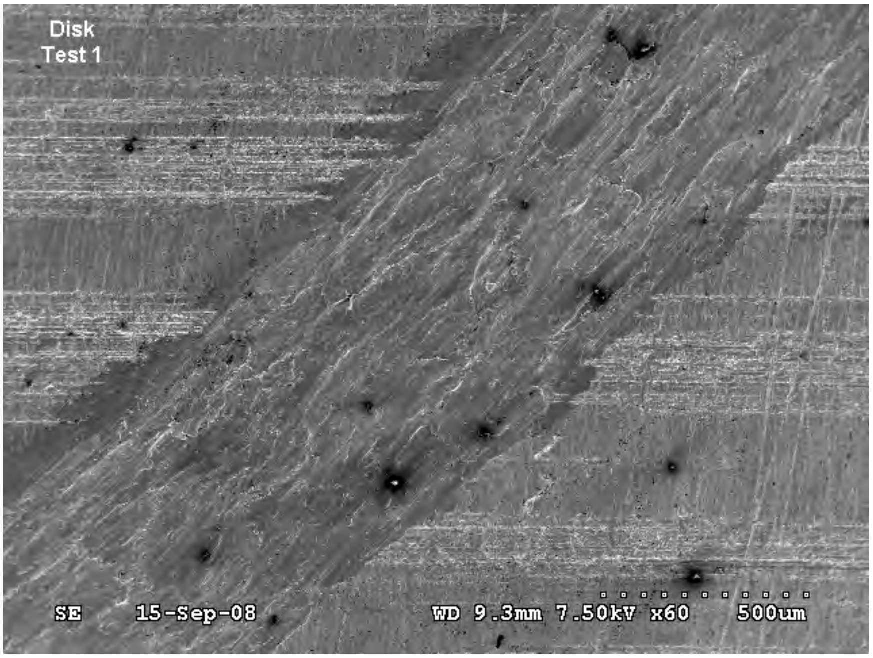


Figure 14 Wear track on the disk under SEM at 60X (Test No. 1).

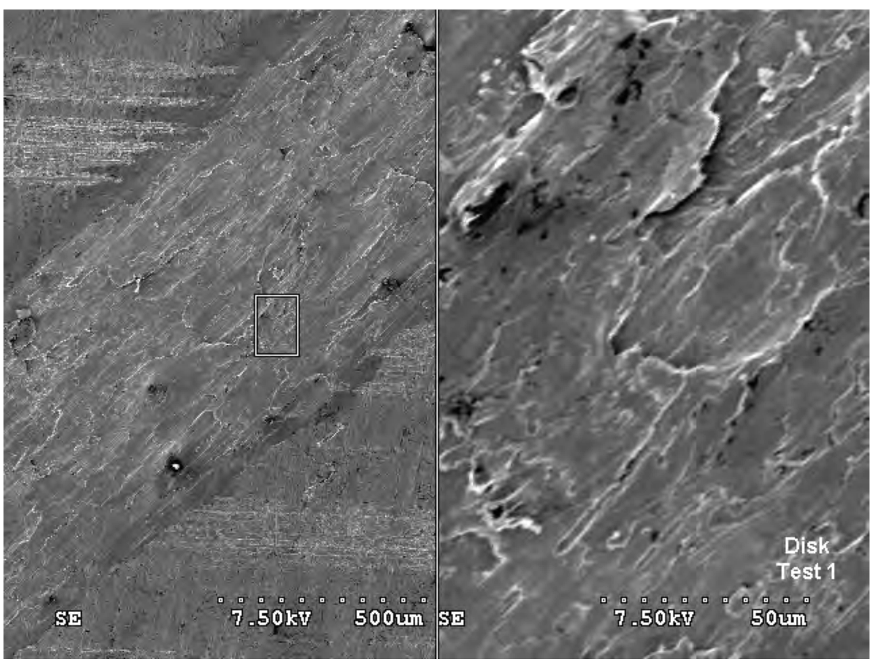


Figure 15 Detailed characterization of wear track on the disk with SEM (Test No. 1).

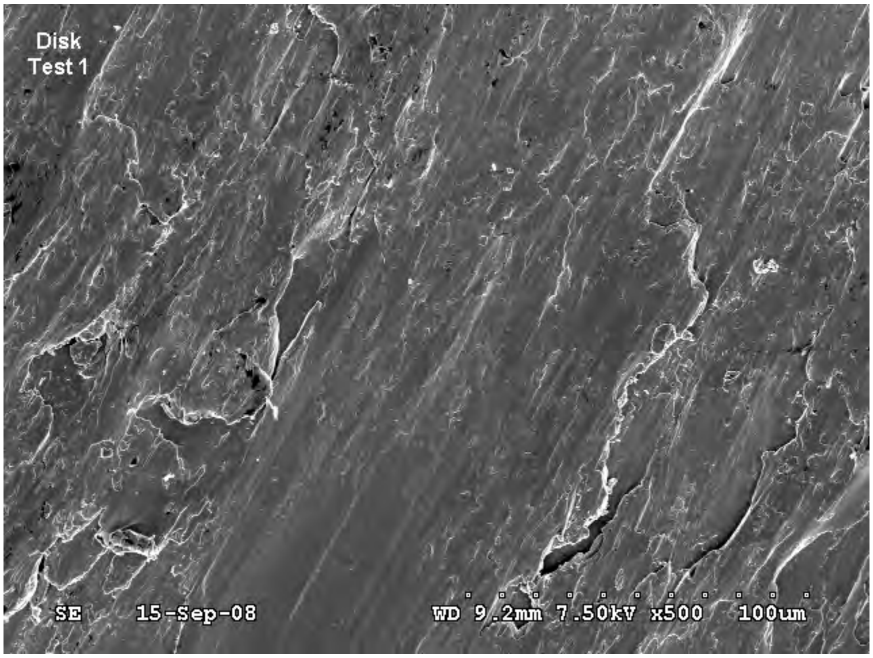


Figure 16 Wear track on the disk with SEM at 500X (Test No. 1).

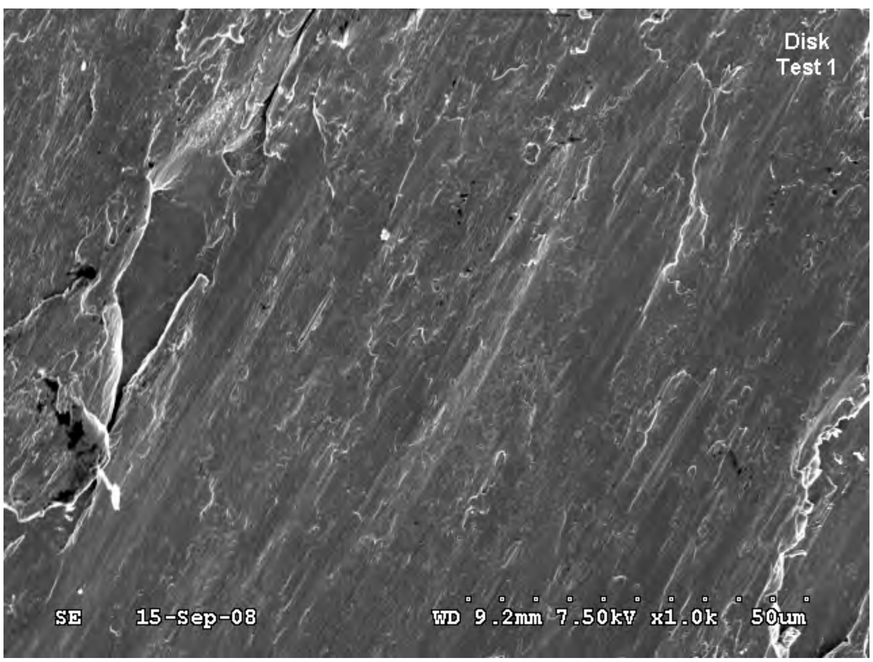


Figure 17 Wear track on the disk under SEM at 1000X (Test No. 1).

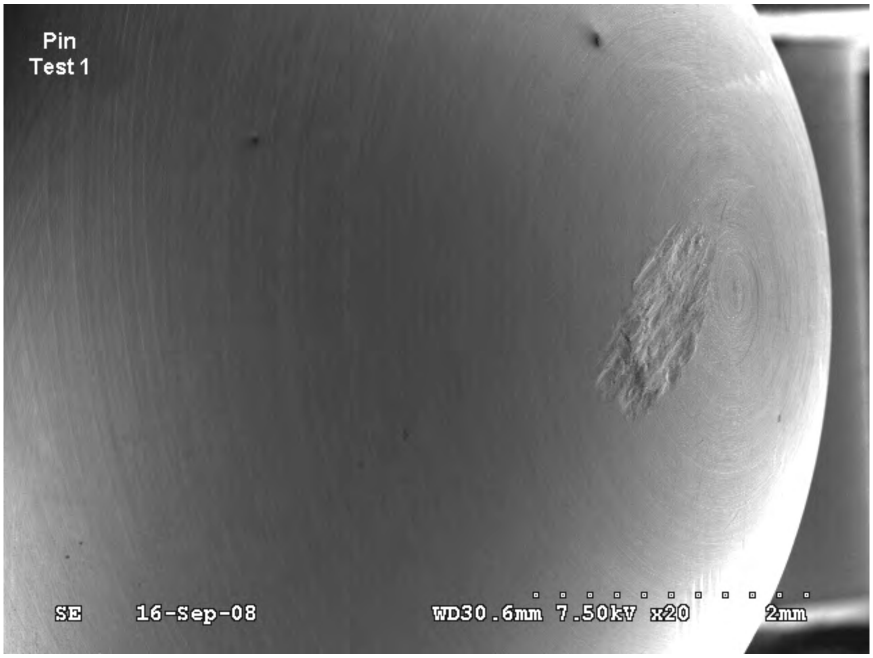


Figure 18 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 1).

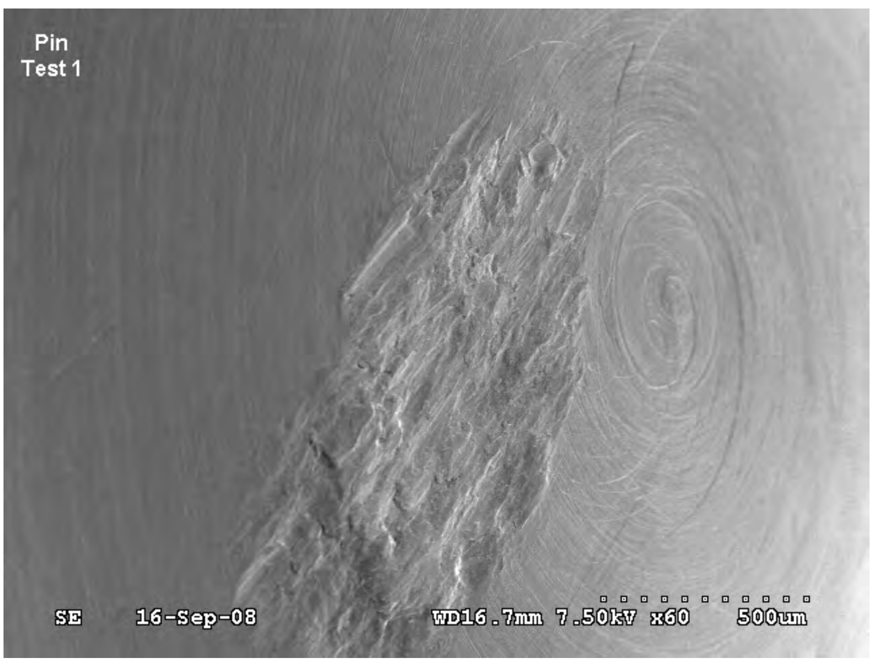


Figure 19 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 1).

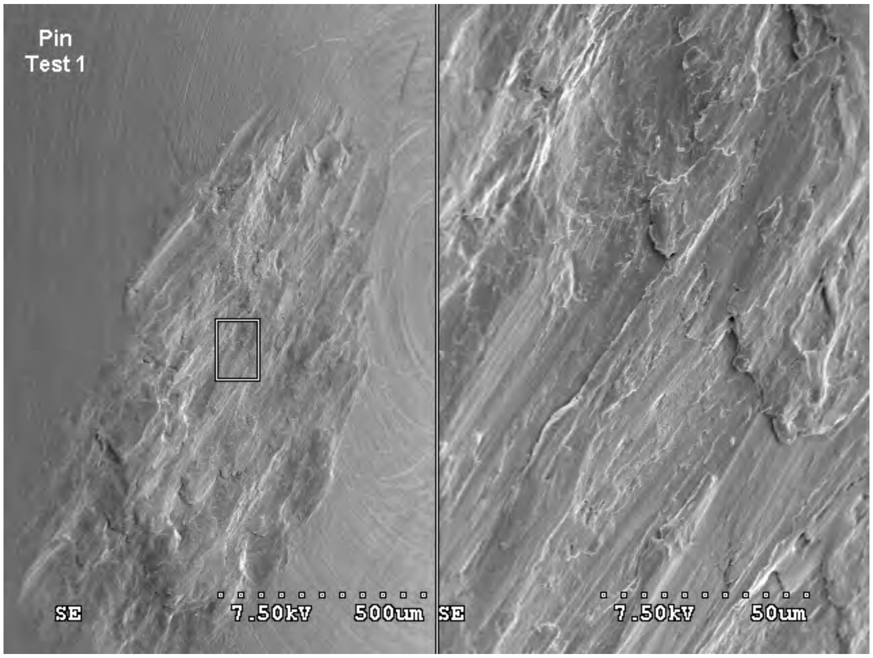


Figure 20 Detailed characterization of wear area on the pin with SEM (Test No. 1).

Figure 21 Wear track on the disk under optical microscope (Test No. 4).

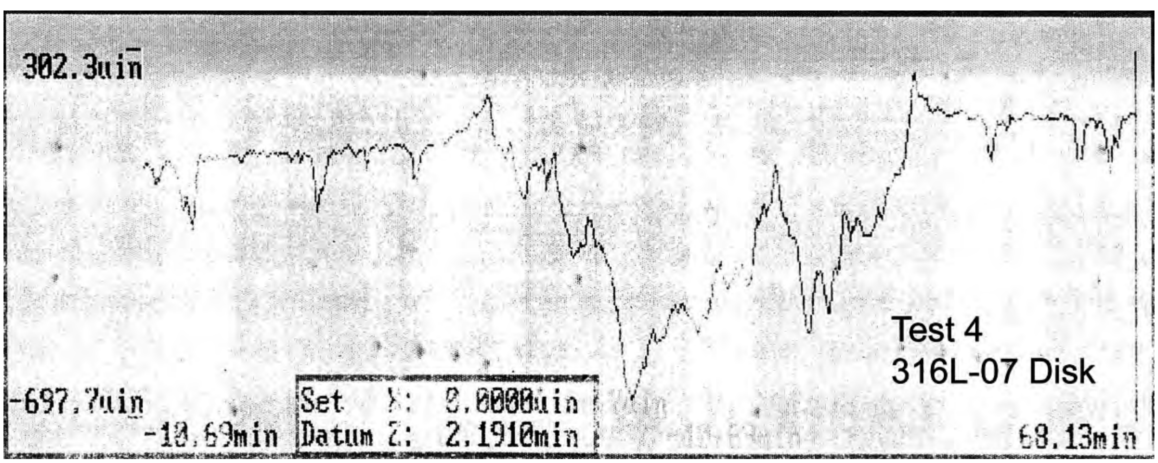


Figure 22 Profilometer trace and measurement across the wear track on the disk (Test No. 4).

Figure 23 Wear area on the spherical surface of the pin under optical microscope (Test No. 4).

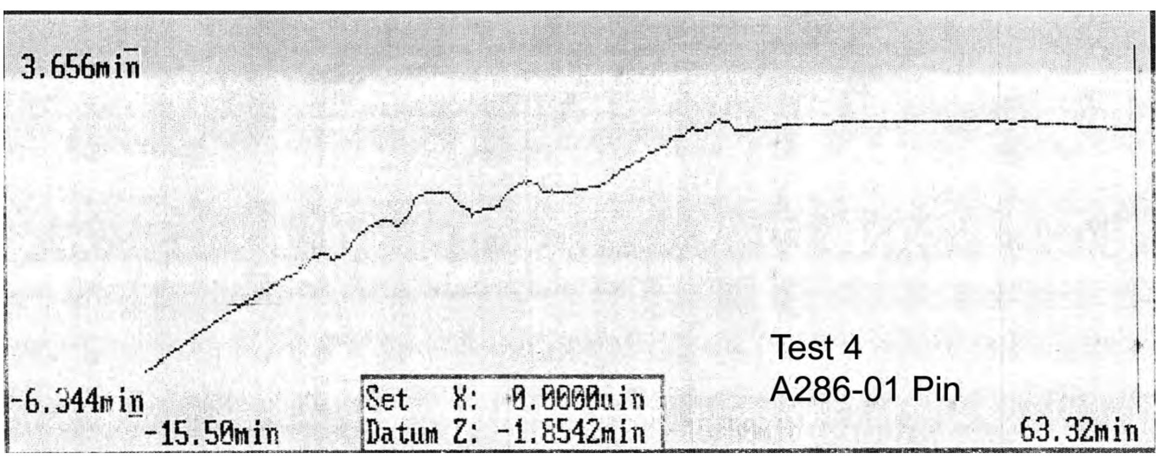


Figure 24 Profilometer trace and measurement across the wear area on the pin (Test No. 4).

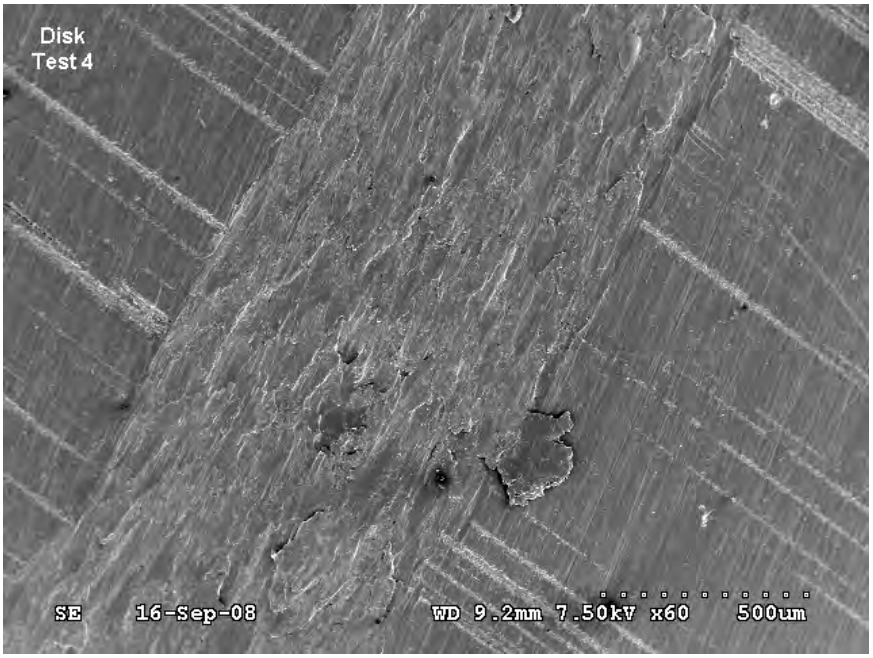


Figure 25 Wear track on the disk under SEM at 60X (Test No. 4).

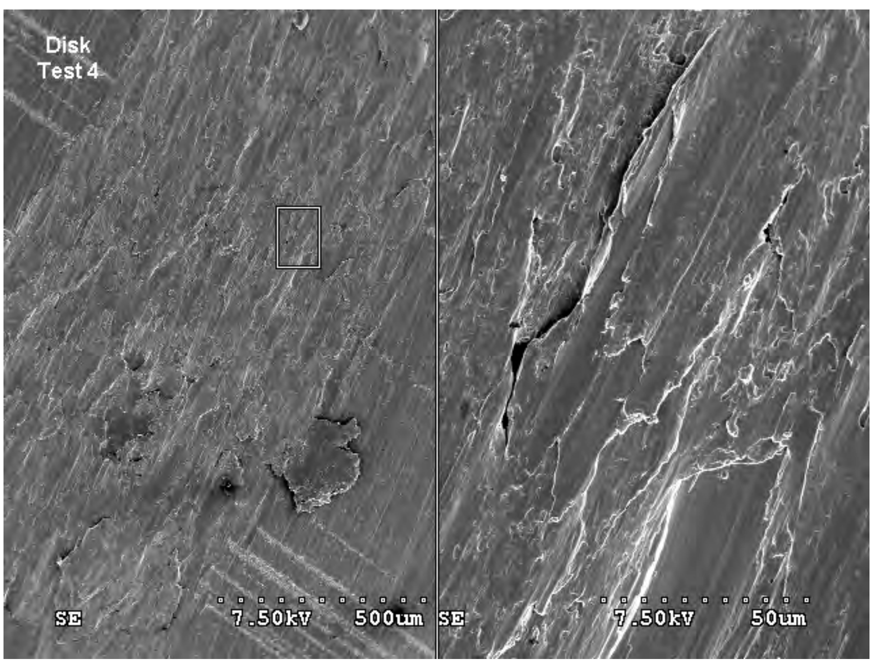


Figure 26 Detailed characterization of wear track on the disk with SEM (Test No. 4).

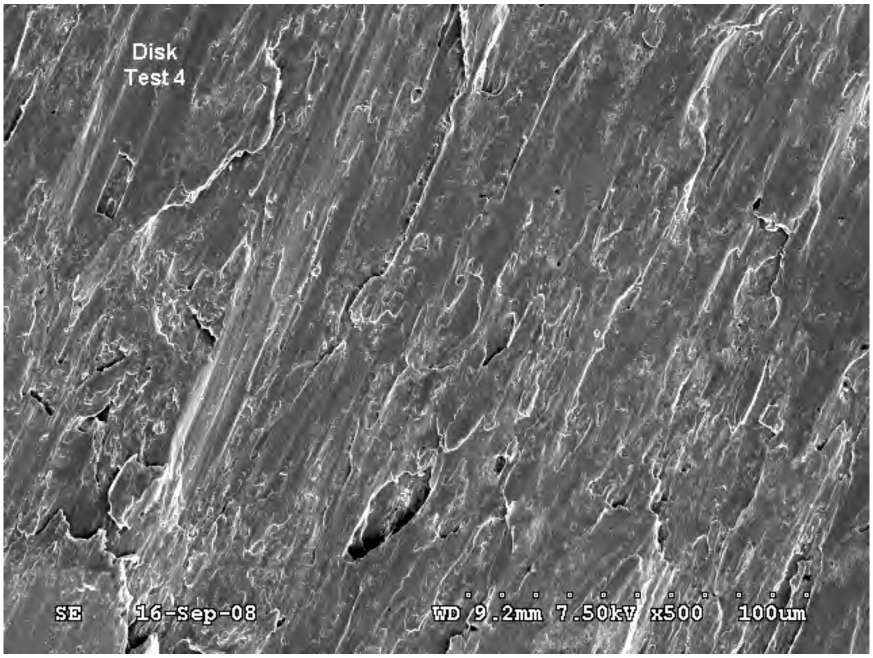


Figure 27 Wear track on the disk with SEM at 500X (Test No. 4).

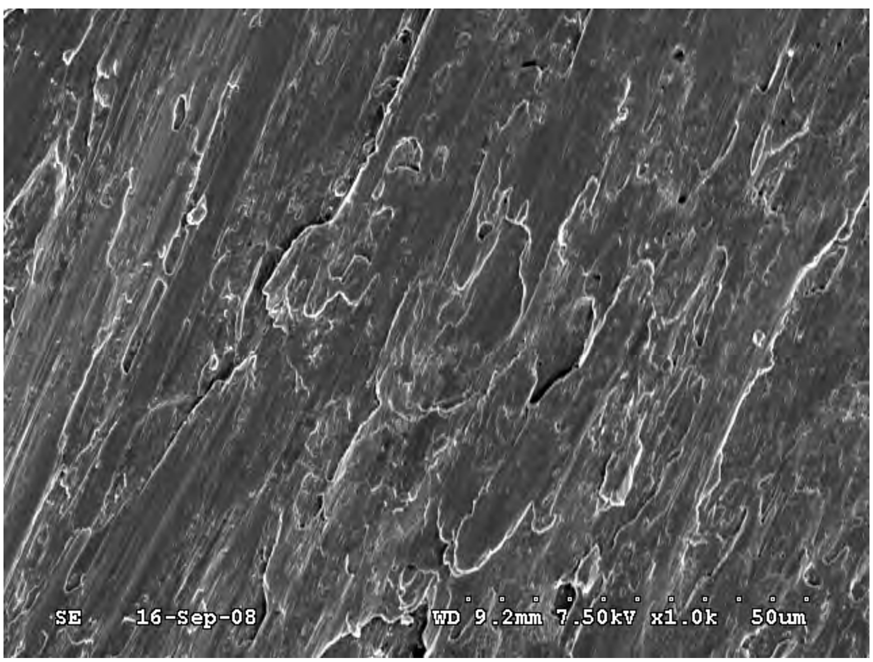


Figure 28 Wear track on the disk under SEM at 1000X (Test No. 4).

Figure 29 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 4).

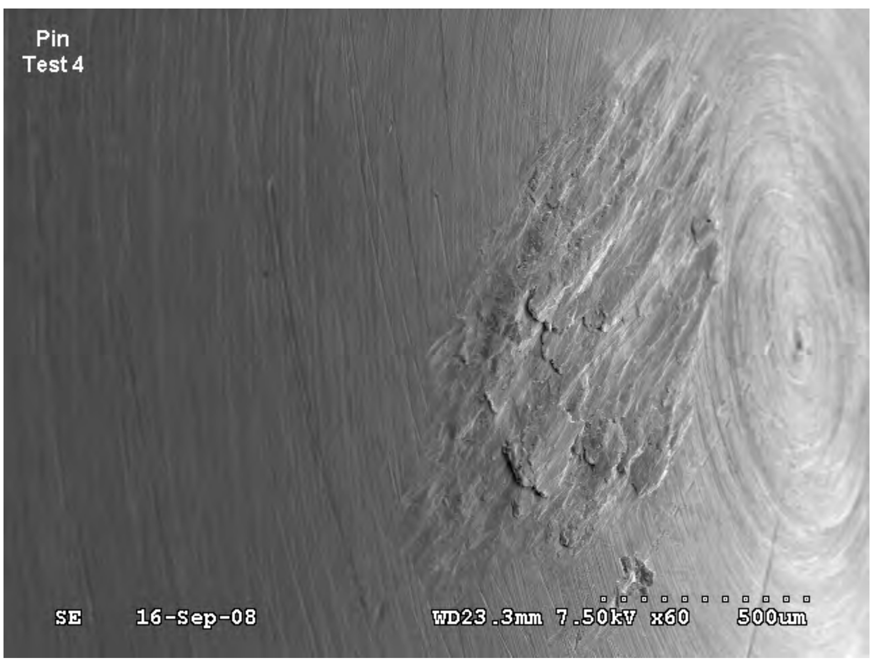


Figure 30 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 4).

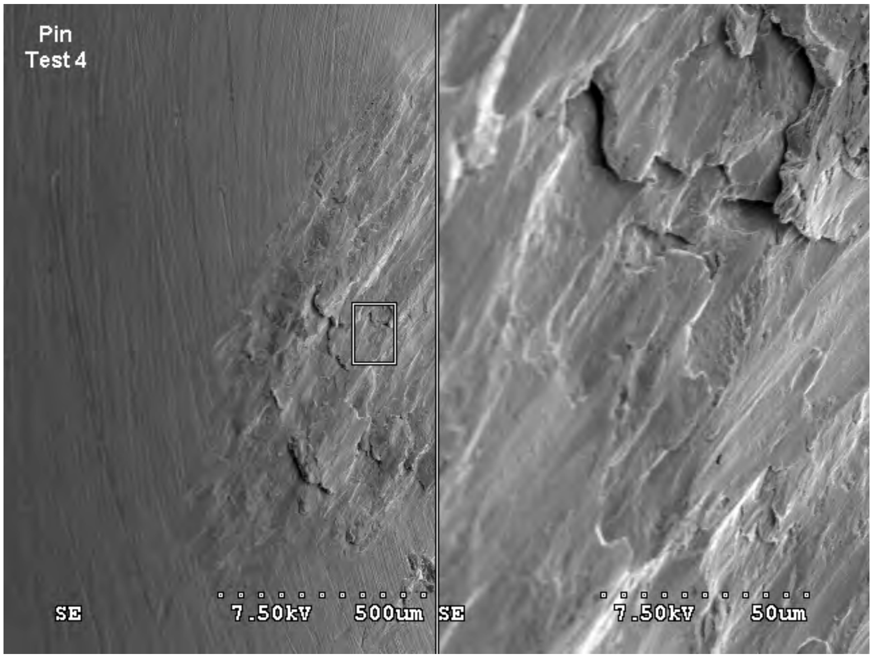


Figure 31 Detailed characterization of wear area on the pin with SEM (Test No. 4).

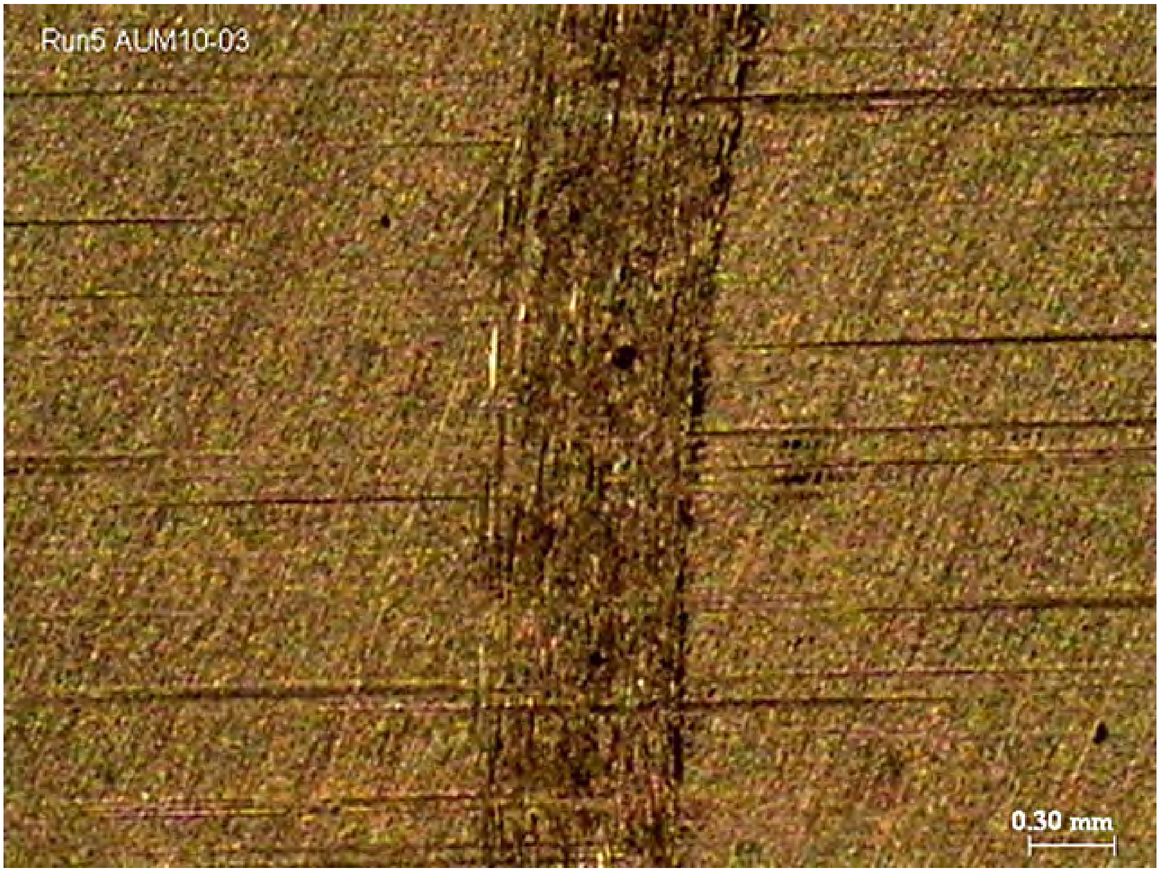


Figure 32 Wear track on the disk under optical microscope (Test No. 5).

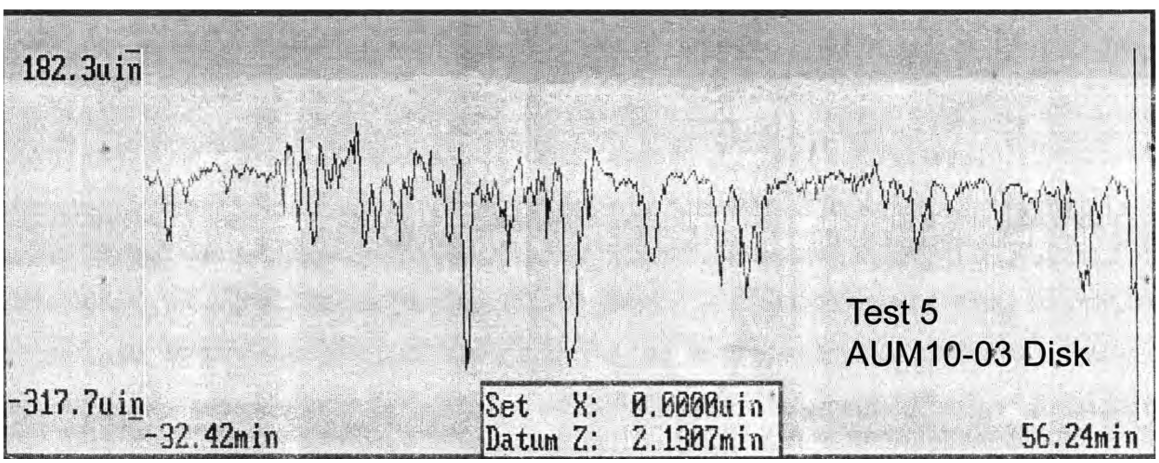


Figure 33 Profilometer trace and measurement across the wear track on the disk (Test No. 5).

Figure 34 Wear area on the spherical surface of the pin under optical microscope (Test No. 5).

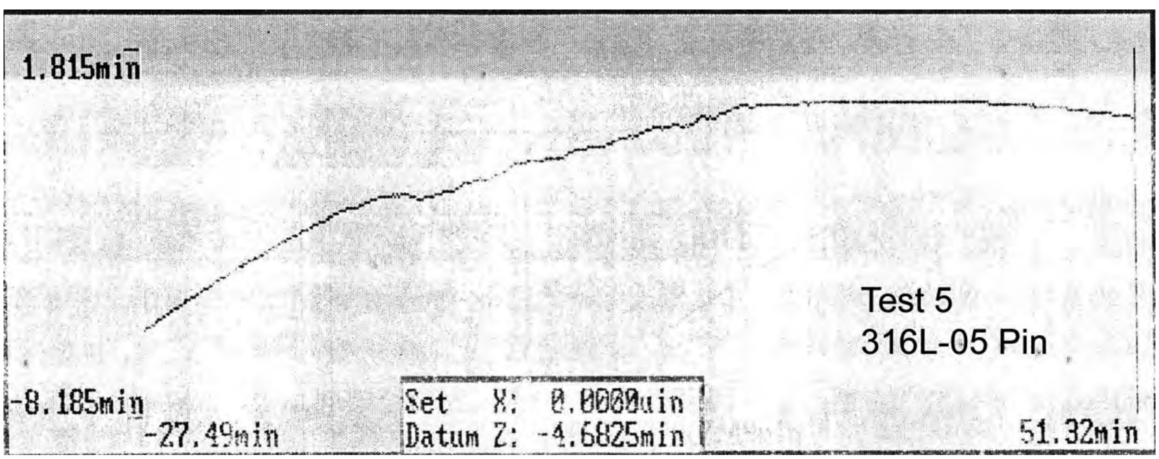


Figure 35 Profilometer trace and measurement across the wear area on the pin (Test No. 5).

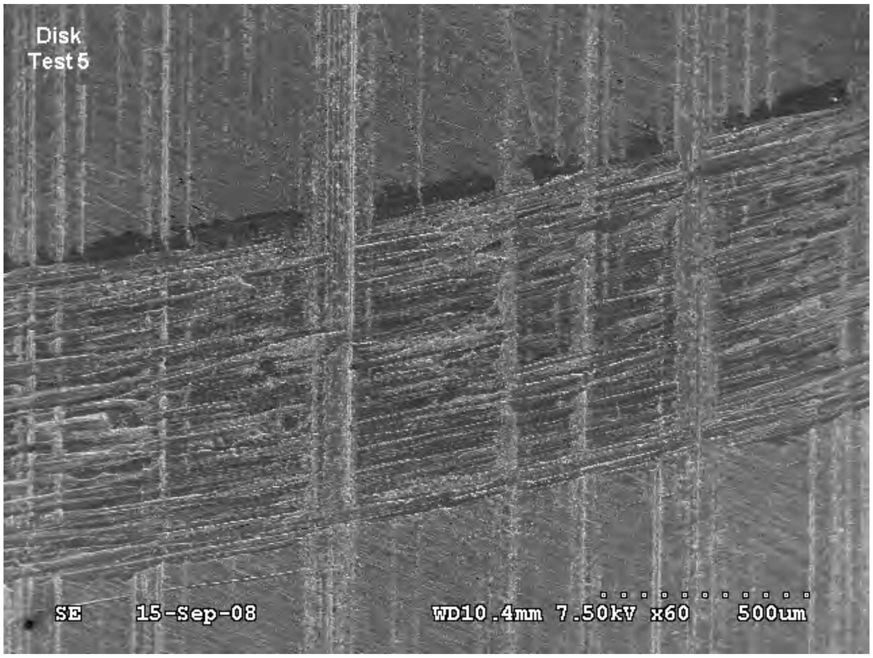


Figure 36 Wear track on the disk under SEM at 60X (Test No. 5).

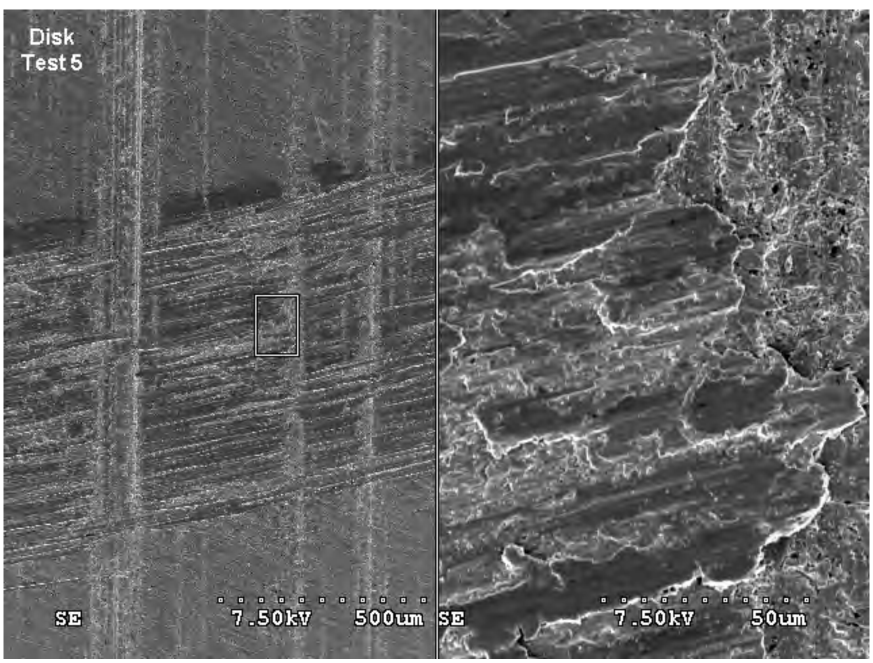


Figure 37 Detailed characterization of wear track on the disk with SEM (Test No. 5).

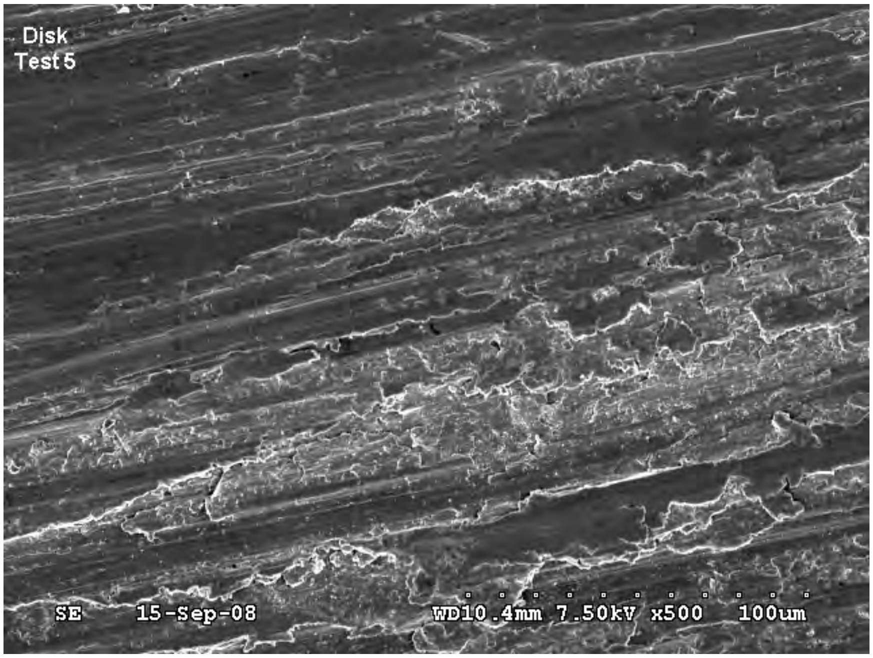


Figure 38 Wear track on the disk with SEM at 500X (Test No. 5).

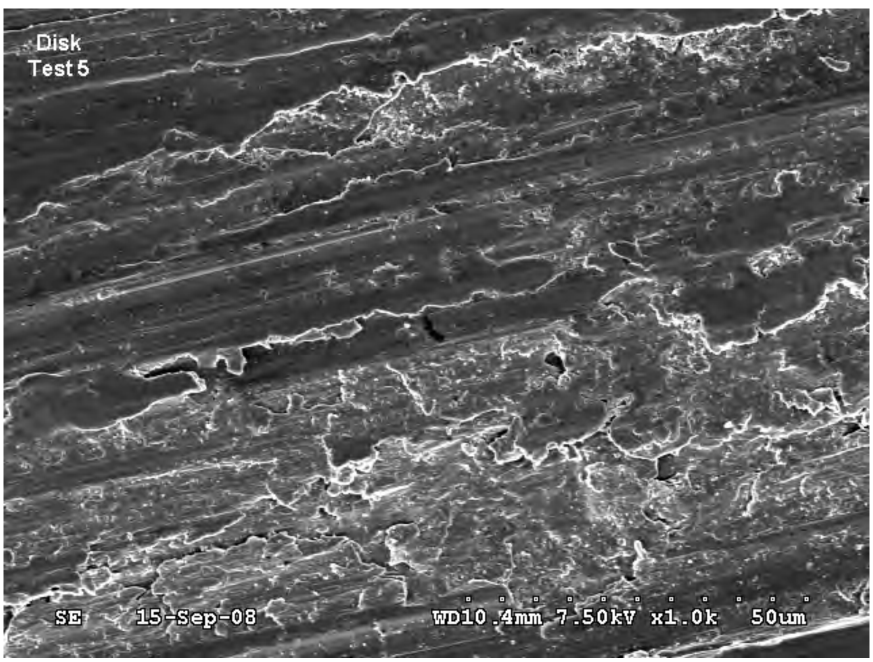


Figure 39 Wear track on the disk under SEM at 1000X (Test No. 5).

