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STUDIES OF THE NATURE OF WEAR

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Trans-Sonics, Incorporated

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13. ABSTRACT

It was shown that spherical particles which are found in fatigue cracks of rolling contact elements, i.e. bearings and gears, are not formed in fatigue cracks generated by tranlational cyclic stress.

Through Ferrographic analysis of a number of oil samples it has been possible to relate the wear particles with the condition of a sliding contact during the wear-in process.

A "Contact Wear Machine" was developed to simulate conditions near the pitch line of gears. Test specimens are a simple cylinder and a rectangular anvil. Contact loads and the ratio of sliding motion to rolling motion may be varied. Experiments have been run using Armco 17-4 PH and EN-8 (SAE1040). Ferrograms made from oil samples taken during the experiment with Armco 17-4 containted a large number of spheres prior to the appearance of typical gear fatigue particles. The tests using EN-8 also produced typical gear fatigue particles but no spheres. The fatigue pits found on the test specimens have the same apparent morphology as those found on gears.

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Contact Wear Machine						
Spherical Particles						
Tallysurf						
Wear Scar						
SEM Microscope						

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TRANS-SONICS, INC.
BURLINGTON, MASSACHUSETTS

OCTOBER 28, 1974

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1.0 INTRODUCTION

The objectives of the work were to provide new insight into wear mechanisms by conducting wear tests and making detailed examinations of the particles produced during wear.

The investigation was aimed at three areas:

A. Scientific

The determination of how surfaces wear in order to obtain a better understanding of the controlling factors to provide information for the design of improved lubricants and to better understand how surface metallurgy, and various surface treatments might reduce wear.

B. The Detection of Failure Initiation

The prediction of failure initiation is referred to as diagnosis. Up to the present time, this type of diagnosis has received considerable attention. Military organizations have been very anxious to find ways and means of predicting engine and system failures before they occur. An advantage of warning of impending trouble is the possibility of scheduling maintenance on a non-emergency basis for the correction of detected discrepancies. Reliable diagnostics make possible maintenance as required instead of scheduled overhauls with their attendant disadvantages of initial run-in with its inherent possible premature failure. The prediction of machine failure before the machine actually fails has an obvious economic value, but the sensing of a gradual deterioration of a machine permits timely maintenance. For example, this may involve scheduling an airplane to reach an overhaul base before an engine will have to be removed.

C. The Determination of the Nature of the Failure

The analysis of wear particles provides a direct means of determining the wear rate and of establishing the operative wear mechanism. Specific mechanisms such as rolling bearings, gears or sliding parts generate characteristic particles. From an assessment of the data an accurate prognosis can be obtained to enable a correct decision to be arrived at regarding action to be taken. For example, if a major overhaul is required or a specific small component requires replacement or adjustment or a change of lubricant is necessary.

An advantage of this technique is that it avoids tearing down good machines in order to find a discrepancy which may be located in an accessory. Occasionally, a simple change such as replacing the oil is all that is needed.

The technique eliminates the costs and dangers inherent in scheduled maintenance in which a machine is taken apart on the basis of time in use rather than need for repair.

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2.0 DISCUSSION

The investigation centered on three areas. The first concerned the mechanism by which spherical particles are generated, the second the process of rubbing wear, and the third the development of a machine for examining the process of contact wear.

The first series of tests was concerned with establishing whether or not fatigue cracks in structures such as cantilever beams generate spherical particles. The objective was to determine whether or not such spheres were generated by ordinary fatigue cracks in cyclically-stressed parts as opposed to the fatigue cracks in rolling bearings which are known to generate spheres. From this investigation, it was concluded that spherical particles are not generated by ordinary fatigue cracks.

The second endeavor was concerned with learning more about the kinds of particles generated by rubbing wear. It had been noticed in earlier work that certain dark pebble-like particles sometimes referred to as metallo-oxides exhibited strong magnetic properties. These particles often appear in the strings of rubbing wear particles on Ferrograms. However, such particles were not generated by rubbing cold-rolled steels such as 1018. On the other hand, when a high carbon steel such as heat-treated 1090 steel was rubbed, dark pebble-like particles appeared in the strings of rubbing wear particles. Ferrograms containing the dark pebble-like particles were forwarded to the National Bureau of Standards. An analysis of a few of these particles indicated that they were composed of the magnetic iron oxide, Fe_3O_4, and that free iron was dissolved in the oxide. At the present time, it is believed that the majority of the dark particles are composed of this oxide.