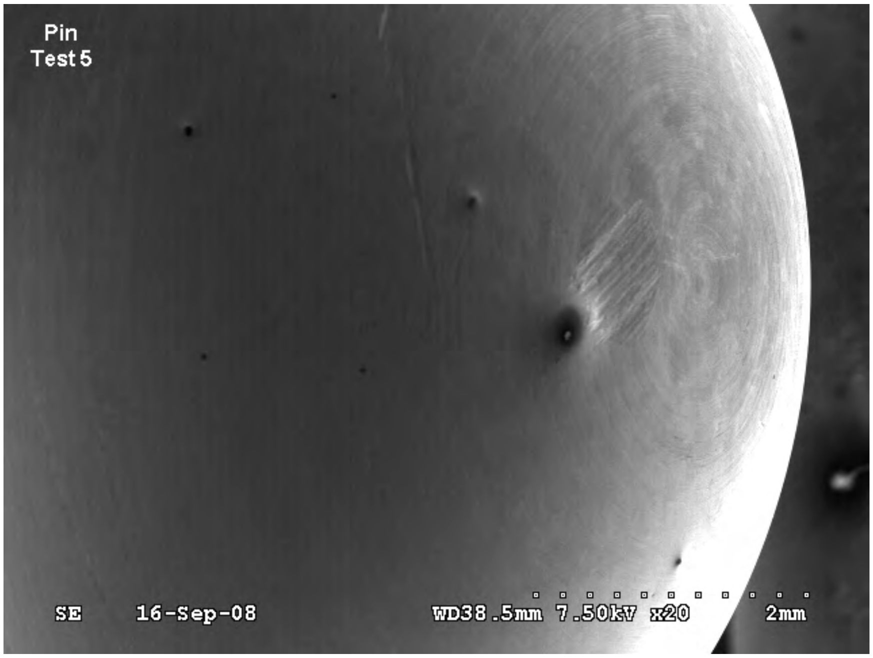


Figure 40 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 5).

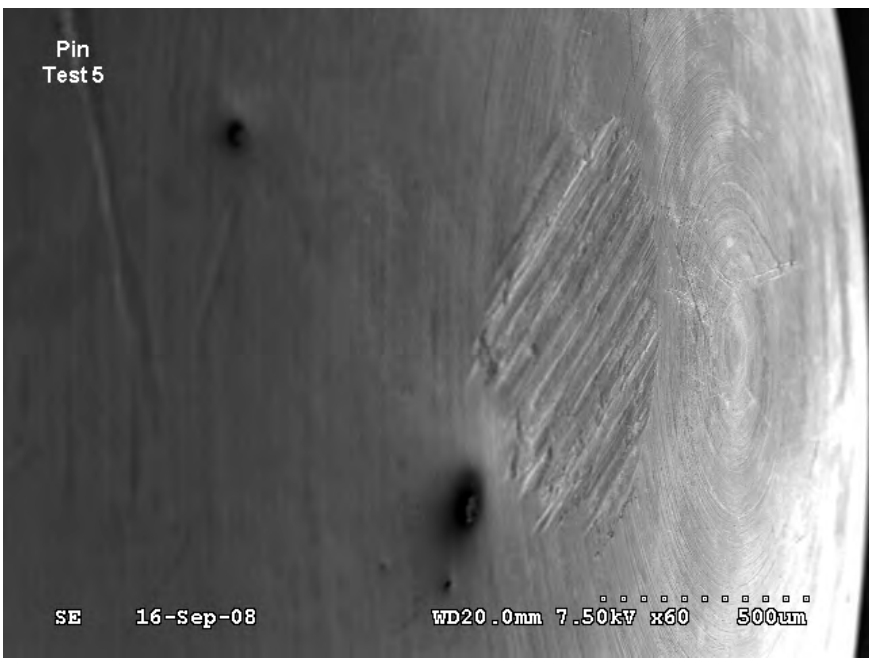


Figure 41 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 5).

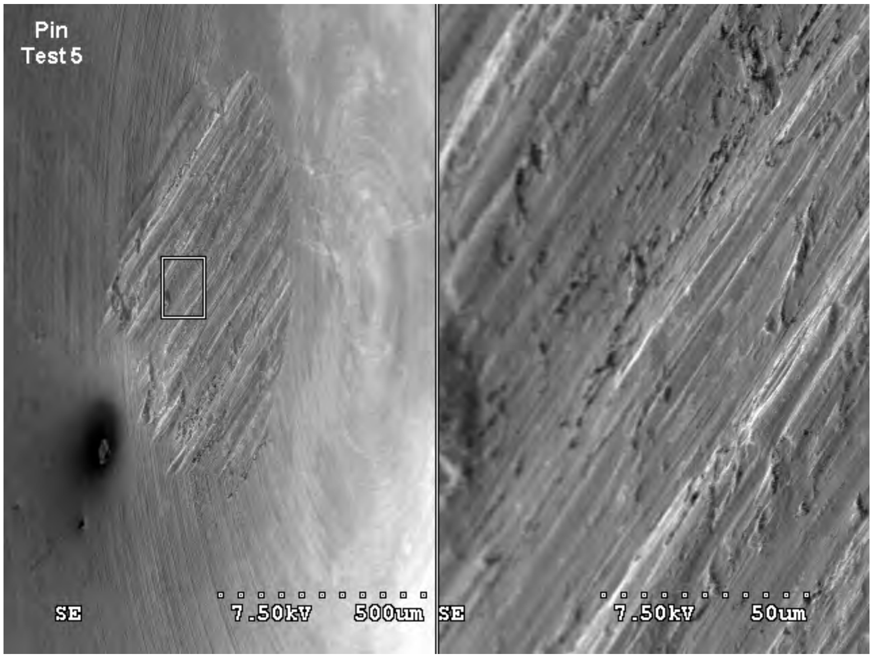


Figure 42 Detailed characterization of wear area on the pin with SEM (Test No. 5).

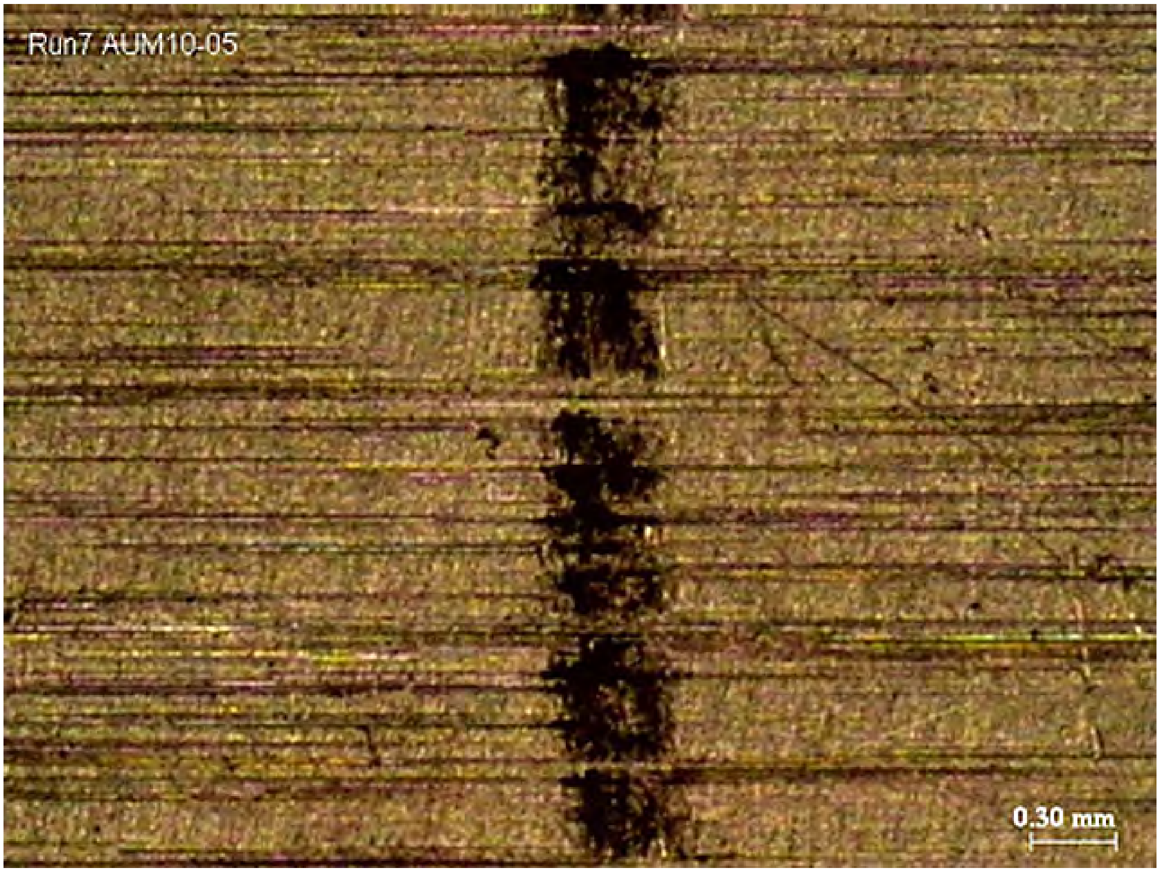


Figure 43 Wear track on the disk under optical microscope (Test No. 7).

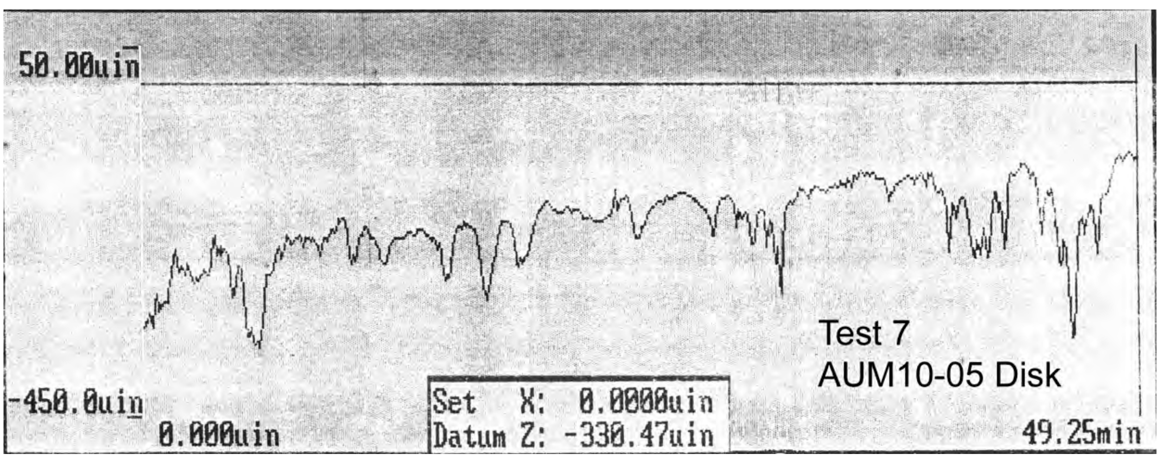


Figure 44 Profilometer trace and measurement across the wear track on the disk (Test No. 7).

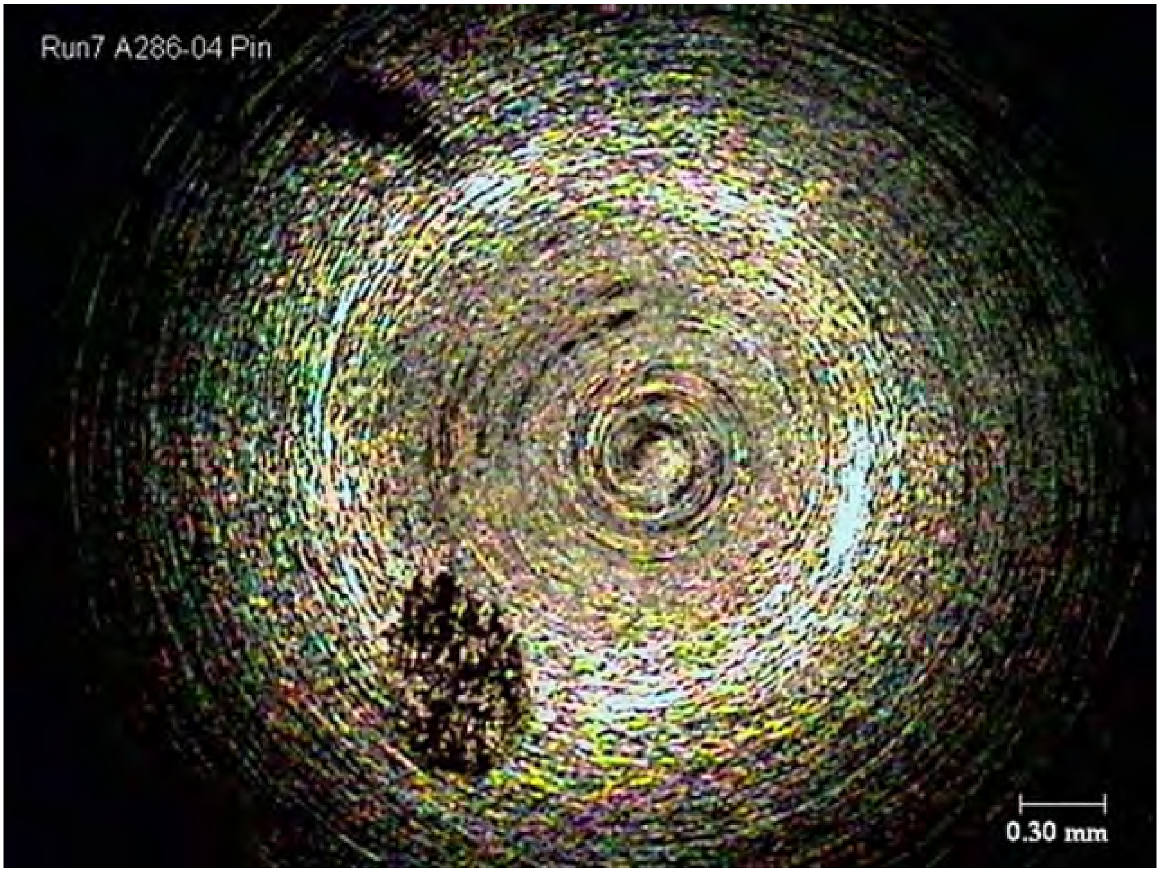


Figure 45 Wear area on the spherical surface of the pin under optical microscope (Test No. 7).

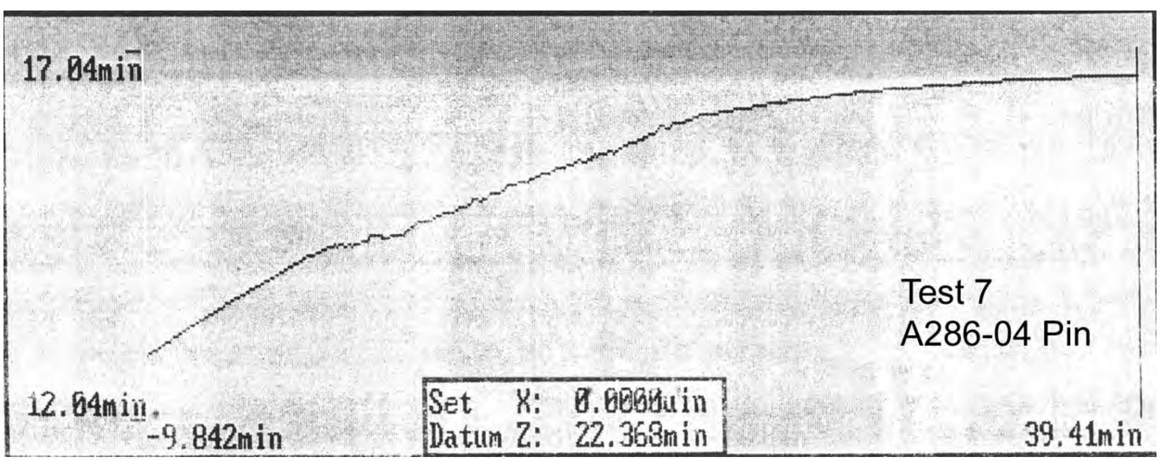


Figure 46 Profilometer trace and measurement across the wear area on the pin (Test No. 7).

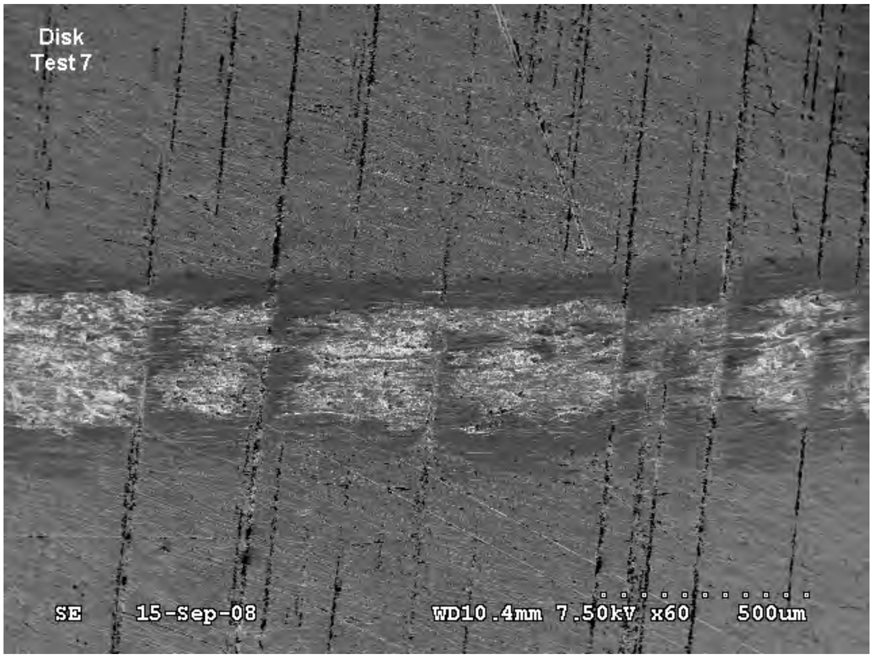


Figure 47 Wear track on the disk under SEM at 60X (Test No. 7).

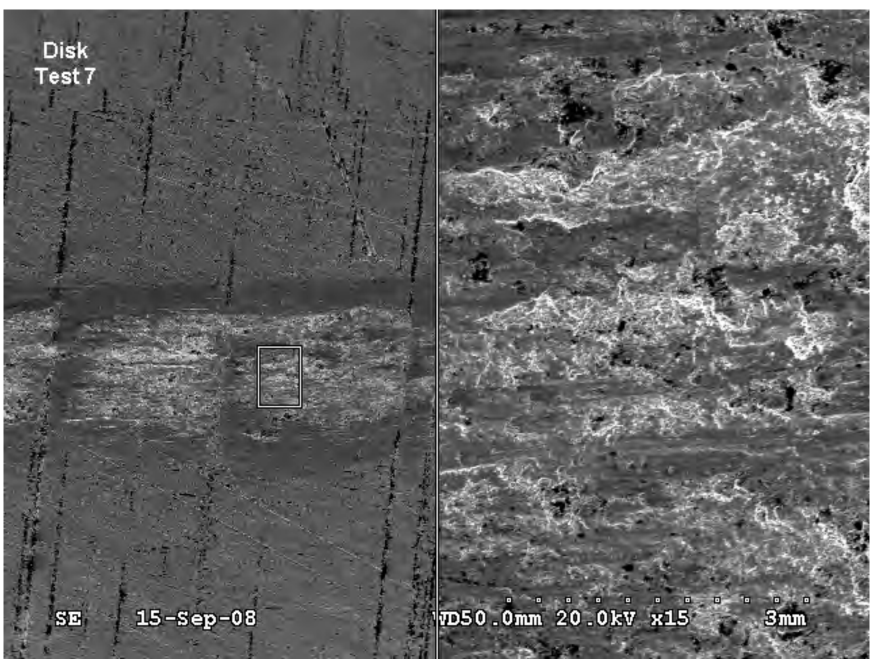


Figure 48 Detailed characterization of wear track on the disk with SEM (Test No. 7).

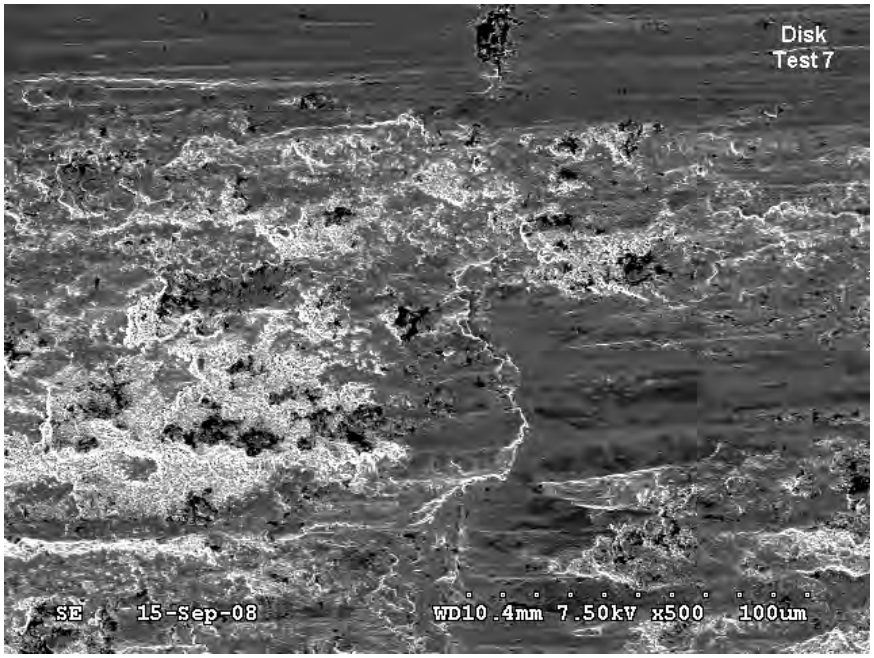


Figure 49 Wear track on the disk with SEM at 500X (Test No. 7).

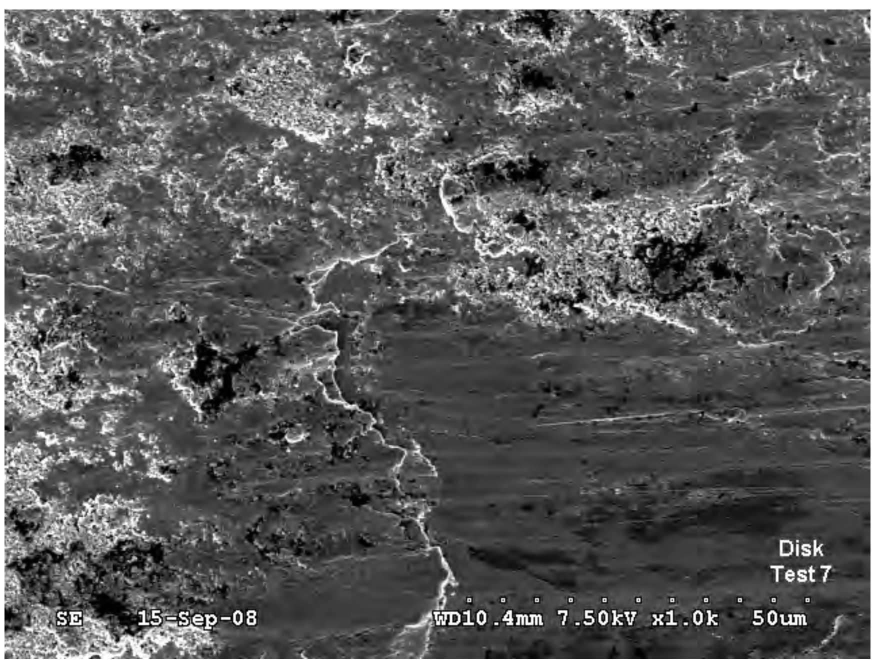


Figure 50 Wear track on the disk under SEM at 1000X (Test No. 7).

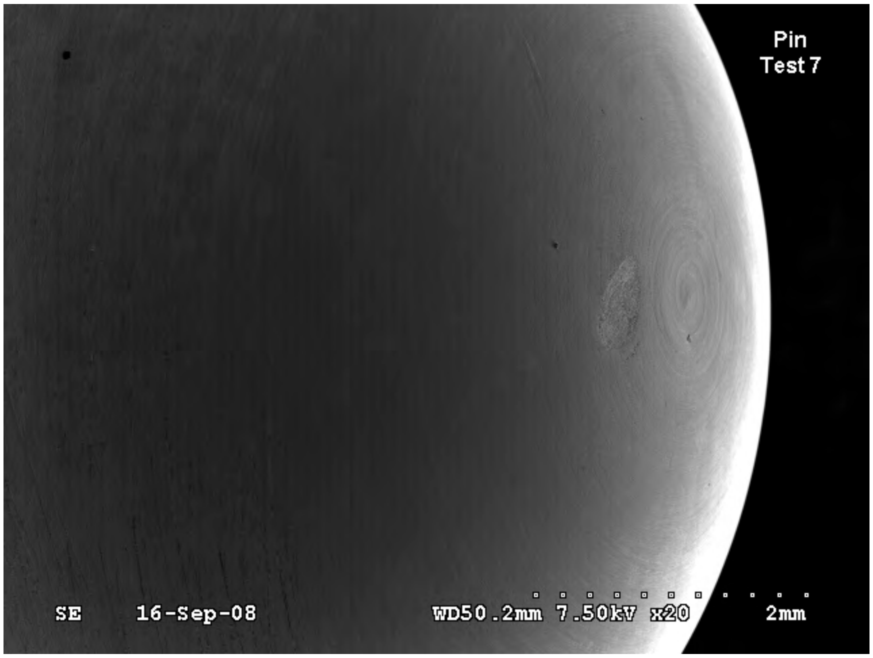


Figure 51 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 7).

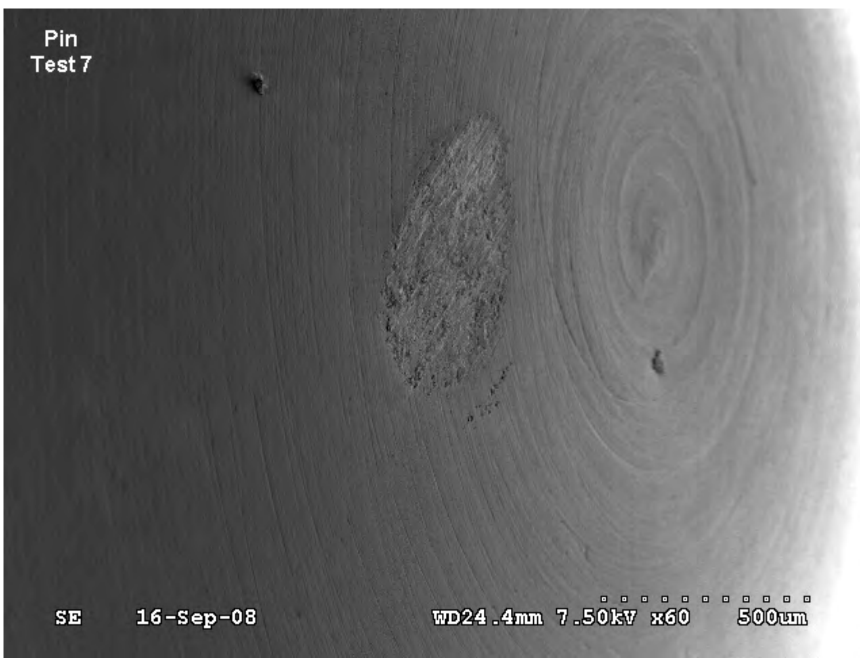


Figure 52 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 7).

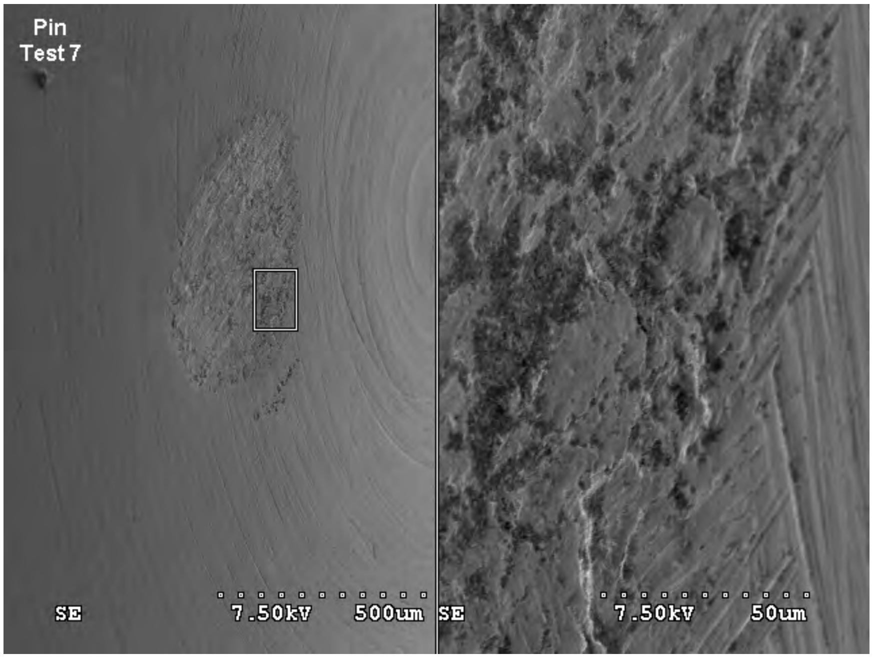


Figure 53 Detailed characterization of wear area on the pin with SEM (Test No. 7).

Hydrogen Test Surfaces

The analysis of the post-test characteristic wear scar surface images (Figs 54 to 97) indicates that disk wear for both the 316L and AUM10 disks by an A286 pin appears to have a less roughened/fragmented surface most similar to a harder object wearing against a softer material. Results, in comparison, for both the 316L and AUM10 disks tested with a 316L pin, display more evidence of surface protrusions and fractures in the wear scar area. In addition, of the two disk materials evaluated in this study (316L and AUM10), analysis of the surface images of the wear scar presented in the figures above, the AUM10 displays the most surface damage as indicated by the increased occurrence of surface asperities/protrusions and fractures.

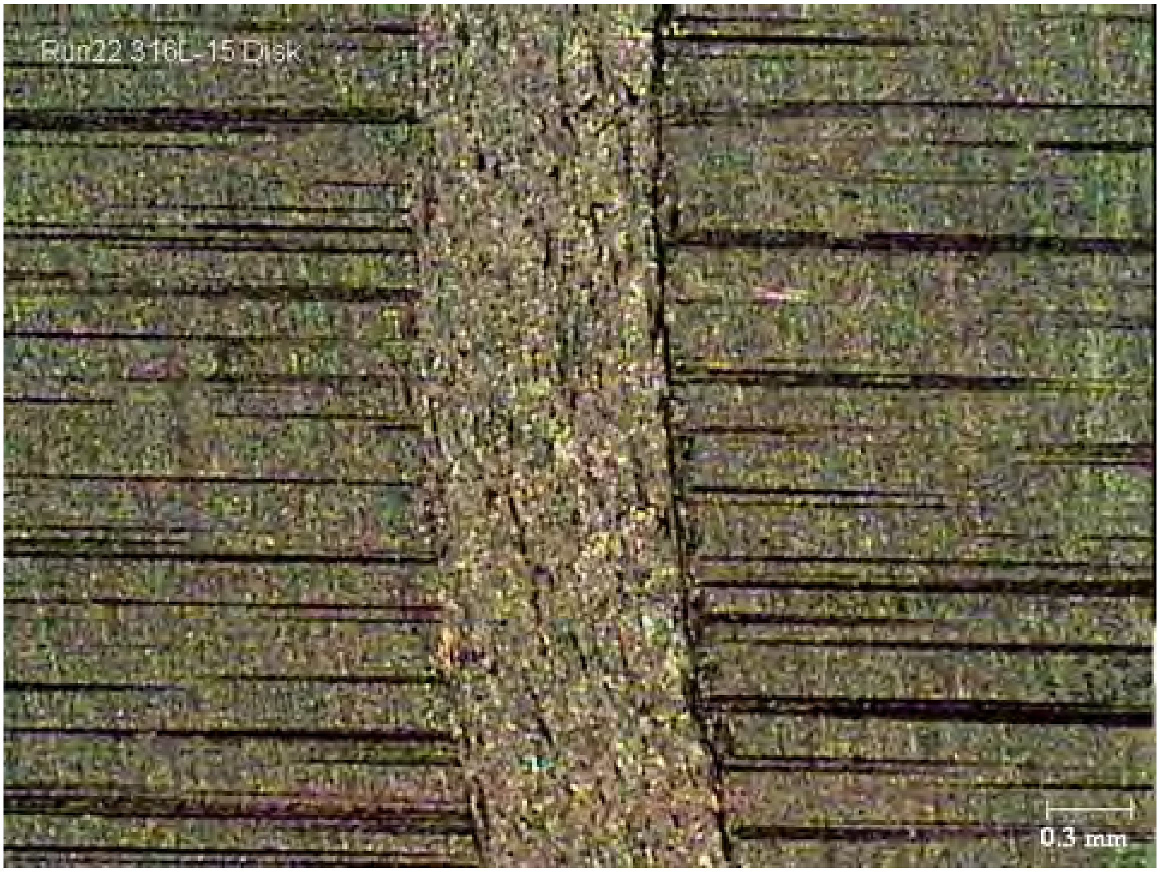


Figure 54 Wear track on the disk under optical microscope (Test No. 22)

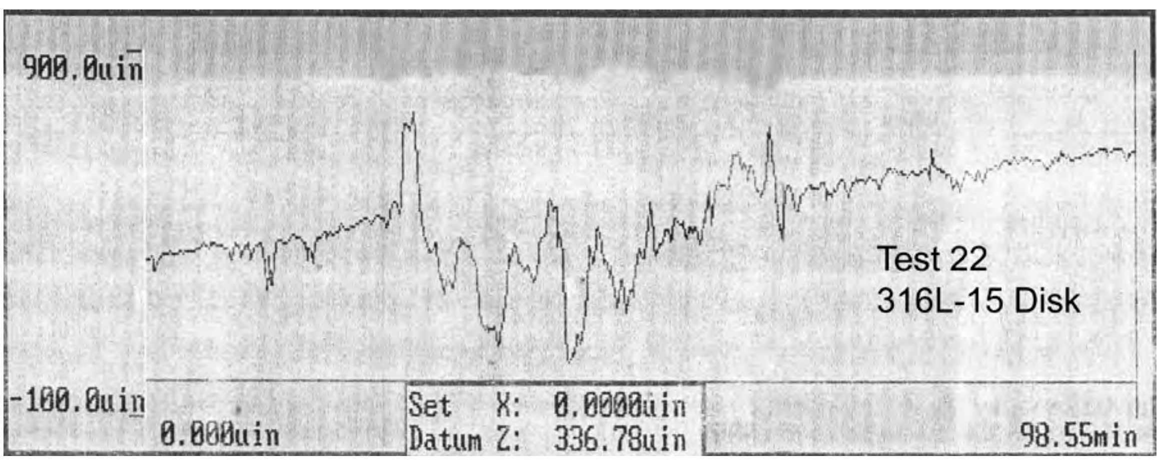


Figure 55 Profilometer trace and measurement across the wear track on the disk (Test No. 22)

Figure 56 Wear area on the spherical surface of the pin under optical microscope (Test No. 22)

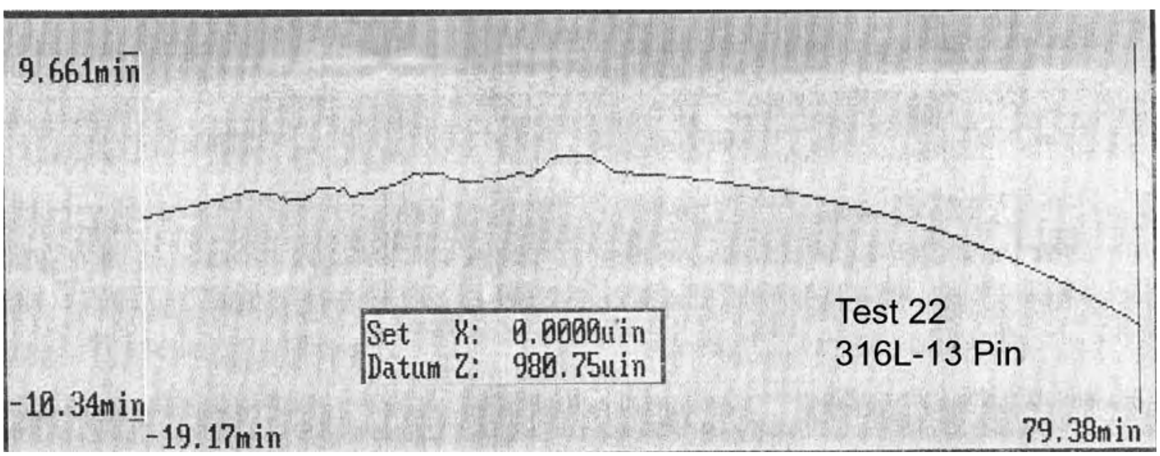


Figure 57 Profilometer trace and measurement across the wear area on the pin (Test No. 22)

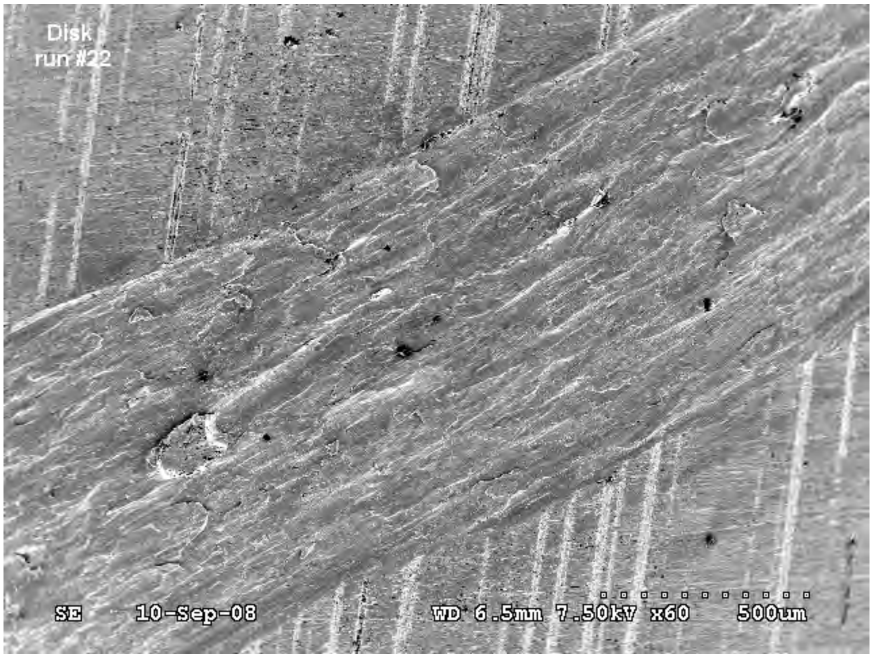


Figure 58 Wear track on the disk under SEM at 60X (Test No. 22).

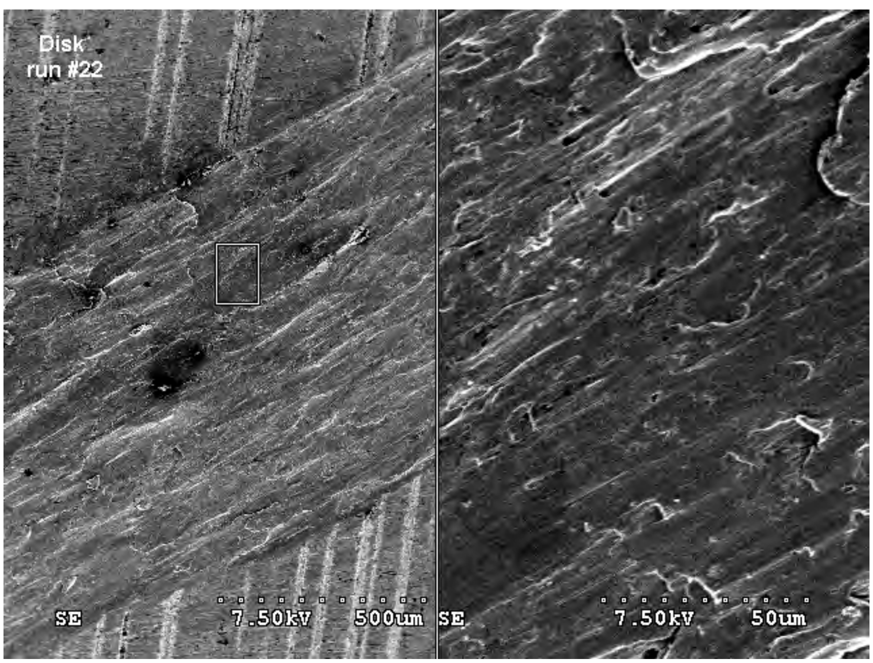


Figure 59 Detailed characterization of wear track on the disk with SEM (Test No. 22)

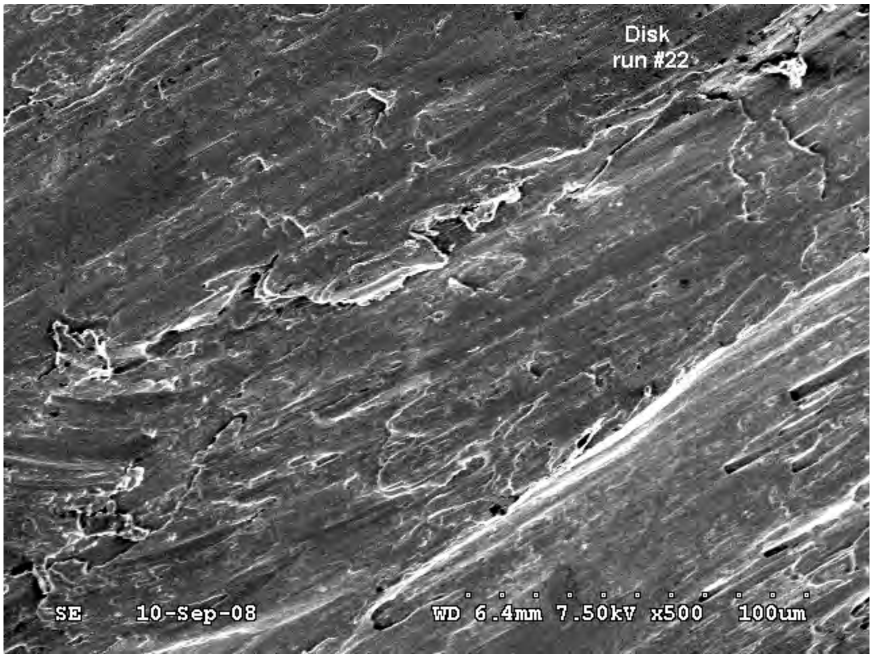


Figure 60 Wear track on the disk with SEM at 500X (Test No. 22)

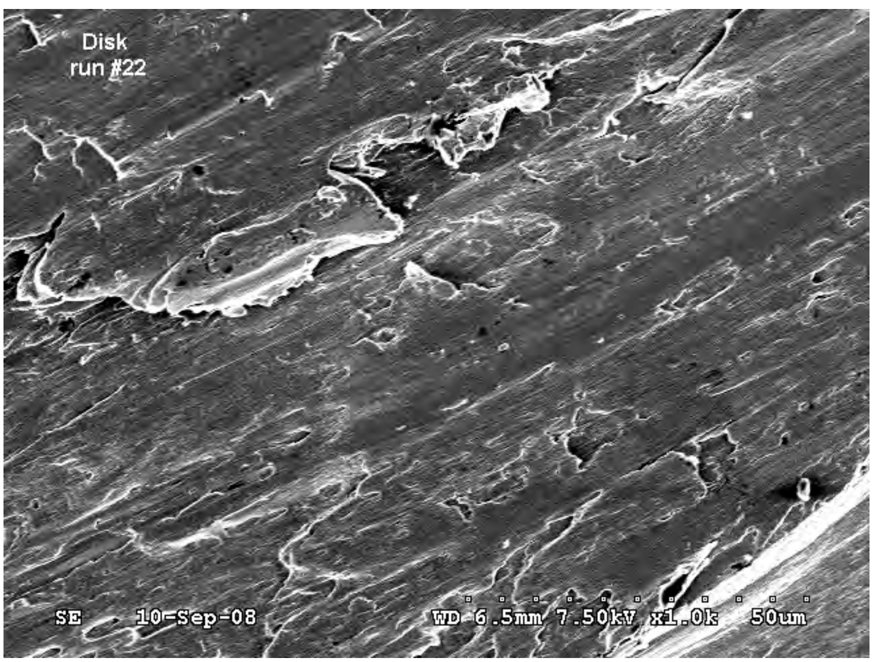


Figure 61 Wear track on the disk under SEM at 1000X (Test No. 22).