At the time that the original observation was made, the dark oxide particles appeared only in those cases where hard steel was rubbed against hard steel and it appeared, therefore, that the presence of these particles might be used as an indication that the wear was occurring at the interface of hard steels as distinct from the softer varieties. The initial objective of the rubbing wear experiments was to determine if such dark particles were always generated when hard steel pieces rubbed or if special conditions were necessary for their generation. The investigation, so far, revealed that under mild wear conditions, a hard steel such as 52100 Rockwell C 60 hardness does not generate the dark particles.

However, it was observed that a unique type of particle which has been frequently seen in connection with wear of jet engines and other machines, is generated as the result of the wear of ground surfaces. The experiment which is described in the body of this report resulted in the generation of thin linear strips from the shear mix layer. These strips were formed as cornices on the top of grinding marks and represent the initial wear of a ground surface. The strips are often ten to fiften μm long, three to five μm wide and approximately 3/4 to 1 μm thick. They are found in numerous cases and it would appear that they are produced from wear of a rough ground surface. Occasionally, these particles are seen in bent form and because of their curved shape, they tend to lie on their side and appear very much like cutting wear particles.

In the course of the work, the fixed cylinder developed a very flat surface of Beilby material. This surface was unique in that it was virtually free of defects, cracks, steps, etc., and appears analogous to fire-polished glass in smoothness. During the generation of this wear spot, the opposing piece which was turning, remained rough and was the source of the Beilby wear particles. It will be necessary to explain how the wear spot becomes so smooth because it is difficult to believe that a rotating part operating as a cutting or milling tool would be capable of generating such a smooth surface.

In the early 1900's Sir George Beilby concluded that the material in polished layers flowed much as a liquid. Many investigators have decided that the evedence indicates localized melting of the metal. However, we believe that this is not so. First, such layers are quite incapable of standing up to high temperatures. Secondly, examination of the Ferrograms shows no indication that the particles from this rubbing situation have been subject to high temperature. Normally, localized high temperatures will lead to interference colors on the particles and these colors are certainly not present in these experiments.

The reason most investigators believe that localized melting occurs, has to do with the relative melting temperatures of polishing compounds and the surfaces being polished. The hardness of the polishing material relative to the hardness of the surface being polished is not in question. To be effective, the polishing compound must melt at a higher temperature than the surface. Consequently, materials such as aluminum oxide, rouge, etc., are used, not because they are hard but because they have high melting temperatures. This has caused investigators to think that melting of the surface is involved. However, the melting temperature of a substance is a measure of the crystalline bond strength and, therefore, when one material has a higher melting temperature than another, it implies that such a material will be harder to smear than the material with the lower melting temperature.

Rubbing breaks up the grain structure of the surface metal resulting in crystallites about 300 Å across. One can visualize little crystallites as metal molecules which are capable of flowing like a liquid during the short time before they adhere to the surrounding crystallites. The implication is that smearing or flowing in one direction makes it possible for the metal to flow freely in a perpendicular direction so that the metal takes on the properties of a liquid in that the surface shape is determined by surface tension. This would explain the great smoothness of the wear spot. In effect, the metal becomes a free flowing molecular liquid whose molecules consist of a few million atoms. Sir George Beilby expressed the belief that surfaces being polished were capable of flowing in the manner of a liquid. Metallurgists have been inclined to discount his conclusions but they have not had an opportunity until very recently to adequately study surfaces. The phenomenon is strictly a surface phenomenon which is not observed with ordinary metallurgical specimens.

The third area has involved the development of a contact wear machine. This machine is intended to simulate conditions near the pitch line of heavily loaded slow moving gears. It is designed to make it possible to study the generation of gear wear particles such as those shown in Figure 18, Appendix 1.

The machine has generated such particles in the manner expected. The pits from which the particles spalled have a characteristic shape in which the cavity walls are nearly perpendicular with the surface and the bottom of the cavity consists of flat surfaces usually parallel with the outer surface of the piece. Parts of the vertical cliff-like side walls break off to form the familiar particles.

A variety of steels were used as test pieces in the contact wear machine. In some of these tests, an unusual series of pits were observed in the surface of the wear

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parts. Section 3.3 covers this subject and illustrates the types of pits seen. The existence of these pits are particularly interesting because their presence on a particle may possibly be used to determine if the particles were generated on a rolling surface. It has been shown that such pits are not present on a surface when sliding is present.

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3.0 EXPERIMENTAL

This section covers the experimental work carried out.

3.1 The Generation of Spherical Particles

One of the tasks under the present contract was to determine if fatigue cracks in structures other than ball bearings would produce spherical particles. This matter is of great importance because the presence of spherical particles is being used as an indicator of bearing failure. An important question is whether spheres are produced by parts other than rolling bearings and gears.

In order to determine whether or not such particles could be produced from fatigue cracks produced by reciprocating stress, special cantilever beams were designed and fabricated. These beams were mounted in a rigid clamp which was securely bolted to a 5 KW vibration test machine. This machine is capable of being tuned over a wide frequency range so that it is possible to tune the system to the resonant frequency of the beam. The beams were designed to resonate at 100 Hz. One set of beams was fabricated from 1018 low carbon, cold rolled steel. Another set was fabricated of 1090 high carbon steel.

The clamps were carefully covered with a silicone polymer to prevent rubbing wear particles generated inside the clamp from escaping and contaminating the oil. It was found that a sufficient quantity of oil would adhere to the beam so that it was not necessary to submerge the beam in oil. A barrier layer was used to prevent the oil from moving away from the region where the crack is formed. The system was operated at selected amplitudes so as to generate fatigue cracks.

In the case of the 1018 steel, it was found that as the crack nucleated the resonate frequency of the system, initially 105 Hz, decreased. This was noted in terms of the electrical output of an accelerometer on the vibrator and by virtue of reduced beam amplitude. The operator was instructed to shut the machine down as soon as this happened so that the cracks could be examined before the beam fractured into two pieces. The oil surrounding the fatigue part of the beam was flushed into a clean beaker, additional clean oil added, and a Ferrogram made. In this way, virtually all of the particles generated were recovered by the Ferrograph.

Examination of the crack under high magnification showed that the crack originated within 90 µm of the expected place. However, the crack's pathway across the surface of the beam was irregular, staggering to the left and right by as much as 50 or 100 µm. It was also noted that a series of small cracks formed parallel with the main crack. In one area cracks perpendicular to the main crack also appeared so that a small area was covered with a series of cracks forming a rectangular grid.

The metal contained between the principal crack and the subsidiary parallel cracks was extremely distorted and had morphological qualities identical with some severely distorted particles seen in connection with machine failure.

Examination of the Ferrograms showed that the principal type of particle was from the Beilby layer. It appears that the surface of the beams has contributed many of these particles. Two or three spherical particles were seen, but too few to indicate that these particles were generated within the crack. The total number of particles was small even though most of the particles generated were recovered. If the total number of particles generated were dispersed in several gallons of oil, the particle density would be absolutely negligible. For this reason, we do not think that this type of crack contributes significant numbers of particles to lubricating systems.

The tests on the 1090 steel beams showed that the resonance band-width was exceedingly narrow (high Q factor). This was expected. When the crack nucleated it proceeded across the beam almost instantaneously and it was not possible to shut down the machine soon enough to prevent the beam from separating into two pieces. The crack was single with few or no parallel cracks. The crack path was straight across the beam without staggers as in the case of low carbon steel. The number of particles generated was even less than were generated by the cold rolled steel and was as low as a few dozen.

We are satisfied that this type of cracking is not a significant source of either spherical particles or Beilby wear particles. With the 1090 steel there were no systems of cracks which had the appearance of the highly distorted particles seen on some Ferrograms. We conclude, therefore, that if particles of this morphology are seen they are likely to be manufactured from the more ductile steels.

In view of the fact that the particles density was so low, it was felt that the necessary information was obtained and no further testing is contemplated.