Figure 62 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 22).

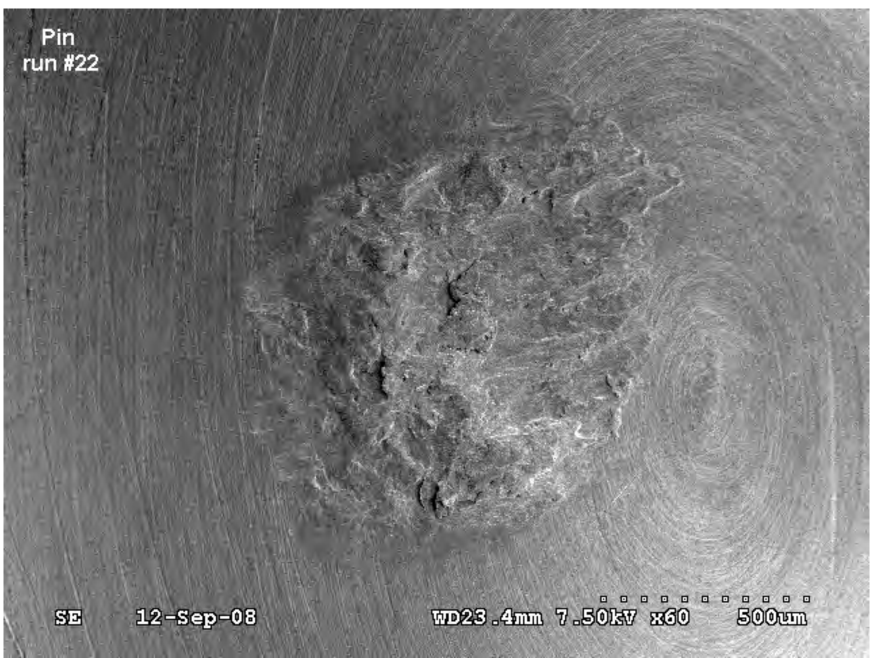


Figure 63 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 22).

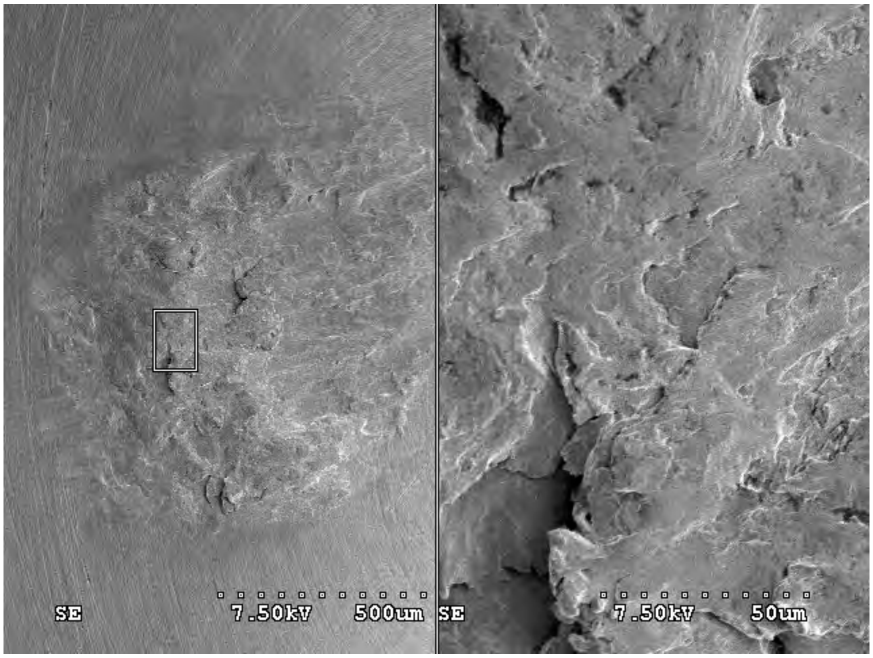


Figure 64 Detailed characterization of wear area on the pin with SEM (Test No. 22).

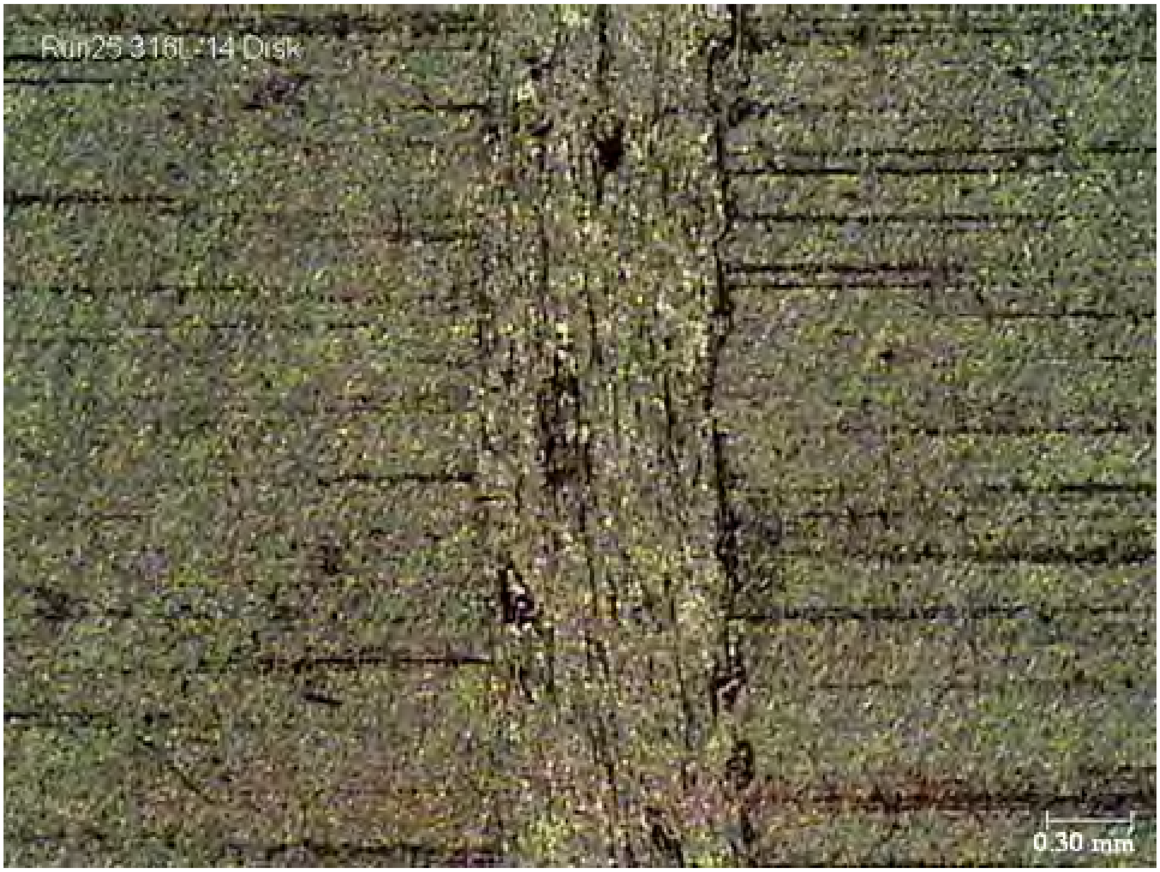


Figure 65 Wear track on the disk under optical microscope (Test No. 25).

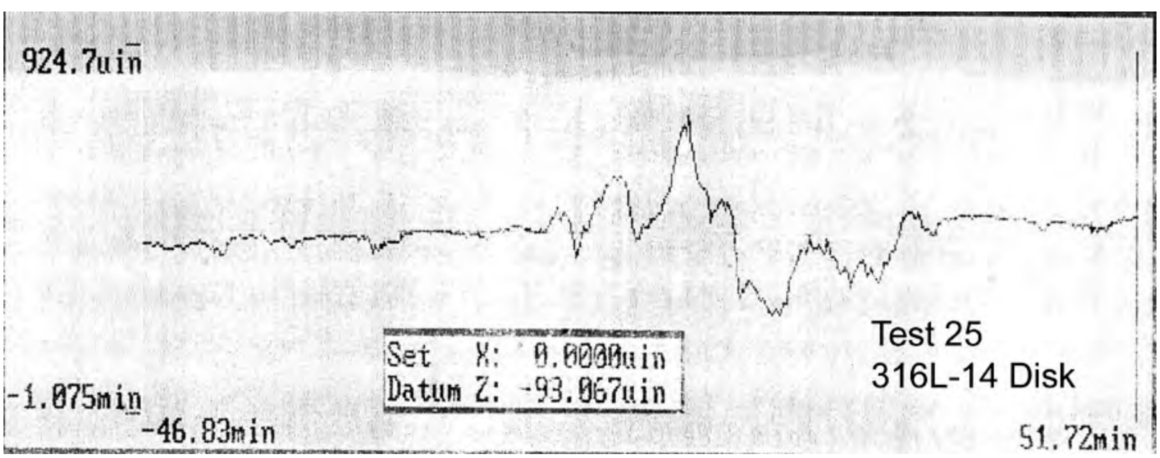


Figure 66 Profilometer trace and measurement across the wear track on the disk (Test No. 25).

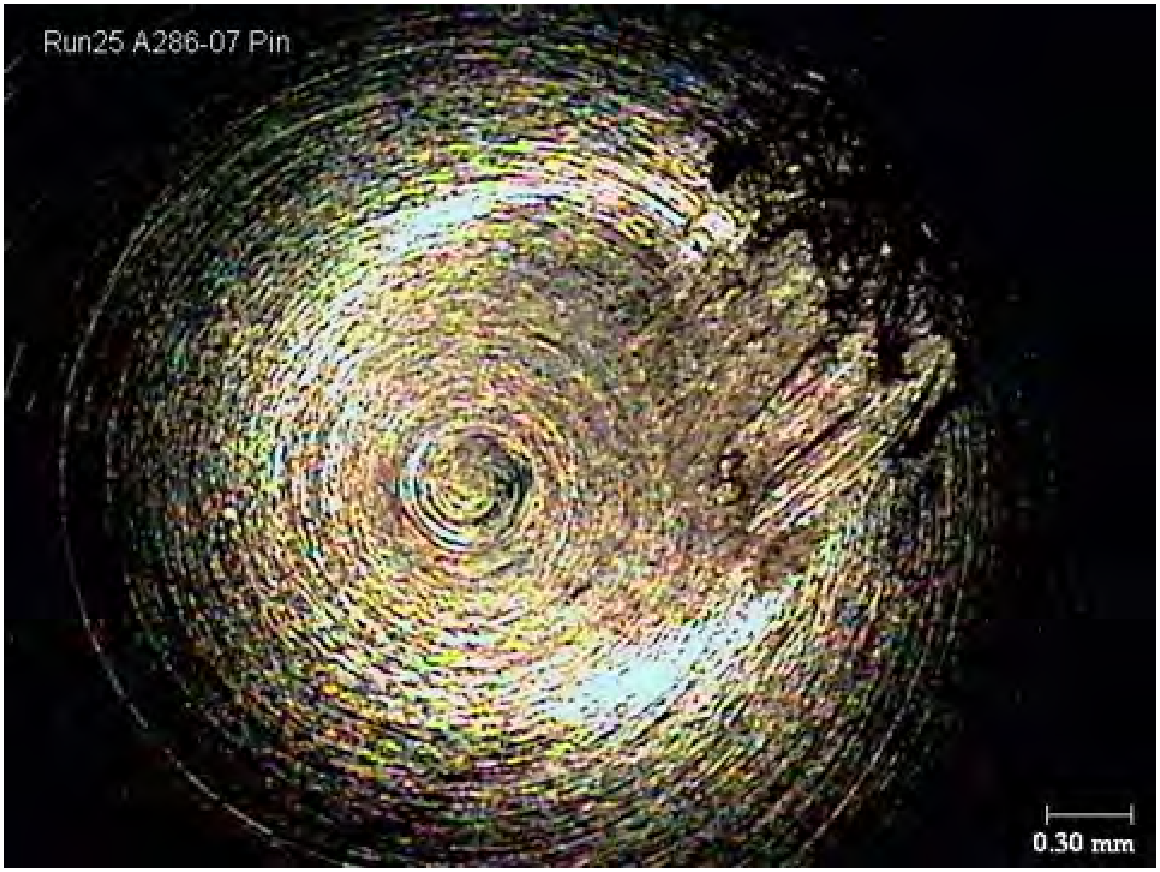


Figure 67 Wear area on the spherical surface of the pin under optical microscope (Test No. 25).

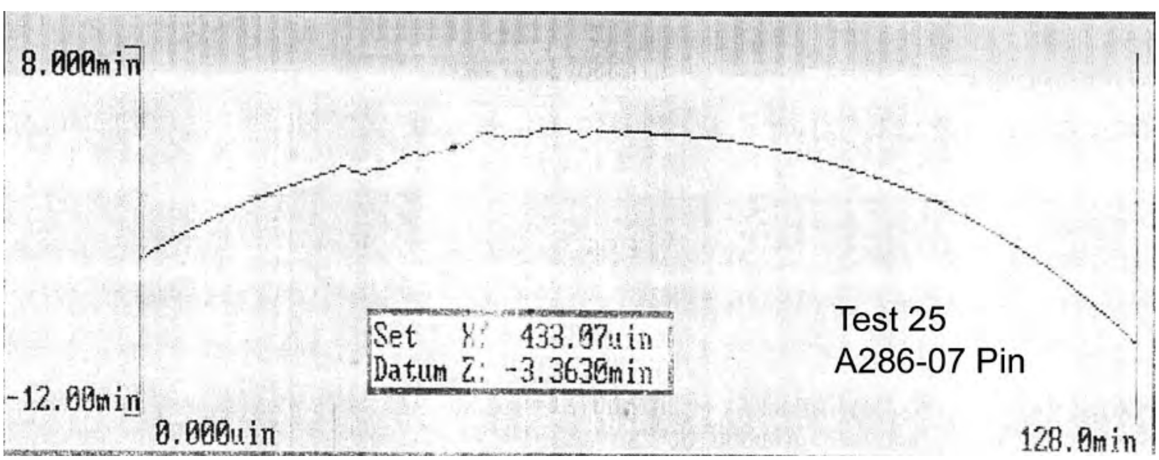


Figure 68 Profilometer trace and measurement across the wear area in the pin (Test No. 25).

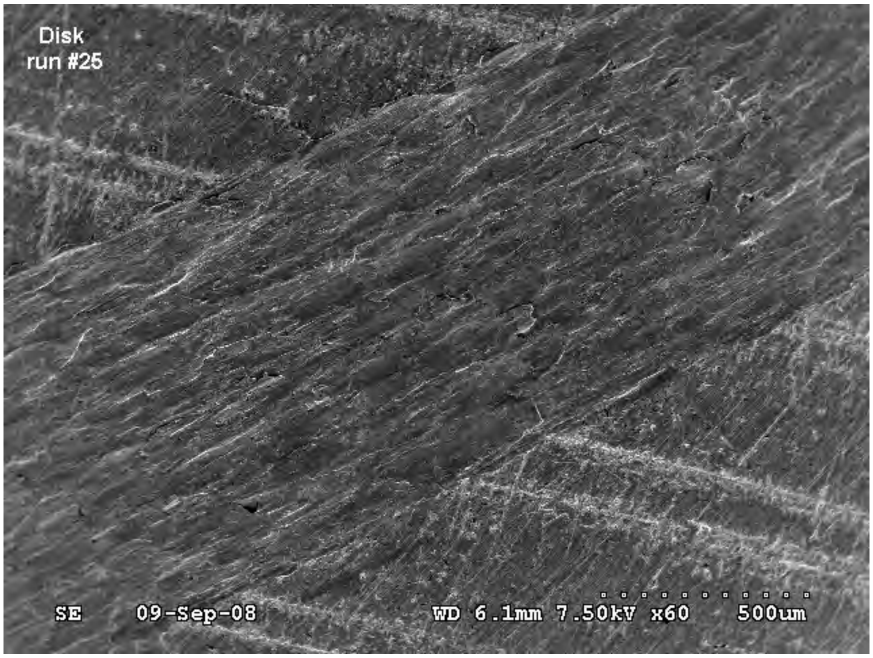


Figure 69 Wear track on the disk under SEM at 60X (Test No. 25).

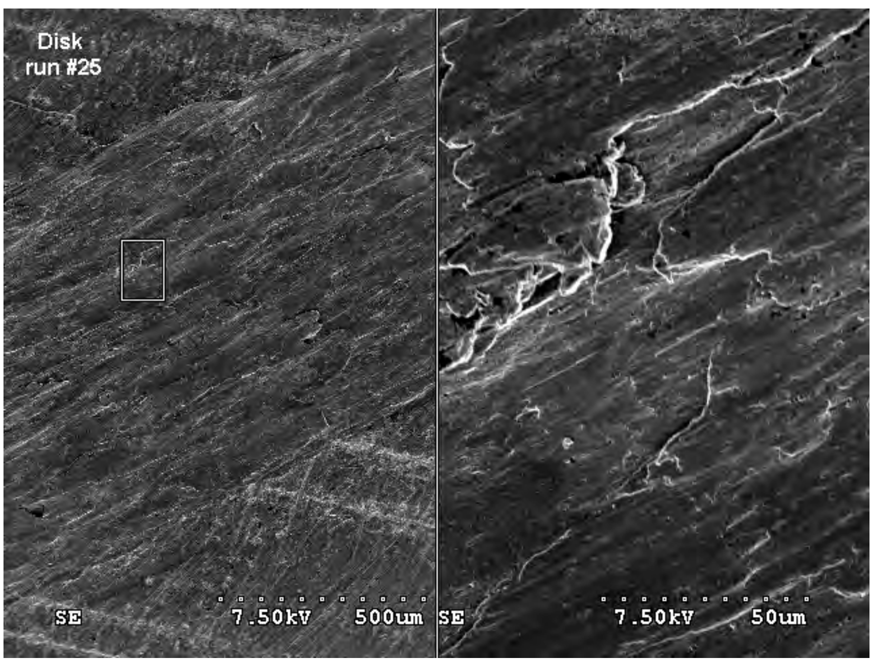


Figure 70 Detailed characterization of wear track on the disk with SEM (Test No. 25).

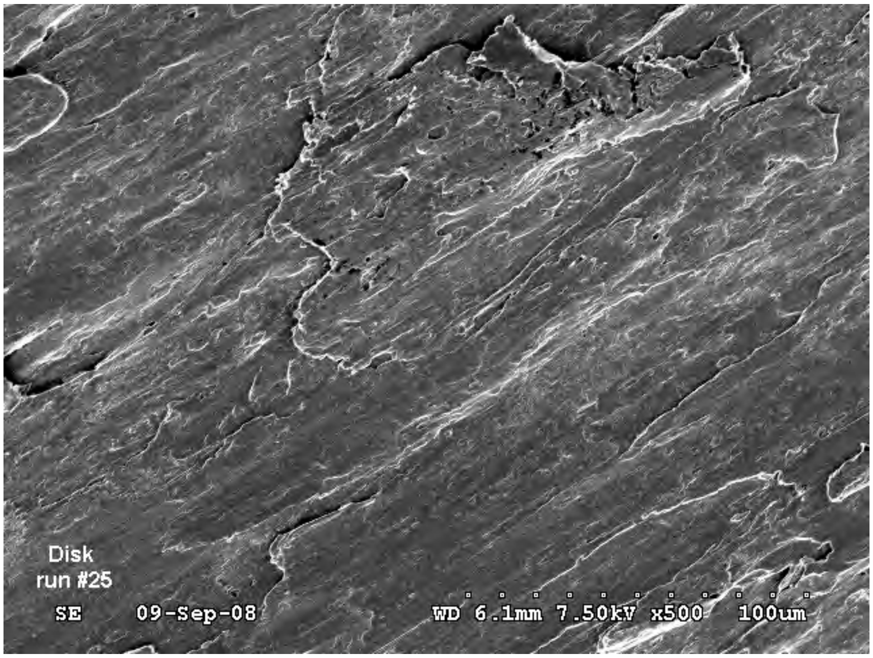


Figure 71 Wear track on the disk under SEM at 500X (Test No. 25).

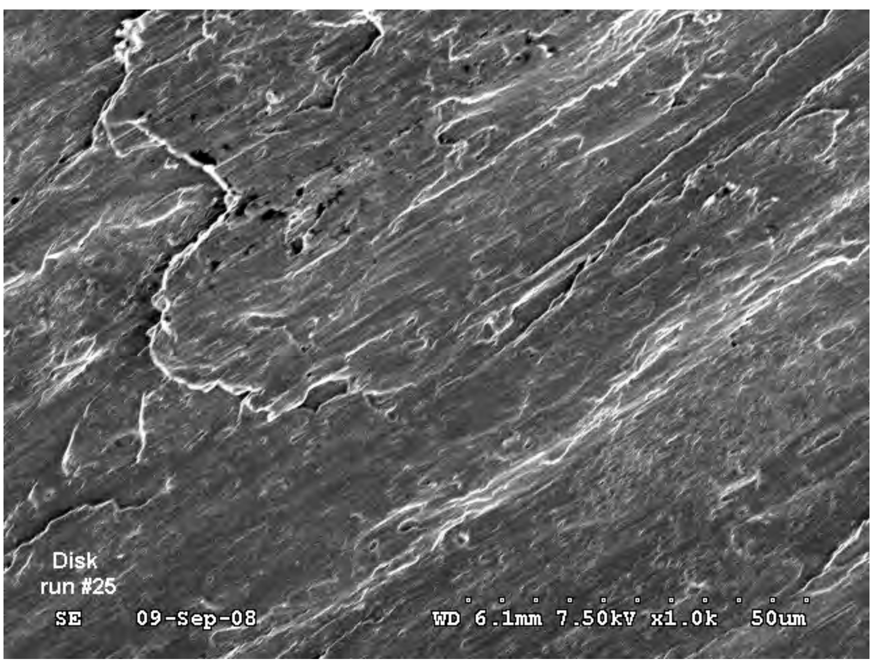


Figure 72 Wear track on the disk under SEM at 1000X (Test No. 25).

Figure 73 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 25).

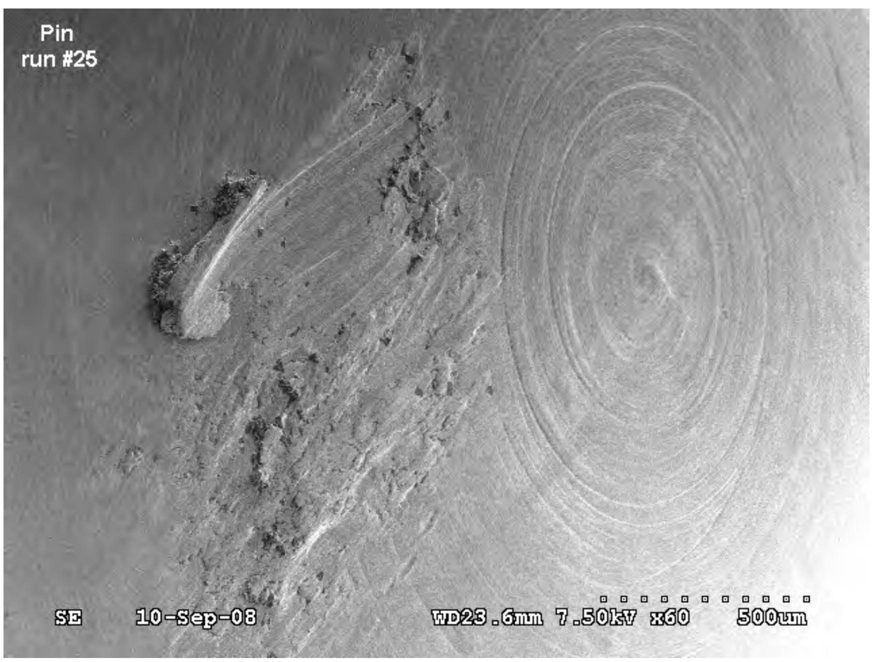


Figure 74 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 25).

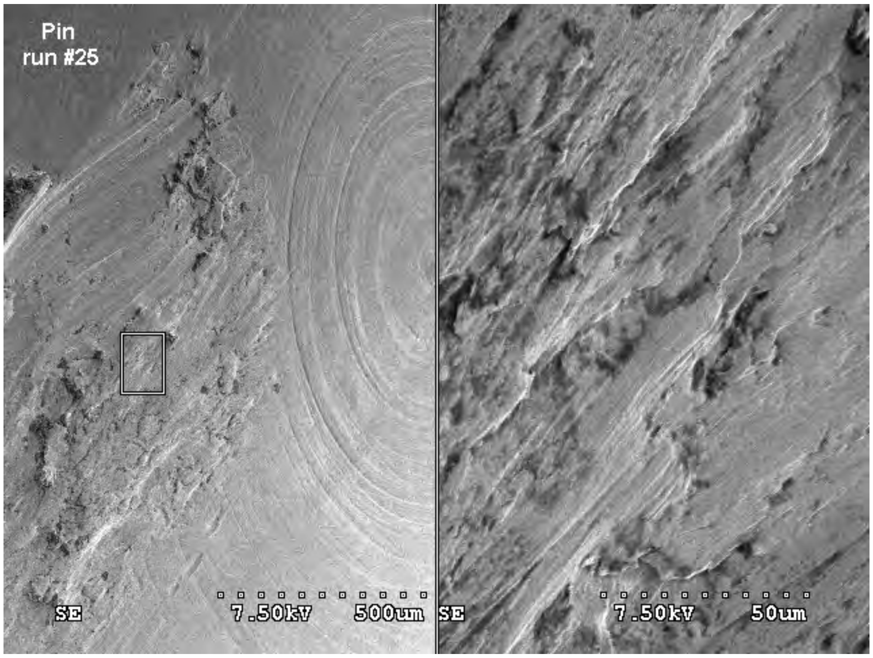


Figure 75 Detailed characterization of wear area on the pin with SEM (Test No. 25).

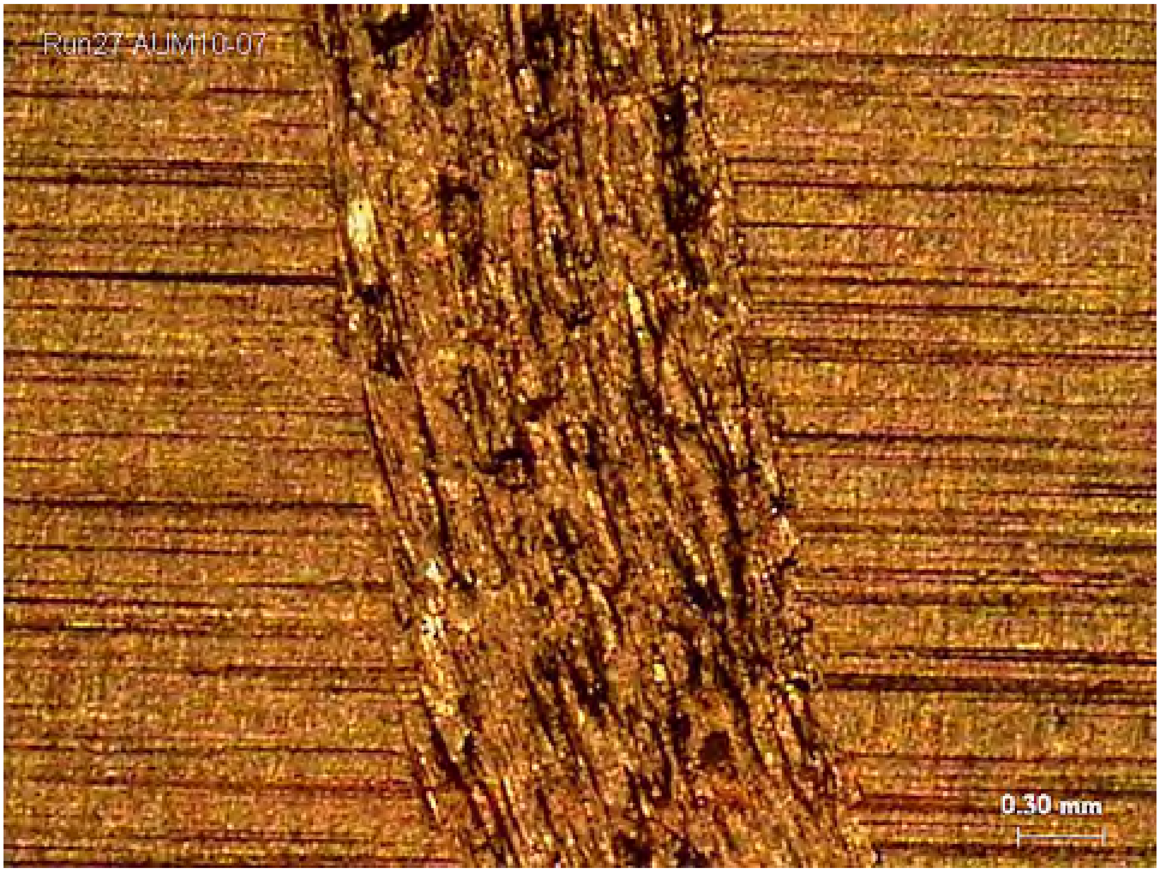


Figure 76 Wear track on the disk under optical microscope (Test No. 27).

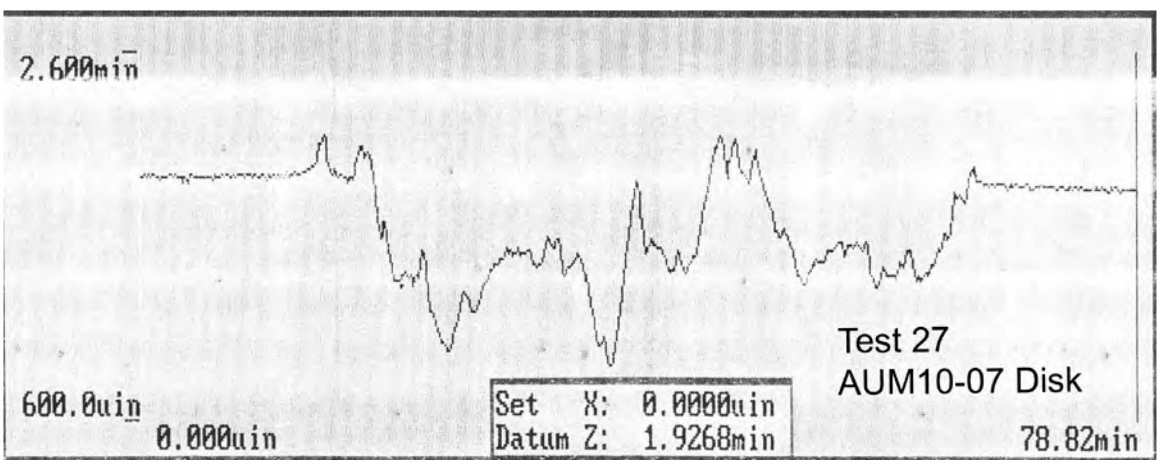


Figure 77 Profilometer trace and measurement across the wear track on the disk (Test No. 27).

Figure 78 Wear area on the spherical surface of the pin under optical microscope (Test No. 27).

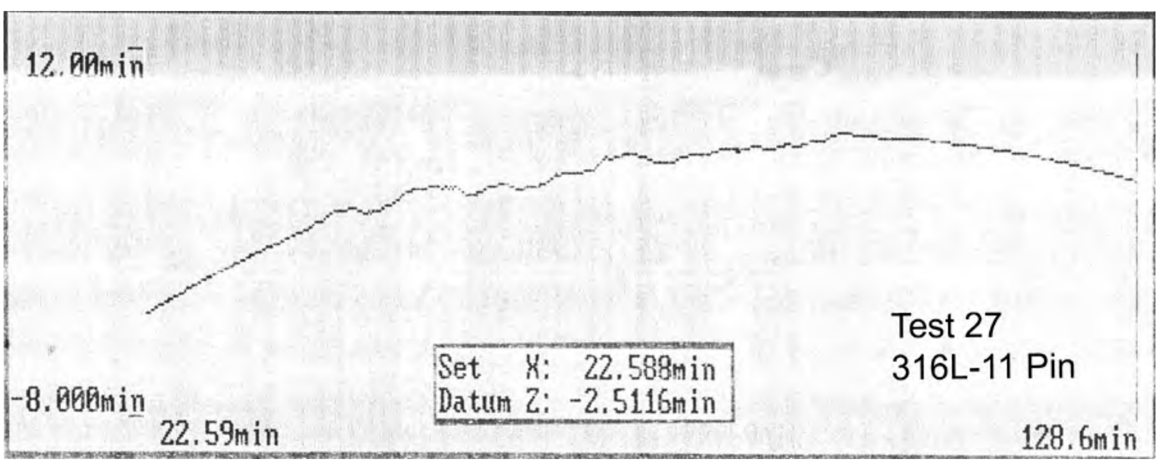


Figure 79 Profilometer trace and measurement across the wear area in the pin (Test No. 27).

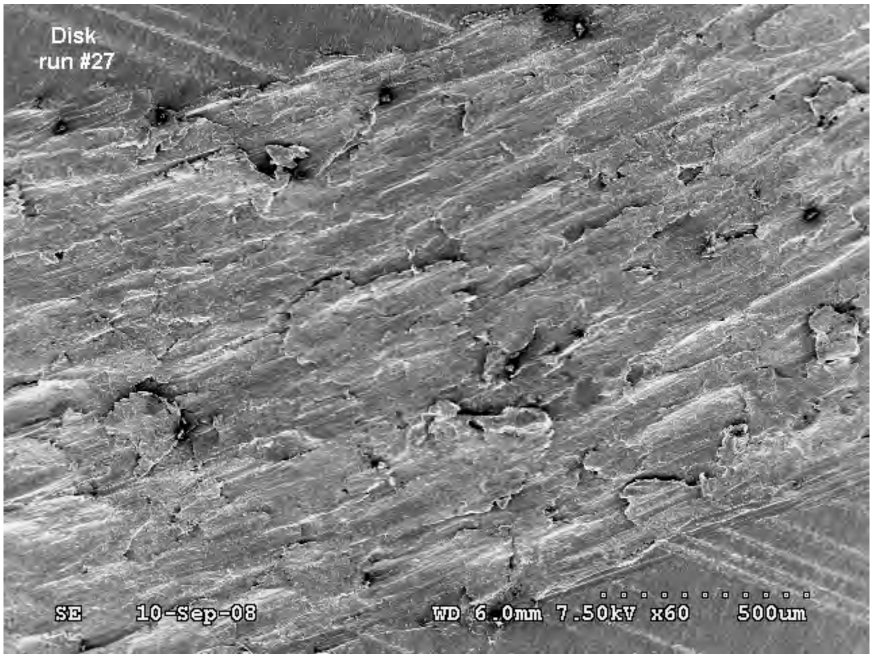


Figure 80 Wear track on the disk under SEM at 60X (Test No. 27).

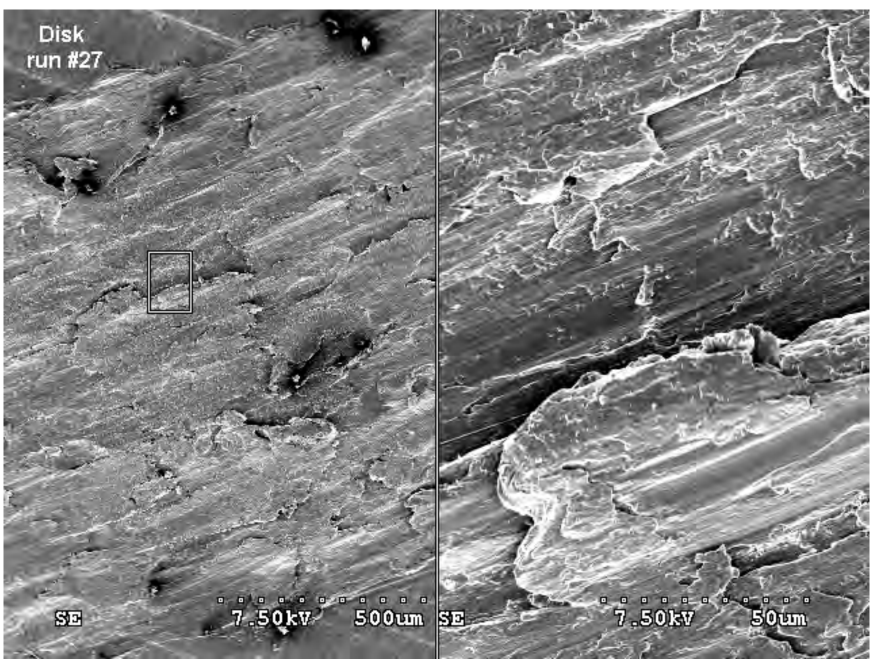


Figure 81 Detailed characterization of wear track on the disk with SEM (Test No. 27).

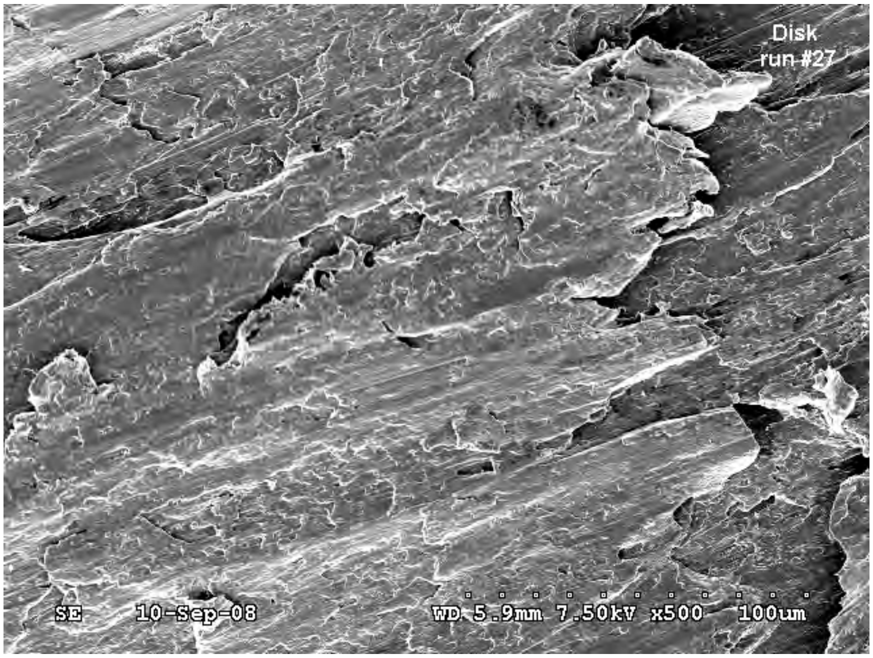


Figure 82 Wear track on the disk under SEM at 500X (Test No. 27).

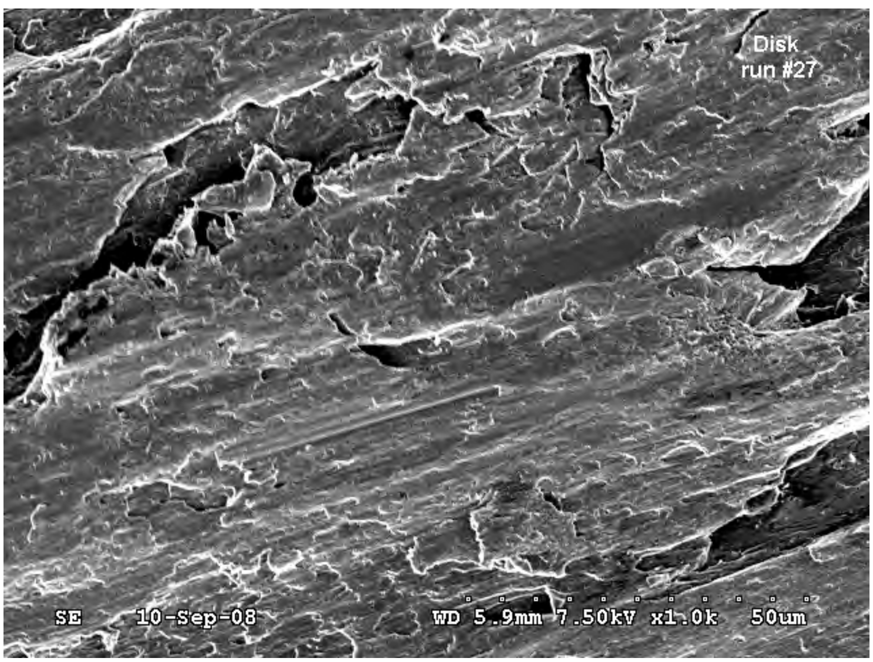


Figure 83 Wear track on the disk under SEM at 1000X (Test No. 27).

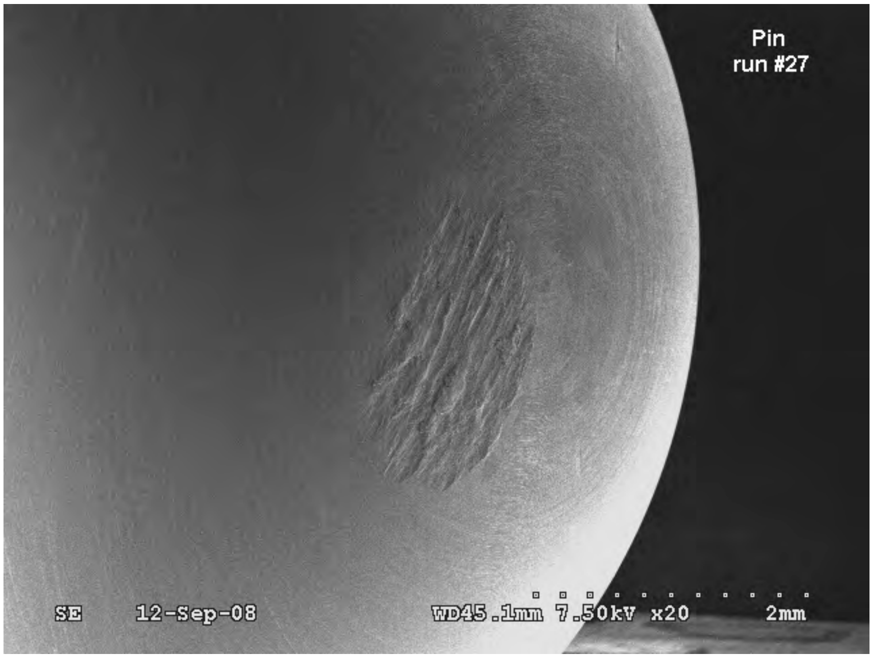


Figure 84 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 27).