PHOTO NO. 3.1-1 **DATE** May 74

MAGNIFICATION: 10X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4038
Beam #5
1018 Steel

OPERATING HISTORY:

15 minutes driven at 9.5g
Frequency 100 Hz

REMARKS:

SEM photomicrograph of specimen at end of test. Fatigue crack is visible.

PHOTO NO. 3.1-2 **DATE** May 74

MAGNIFICATION: 55X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4038
Beam #5
1018 Steel

OPERATING HISTORY:

As above.

REMARKS:

Wall of crack seen above. General view of fracture surface. Fracture iniated in lower left corner.

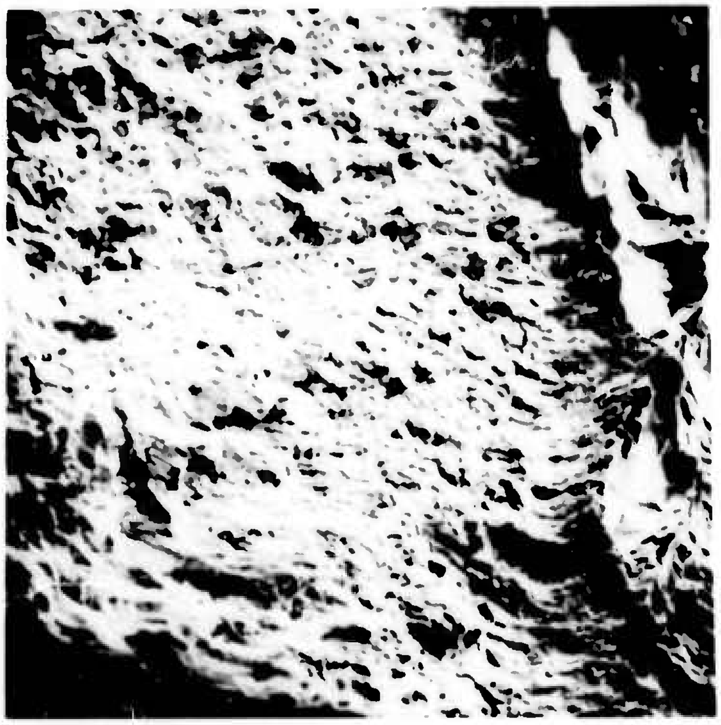


PHOTO NO. 3.1-3 **DATE** May 74

MAGNIFICATION: 140X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4038
Beam #5
1018 Steel

OPERATING HISTORY:

As above.

REMARKS:

Initiation area of the fatigue fracture. View is of lower left corner of photo 3.1-2.

PHOTO NO. 3.1-4 **DATE** May 74

MAGNIFICATION: 1400X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4038
Beam #5
1018 Steel

OPERATING HISTORY:

As above.

REMARKS:

Same view as above with increased magnification. Note the surface shows evidence of rubbing wear.

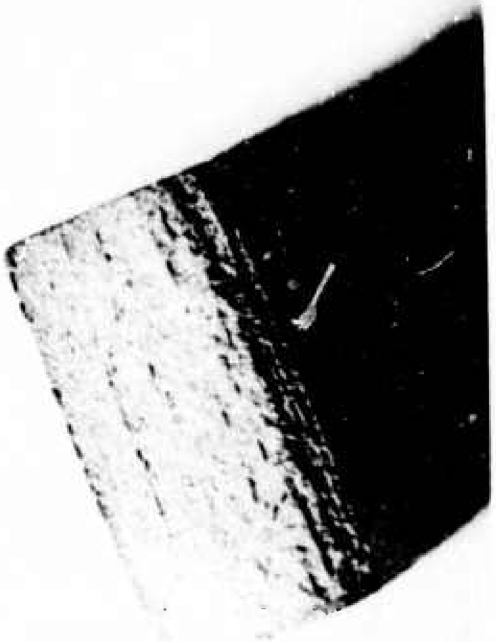


PHOTO NO. 3.1-5 DATE May 74

MAGNIFICATION: 18X

LOCATION ON
FERROGRAM: N.A

SAMPLE IDENTIFICATION:

Test No. 4045
Beam #7
1090 Steel

OPERATING HISTORY:

27 minutes driver at 0.8G
Frequency 117 Hz.