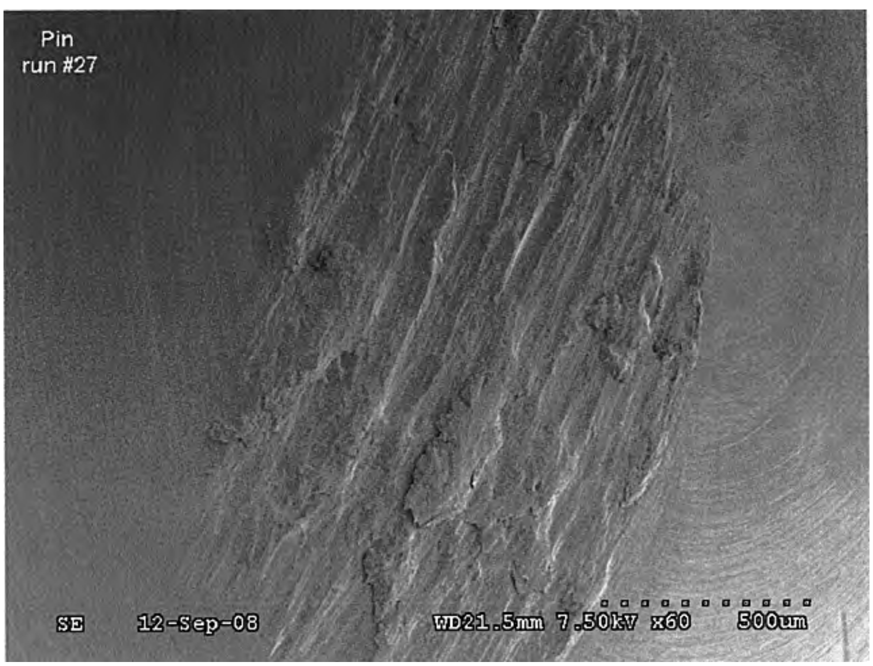


Figure 85 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 27).

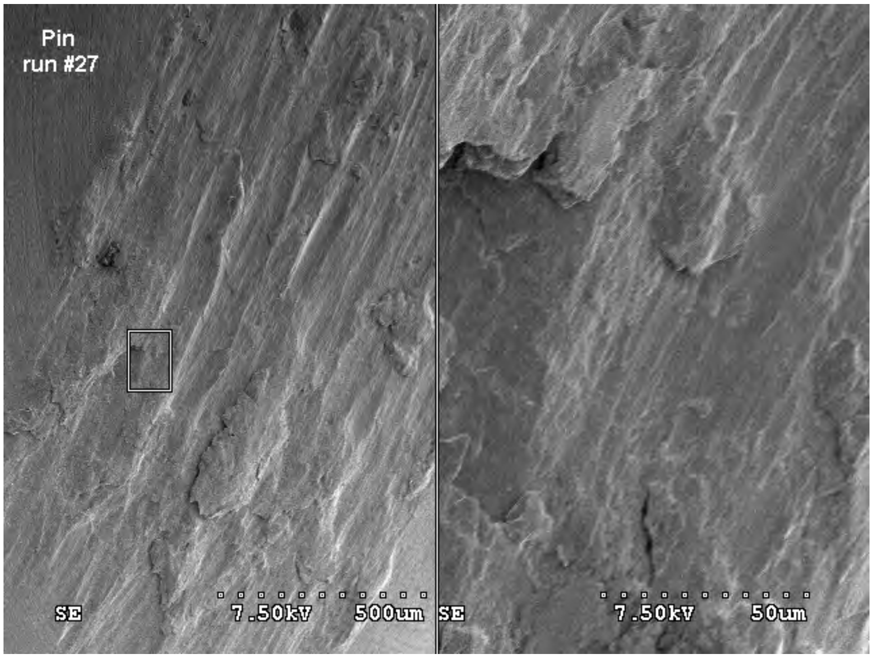


Figure 86 Detailed characterization of wear area on the pin with SEM (Test No. 27).

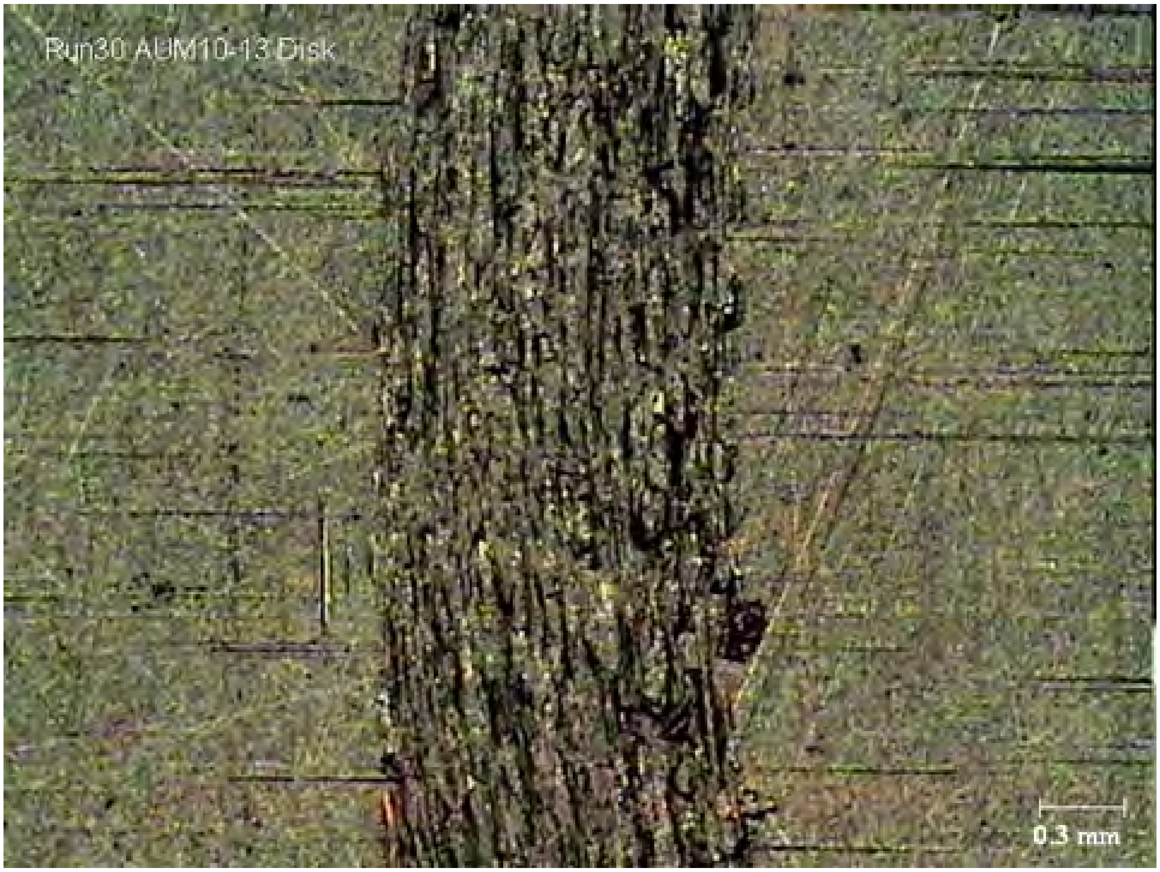


Figure 87 Wear track on the disk under optical microscope (Test No. 30).

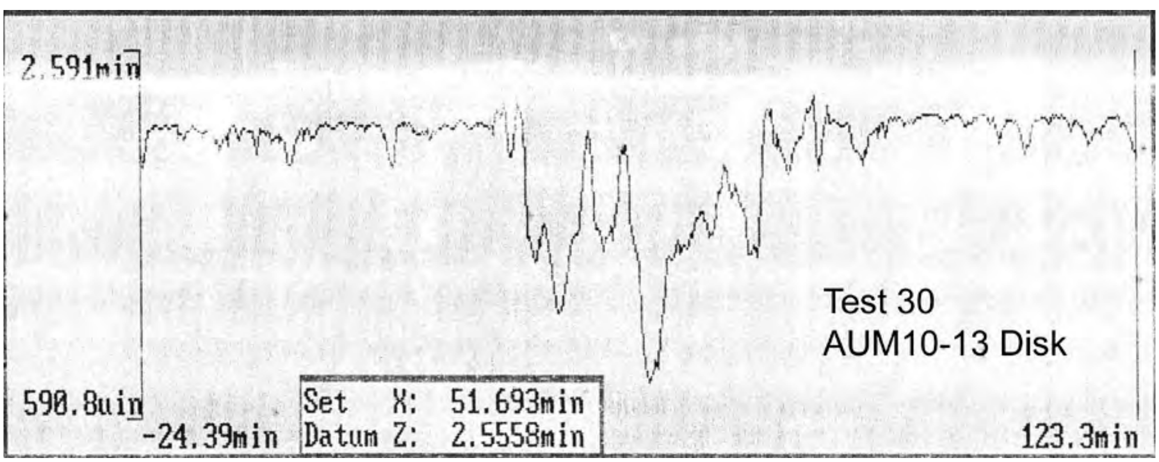


Figure 88 Profilometer trace and measurement across the wear track on the disk (Test No. 30).

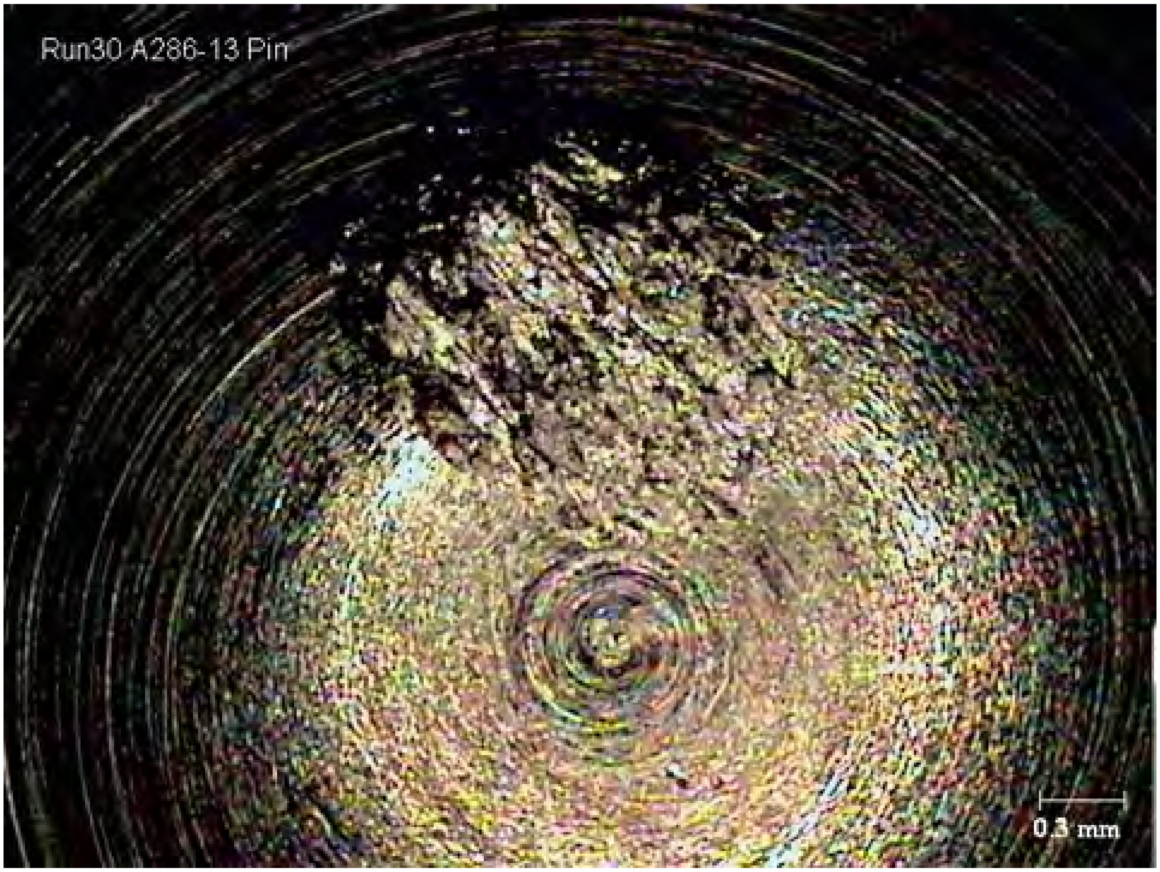


Figure 89 Wear area on the spherical surface of the pin under optical microscope (Test No. 30).

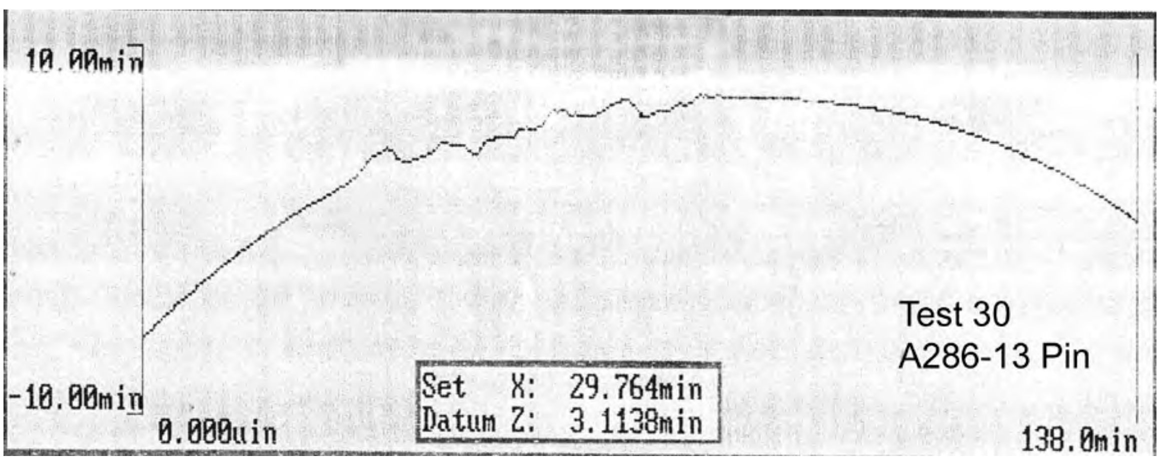


Figure 90 Profilometer trace and measurement across the wear area in the pin (Test No. 30).

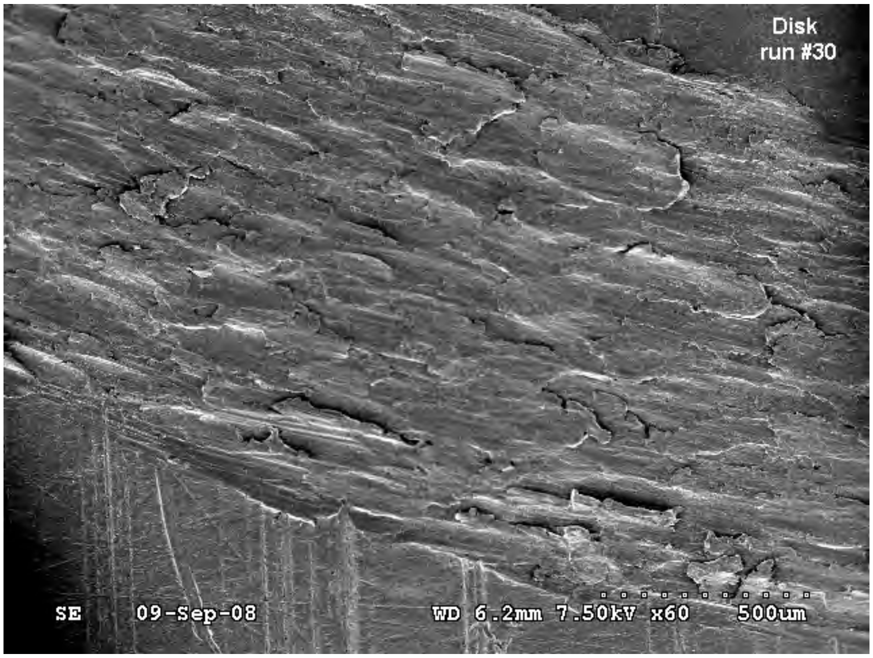


Figure 91 Wear track on the disk under SEM at 60X (Test No. 30).

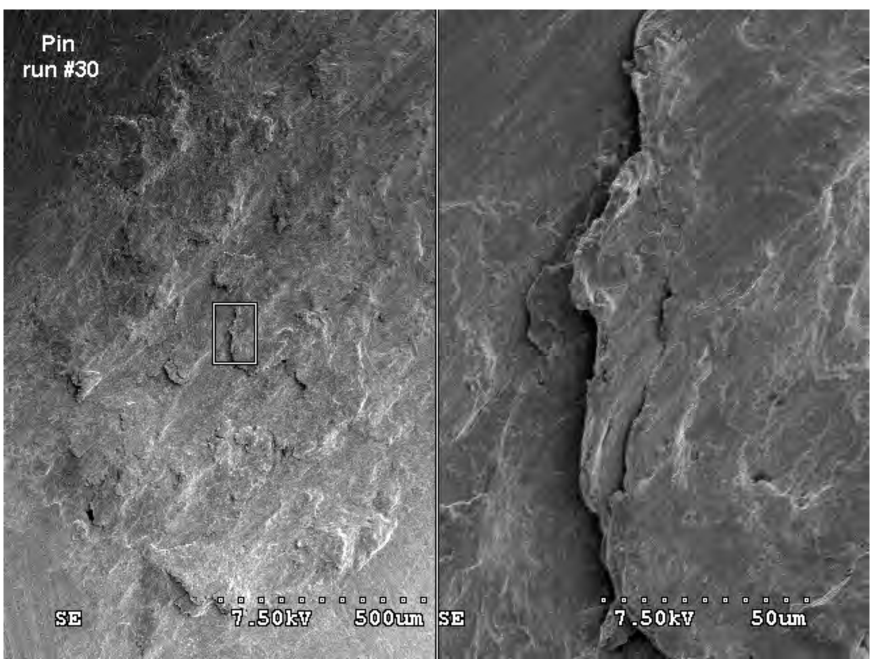


Figure 92 Detailed characterization of wear track on the disk with SEM (Test No. 30).

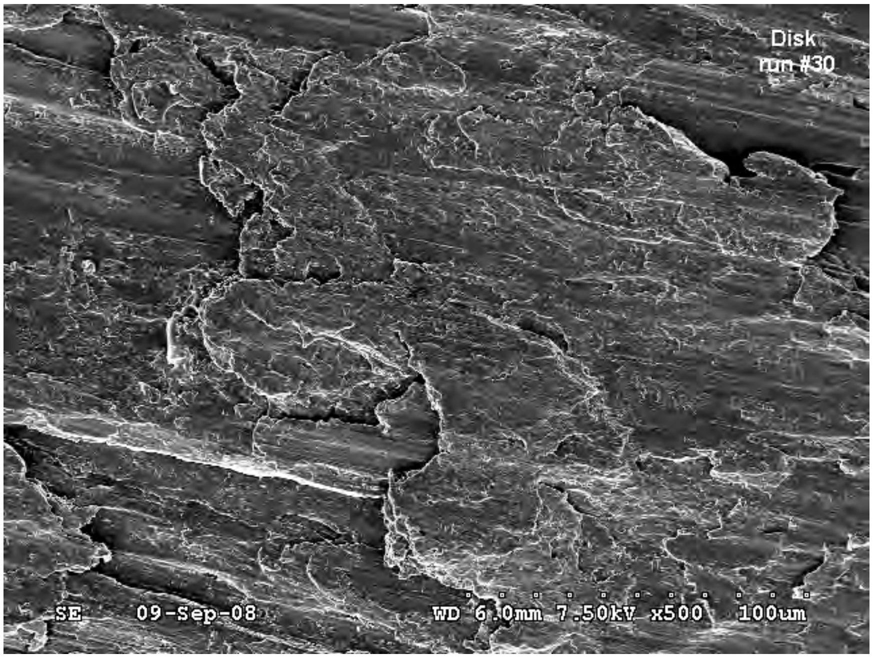


Figure 93 Wear track on the disk under SEM at 500X (Test No. 30).

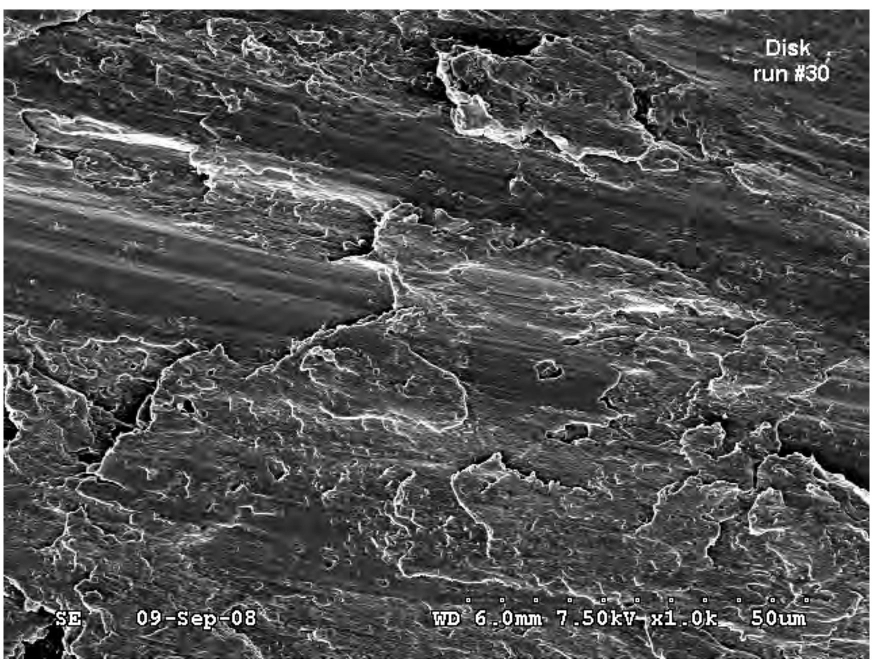


Figure 94 Wear track on the disk under SEM at 1000X (Test No. 30).

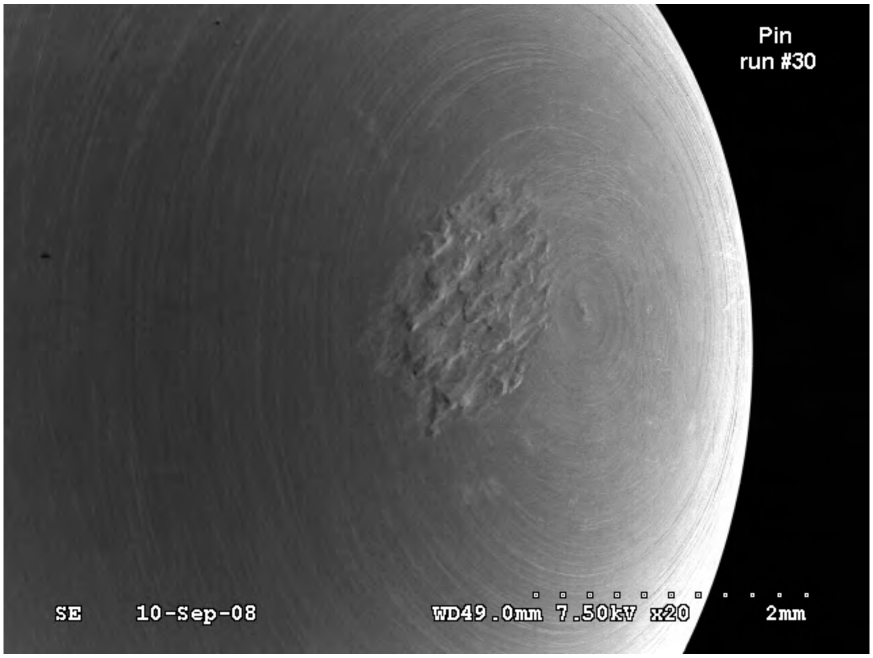


Figure 95 Wear area on the spherical surface of the pin under SEM at 20X (Test No. 30).

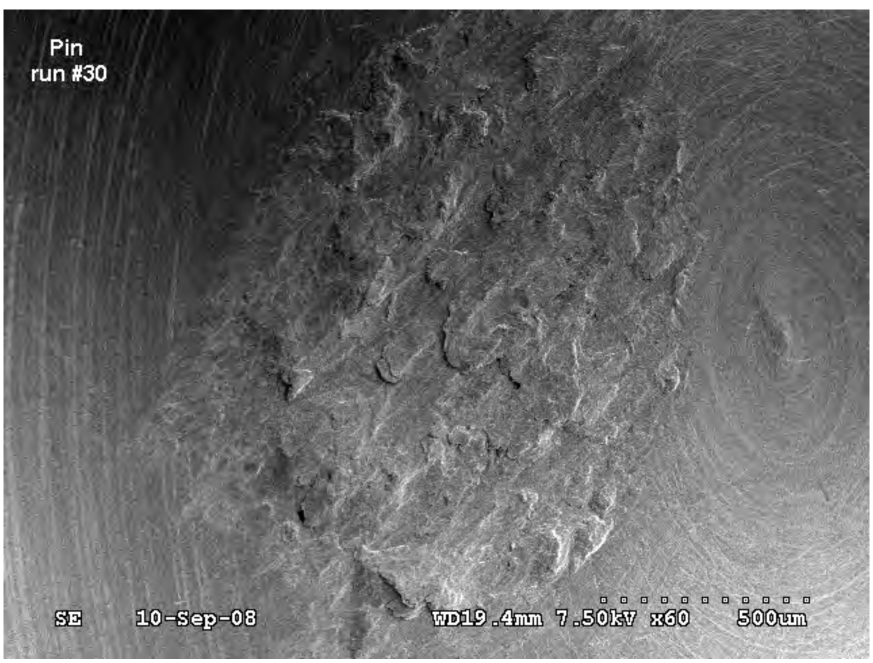


Figure 96 Wear area on the spherical surface of the pin under SEM at 60X (Test No. 30).

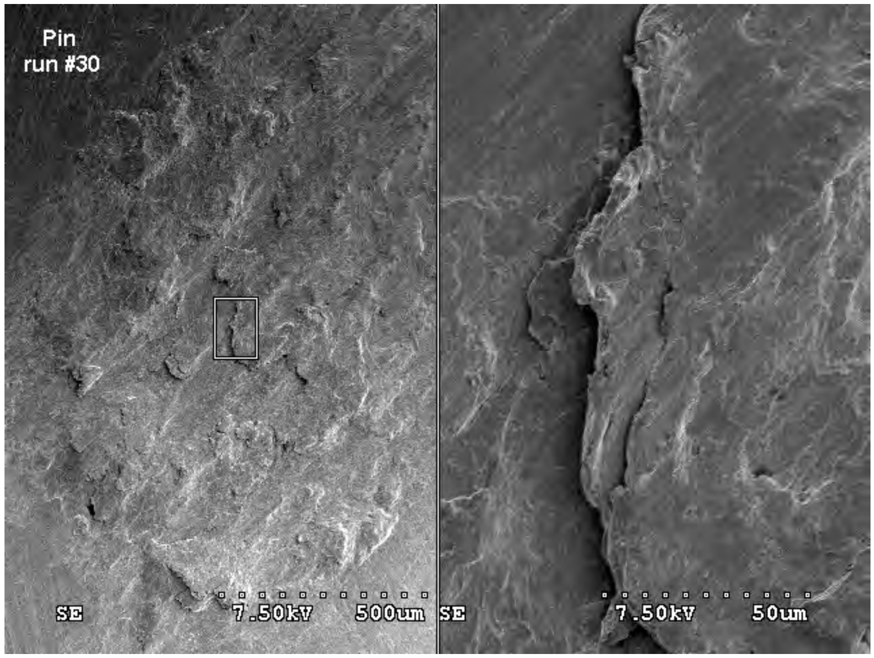


Figure 97 Detailed characterization of wear area on the pin with SEM (Test No. 30).

A comparison of the SEM wear scar surface images for the disk and pin materials tested in air and hydrogen indicates an increase in the overall roughening, protrusion development, and fragmentation for the AUM10 disk material tested in hydrogen. Results for the 316L disk material indicate minimal change or a reduction of the wear scar surface roughening and fragmentation in hydrogen.

RESULTS

Weight Change

As discussed in a previous section, the weight change of the samples was obtained independently by (1) weighing the sample with a five-place balance before and after the test, and (2) using profilometer to trace the surface roughness with a planimeter to estimate the area of wear and with integration along the wear path (for disks), or over the wear region (for pins) to estimate the volume change due to wear. The weight changes are shown in Tables 5 and 6, respectively, for the disks and for the pins. The results are shown graphically in Figures 54 to 55. The results show the AUM10 disk material to have a slightly higher wear rate than the 316L disk materials in air, and a significantly higher wear rate in hydrogen. Additionally, results from this initial dataset do indicate a small trend of increased wear in the gaseous hydrogen environment for both AUM10 and 316L materials.

Table 5 Test results for disks – wear track measurement and weight change

Test No.	Disk Material	Pin Material	Amb. Gas	Ambient Pressure (psig)	Disk Track Width (in)	Disk Track Finish (μ–inch)	Calculated Disk Vol. (in^3)	Calculated Disk Wt. Loss (g)	Measured Disk Wt. Loss (g)
1	316L	316L	Air	0	0.030	64	4.00E-06	0.00052	0.00070
3	316L	316L	Air	0	0.039	78	1.70E-06	0.00022	0.00097
2	316L	316L	Air	0	0.015	11.7	n.m.	n.m.	0.00021
21	316L	316L	Air	0	0.015	11.7	n.m.	n.m.	-0.00036*
9	316L	316L	H_2	1000	0.013	21	4.00E-06	0.00052	0.00034
11	316L	316L	H_2	1000	0.010	6.03	1.40E-05	0.00183	0.00002
12	316L	316L	H_2	1000	0.046	33.2	5.30E-05	0.00693	0.00092
13	316L	316L	H_2	1000	0.042	38.3	1.00E-06	0.00013	0.00040
20	316L	316L	H_2	2000	0.045	53.3	2.50E-05	0.00327	0.00156
22	316L	316L	H_2	2000	0.039	157	9.00E-06	0.00118	0.00061
23	316L	316L	H_2	2000	0.048	38.4	1.10E-05	0.00144	0.00042
24	316L	316L	H_2	2000	0.046	26.6	9.00E-06	0.00118	0.00021
4	316L	A286	Air	0	0.034	22.4	2.70E-05	0.00353	0.01406
6	316L	A286	Air	0	0.030	57	gain	gain	n.m.
14	316L	A286	H_2	1000	0.018	23.3	1.00E-06	0.00013	0.00097
15	316L	A286	H_2	1000	0.040	63.2	1.40E-05	0.00183	0.00046
25	316L	A286	H_2	2000	0.039	95.4	4.00E-06	0.00052	0.00106
26	316L	A286	H_2	2000	0.008	27.3	0.00E+00	0	-0.00101*
5	AUM10	316L	Air	0	0.031	28.5	3.00E-06	0.00039	0.00088
8	AUM10	316L	Air	0	0.027	14	5.50E-04	0.07193	-0.00006*
16	AUM10	316L	H_2	1000	0.015	32.5	n.m.	n.m.	0.00005
17	AUM10	316L	H_2	1000	0.057	88.6	6.30E-05	0.00824	0.00578
27	AUM10	316L	H_2	2000	0.055	100	8.30E-05	0.01085	0.00943
28	AUM10	316L	H_2	2000	0.031	32.6	n.m.	n.m.	0.00064
7	AUM10	A286	Air	0	0.020	14.7	4.00E-06	0.00052	0.00014
10	AUM10	A286	Air	0	0.044	51	7.00E-06	0.00092	0.00032
18	AUM10	A286	H_2	1000	0.061	129	2.82E-03	0.36879	0.01156
19	AUM10	A286	H_2	1000	0.002	14.4	3.10E-04	0.04054	0.00027
29	AUM10	A286	H_2	2000	0.056	94.2	4.40E-05	0.00575	0.00185
30	AUM10	A286	H_2	2000	0.05	135.7	1.04E-04	0.01360	0.00888

Note - n.m.: Not Measurable

gain: Profile of surface roughness in the wear area (wear track) showed more material above the undisturbed surface baseline.

* (negative): Possibly due to measurement error or material transferred from the pin.

Table 6 Test results for pins – wear area measurement and weight change

Test No.	Disk Material	Pin Material	Amb. Gas	Ambient Pressure (psig)	Pin Wear Finish (μ-inch)	Pin Wear Width (inch)	Pin Wear Length (inch)	Calculated Pin Wt. Loss (g)	Measured Pin Wt. Loss (g)
1	316L	316L	Air	0	74	0.031	0.058	0.00013	0.00003
3	316L	316L	Air	0	21	n.m.	n.m.	0.00000	gain §
2	316L	316L	Air	0	3.4	0.017	0.024	0.00000	0.00003
21	316L	316L	Air	0	17.8	0.028	0.036	0.00006	gain §
9	316L	316L	H_2	1000	1	0.021	0.015	0.00000	0.00000
11	316L	316L	H_2	1000	4	0.014	0.015	0.00005	0.00002
12	316L	316L	H_2	1000	42.1	0.053	0.058	0.00018	-0.00014 §
13	316L	316L	H_2	1000	29.4	0.0429	0.0475	0.00010	0.00017
20	316L	316L	H_2	2000	72.6	0.031	0.065	0.00006	0.00011
22	316L	316L	H_2	2000	103	0.0374	0.058	0.00013	-0.00020*
23	316L	316L	H_2	2000	63.6	0.052	0.059	0.00029	0.00018
24	316L	316L	H_2	2000	32.1	0.0474	0.053	0.00025	0.00036
4	316L	A286	Air	0	104	0.032	0.056	0.00010	0.00059
6	316L	A286	Air	0	30	0.011	0.06	0.00001	gain §
14	316L	A286	H_2	1000	30.3	0.014	0.052	0.00000	0.00097
15	316L	A286	H_2	1000	74.4	0.036	0.063	0.00010	0.00026
25	316L	A286	H_2	2000	85.2	0.328	0.033	0.00060	-0.00045 §
26	316L	A286	H_2	2000	1.6	0.018	0.016	0.00000	0.00046
5	AUM10	316L	Air	0	61.6	0.032	0.036	0.00006	0.00030
8	AUM10	316L	Air	0	5.3	0.023	0.0102	0.00000	gain §
16	AUM10	316L	H_2	1000	5	0.0235	0.029	0.00001	0.00005
17	AUM10	316L	H_2	1000	72.1	0.061	0.76	0.00023	0.00049
27	AUM10	316L	H_2	2000	108	0.058	0.0737	0.00051	-0.00004 §
28	AUM10	316L	H_2	2000	60.7	0.033	0.044	0.00006	0.00060
7	AUM10	A286	Air	0	12.1	0.019	0.027	0.00001	0.00014
10	AUM10	A286	Air	0	39	0.033	0.056	0.00018	0.00018
18	AUM10	A286	H_2	1000	52	0.051	0.084	0.00004	0.00045
19	AUM10	A286	H_2	1000	3.1	0.0207	0.023	0.00001	0.00006
29	AUM10	A286	H_2	2000	69.6	0.05	0.091	0.00054	0.00057
30	AUM10	A286	H_2	2000	142.9	0.056	0.073	0.00030	0.00037

Note - n.m.: Not Measurable

gain: Profile of surface roughness in the wear area showed more material above the undisturbed surface baseline.

§: (negative): Possibly due to measurement error or material transferred from the disk track.

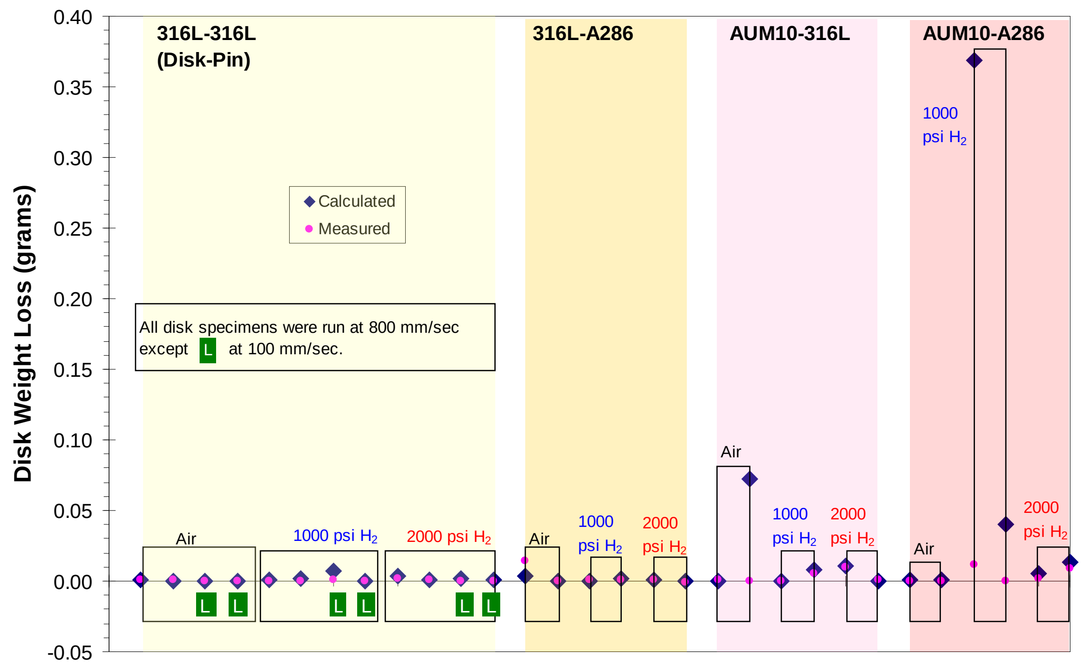


Figure 98 Disk weight change (loss) after 500 m of travel distance and under a pin load of 45.4 g (0.1 lb).

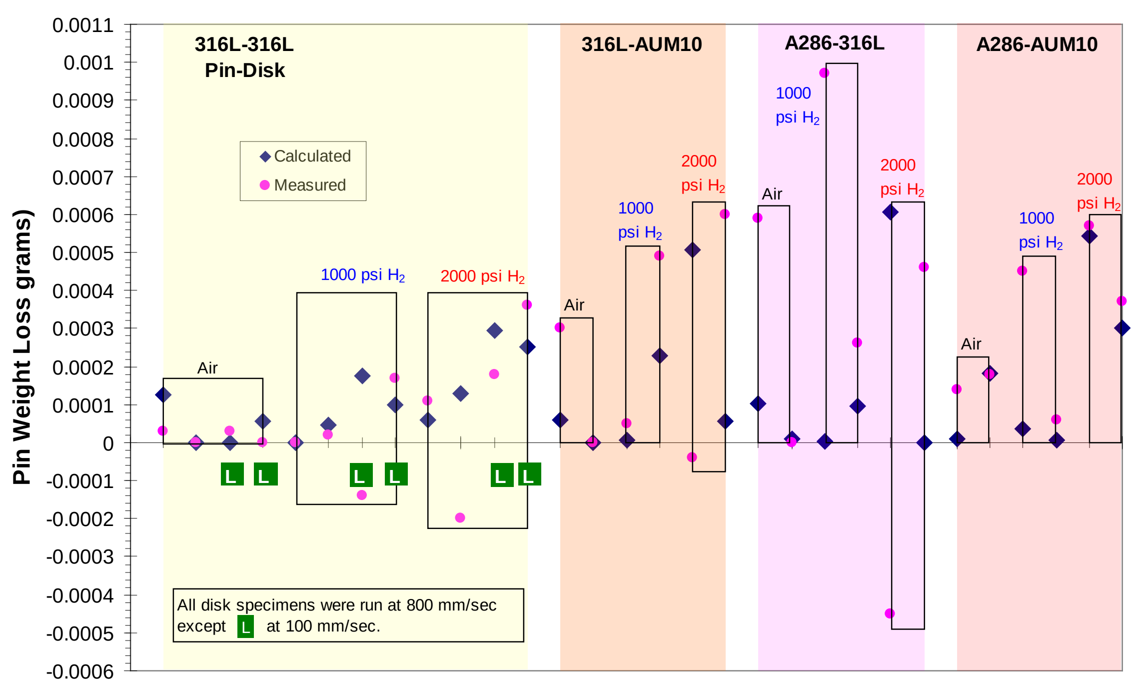


Figure 99 Pin weight change (loss) after 500 m of disk travel distance and under a pin load of 45.4 g (0.1 lb).

Wear Coefficient (K_W)

A wear coefficient was calculated based on the Archard Equation [3-6] 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 [3]. 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 [3].

A wear equation was proposed by Holm in 1946 [4] and later was derived analytically by Archard in 1953 [5,6] as

W=kL/3p,

where W is the wear rate (volume loss per unit sliding distance), L is the external load 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 [3].

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:

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

The wear coefficient for each of the test case is shown in Figure 56. About one-half (16) of the tests resulted in $K_w<0.001$, which is consistent with the observation by Robinowicz (Table 6.1 of Ref. 3), in which he reported that k= 21×10^{-3} (equivalently, $K_w=7\times10^{-3}$). Robinowicz 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. 3).

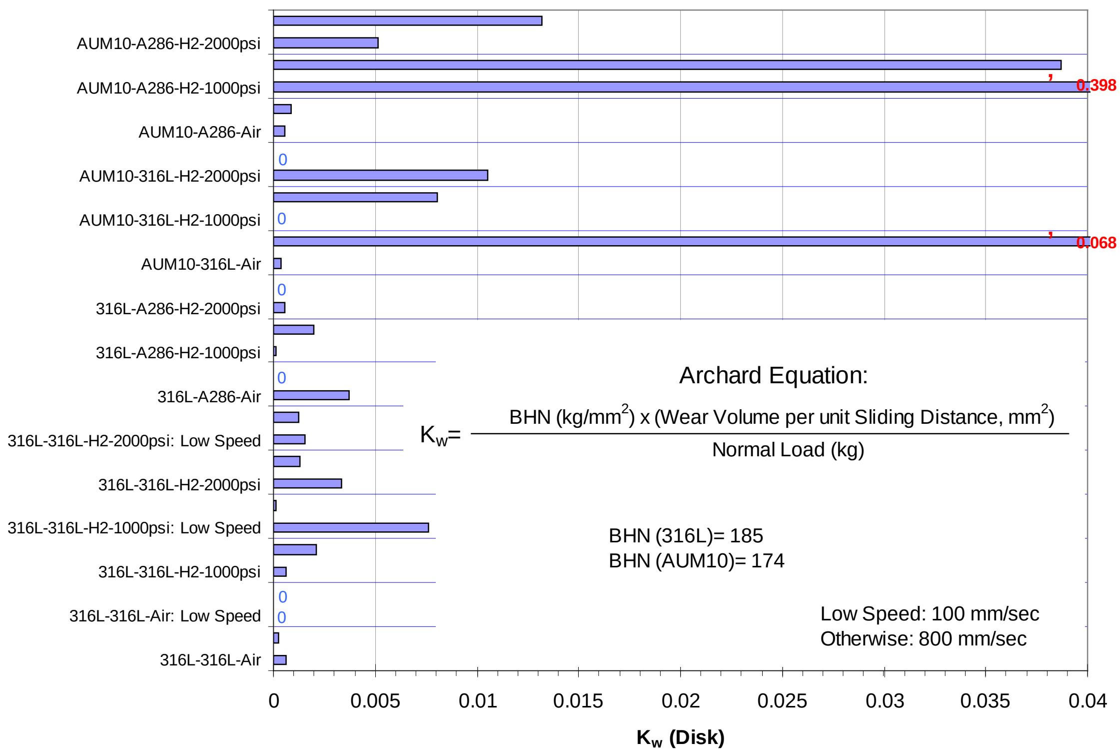


Figure 100 The wear coefficients calculated for all wear test cases.