REMARKS:

SEM photomicrograph of beam fracture surface. Fracture initiated in lower left corner.

PHOTO NO. 3.1-6 DATE May 74

MAGNIFICATION: 160

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4045
Beam #7
1090 Steel

OPERATING HISTORY:

As above

REMARKS:

Enlarge view of fracture initiation area.

PHOTO NO. 3.1-7 **DATE** May 74

MAGNIFICATION: 1600X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4045
Beam #7
1090 Steel

OPERATING HISTORY:

As above.

REMARKS:

Rubbing marks and surface debris at fracture initiation surface. Some of the surface material is oxidized.

PHOTO NO. 3.1-8 **DATE** May 74

MAGNIFICATION: 6400X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4045
Beam #7
1090 Steel

OPERATING HISTORY:

As above

REMARKS:

A spherical particle found on the surface. X-ray energy analysis shows it is likely an inclusion in the steel. It contains Cl, P, Ca, and only a trace of Fe.

3.2 Rubbing Wear Investigation

Task 2 of this contract provides for the study of rubbing or normal wear. Current texts on tribology, and most analyses, treat wear as single event interaction of surface asperities. Examination of a large number of Ferrograms by both optical and scanning electron microscopy show that the rubbing wear particles are not the result of a single interaction and doesn't confirm the theoretical postulates! They are flat platelets generally less than 1 μm thick smeared as though spread like hard butter. They appear to have broken away from a top crust of "polished" metal referred to as the shear mixed layer, or the Beilby layer (after Sir George Beilby).

A series of tests were run to determine the characteristics of rubbing wear particles obtained from various steels. A heavy-duty lathe was assigned to this work. Wear particles are produced by rotating a cylinder under a shoe or ring. The cylinder extends into the oil (Mil-L-23699). Rubbing wear tests with 1018 steel exhibit normal rubbing (Beilby) wear particle strings on the Ferrogram. It has been possible through a series of Ferrograms made from oil changed once every hour to determine how the particle numbers, sizes, and type change as the contacting surface wear-in.

During the process of wearing-in, the wear rate changed by more than two orders of magnitude. With time, the size and number of the rubbing wear particles decreased. With 1018 steel a large number of laminar wear particles were also found. Such particles which have holes in their surface are similar to those almost always seen in connection with ball bearing failures. The reason for their generation and the relationship between this type of rubbing wear and ball bearings wear is a subject for further investigation.

It was also noted that with 1018 low carbon steel, no dark metallo oxide particles (Fe_3O_4) were found on the Ferrograms. Such particles are normally associated with wear of hard steels.

A second series of tests were run with 52100 steel. To simulate ball bearing material, the outer races of actual bearings were employed as test specimens. The surface finish produced by circumferential grinding consisted of parallel circumferential marks. As the tests progressed, it was observed that a Beilby layer formed on the tops of the grinding marks of the rotating piece. The fixed piece quickly wore down to a smooth Beilby layer at the point of contact resulting in a highly polished finish. During wear-in, the average size of the particles decreased rapidly. As with other steels the final density of particles observed on the Ferrograms decreased by about 3 orders of magnitude. Initially, large particles (pieces of the original surface material) were seen. As the wear-in continued, this type of particle gradually disappeared. The Ferrograms contained very few red oxide (Fe_2O_3) particles.

During tests on 52100 steel many strip-like rubbing wear particles were generated typically three to five micrometers wide and 10 to 30 micrometers long, Photomicrograph 3.2-1. An examination of the worn surface of the rotating piece reveals similar strips extending from the top surfaces of the grinding ridges. It appears that the particles are generated by breaking off of these strips. Similar particles have been seen in connection with jet engine failure and also on certain marine machinery. The presence of the strip-like particles indicates that a surface with parallel grinding marks is being worn. If found on Ferrograms prepared from the lubricant of machines in service, it is indicated that the wear is occurring on one of the very few rougher ground surfaces.

An interesting aspect of these wear tests is the astonishing smoothness of the wear scar surface on the static piece. When examined optically at high magnification (700X), the wear surface appears polished. The highly reflecting optical quality surface is devoid of irregularities as if formed from the molten state, Photomicrographs 3.2-2,-3,-4. A Tallysurf measurement shows the surface to be better than 0.2 µm in peak to peak surface finish, Figure 3.2-5.

One of the objectives of running 52100 steel was to determine conditions necessary for the generation of metallo oxide particles often associated with rolling bearing wear. Black metallo oxide particles have been found to be mixtures of iron (ferrous) oxide and free iron. Preliminary experiments conducted nearly two years ago were sucessful in producing such particles from 1090 high carbon steel. None of the wear tests uding the 52100 steel in the crossed cylinder machine have produced such particles. It is thought that the maximum Hertzian stress (27,000 PSI) used under this experimental condition is too low.

A linear relationship was found between this wear scar area of the static specimen and apparent load. Thus, equilibrium contact conditions of elastohydrodynamic lubrication are maintained.

A second test series was made to confirm the findings. The surface of the rotating race was prepolished using 600 grit silicon carbide paper, Figure 3.2-4 shows the load-area relationship for the two tests. The area of the wear scar on the static race at the end of the test series was 0.0193 sq. in. for the unpolished race and .0064 sq. in. for the polished race. Yet both tests showed the same area-load relationship.

During one test using 52100 steel, a few spherical particles were observed on the Ferrograms of the later samples. These coincided with the appearance of a crack in the surface rotating piece, Photomicrograph 3.2-5.

PHOTO NO. 3.2-1 DATE 4/15/74

MAGNIFICATION: 1120X

LOCATION ON
FERROGRAM: 54.1mm

SAMPLE IDENTIFICATION:

Test No. 4102. Ferrogram No. 2765 made from 4th 1 hr. oil sample.

OPERATING HISTORY:

1/2 hr. at 21 lb. load
3 hrs. at 90 lb. load
1 hr. at 180 lb. load

REMARKS:

A Bichromatic photomicrograph of a linear strip-like rubbing wear particle. These are the "cornices" as seen on the static piece after having been broken off.

PHOTO NO. 3.2-2 DATE 5/6/74

MAGNIFICATION: 520X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4102. Wear scar on the static race.

OPERATING HISTORY:

1/2 hour at 21 lb. load
3 hours at 90 lb. load
3 hours at 180 lb. load
3 hours at 270 lb. load

REMARKS: Optical Photomicrograph

The extreme smoothness of the wear surface is evident. Note the "cornices" of metal formed over the grinding grooves at the edge of the scar. Metal is flowing from bottom to top.

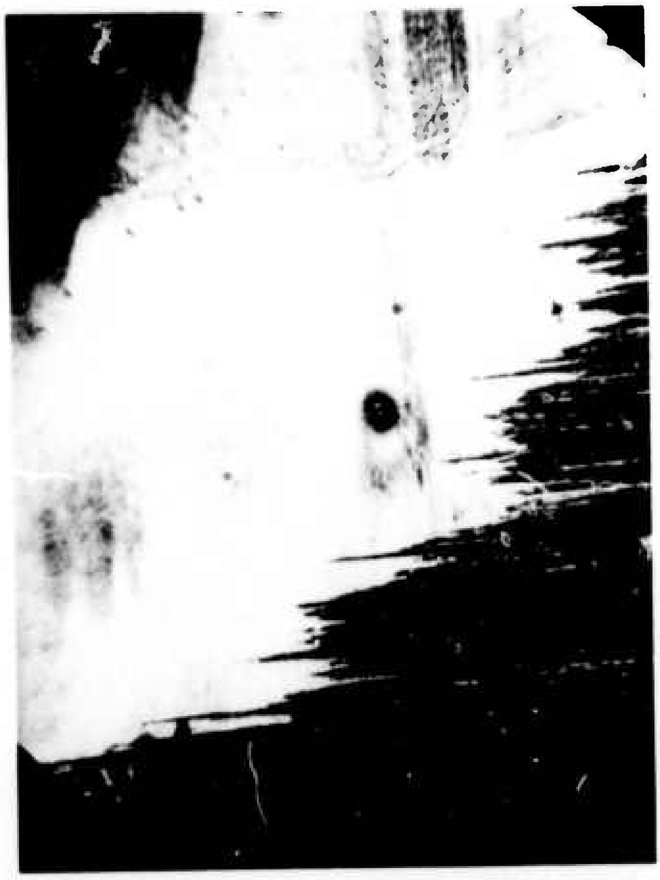


PHOTO NO. 3.2-3 DATE 5/6/74

MAGNIFICATION: 110X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4102. Wear Scar on the static race.