Examination of the wear coefficient data displayed in Figure 56 indicates that the AUM10 disk material exhibits more wear in comparison to the 316L disk material in all conditions tested in this initial study (air and hydrogen). This result trend is consistent with the other previously shown data for weight change and wear scar surface analysis that also indicated increased wear for the AUM10 material.

CONCLUSIONS

Based on the current data collected for a travel distance of 500 m and a load of 45.4 g, the tribological effects of the stainless disks (316L and AUM10) and the pins (316L and A286) are not significant. However, the results do show a tendency for higher wear of materials sliding against each other in a gaseous hydrogen environment. The effect on wear in gaseous hydrogen appears to be more pronounced for the AUM10 disk alloy.

The lack of overall significant wear in terms of weight loss for the testing may be due to the combination of low test loads in conjunction with relatively short travel distances. It may also be attributed to the nature of adhesive wear, which is characterized by macroscopic plastic deformation such as scoring, scuffing, and galling - to form excrescences (bulging and protuberating) until the local strain limit is reached and the debris breaks away from the surface. Material transfer between the stationary pin and the rotating disk may also be likely. All these factors will affect the weight change assessment by weighing the pre/post-testing specimens or by integrating the area based on profilometer tracing.

The apparent initial impact of gaseous hydrogen on the wear of the stainless steel may be attributed to the hydrogen diffusivity in these materials. The hydrogen diffusion in stainless steels is known to be slower [8,9] in comparison to carbon steels [10-12]. Thus, the hydrogen effects on wear in gaseous hydrogen are expected to be affected by exposure time in the hydrogen. Testing condition options such as increased travel distance, increased load, and pre-charging of pin and disk samples can be explored in future tests.

PATH FORWARD

It has been recommended that surface deposition technologies be considered in improving the metal-to-metal sliding wear, in particular, by applying the amorphous carbon coating (i.e., the diamond-like coating or DLC) because of its superior mechanical and physical properties (high toughness, high elastic modulus, high electrical resistance, high thermal conductivities, and chemical inertness) with no post-fabrication surface finish. Additional experimental techniques and characterization methodologies should be developed to evaluate the tribological properties of these coatings and to determine their optimal thickness in hydrogen [13]. The Savannah River National laboratory is currently in discussions with the Toyota Research Institute North America to develop a continuation work scope that will evaluate surface coating effects of wear properties in both air and hydrogen.

ACKNOWLEDGMENTS

SRNL would like acknowledge Toyota Research Institute North America for funding support under CRADA Agreement PTS-03. Additionally, we would like to recognize and thank both Craig Stripling and Doug Leader of SRNL for equipment design, fabrication, installation, and test support. Furthermore, we would also like to acknowledge Daryl Hudson for profilometry support, Zane Nelson for sample photography, and Tony Curtis for performing scanning electron microscopy.

REFERENCES

[1] Budinski, K. G., Guide to Friction, Wear, and Erosion Testing, ASTM International, West Conshohocken," PA, 2007.

[2] Review of the Wear and Galling Characteristics of Stainless Steels, A Designers' Handbook Series, Committee of Stainless Steel Producers, American Iron and Steel Institute, Washington, D.C., 1978.

[3] Rabinowicz, E., Friction and Wear of Materials, John Wiley and Sons, Inc., New York, 1965.

[4] Holm, R. and Heijne, A. V., Electric Contacts, H. Geber, Stockholm, 1946.

[5] Archard, J. F., "Contact and Rubbing of Flat Surfaces," Journal of Applied Physics, Vol. 24, pp. 981-988, 1953.

[6] Archard, J. F. and Hirst, W., "Wear of Metals under Unlubricated Conditions," Proceedings of Royal Society, Vol. A-236, pp. 397-410, 1956.
[7] Private Communication with Professor Naoya Tada, Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushimanaka, Okayama, 700-8530, Japan, August 25, 2008.
[8] Kim, Y., Chao, Y. J., Morgan, M. J., and Lam, P.-S., "Comparison of Decoupled and Coupled Analyses for Hydrogen Transport in Fracture Specimens," Paper No. PVP2007-26389, Proceedings of ASME Pressure Vessels and Piping Conference, San Antonio, Texas, July 2007.
[9] Taha, A. and Sofronis, P., "A micromechanics approach to the study of hydrogen transport and embrittlement", Engineering Fracture Mechanics, Vol.68, pp.803-837, 2001.
[10] Duncan, A. J., Lam, P.-S., and Adams, T. M., "Tensile Testing of Carbon Steel in High Pressure Hydrogen," Paper No. PVP2007-26736, Proceedings of ASME Pressure Vessels and Piping Conference, San Antonio, Texas, July 2007.
[11] Lam, P. S., Sindelar, R. L., and Adams, T. M., "Literature Survey of Gaseous Hydrogen Effects on the Mechanical Properties of Carbon and Low Alloy Steels," Paper No. PVP2007-26730, Proceedings of ASME Pressure Vessels and Piping Conference, San Antonio, Texas, July 2007.
[12] Lam, P. S., "Hydrogen Effects on the Mechanical Properties of Austenitic Stainless Steels - a Compendium of Data from Testing at the Savannah River Laboratory in Support of High Pressure Hydrogen Service (U)," WSRC-STI-2008-00043, Washington Savannah River Company, Aiken, South Carolina, July 2008.
[13] Li, X. and Bhushan, B., "Micro/nanomechanical and tribological characterization of ultrathin amorphous carbon coatings," Journal of Materials Research, Vol. 14, pp. 2328-2337, 1999.

APPENDIX

Vendor Certifications

A. Stainless Steel Type 316L (for Disks)
B. Stainless Steel Type 316L (for Pins)
C. Stainless Steel Type A286 (for Pins)
D. Stainless Steel Type AUM10 (for Disk)
E. Additional Contact Profilometry Scan Data
F. Additional Macrophotographs of Wear Tracks on Disk and Pins

Appendix A Stainless Steel Type 316L (for Disks)

Where Quality Isn't Expensive.....It's Priceless!

DIVERSIFIED METALS
INCORPORATED

TOLL FREE: 800-628-3035
EMAIL: SALES@DIVERSIFIEDMETALS.COM
WEBSITE: WWW.DIVERSIFIEDMETALS.NET
49 MAIN STREET MONSON, MA 01057-0065

FAX: 413-267-3151
PHONE: 413-267-5101
CAGE CODE: 57067
PO BOX 65

TEST CERTIFICATE

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

Scanned

Acciaierie Valbruna S.p.A.

CERTIFICATO DI COLLAUDO
ABNAHMEPRUEFZEUGNIS
INSPECTION CERTIFICATE
CERTIFICAT DE RECEPTION
EN 10204 , 3.1.B

36100 VICENZA (Italia) - Viale della scienza, 25 z.i.
Stab.: 39100 BOLZANO (Italia) - Via A. Volta, 4

Cliente: VALBRUNA CORP.
31 IRON HORSE ROAD
USA-OAKLAND NJ 07436-USA

Avviso di Spedizione: D-BZ05001142

Certificato nr: MEST184033/2005/ 2

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 96 316/316L

AMS 5648 K S31600
ASME (1) SA193 2001 B8M (1)
ASME (1) SA484 2001 .
ASTM A194 99 8M
ASTM A314 97 S31600/03
ASTM A473 99 S31600/03
NACE MR0175 2002 S31600/03
QQ-S-763 E/1 316/316L

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) 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

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

APPROVED BY CJR
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

Controllo antimescolanza: OK

Controllo visivo e dimensionale: soddisfa le esigenze:

TEST	Provetta/ mm	°F	Posiz. Saggio	Snervamento Rp 0,2% k.s.i.	Snervamento	Resistenza 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=longitudinal/längs, Q=transversal/quer, T=Tangential/tangential

Grain size for ASTM E112 : 5

Analisi chimica

Colata	C %	Si %	Mn %	Cr %	Mo %	Cu %	Ni %	P %	S %	N %					
min - max	- 0,030	- 1,00	1,25 2,00	15,50 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

DIVERSIFIED METALS, INC.
49 MAIN STREET, MONSON, MA 01057
PH 413-267-5101/FAX 413-267-3151
SOLD TO:
CUSTOMER: WASHINGTON SAVANNAH CO.
P.O. # 7P5896
ITEM# 3

Bolzano,15/11/05	Il collaudatore di stabilimento / der Werkssachverständige / Works inspector / L'agent d'usine: R.Criste [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 BRINELL	HARDNESS ROCKWELL "B"	HARDNESS ROCKWELL "C"	AS SHIPPED HARDNESS

OTHER TEST(S) AND / OR REQUIREMENTS

AMS 5648 K S31600	AMS 5653 FS31603	(1) Chemical analysis only and mechanical properties
ASME (1) SA193 2001 B8M(1)	ASME (1) SA320 2001 B8M (2)	(2) SEC 11PT A 2001 EDITION ADD 2002
ASME(1) SA484 2001	ASTM A182 2002 S31600/03 (4)	(4) Chemical analysis only
ASTM A194 99 8M	ASTM A262 2002A	
ASTM A314 97 S31600/03	ASTMA320 2004 B8M	
ASTM A479 99 S31600/03	ASTM A479 2004S31600/03	
NACE MR0175 2002 S31600/03	QQ-S-763 F 316316L	
QQ-S-763 E/1 316/316L		

NOTES

"Statement of Compliance"
"This material, is produced by Accialerie 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 316L (for Pins)

Where Quality Isn't Expensive.....It's Priceless!

DIVERSIFIED METALS
INCORPORATED

TOLL FREE: 800-628-3035
EMAIL: SALES@DIVERSIFIEDMETALS.COM
WEBSITE: WWW.DIVERSIFIEDMETALS.NET
49 MAIN STREET MONSON, MA 01057-0065

FAX: 413-267-3151
PHONE: 413-267-5101
CAGE CODE: 57067
PO BOX 65

TEST CERTIFICATE

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.: 2

PN: NONE

Dimensions: 0.375 IN. DIA. X 12.05 FEET

Alloy/Grade: STAINLESS 316

Specification/Grade: QQ-S-763F

No. Of Boxes	*No of Pieces*	*Length*	*Weight*	*Packing Slip No.*	*Heat No.*	*Lot No.*
1	2	12.05 FEET	5.0 LBS	59927	OLV2	NONE

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: December 5, 2007

Mill Cert. – REV 2. – 2/27/2007

DIVERSIFIED METALS, INC.
49 MAIN STREET, MONSON, MA 01057
PH 413-267-5101/FAX 413-267-3151
SOLD TO:
CUSTOMER: Washington Savannah River
P. O. # 7P5896
ITEM# 2

APPROVED BY CTR
DATE 12/3/07
CAROL RALPH
Q.C. MANAGER

NORTH AMERICAN STAINLESS INSPECTION CERTIFICATE

North American Stainless
6870 Highway 42 East
Ghent, Kentucky 41045-9615
Telephone: (502) 347-6000
FAX: (502) 347-6001

Email: customerservice@northamericanstainless.com

2006 / 98002	DATE 11/21/2006
PACKING LIST # 2006 /67172	NUMBER 1
GRADE NAS-264 P.O.# :P60828AM007 AISI (316L/316) ✓	Item Code:

CUSTOMER	TOLERANCE	PRODUCT ✓
	ASTM-A-484-00	Round bar, annealed, cold drawn.

ORDER NUMBER	MARK# / PROD ID	HEAT NUM	WEIGHT
LN29839	39001/BB22554	0LV2	2313
"	39002/BB22555	0LV2	1830

REQUIREMENTS AISI

LENGTH 12.00 ft
SIZE .3750 Inches

SURFACE AND DIMENSION CONTROL: WITHOUT OBJECTIONS

MECHANICAL PROPERTIES

HEAT NUM	Rm UTS KSI ✓	Rp 0.2 YS KSI	Rp 1.0 YS KSI	Z% RA	ELONG A % L4d	HARDNESS HB	RESILIENCE J	A% %L_d 5
0LV2	104	88		74	41	207		
Required Values	90 115	30 100		50 100		140 255		000000

INTERGRANULAR CORROSION ✓
ASTM A262-02a
PRACTICE "E"
SATISFACTORY

CHEMICAL COMPOSITION % CM(Country of Melt) ES(Spain) US(United States)

CM	HEAT	C ✓	P ✓	S ✓	Si ✓	Mn ✓	Cr ✓	Ni ✓	Mo ✓	N ✓	Cu ✓	Co		
US	0LV2	.0240	.0284	.0205	.3195	1.4962	17.0850	10.6872	2.1169	.0421	.4312	.1766		
REQUIRED VALUES		.0300	.0450	.0300	1.0000	2.0000	16.0000 18.0000	10.0000 14.0000	2.0000 3.0000	.1000				

STEELMAKING PROCESS
EAF+AOD+CC

OBSERVATIONS/SPECIFICATIONS ✓

UNS S31600/31603;GRAIN SIZE = 4-6,ASTM A276/04;ASTM A479/04;QQS-763F COND A,AMS QQS 763A.
EN 10204 3.1B, AMS 5648K/AMS 5653F, ASME SA479/04, ASTM A484/03, ASTM A182-02(CHEM ONLY)
MELTED AND MANUFACTURED IN 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.

QUALITY INSPECTOR
Eric Hess
Quality Control Representative

28PH011-1 DIVERSIFIED MET PO: 46883 Part #:
1.00PC

Appendix C Stainless Steel Type A286 (for Pins)

Where Quality Isn't Expensive.....It's Priceless!

DIVERSIFIED METALS
INCORPORATED

TOLL FREE: 800-628-3035
EMAIL: SALES@DIVERSIFIEDMETALS.COM
WEBSITE: WWW.DIVERSIFIEDMETALS.NET
49 MAIN STREET MONSON, MA 01057-0065

FAX: 413-267-3151
PHONE: 413-267-5101
CAGE CODE: 57067
PO BOX 65

TEST CERTIFICATE

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.: 1

PN: NONE

Dimensions: 0.375 IN. DIA. X 72.00 INCHES

Alloy/Grade: A286 ALLOY STEEL

Specification/Grade: AMS 5737N

No. Of Boxes	*No of Pieces*	*Length*	*Weight*	*Packing Slip No.*	*Heat No.*	*Lot No.*
1	1	72.00 INCHES	2.0 LBS	59849	302417	514600660

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

Scanned

Acciaierie Valbruna S.p.A.

36100 VICENZA (Italia) - Viale della scienza, 25 z.i.
Stab.: 39100 BOLZANO (Italia) - Via A. Volta, 4

CERTIFICATO DI COLLAUDO
ABNAHMEPRUEFZEUGNIS
INSPECTION CERTIFICATE
CERTIFICAT DE RECEPTION
EN 10204 , 3.1.B

DIVERSIFIED METALS, INC.
49 MAIN STREET, MONSON, MA 01057
PH 413-267-5101/FAX 413-267-3151
SOLD TO:
CUSTOMER: WASHINGTON SAVANNAH Co.
P.O. # 125896
ITEM# 1

Cliente / Besteller/Purchaser/Client
VALBRUNA STAINLESS INC.
2400 TAYLOR STREET WEST
USA-FORT WAYNE, IN 46801-USA

Avviso di Spedizione: D-VI06001121
Lieferanzeige/Packing list/B.L.

Certificato nr: MEST302257/2006/ 1
Prüfung/Test/Essai

Conferma ordine nr: SP05000143
Werks/Our Order/Ref nr.

Produttore: **ACCIAIERIE VALBRUNA S.P.A.**
Hersteller/Item/Usine productice

Ordine nr: 14569:DIFERSIFIELD METALS
Bestell/Your order/Commande

Marchio di Fabbrica:
Zeichen des Lieferwerkes
Trade mark
Sigle de l'usine productice

Oggetto Prove: - Aged Bright Ground C-Exec
Prüfgegenstand/Item inspected/Pièce essayée

Tipo di Elaborazione: E+AOD+ESR
Erschmelzungsart/Melting process/Mode d'elaboration

Punzone del Collaudatore: MR
Stempel des Werkssachverständigen
Inspector's stamp/Poinçon de l'essayeur

Specifiche:
Anforderungen / Requirements / Exigences
VAL CORP 2004 660 CL.A/T.1 AGED
ASTM A638 2000 660
(0) * ISO 15156-3

AMS 5737 N S66286
NACE MR0175* 2003 S66286 SA,AG (0)

ASTM A453 2004 660

APPROVED BY CTR
DATE 9/20/06
CAROL RALPH
Q.C. MANAGER

Qualità: 660 CL.A/T.1
Werkstoff/Grade/Nuance

Marca: AN5
Markenbezeichnung/Brand/Nuance

Punzonatura: S66826
Kennzeichnung/Marking/Marquage

Pos. nr.	Oggetto	Dimensioni - in	Tolleranza	Lunghezza - Ft	Colata	Pezzi	Peso - LB	Lotto nr.
0010	Round	0,3750	ASREQ	10 / 14	302417		2.302	514600660

Sono state soddisfatte tutte le condizioni richieste
Die gestellten Anforderungen sind lt. Anlage erfüllt
The material has been furnished in accordance with the requirements
Le matériel a été trouvé conforme aux exigences

Controllo antimescolanza: OK
Verwechslungsprüfung: spectralanalytisch durchgeführt
Antimixing testing performed: OK
Contrôle antimelange fait: r.a.s.

Controllo visivo e dimensionale: soddisfa le esigenze:
Besichtigung und Ausmessung: ohne Beanstandung
Visual inspection and dimensional check satisfactory
Contrôle visuel et dimensions: satisfaisant

TEST	Provetta mm	°F	Posiz. Saggio 1)	Snervamento Rp 0,2% k.s.i.	Snervamento	Resistenza Rm k.s.i.	Allungamento	Allungamento E 4d %	Strizione	Strizione RA %	Resilienza			Durezza HB		
Valori richiesti 1		min max		95	-	140	-	15	-	18	-			277 341		
A	8,75	68	L	149		180		18		44				335		

TEST	Provetta mm	°F	Posiz. Saggio 1)	Carico k.s.i.	Durata t h	Allungamento	Allungamento E %	Strizione	Strizione
Valori richiesti 1		min max		- -	100	-	5	-	-
B	9,07	1.202	L	56	135		9		

TEST	Provetta mm	°F	Posiz. Saggio 1)	Carico k.s.i.	Durata t h	Allungamento	Allungamento E %	Strizione	Strizione
Valori richiesti 1		min max		- -	23	-	5	-	-
C	9,07	1.202	L	65	60		6		

1) L=longitudinale/längs, Q=trasversale/quer, T=Tangenziale/tangential

TEST A HRc MIN MAX 35,0 VAL 33,0
Grain size for ASTM E112 : 5

Analisi chimica

Chemische Zusammensetzung/Chemical Analysis/Analyse chimique

Colata / Heat / Schmelze / Coulée	C %	Si %	Mn %	Cr %	Mo %	Cu %	Ni %	Co %	Ti %	Al %	P %	S %	V %	B %
min - max	- 0,080	- 1,00	- 2,00	13,50 16,00	1,00 1,50	- 0,50	24,00 27,00	- 1,00	1,90 2,35	- 0,35	- 0,025	- 0,025	0,10 0,50	0,0030 0,0100
302417	0,040	0,35	1,45	15,38	1,26	0,37	25,06	0,09	2,27	0,25	0,021	0,001	0,29	0,0050

Vicenza,14/09/06
Mod./VCO012

Il collaudatore di stabilimento / der Werkssachverständiger / Works inspector / L'agent d'usine
M.Rizzotto [redacted]

Pagina - 1 di 2

Scanned

Acciaierie Valbruna S.p.A.

36100 VICENZA (Italia) - Viale della scienza, 25 z.i.
Stab.: 39100 BOLZANO (Italia) - Via A. Volta, 4

CERTIFICATO DI COLLAUDO
ABNAHMEPRUEFZEUGNIS
INSPECTION CERTIFICATE
CERTIFICAT DE RECEPTION
EN 10204 , 3.1.B

Cliente / Besteller/Purchaser/Client
VALBRUNA STAINLESS INC.
2400 TAYLOR STREET WEST
USA-FORT WAYNE, IN 46801-USA

Avviso di Spedizione: D-VI06001121
Lieferanzeige/Packing list/B.L.

Certificato nr: MEST302257/2006/
Prüfung/Test/Essai

Conferma ordine nr: SP05000143
Werks/Our Order/Ref nr.

Produttore: **ACCIAIERIE VALBRUNA S.P.A.**
Hersteller/Item/Usine productrice

Ordine nr: 14569:DIFERSIFIELD METALS
Bestell/Your order/Commande

Marchio di Fabbrica:
Zeichen des Lieferwerkes
Trade mark
Sigle de l' usine productrice

Oggetto Prove: - Aged Bright Ground C-Exec
Prüfgegenstand/Item Inspected/Pièce

Tipo di Elaborazione: E+AOD+ESR
Erschmelzungsart/Melting process/Mode d' elaboration

Punzone del Collaudatore: MR
Stempel des Werkssachverständigen
Inspector' s stamp/Poinçon de l' essayeur

Solution treated 1650F for 2h / water,
precipitation treated 1325F/16h air cool
Produced without class I-II Ozone depleting substances.

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

Vicenza,14/09/06 Mod./VOC010	Il collaudatore di stabilimento / der Werkssachverständige / Works inspector / L' agent d' usine M.Rizzotto [redacted]	Pagina - 2 di 2

Appendix D 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	鋼種＼特性	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) AUM6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

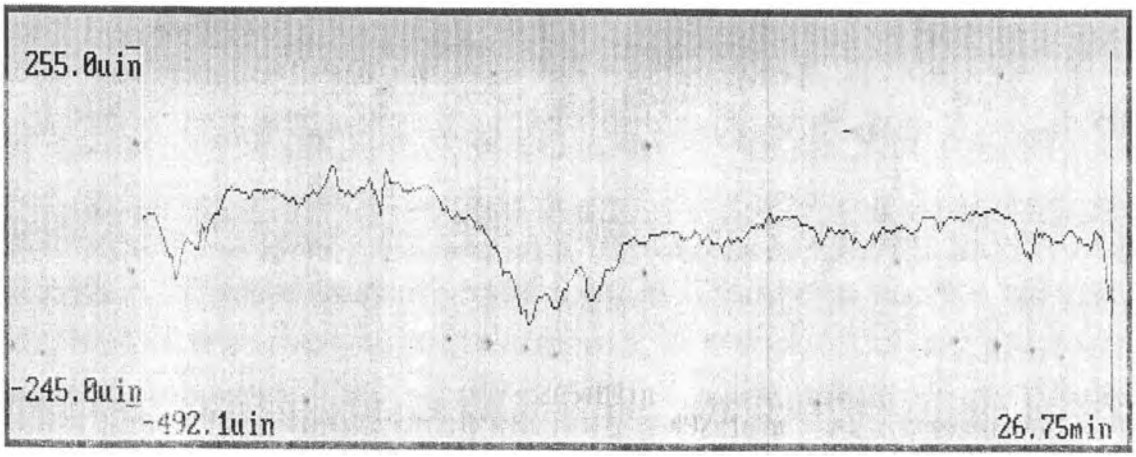
軟磁性ステンレス鋼AUM10の機械的性質

熱処理　焼鈍 900℃×2Hr での機械的性質を下記に示します。

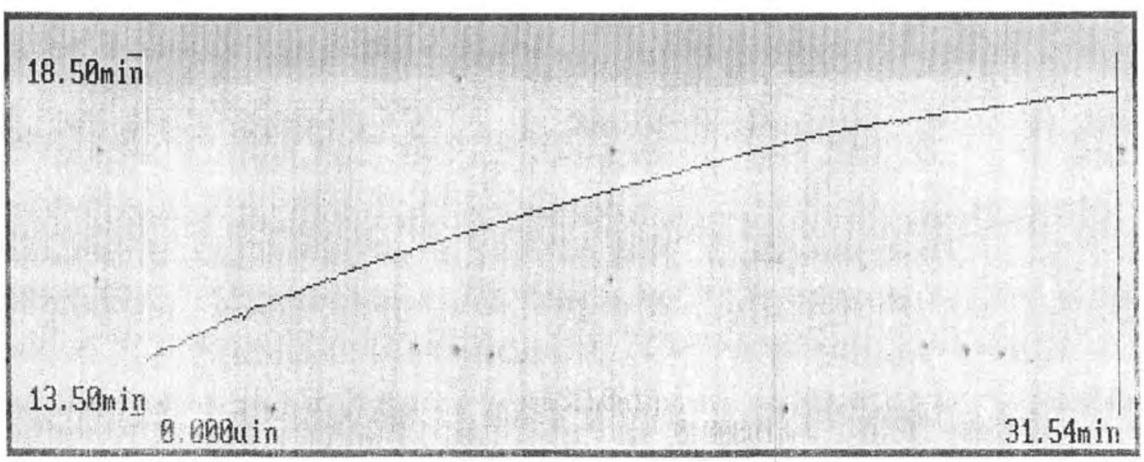
0.2%耐力(N／mm2)	：290以上（代表例 390）
引張強さ(N／mm2)	：490以上（代表例 530）
伸び(%)	：30以上（代表例 37）
絞り(%)	：55以上（代表例 74）
硬さ(HRB)	：83～95（代表例 88）

以上

Appendix E: Additional Contact Profilometry Scan Data

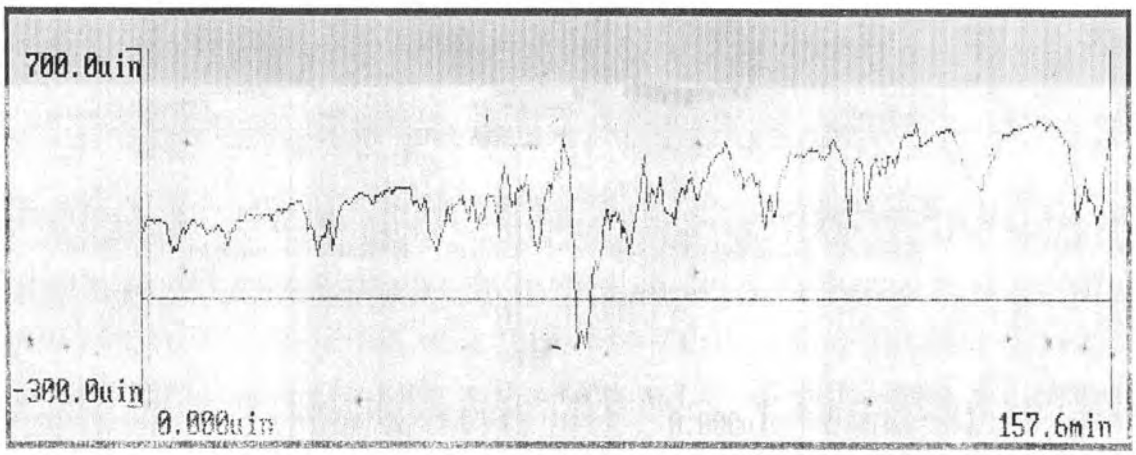


(a)

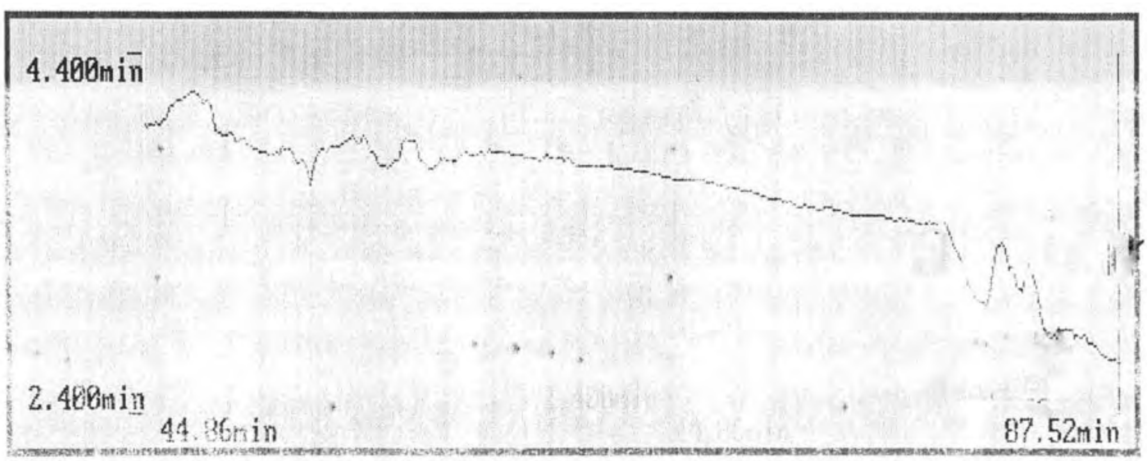


(b)

Figure E1. Contact Profilometry Data for Test #2 (a) Disk and (b) Pin

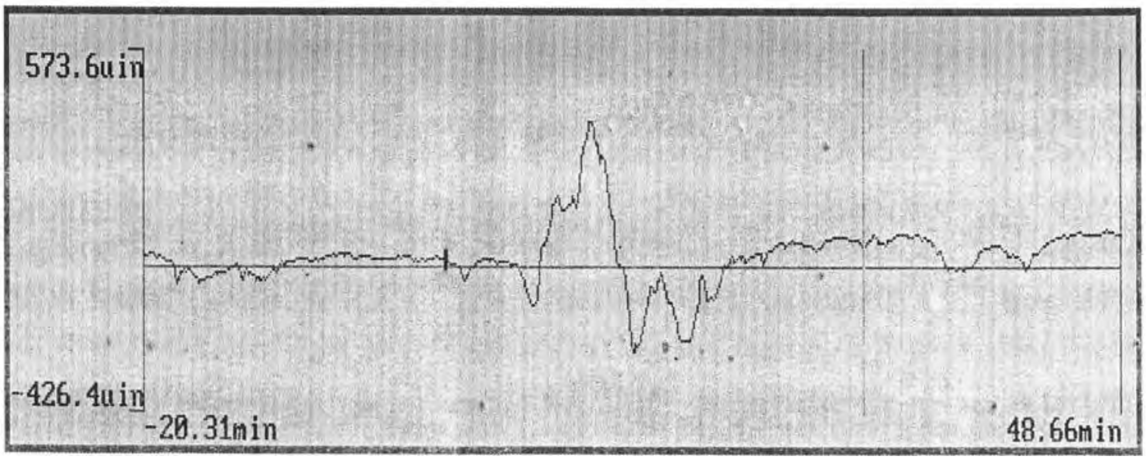


(a)

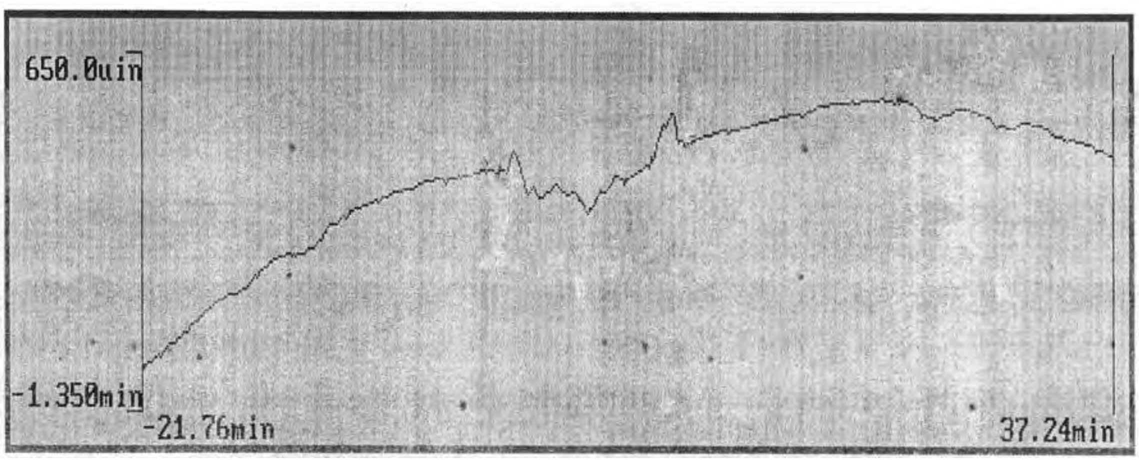


(b)

Figure E2. Contact Profilometry Data for Test #3 (a) Disk and (b) Pin



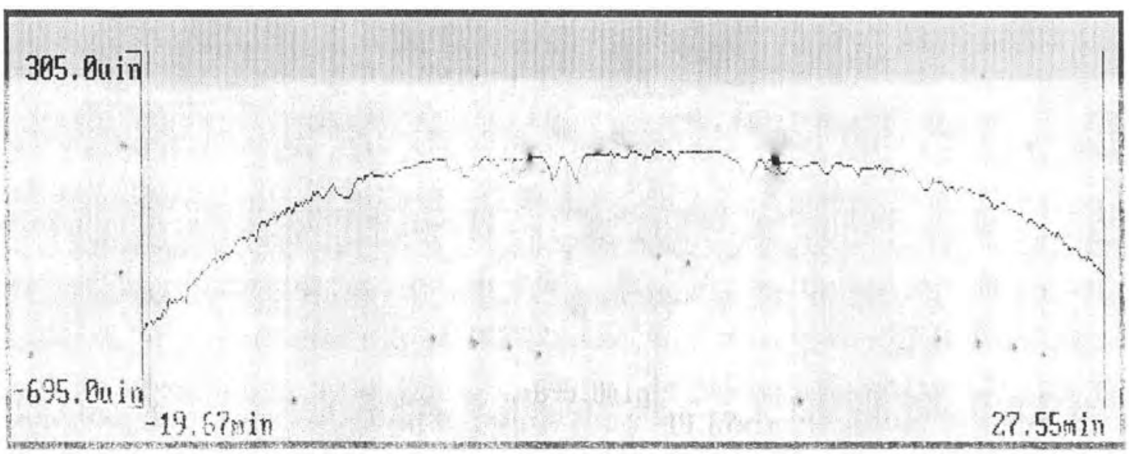
(a)



(b)

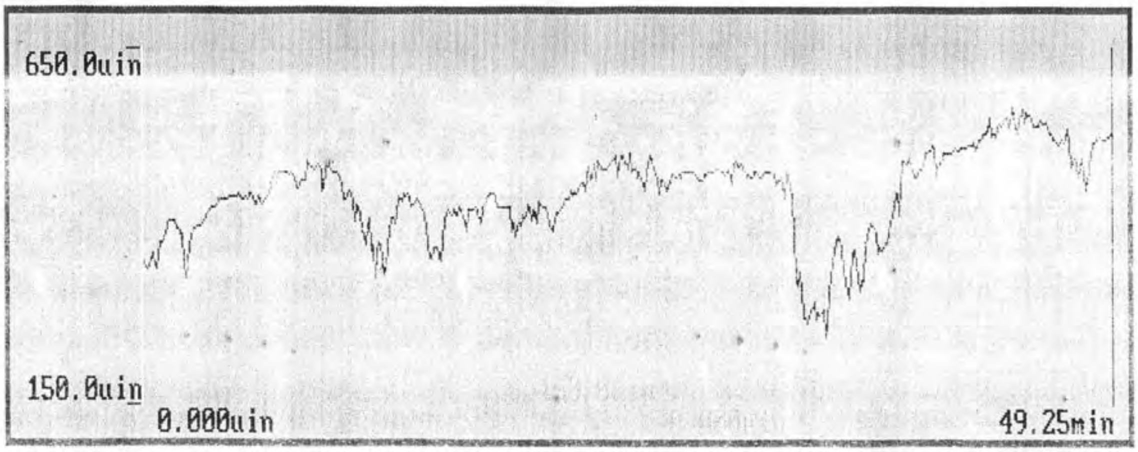
Figure E3. Contact Profilometry Data for Test #6 (a) Disk and (b) Pin

(a)

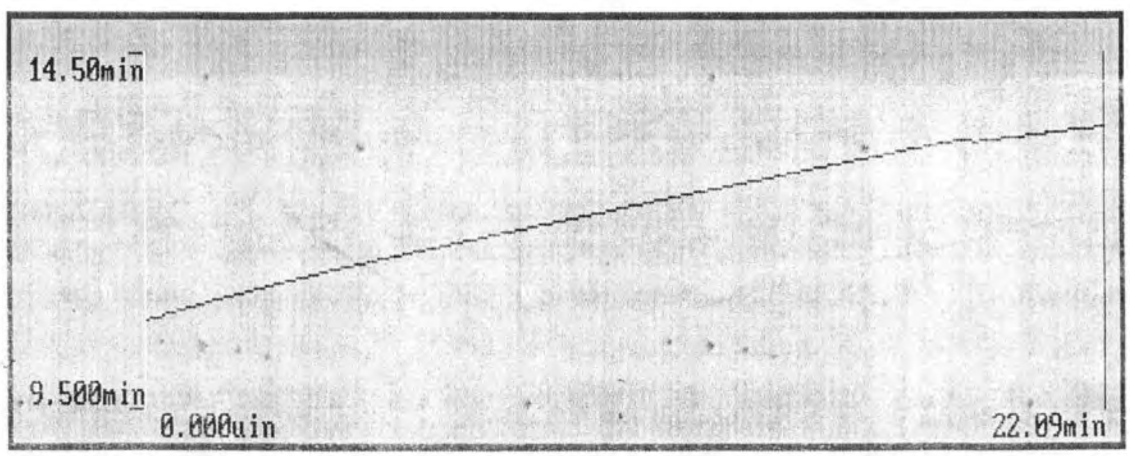


(b)

Figure E4. Contact Profilometry Data for Test #8 (a) Disk and (b) Pin

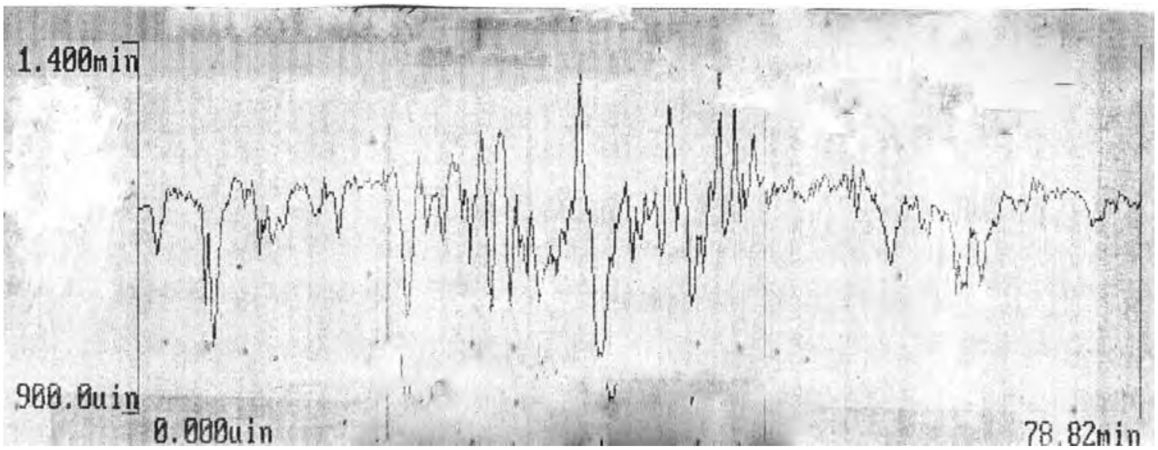


(a)

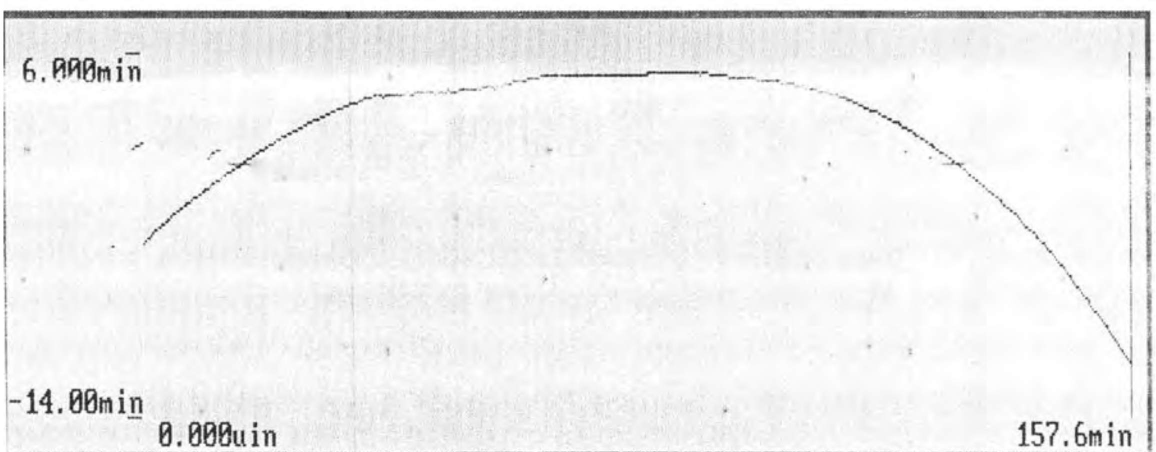


(b)

Figure E5. Contact Profilometry Data for Test #9 (a) Disk and (b) Pin

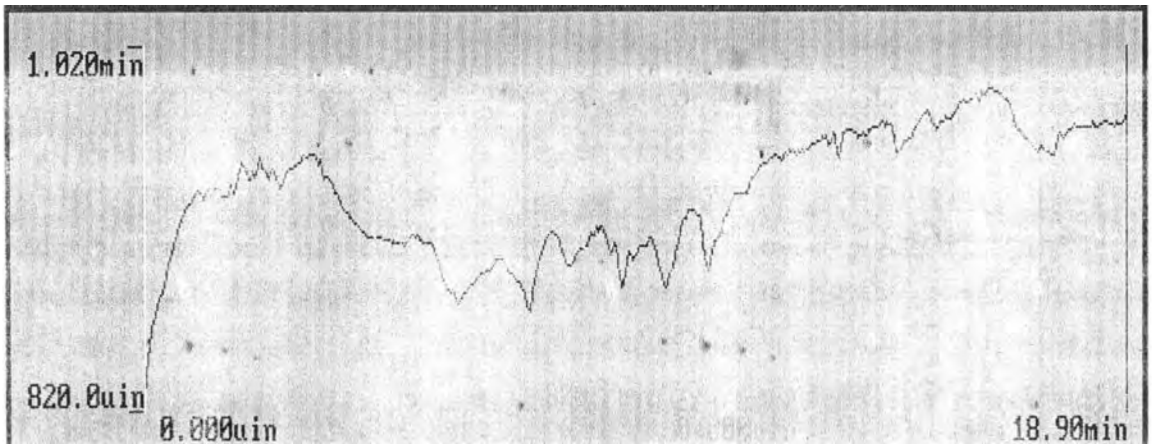


(a)