OPERATING HISTORY:

1/2 hr at 27 lb load
3 hr at 90 lb load
3 hr at 180 lb load
3 hr at 270 lb load

REMARKS:

Note the extreme smoothness of the worn surface. Original ground surface in the lower right.

PHOTO NO. 3.2-4 DATE 4/15/74

MAGNIFICATION: 110X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4093. Wear scar on the static race.

OPERATING HISTORY:
1/2 hr at 27 lb load
3 hr at 90 lb load
3 hr at 180 lb load
1 hr at 270 lb load

REMARKS:

As above, note the smoothness of the scar surface. Original surface is on left.

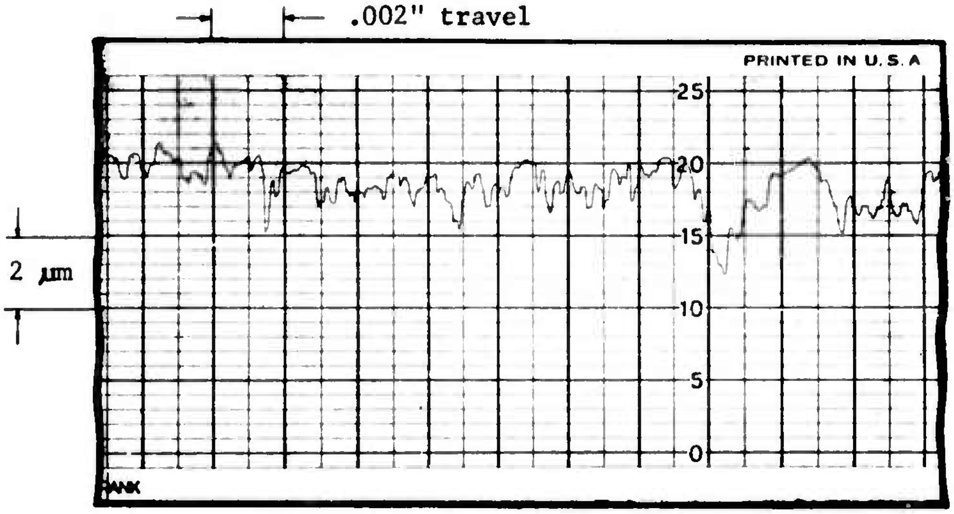


Figure 3.2-5a. Tally surf trace of the original outer surface of the rotating race used in test no. 4093.

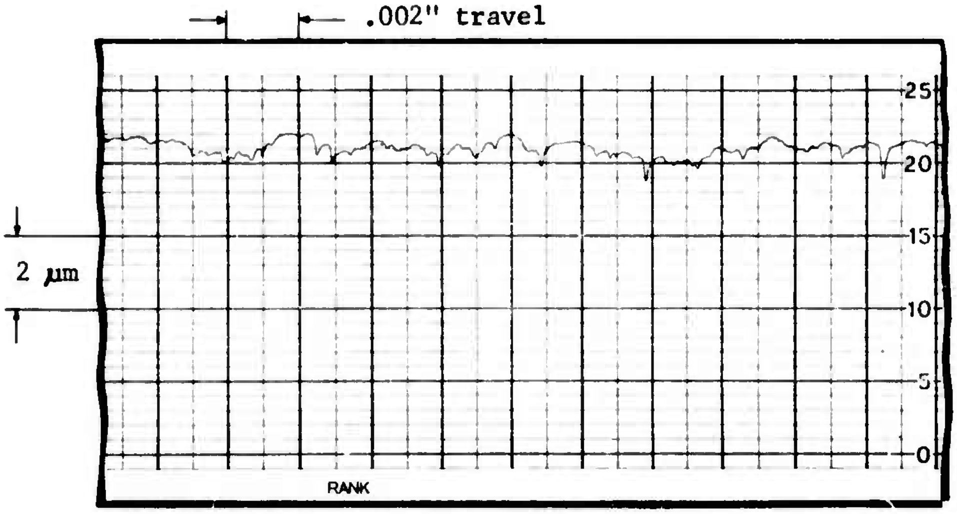


Figure 3.2-5b. A Tally surf of surface of rotating race from test no. 4093 after wearing.