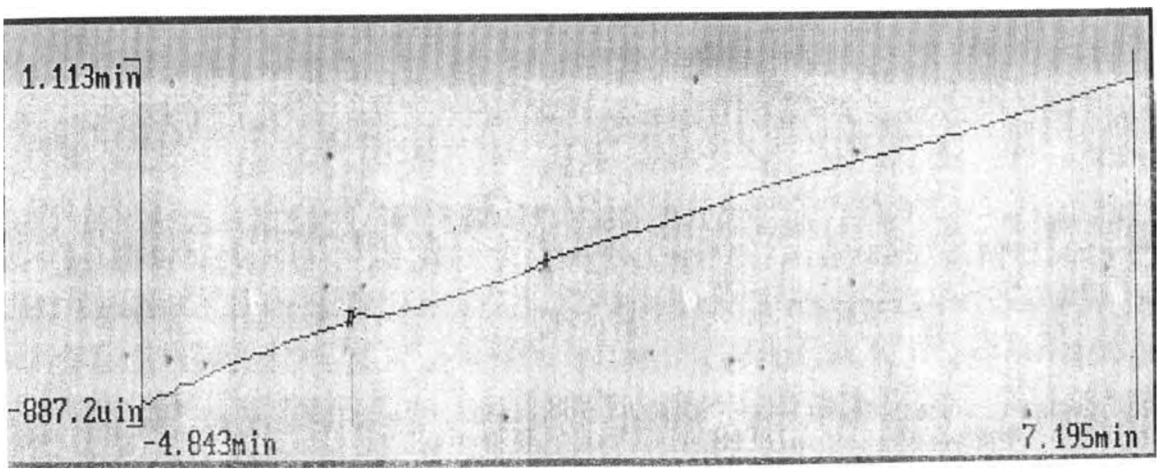


(b)

Figure E6. Contact Profilometry Data for Test #10 (a) Disk and (b) Pin

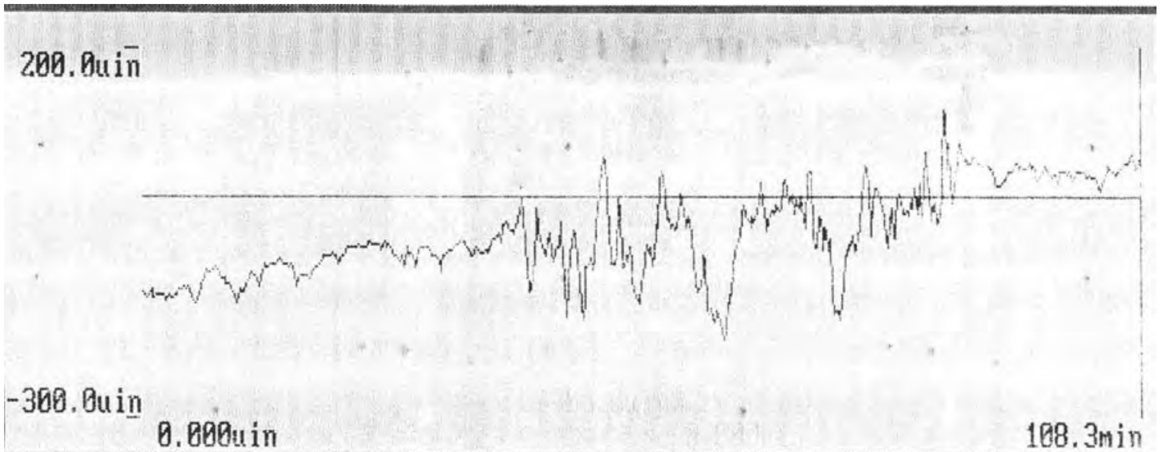


(a)

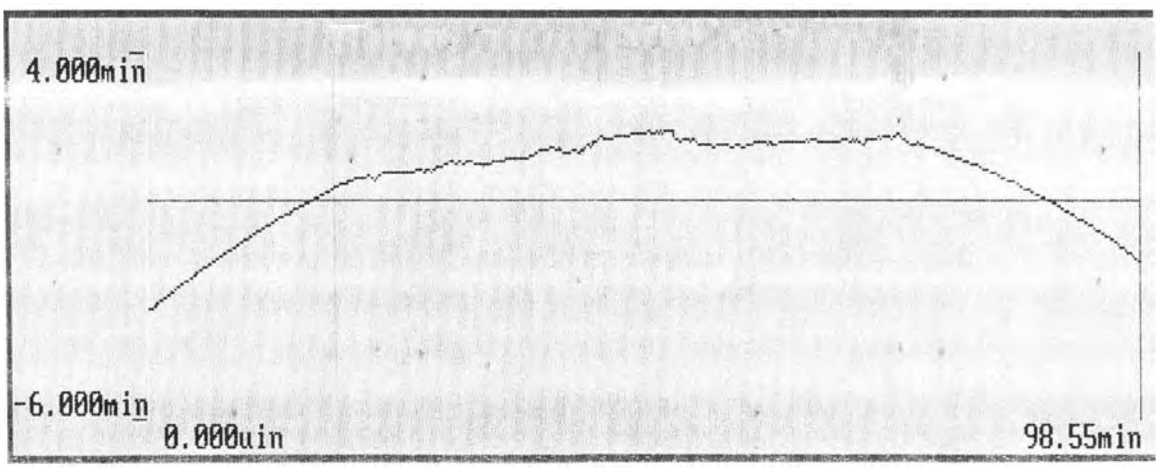


(b)

Figure E7. Contact Profilometry Data for Test #11 (a) Disk and (b) Pin

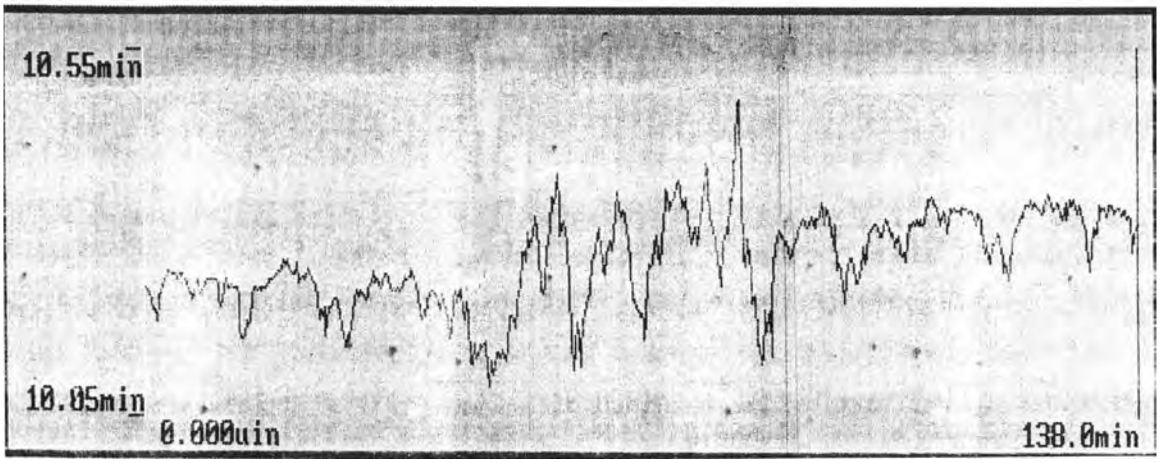


(a)

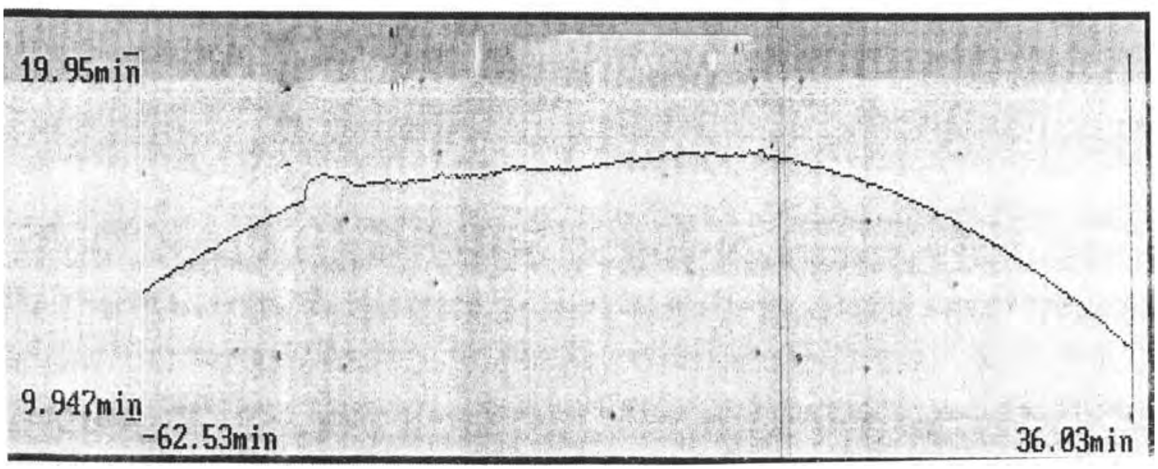


(b)

Figure E8. Contact Profilometry Data for Test #12 (a) Disk and (b) Pin

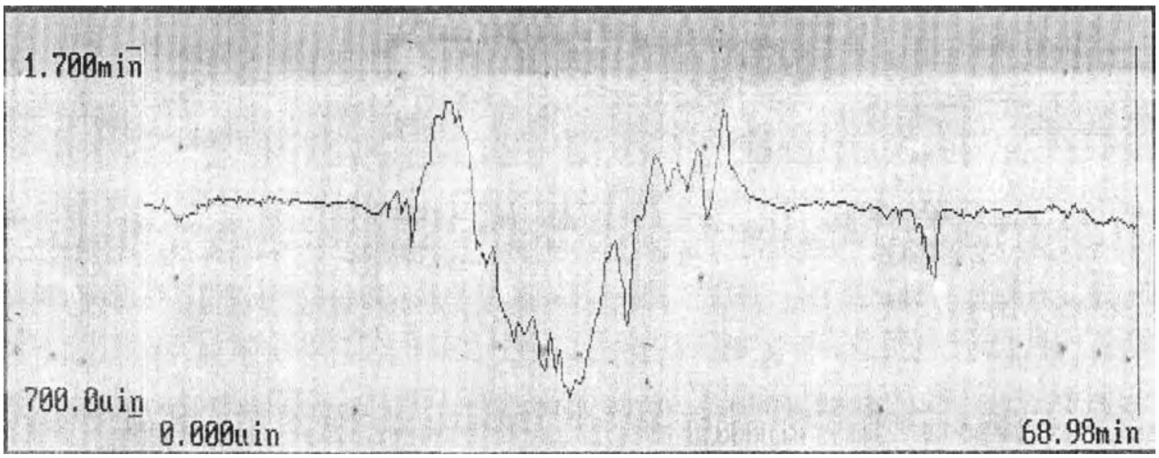


(a)

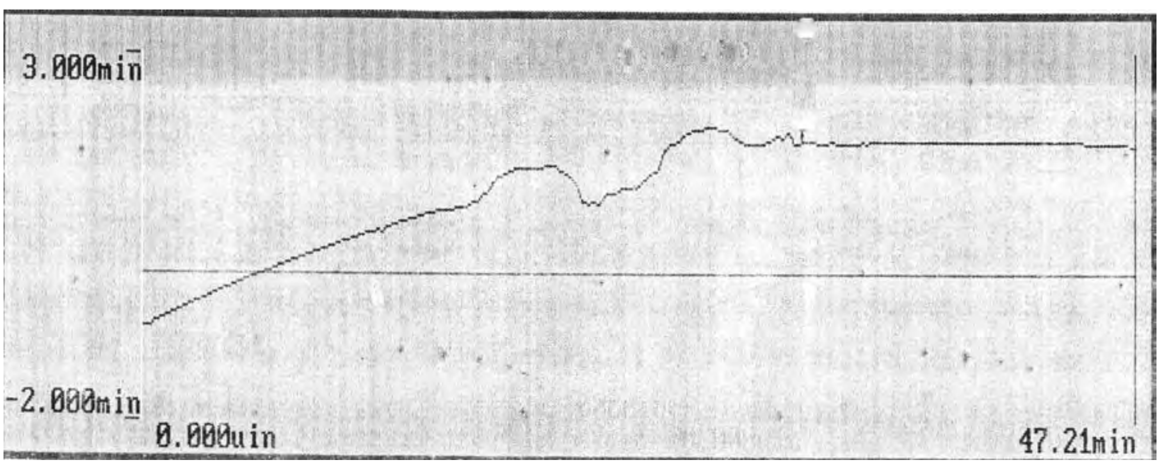


(b)

Figure E9. Contact Profilometry Data for Test #13 (a) Disk and (b) Pin

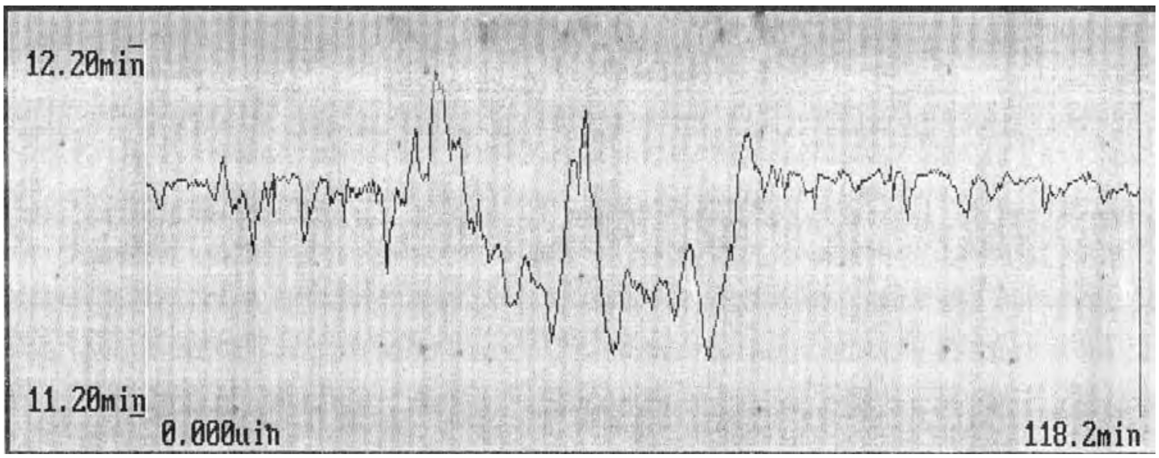


(a)

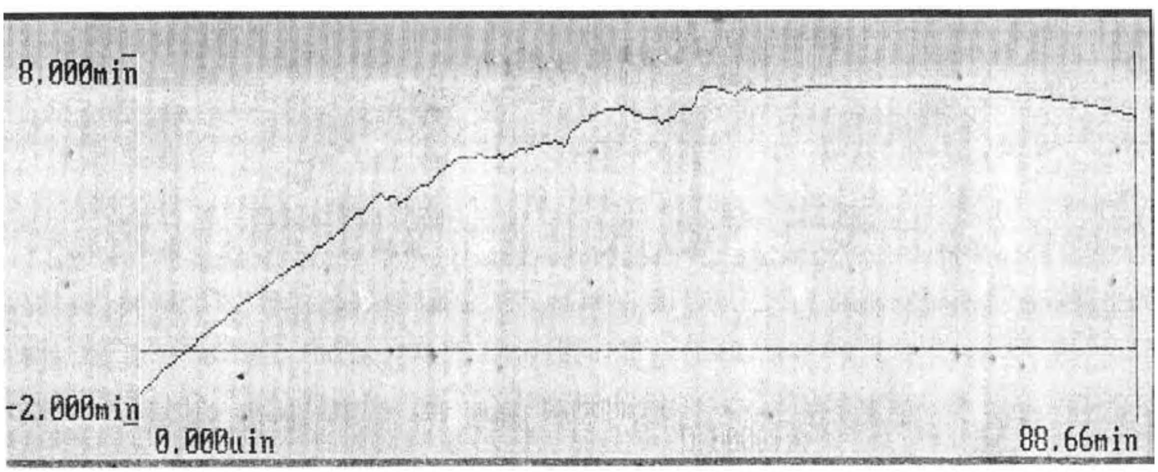


(b)

Figure E10. Contact Profilometry Data for Test #14 (a) Disk and (b) Pin

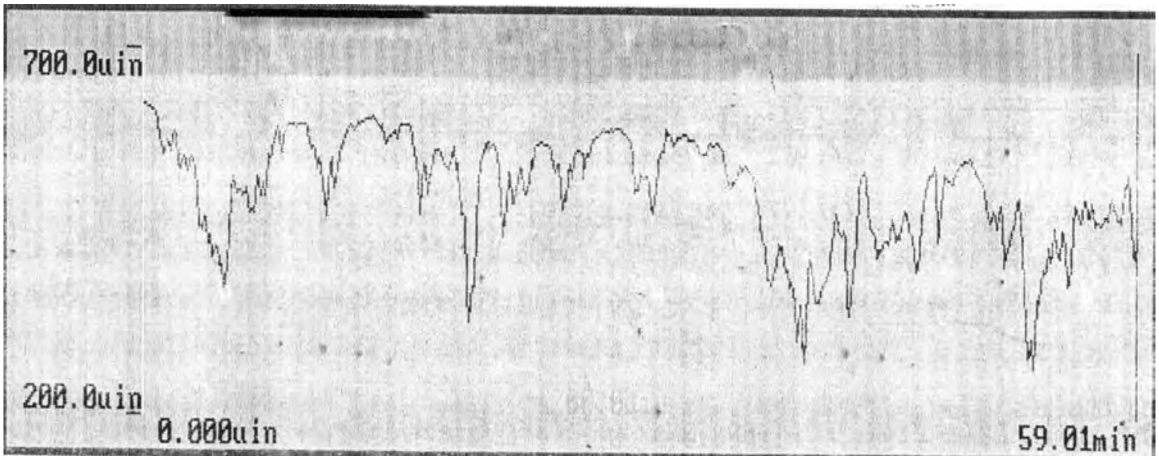


(a)

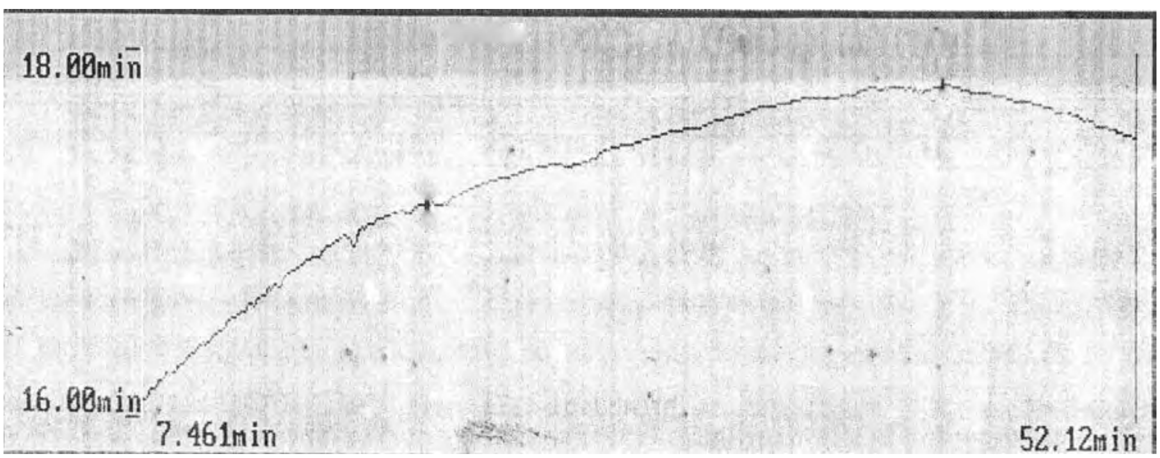


(b)

Figure E11. Contact Profilometry Data for Test #15 (a) Disk and (b) Pin

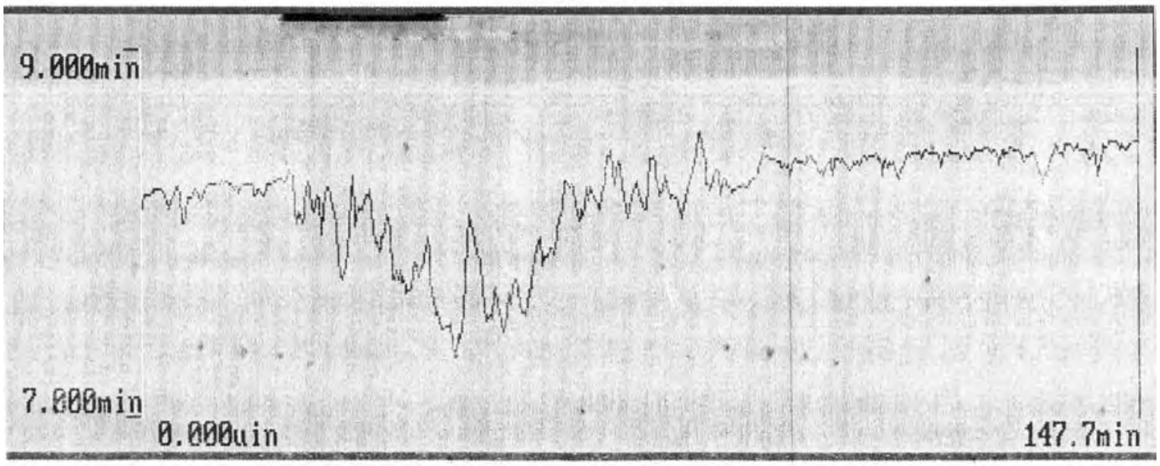


(a)

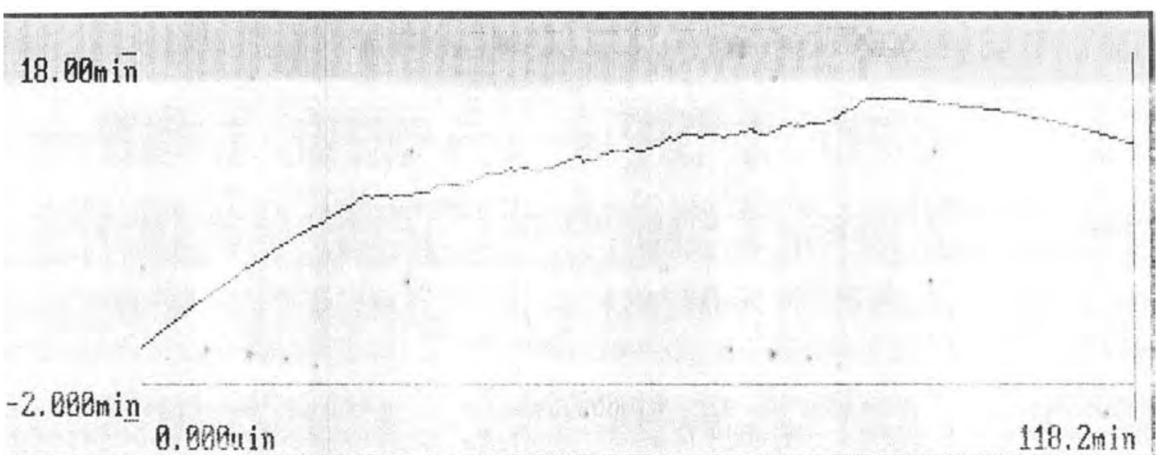


(b)

Figure E12. Contact Profilometry Data for Test #16 (a) Disk and (b) Pin

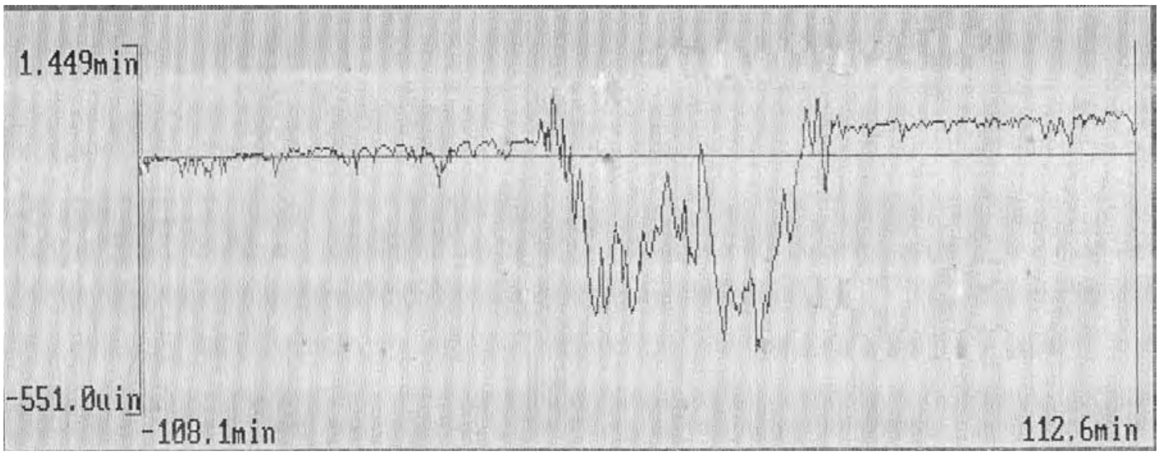


(a)

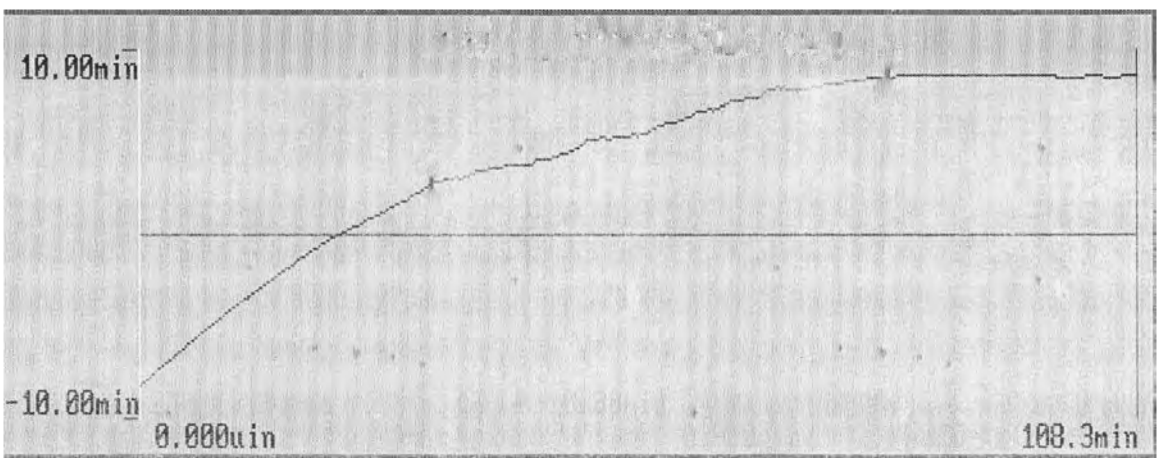


(b)

Figure E13. Contact Profilometry Data for Test #17 (a) Disk and (b) Pin

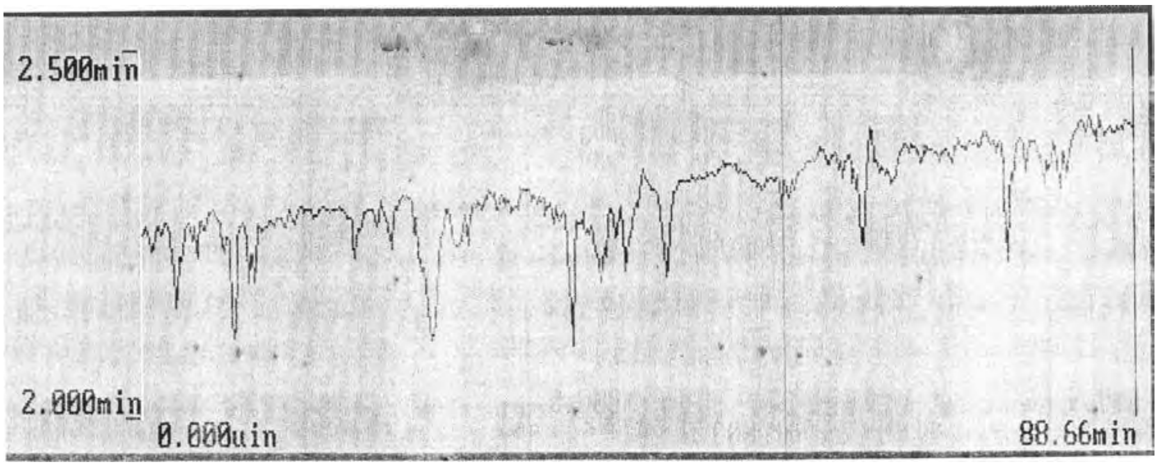


(a)

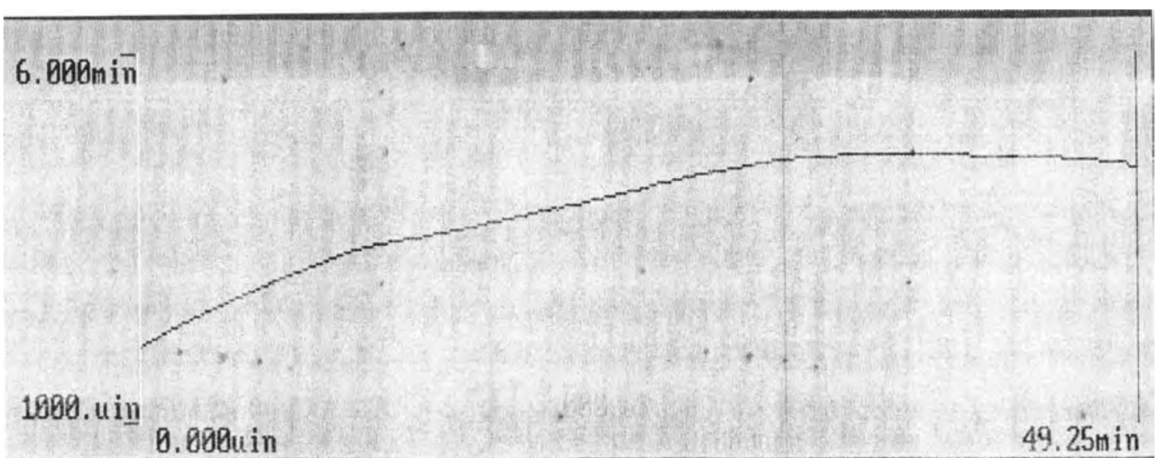


(b)

Figure E14. Contact Profilometry Data for Test #18 (a) Disk and (b) Pin

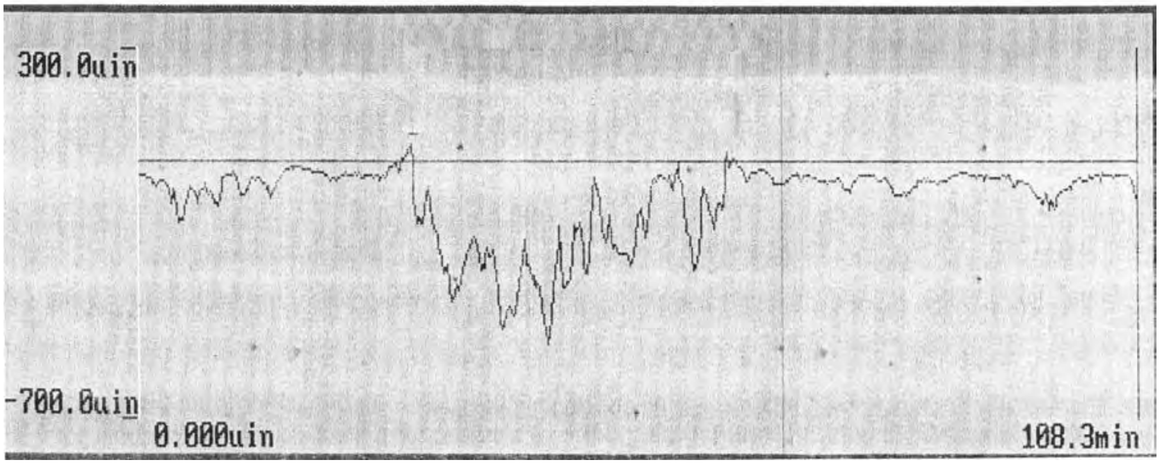


(a)

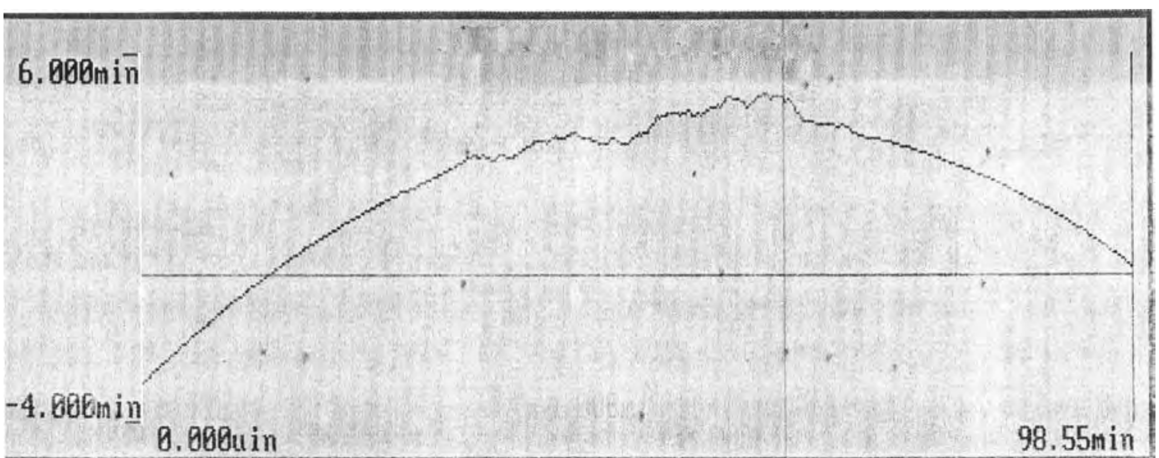


(b)

Figure E15. Contact Profilometry Data for Test #19 (a) Disk and (b) Pin

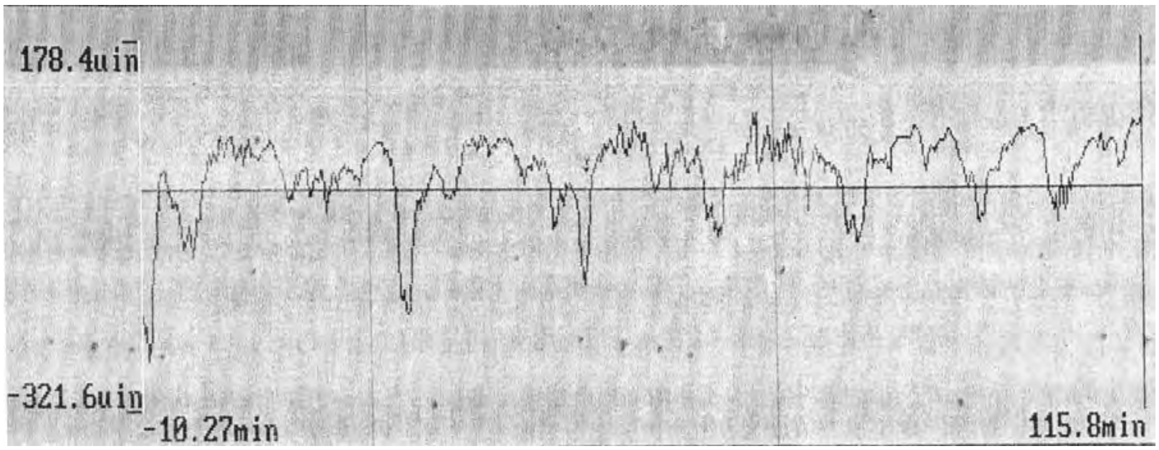


(a)

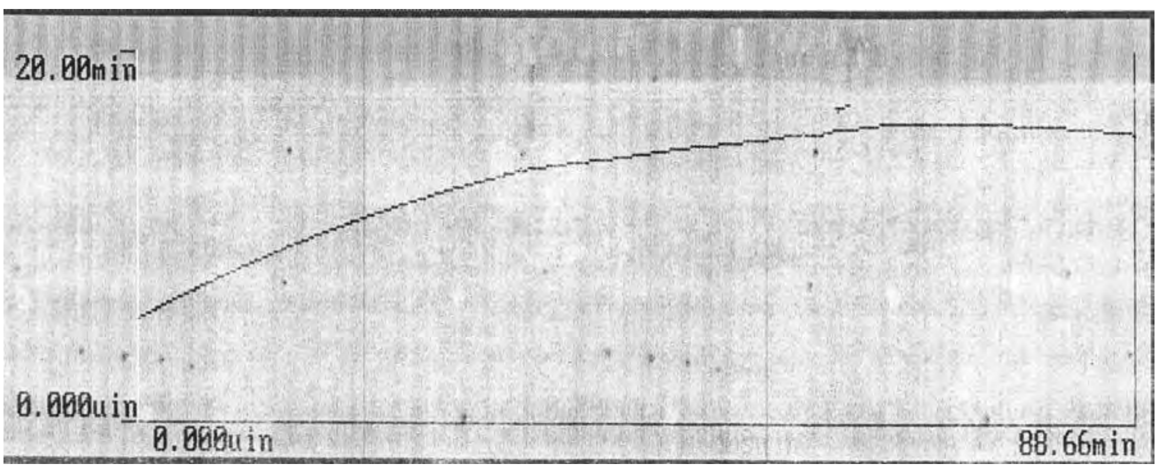


(b)

Figure E16. Contact Profilometry Data for Test #20 (a) Disk and (b) Pin

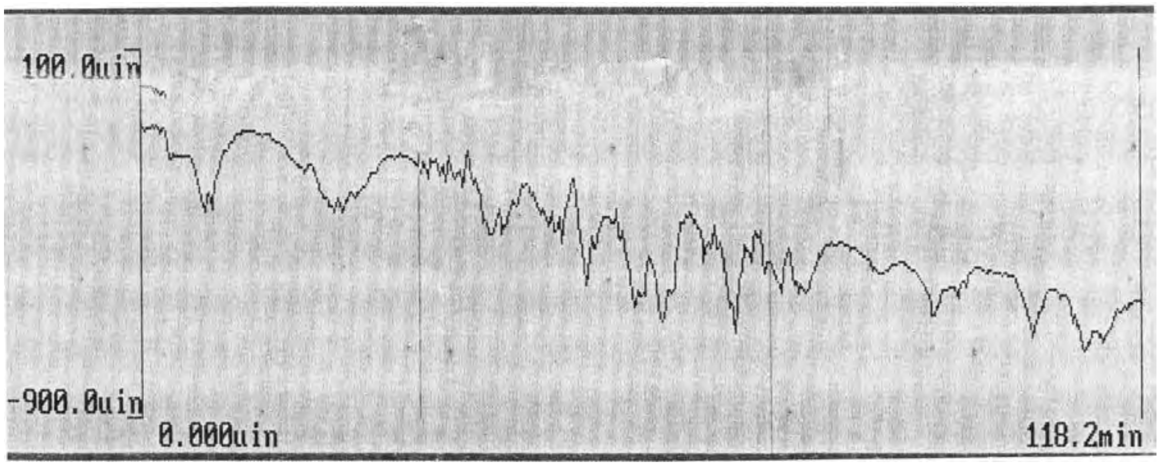


(a)

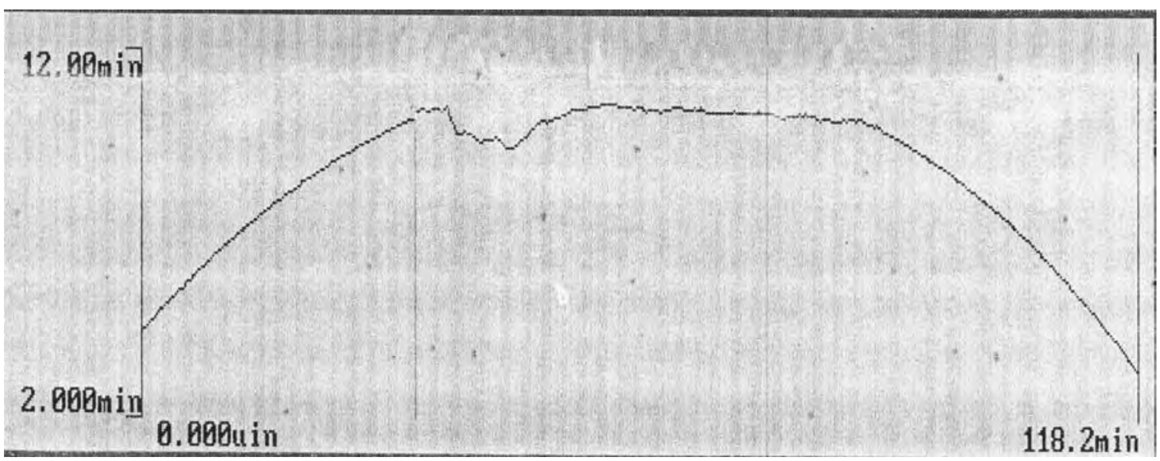


(b)

Figure E17. Contact Profilometry Data for Test #21 (a) Disk and (b) Pin

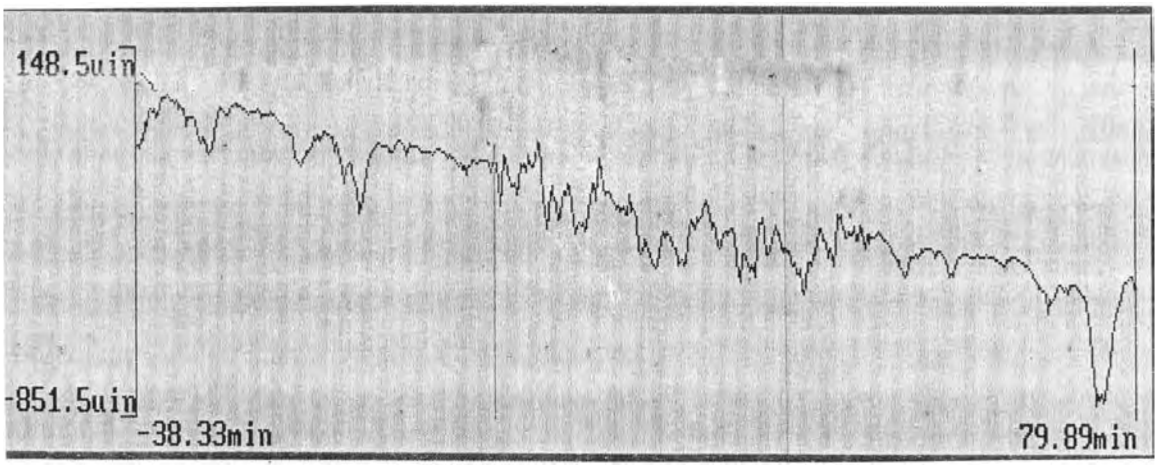


(a)

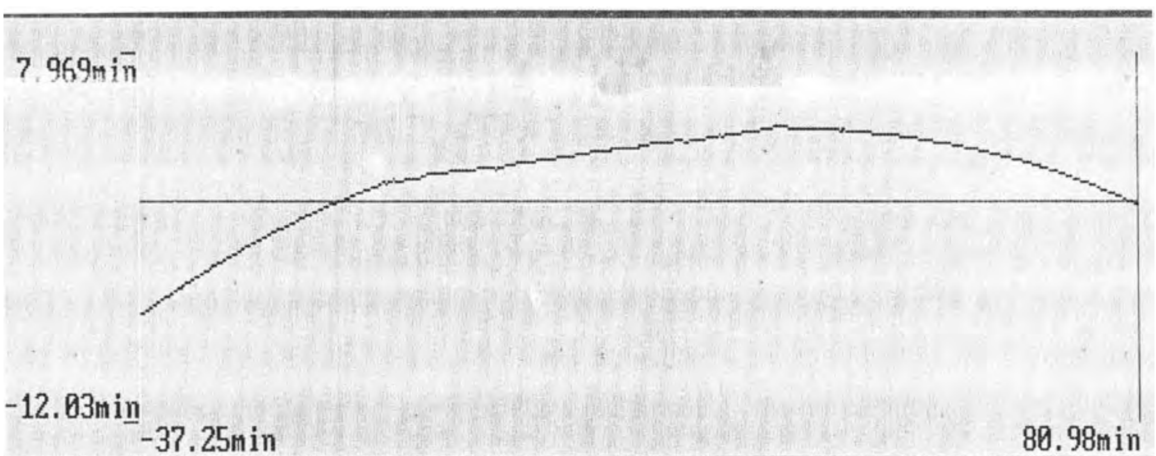


(b)

Figure E18. Contact Profilometry Data for Test #23 (a) Disk and (b) Pin

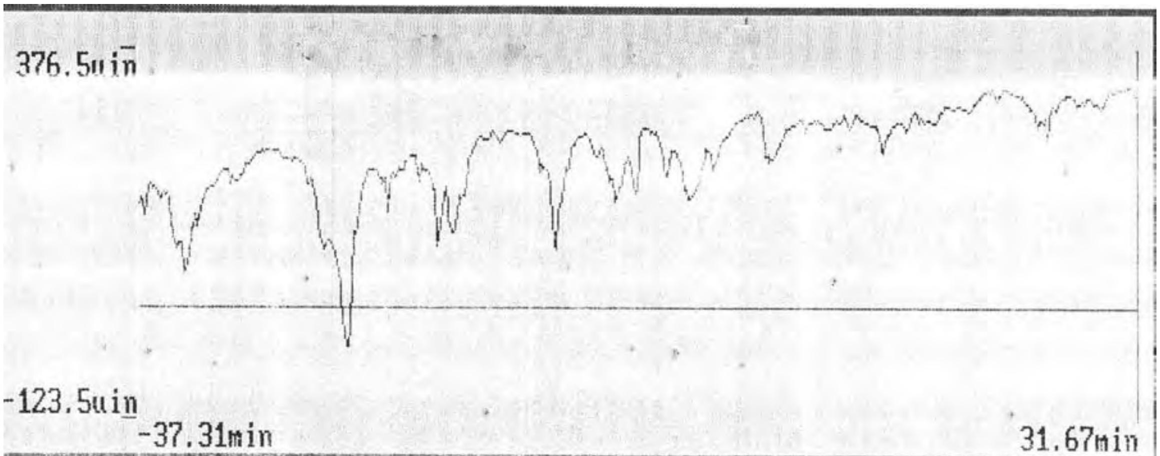


(a)

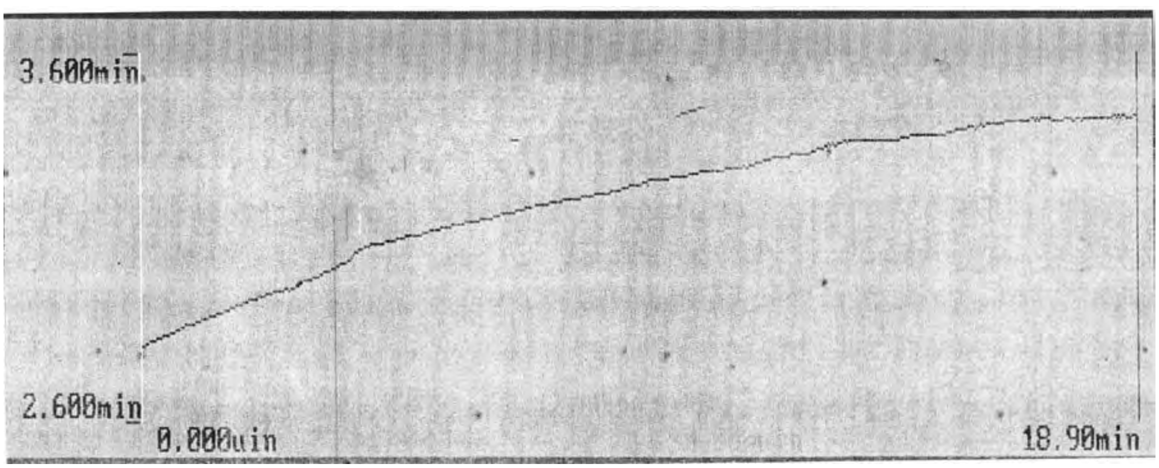


(b)

Figure E19. Contact Profilometry Data for Test #24 (a) Disk and (b) Pin

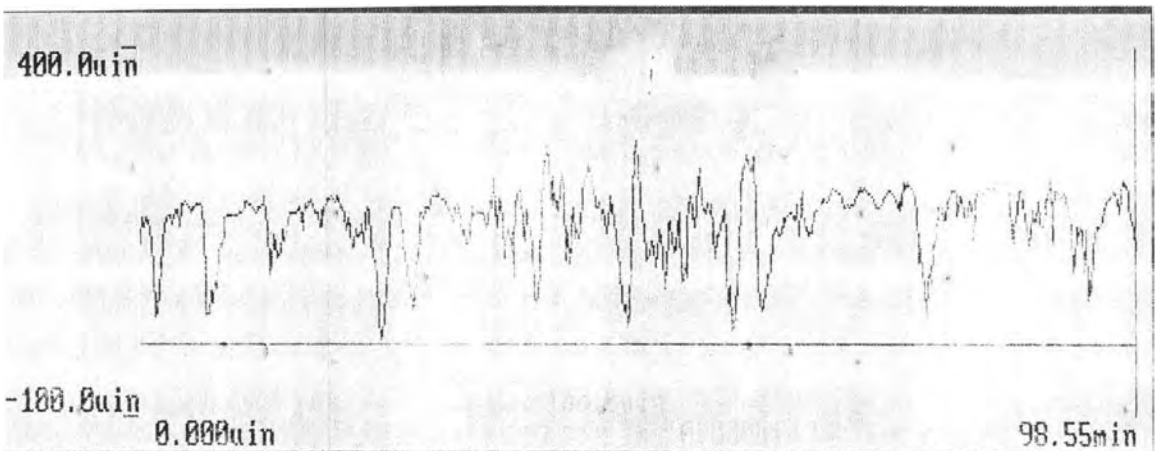


(a)

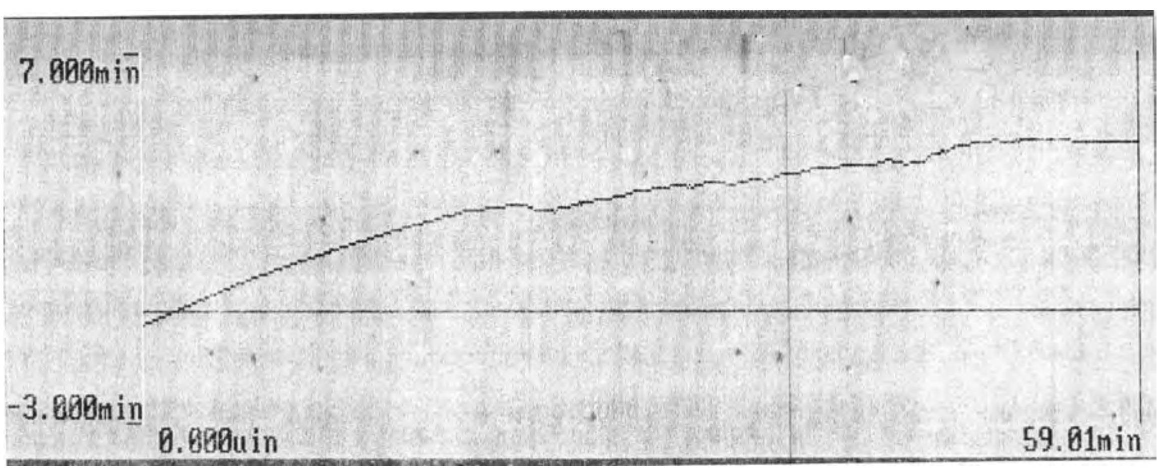


(b)

Figure E20. Contact Profilometry Data for Test #26 (a) Disk and (b) Pin

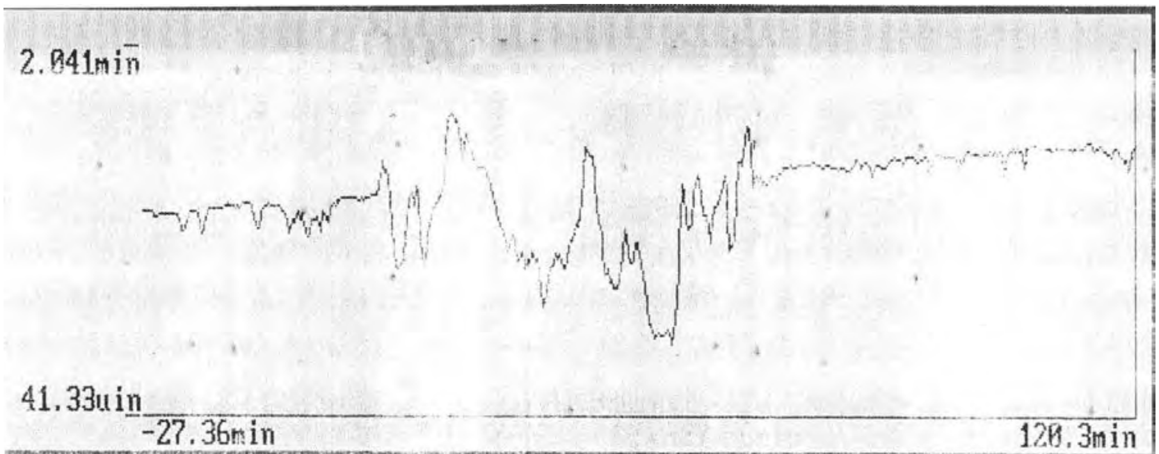


(a)

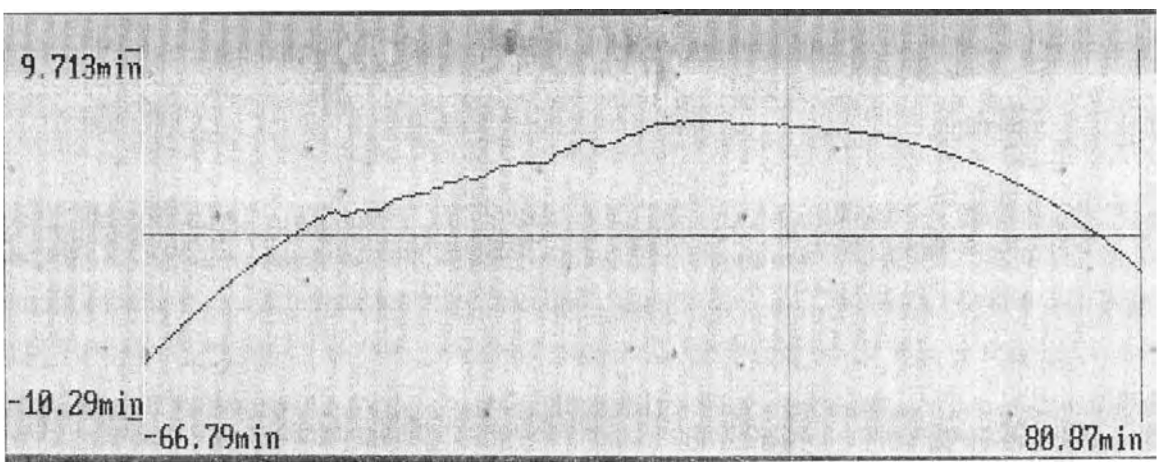


(b)

Figure E21. Contact Profilometry Data for Test #28 (a) Disk and (b) Pin



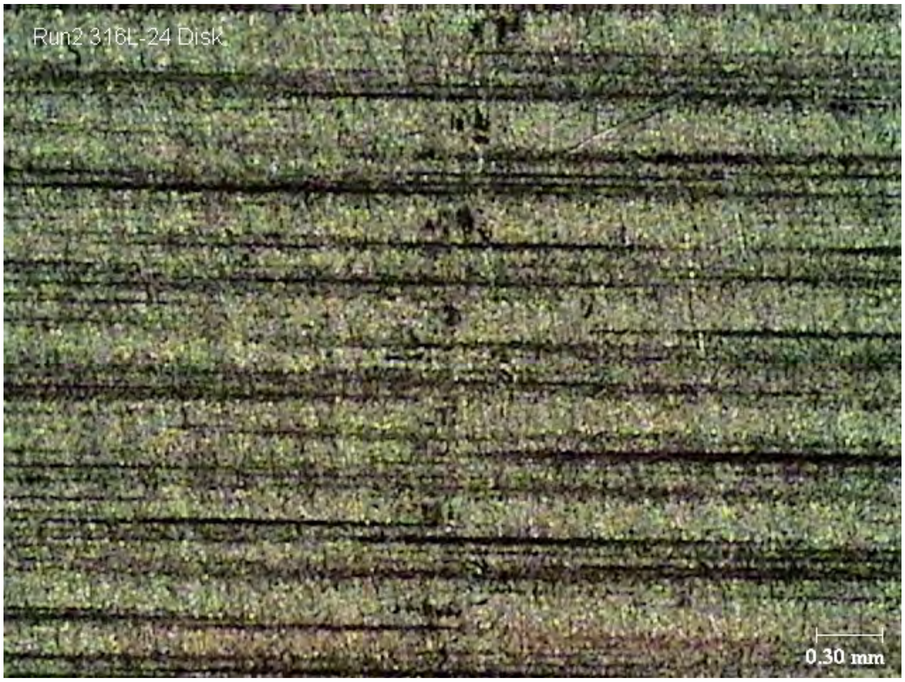
(a)



(b)

Figure E22. Contact Profilometry Data for Test #29 (a) Disk and (b) Pin

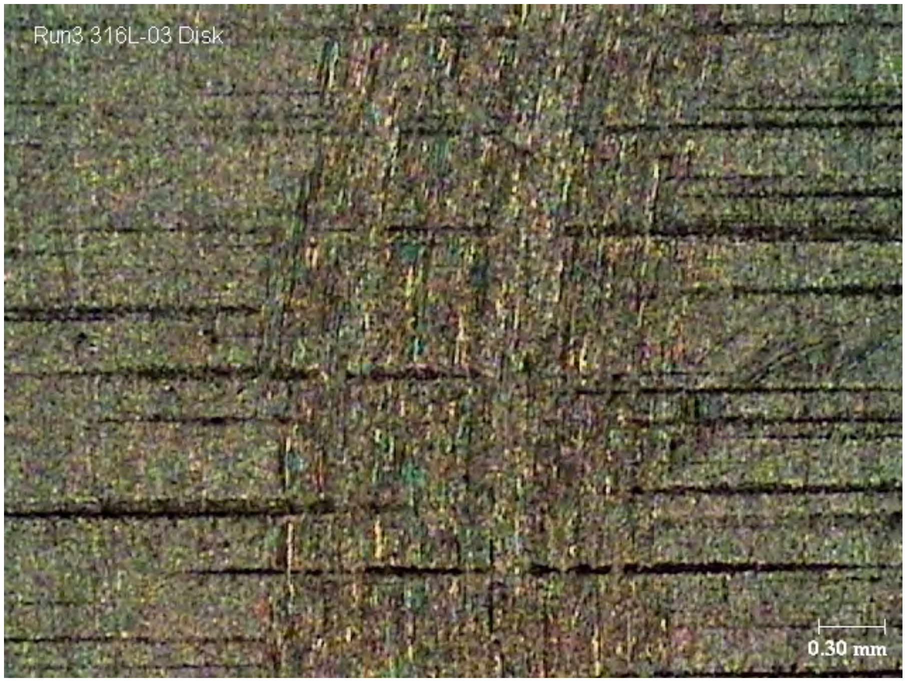
Appendix F: Macrophotographs of Sample Wear Areas



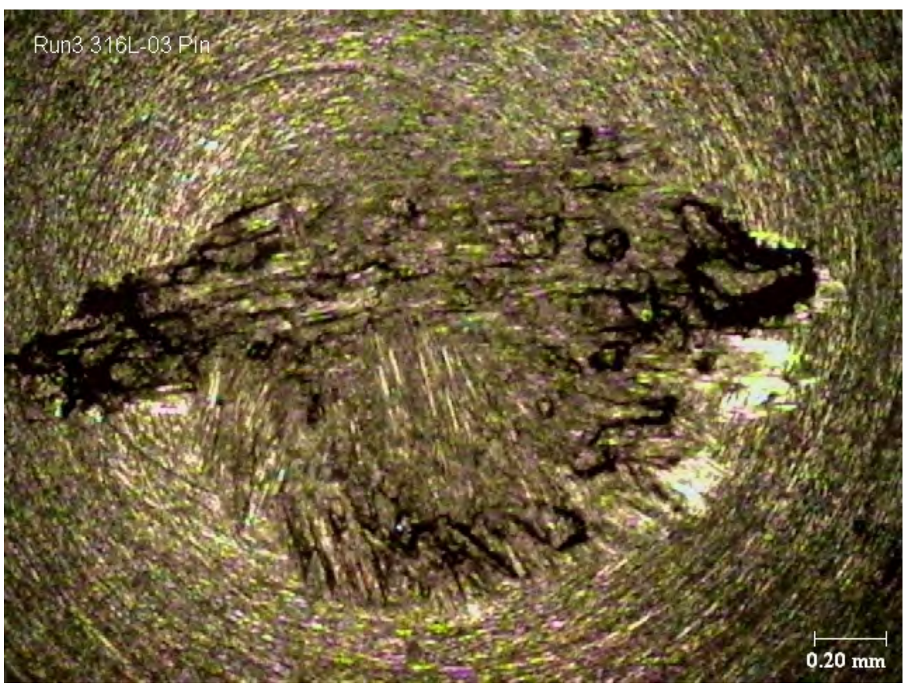
(a)

(b)

Figure F1. Macrophotographs of Test #2 wear areas (a) disk and (b) pin

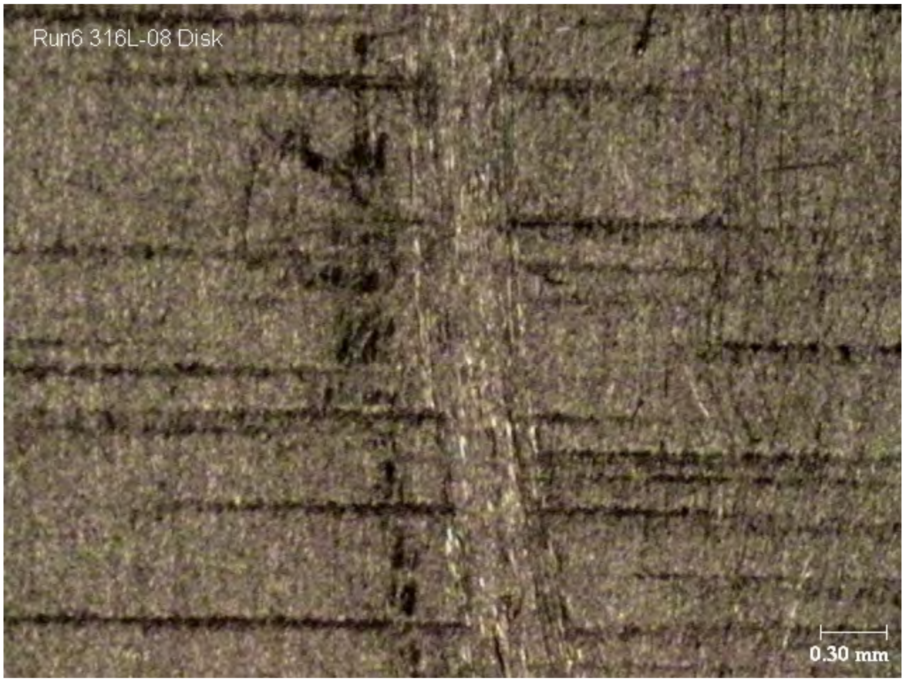


(a)

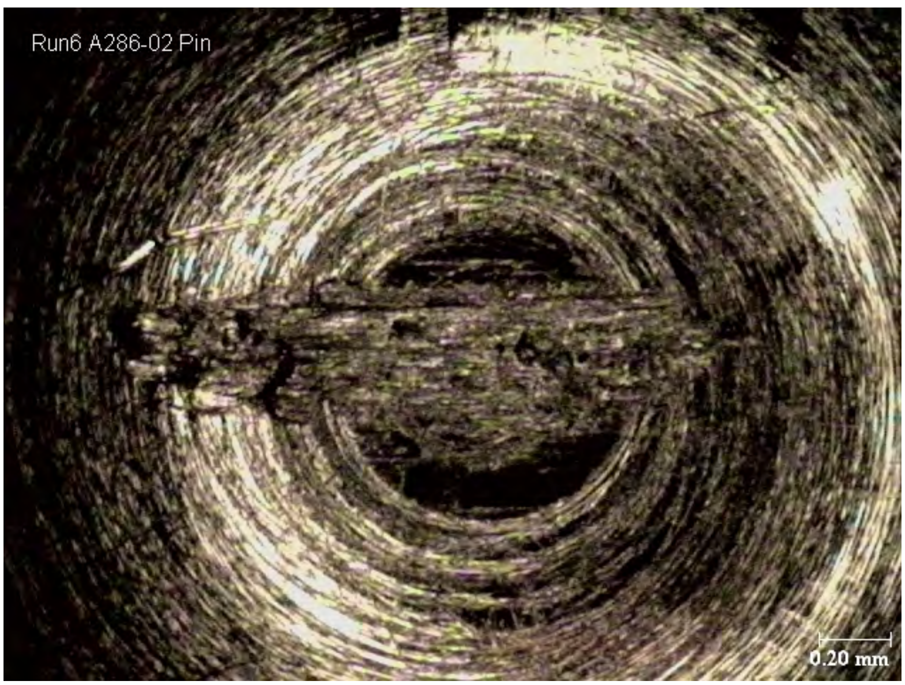


(b)

Figure F2. Macrophotographs of Test #3 wear areas (a) disk and (b) pin

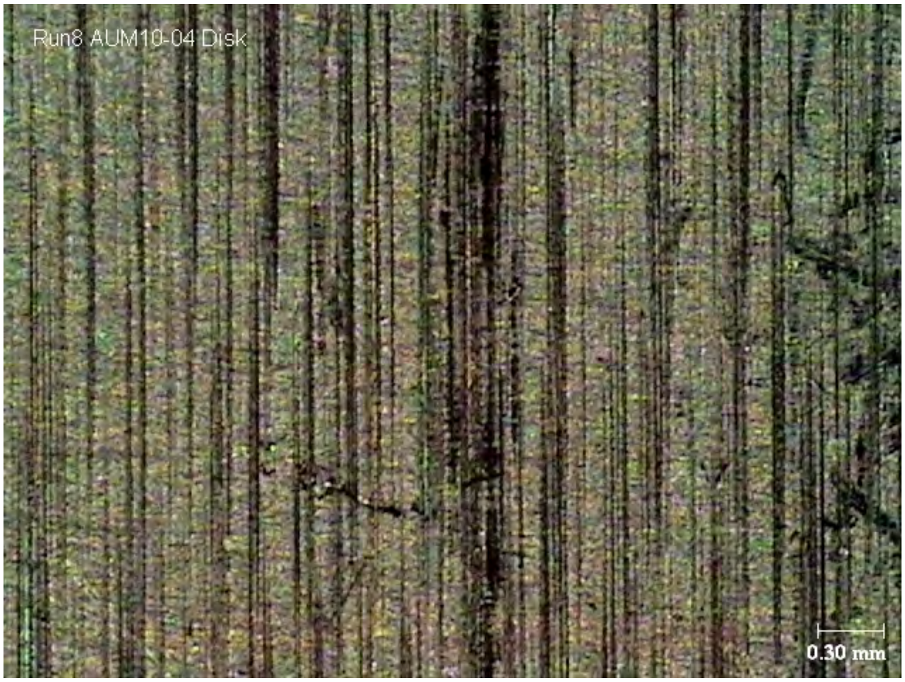


(a)

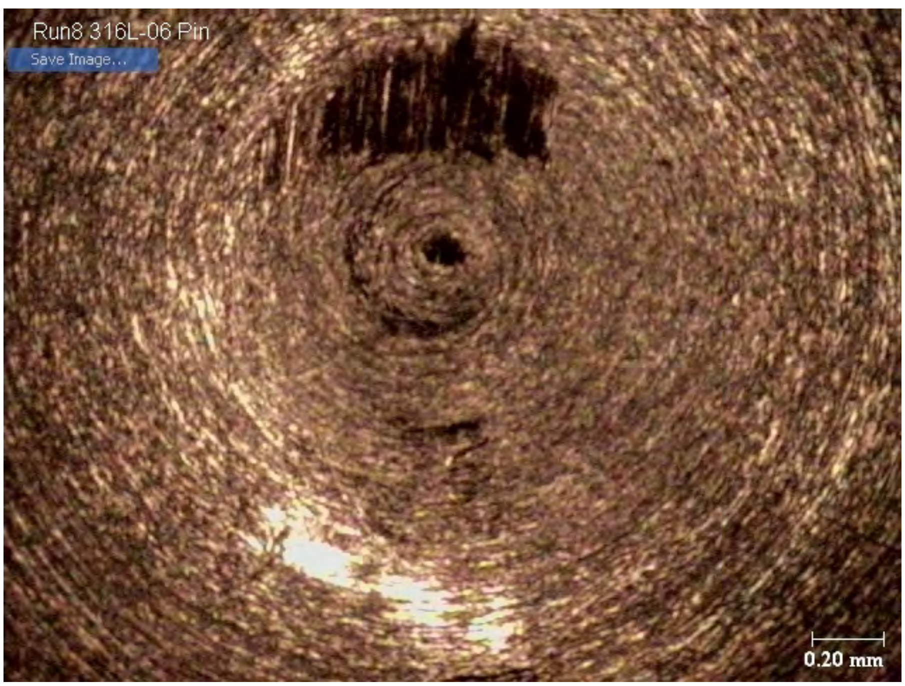


(b)

Figure F3. Macrophotographs of Test #6 wear areas (a) disk and (b) pin

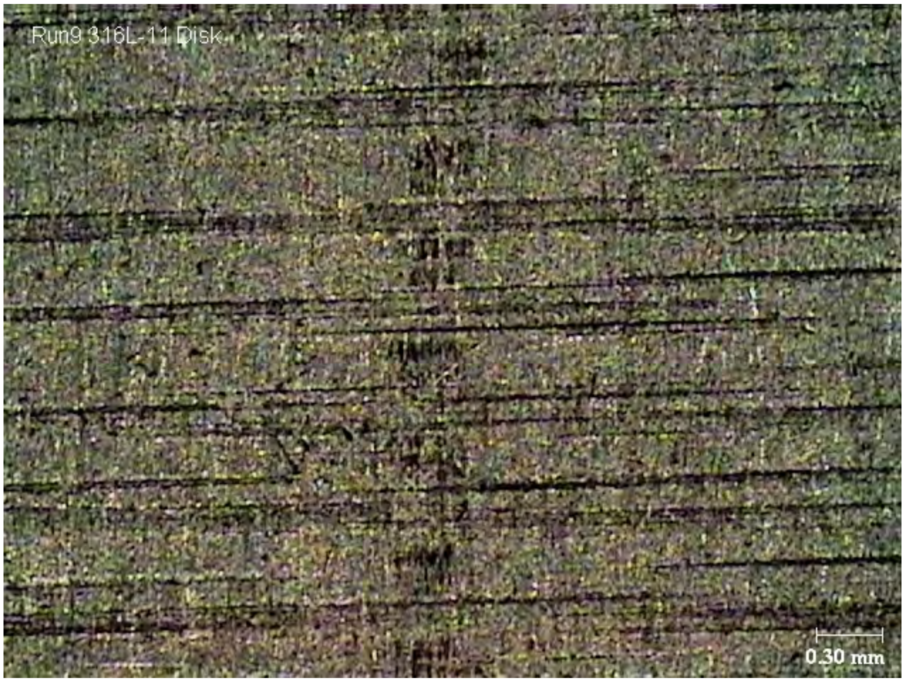


(a)

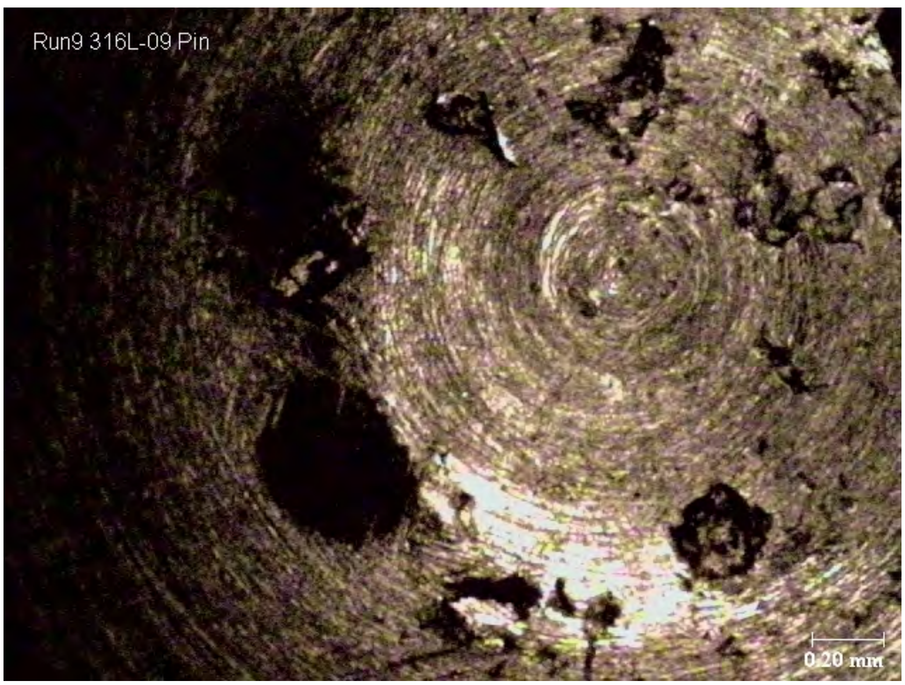


(b)

Figure F4. Macrophotographs of Test #8 wear areas (a) disk and (b) pin



(a)



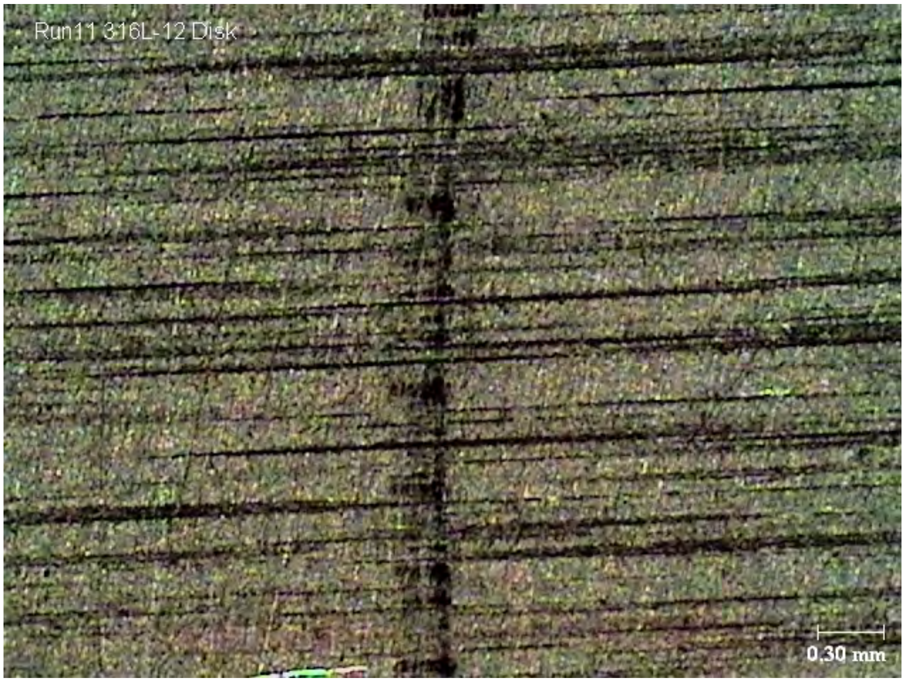
(b)

Figure F5. Macrophotographs of Test #9 wear areas (a) disk and (b) pin

(a)

(b)

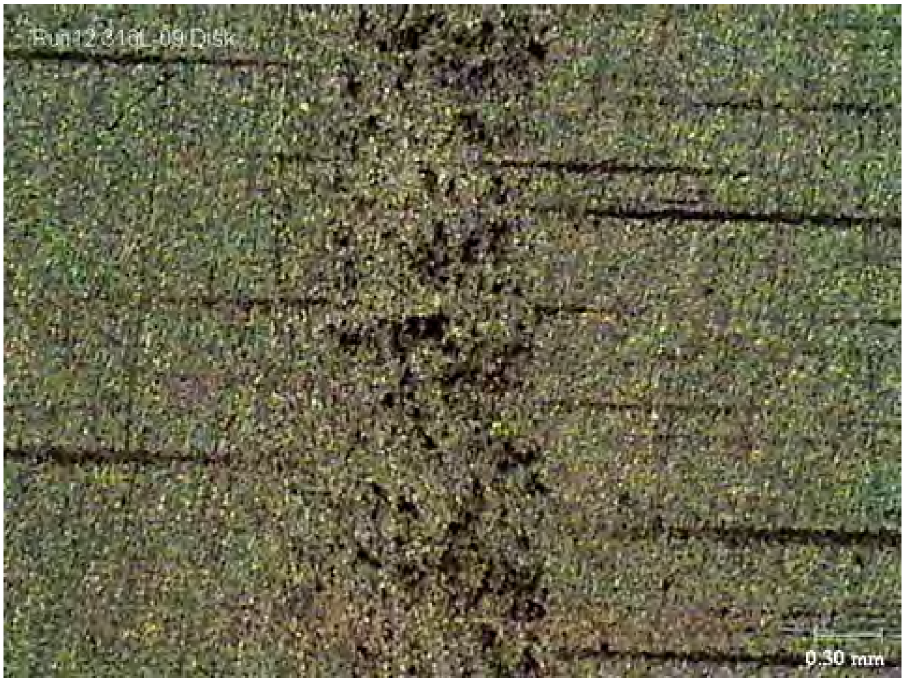
Figure F6. Macrophotographs of Test #10 wear areas (a) disk and (b) pin



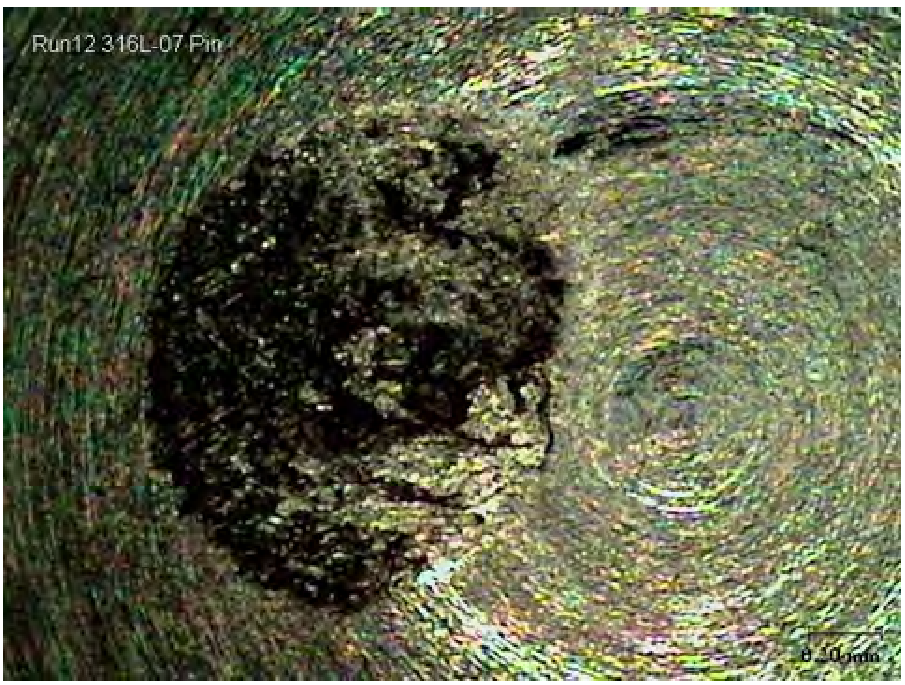
(a)

(b)

Figure F7. Macrophotographs of Test #11 wear areas (a) disk and (b) pin

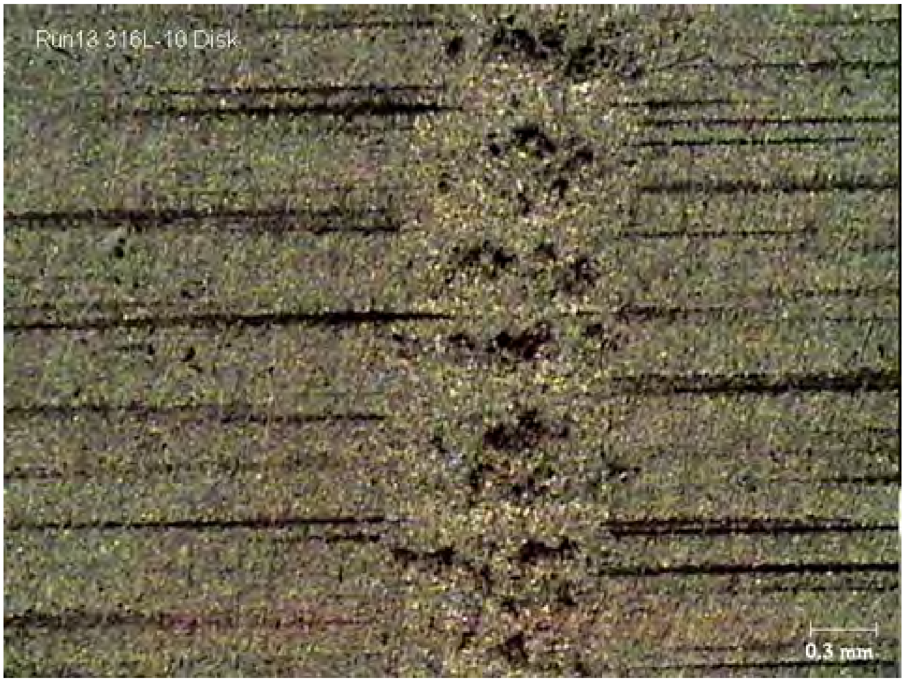


(a)

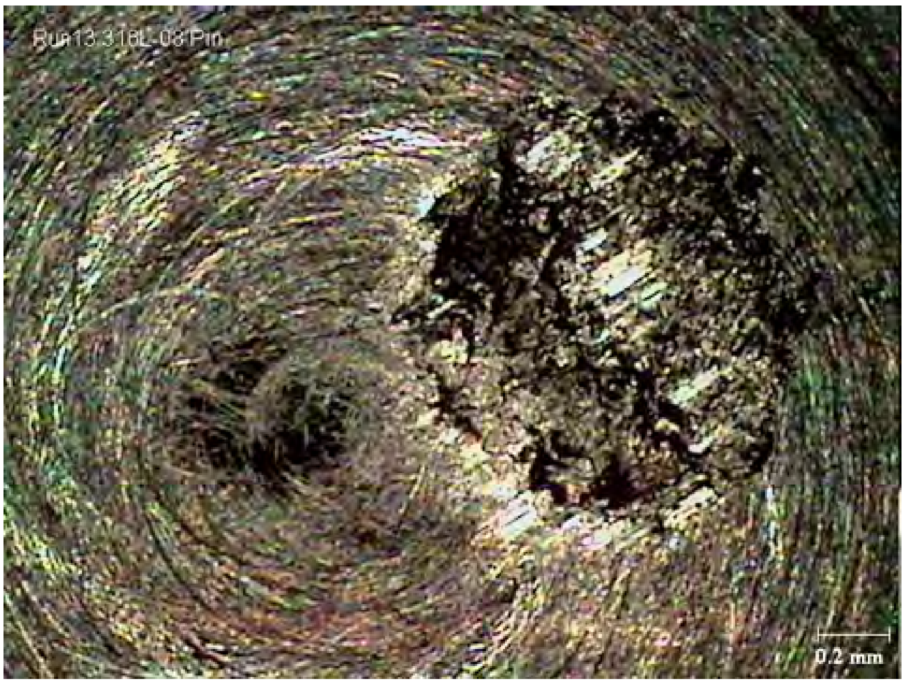


(b)

Figure F8. Macrophotographs of Test #12 wear areas (a) disk and (b) pin

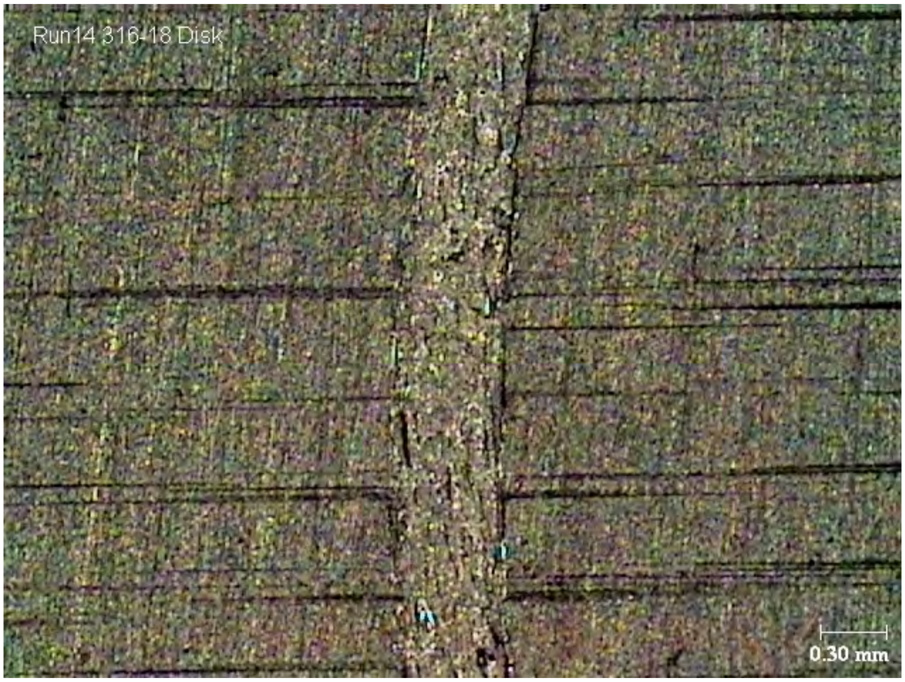


(a)

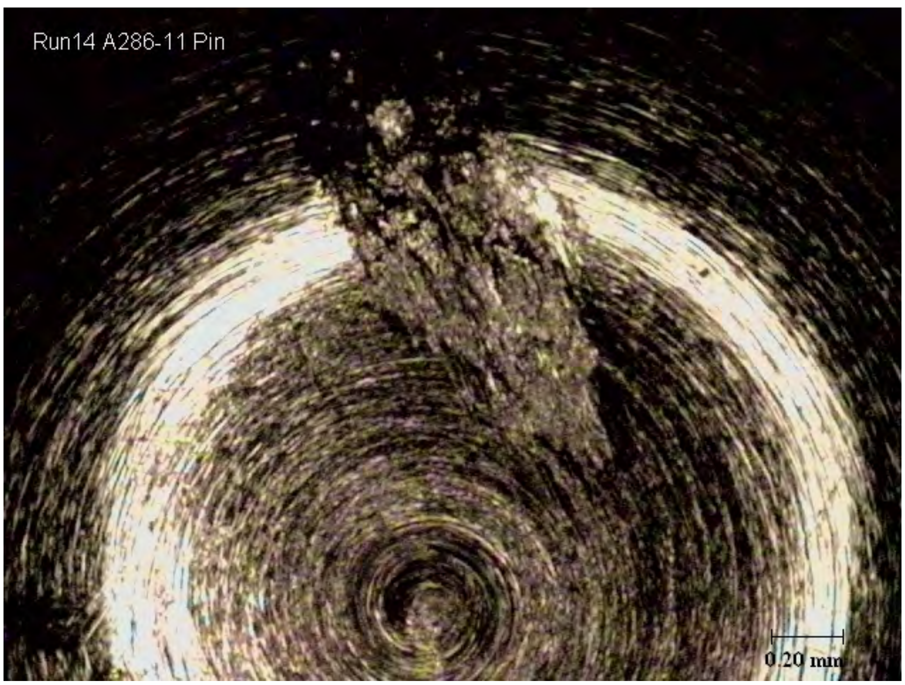


(b)

Figure F9. Macrophotographs of Test #13 wear areas (a) disk and (b) pin

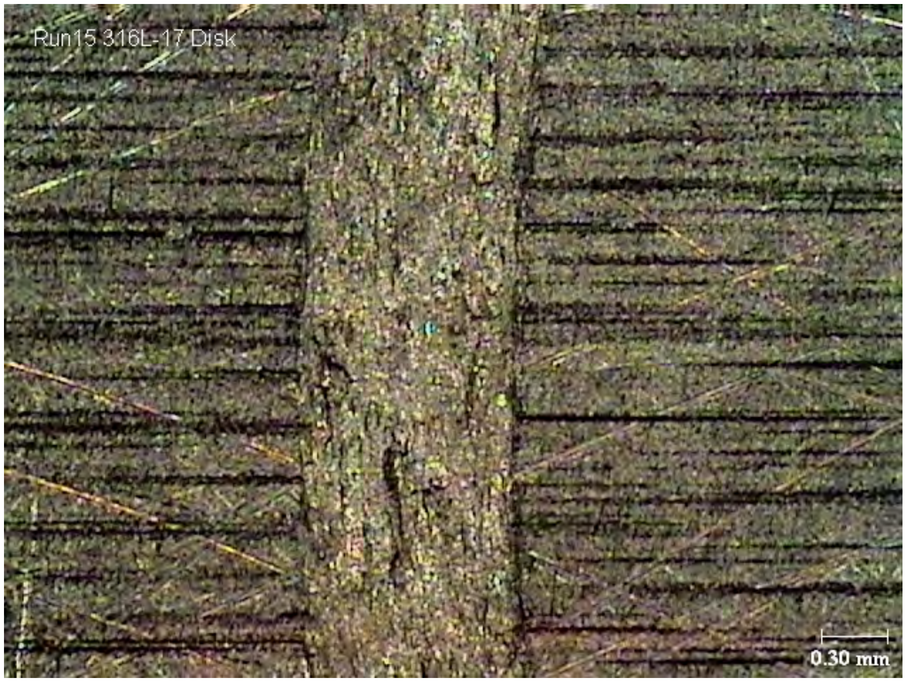


(a)

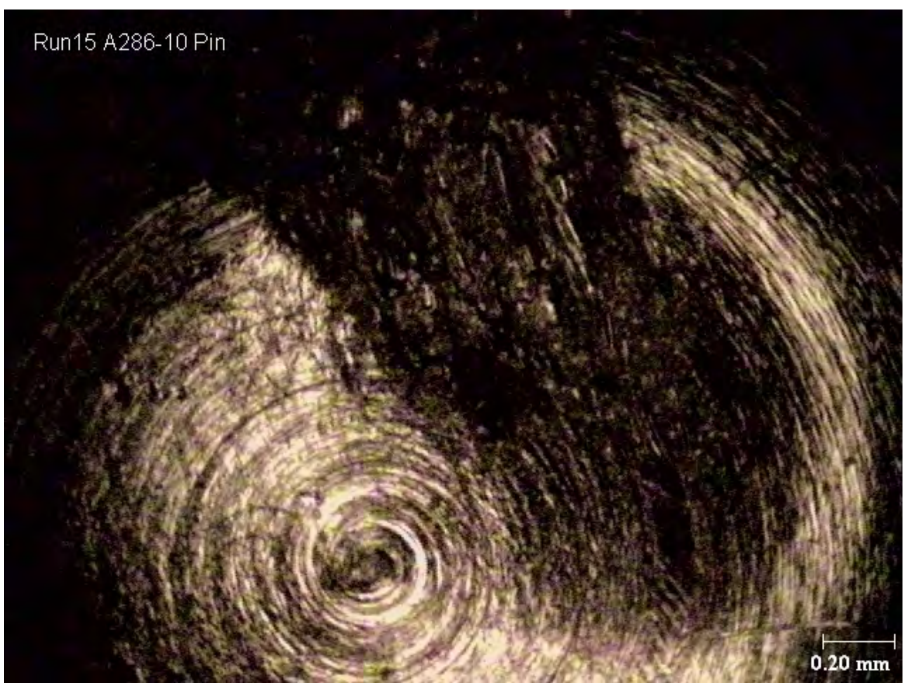


(b)

Figure F10. Macrophotographs of Test #14 wear areas (a) disk and (b) pin

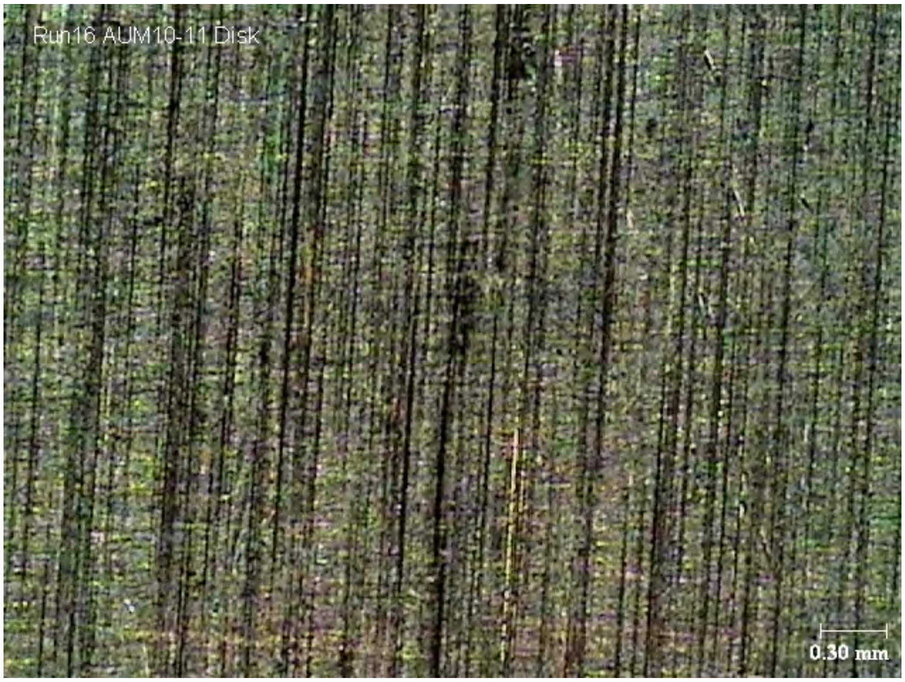


(a)

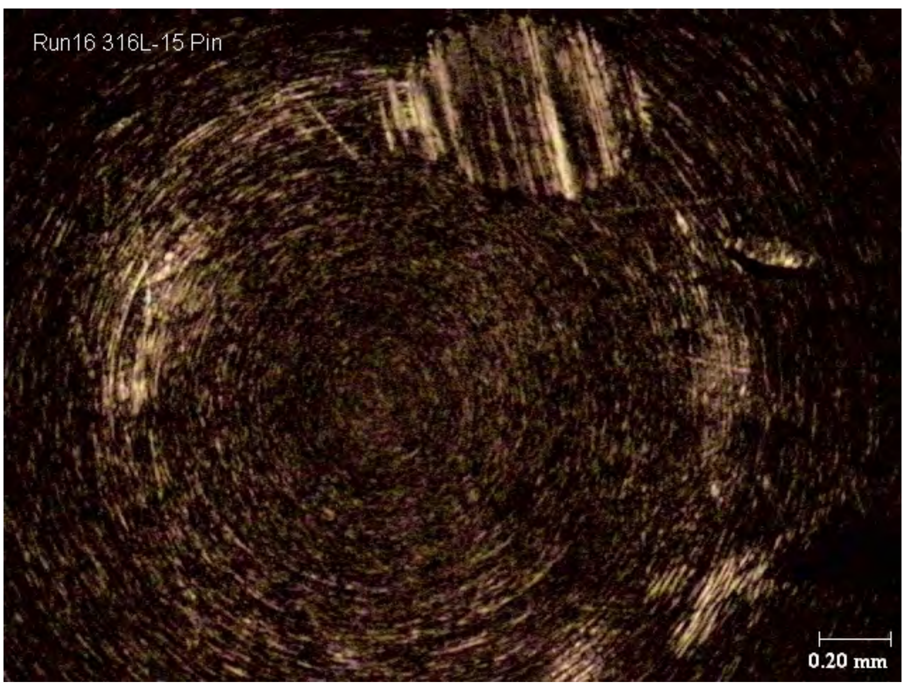


(b)

Figure F11. Macrophotographs of Test #15 wear areas (a) disk and (b) pin

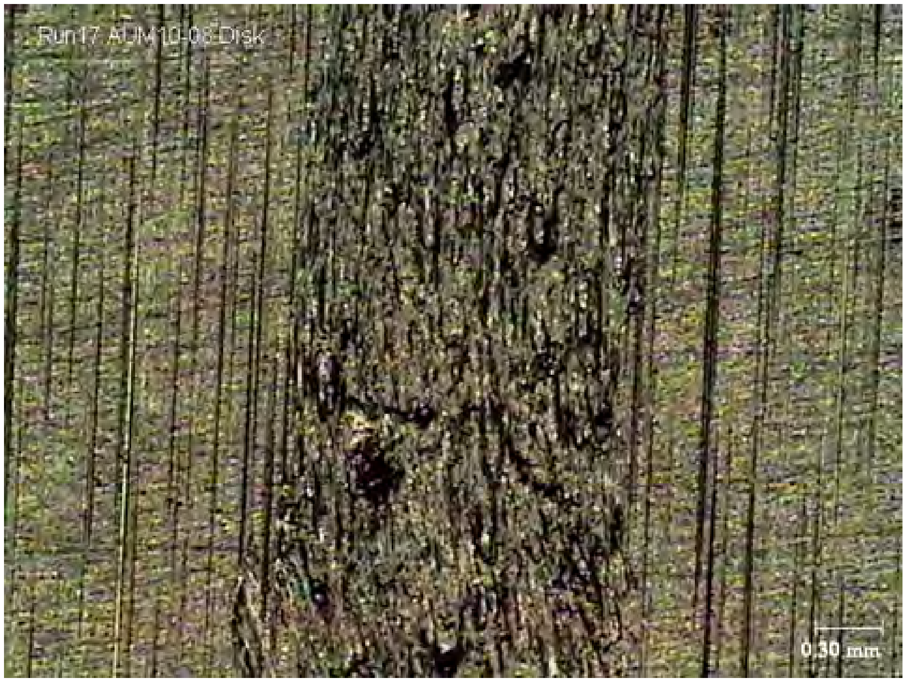


(a)

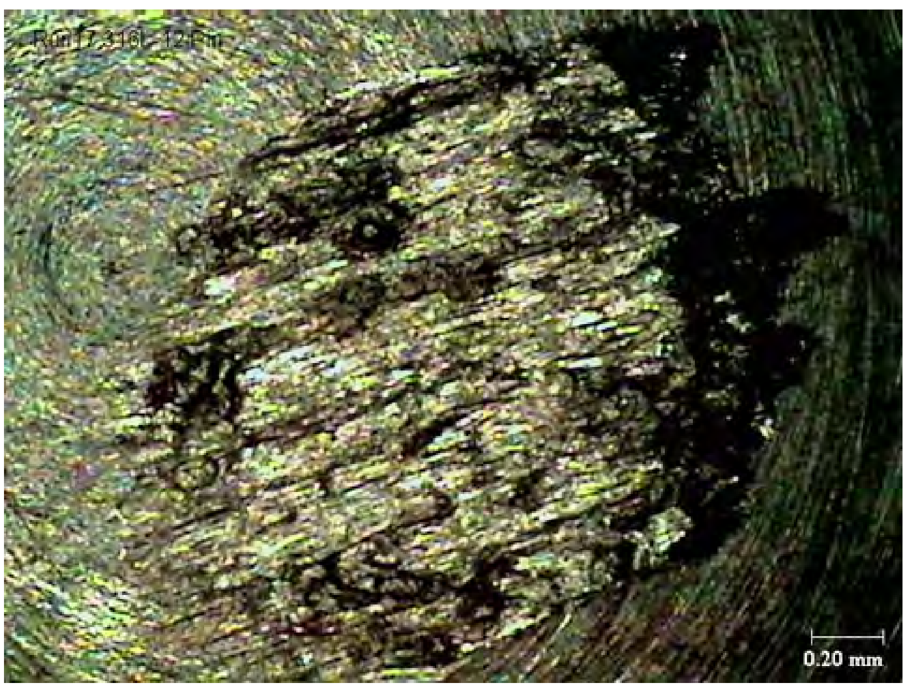


(b)

Figure F12. Macrophotographs of Test #16 wear areas (a) disk and (b) pin

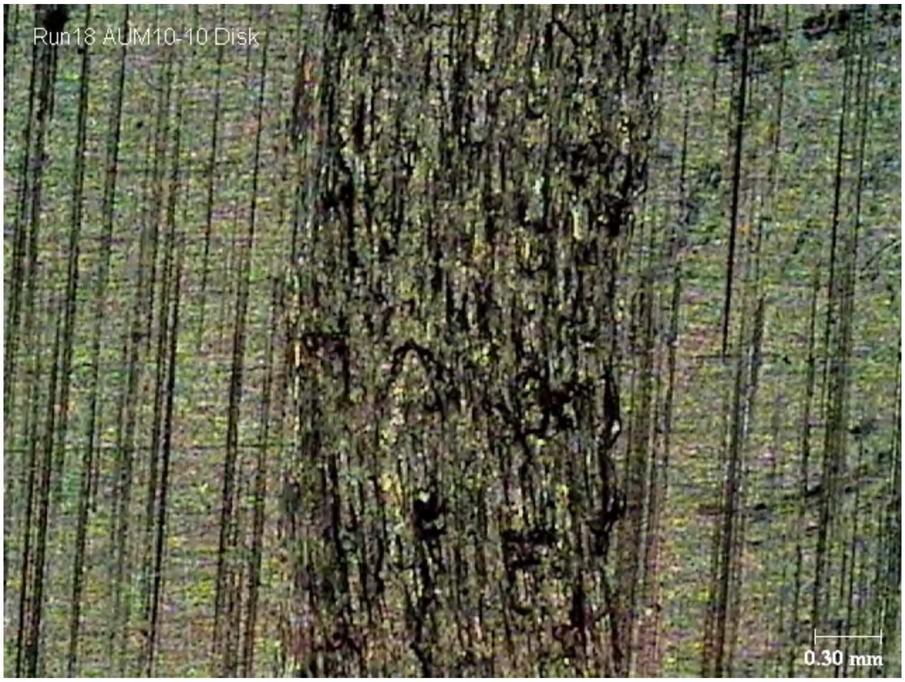


(a)

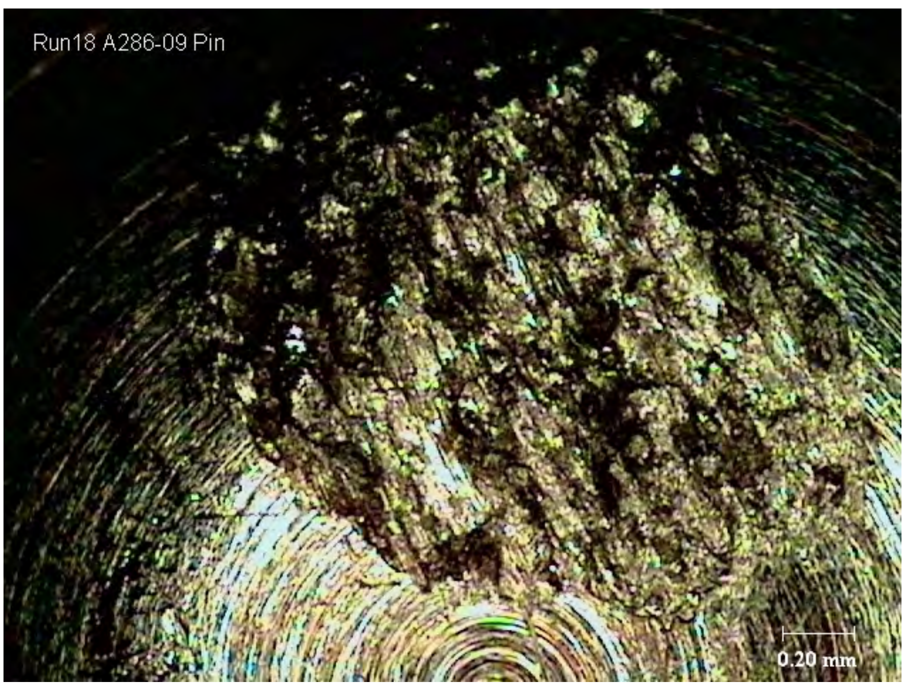


(b)

Figure F13. Macrophotographs of Test #17 wear areas (a) disk and (b) pin



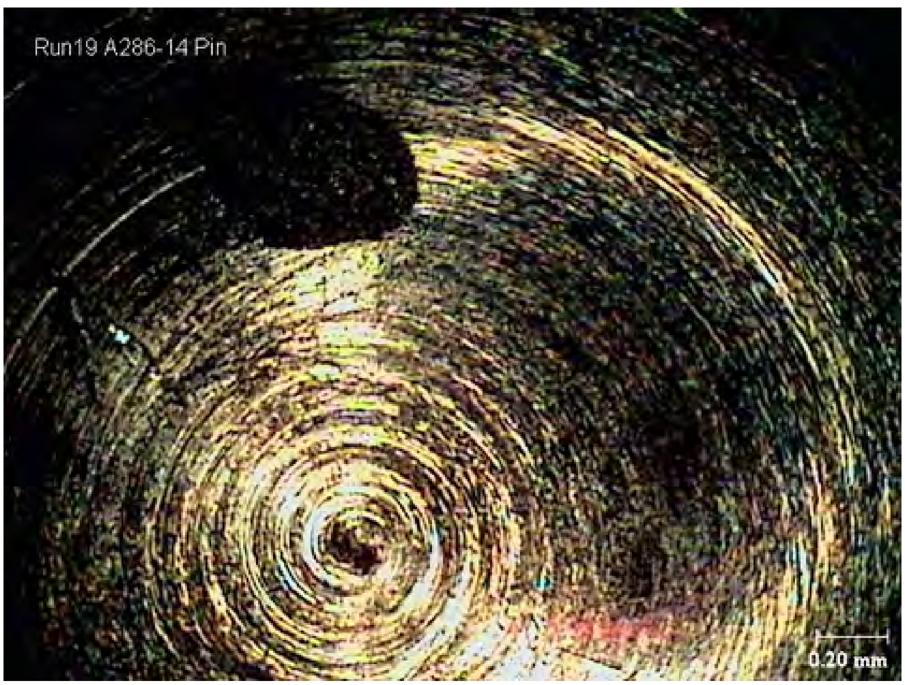
(a)



(b)

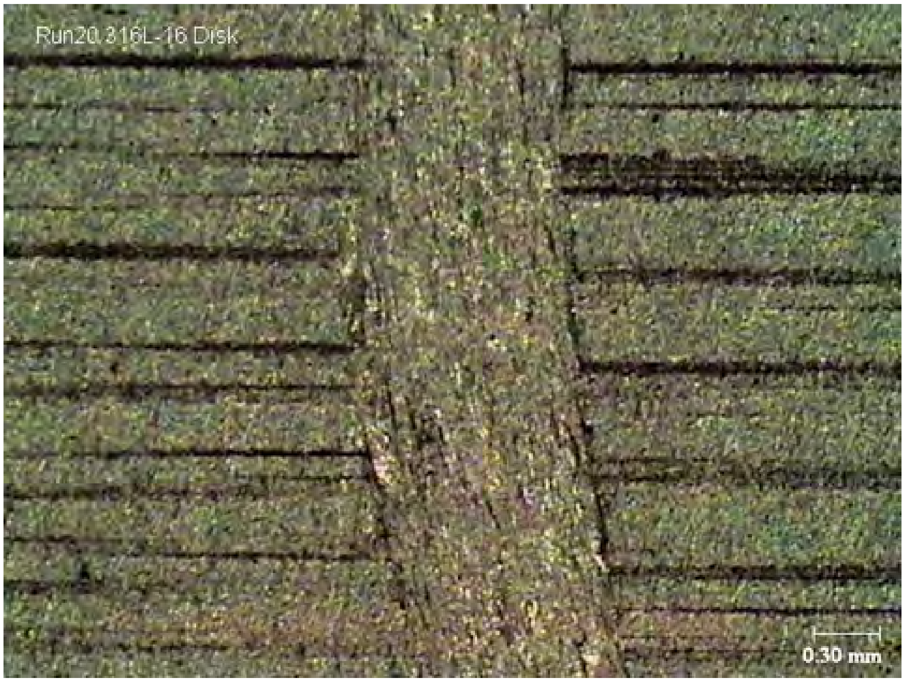
Figure F14. Macrophotographs of Test #18 wear areas (a) disk and (b) pin

(a)

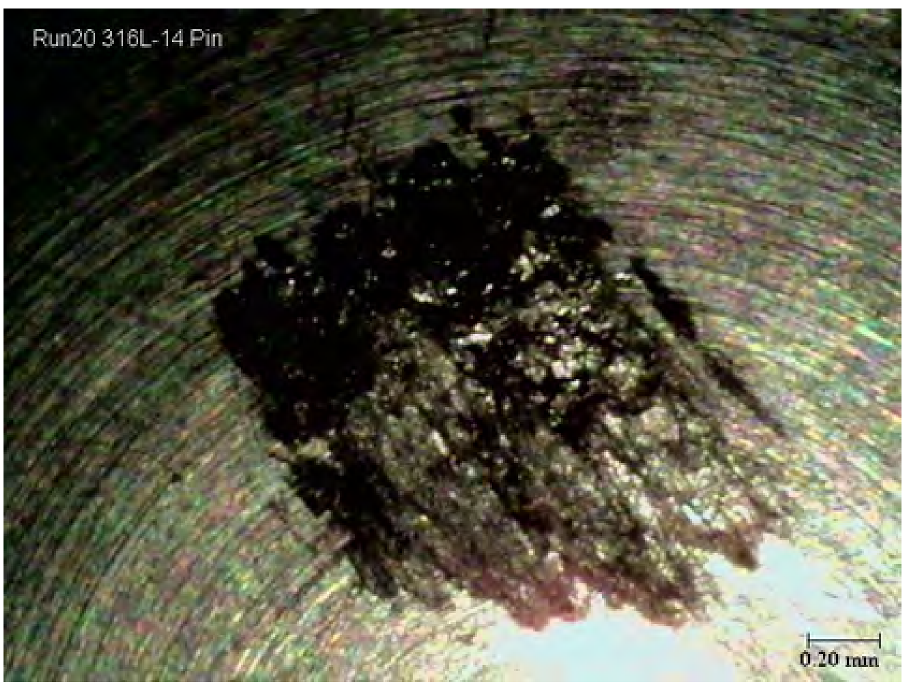


(b)

Figure F15. Macrophotographs of Test #19 wear areas (a) disk and (b) pin



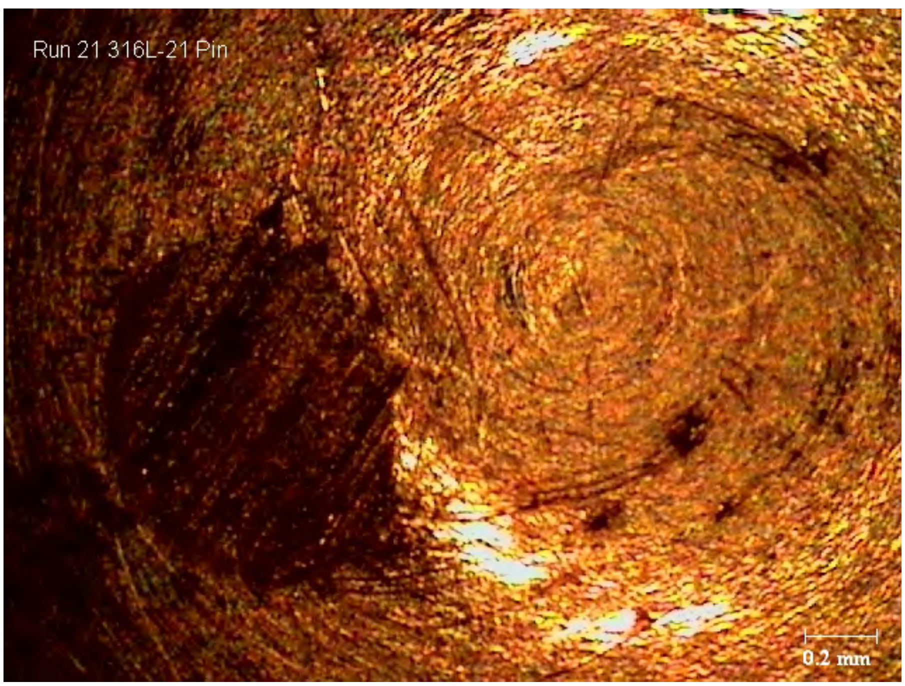
(a)



(b)

Figure F16. Macrophotographs of Test #20 wear areas (a) disk and (b) pin

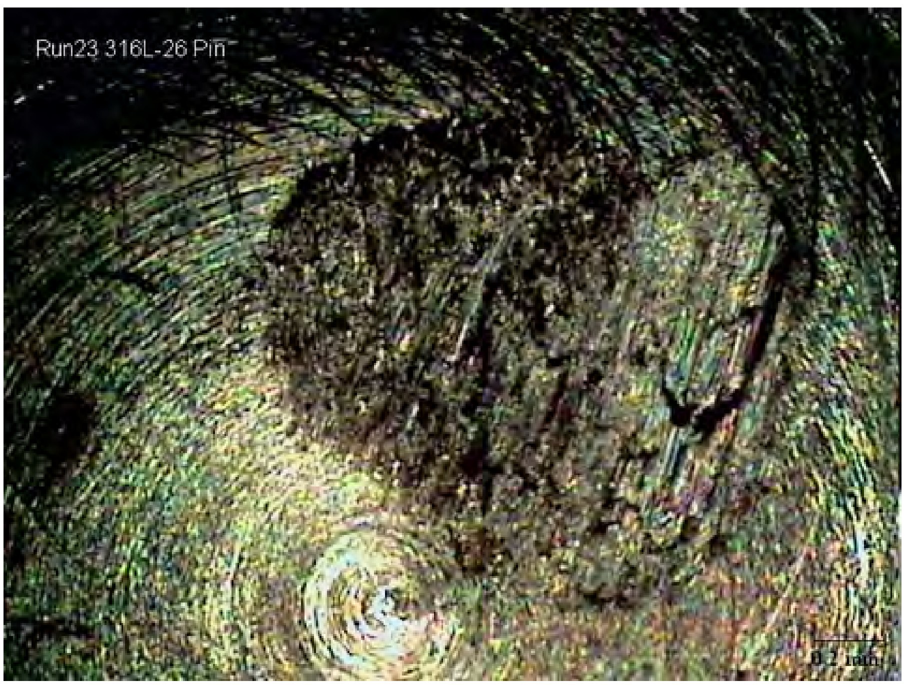
(a)



(b)

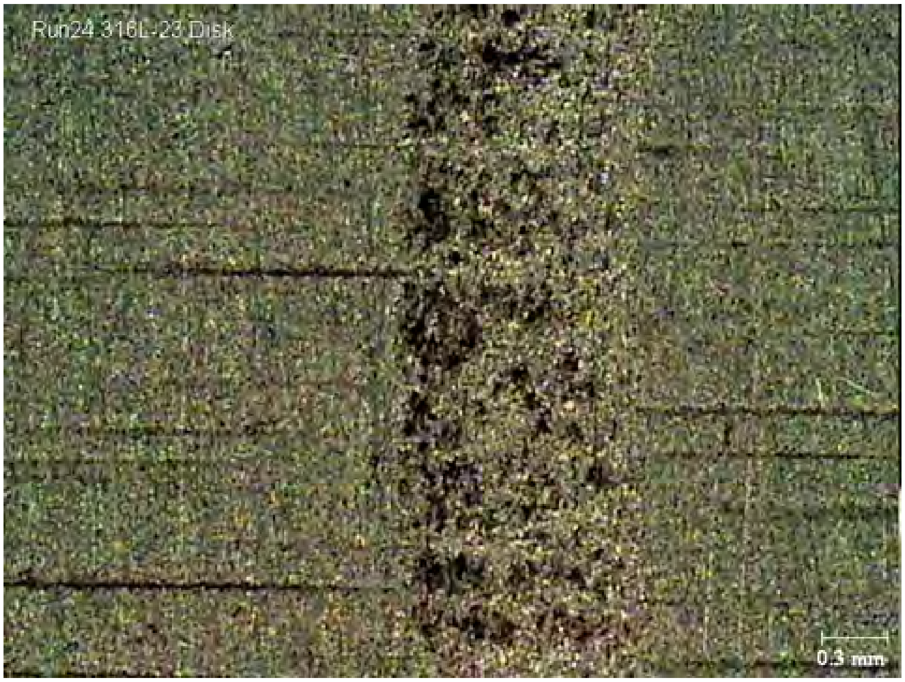
Figure F17. Macrophotographs of Test #21 wear areas (a) disk and (b) pin

(a)

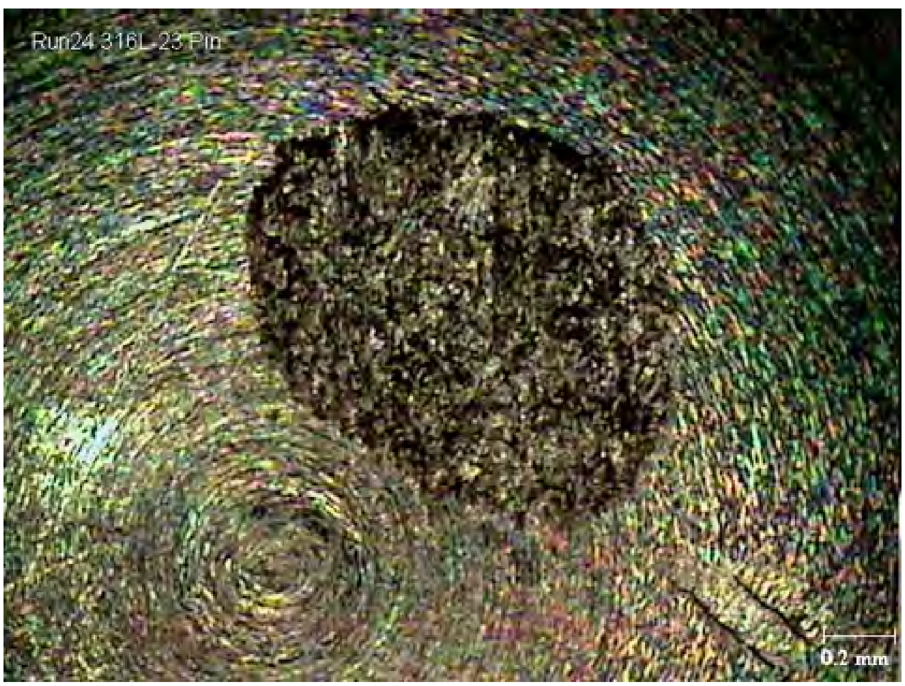


(b)

Figure F18. Macrophotographs of Test #23 wear areas (a) disk and (b) pin



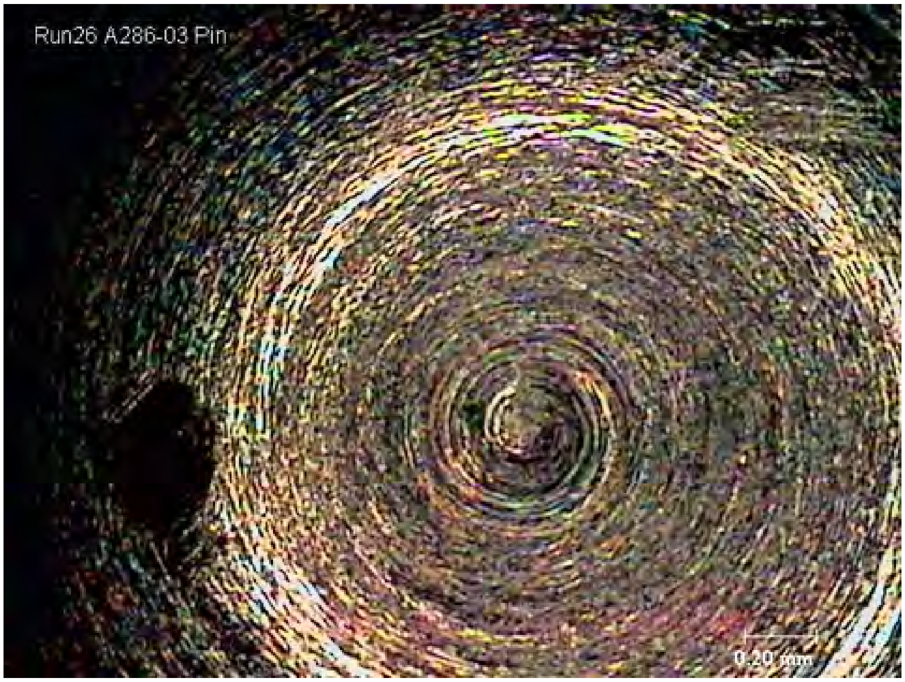
(a)



(b)

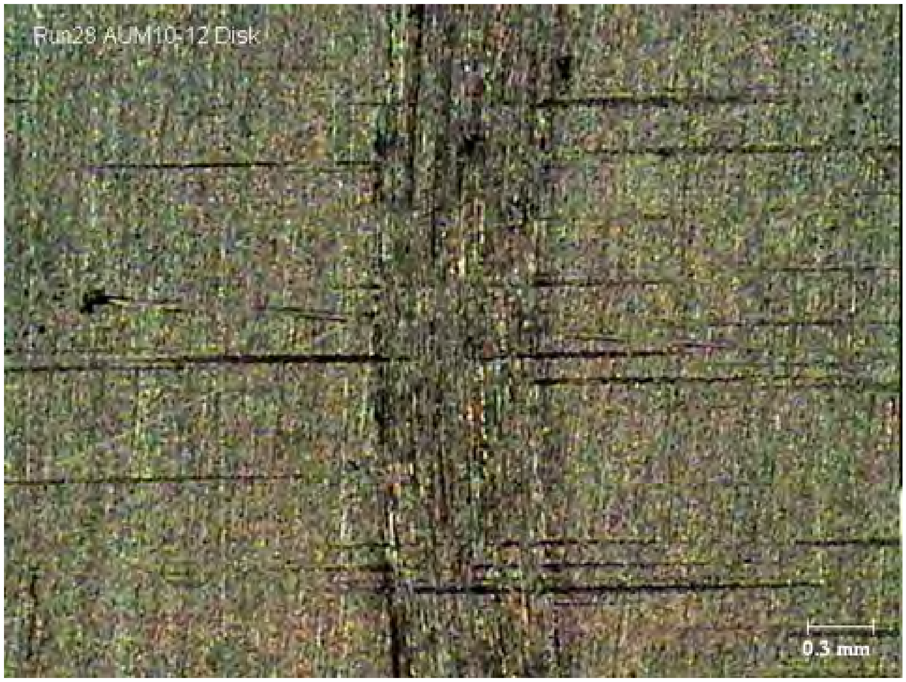
Figure F19. Macrophotographs of Test #24 wear areas (a) disk and (b) pin

(a)

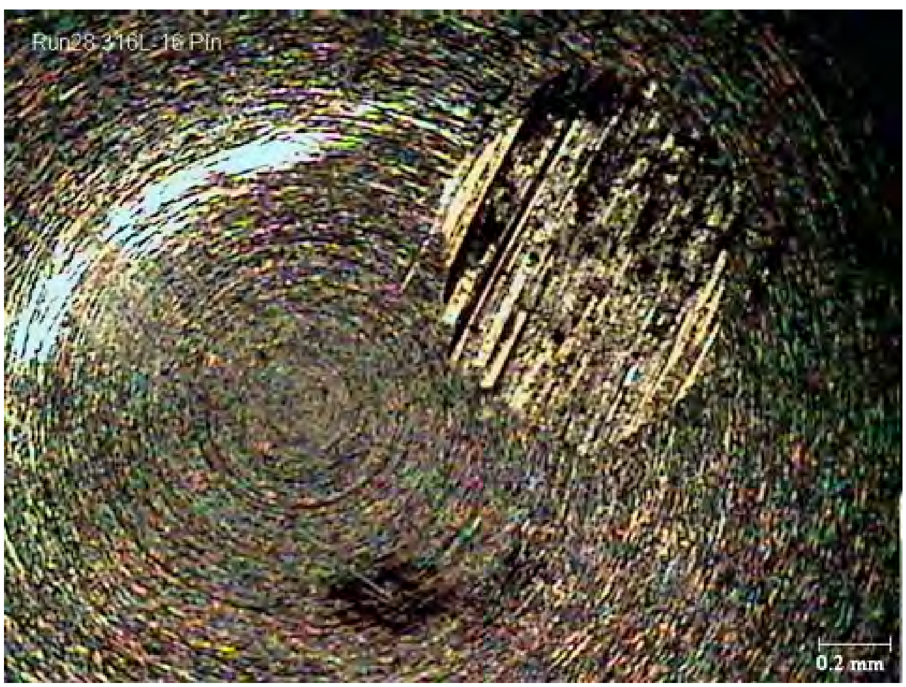


(b)

Figure F20. Macrophotographs of Test #26 wear areas (a) disk and (b) pin

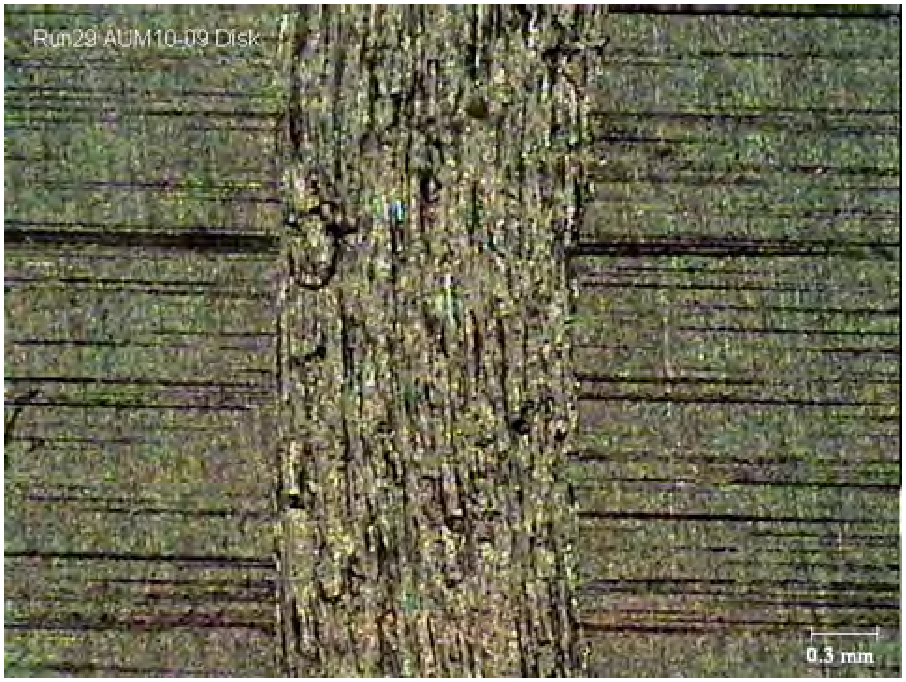


(a)

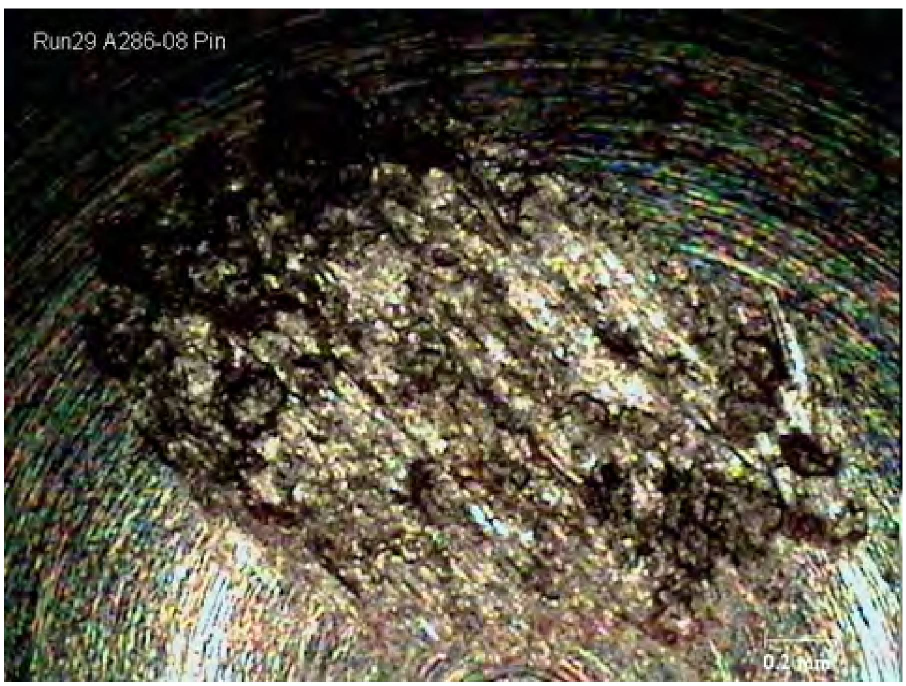


(b)

Figure F21. Macrophotographs of Test #27 wear areas (a) disk and (b) pin



(a)



(b)

Figure F22. Macrophotographs of Test #29 wear areas (a) disk and (b) pin

SRNS-STI-2008-00100

DISTRIBUTION

SAVANNAH RIVER SITE

N. C. Iyer, 773-41A
R. L. Sindelar, 773-41A
T. M. Adams, 773-41A
T. Motyka, 719-18A
P. S. Lam, 773-41A

EXTERNAL

Rana Mohtadi, Toyota Research Institute North America
Taisuke Miyamoto**,** Toyota Motor Corporation