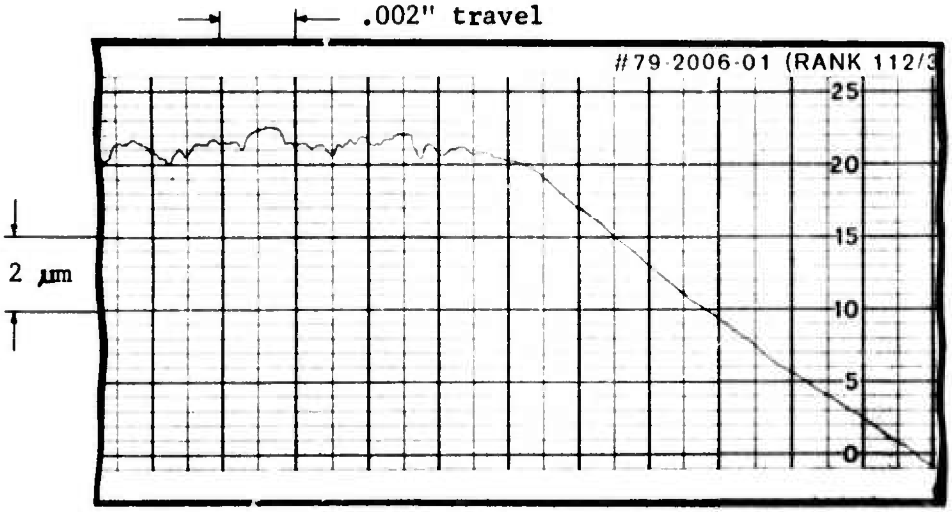


Figure 3.2-5c. A Tally surf trace of the wear surface of the static piece from test no. 4093 after wearing.

Figure 3.2-5

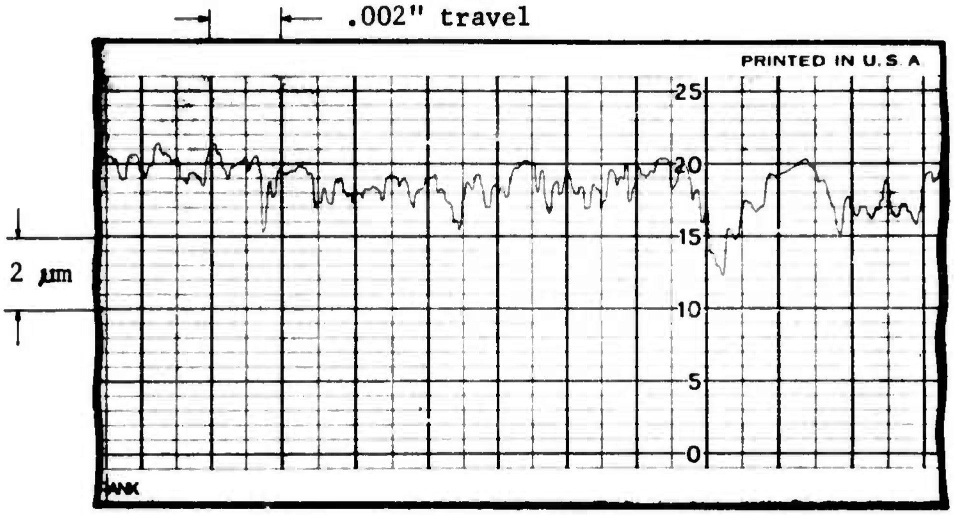


Figure 3.2-5a. Tally surf trace of the original outer surface of the rotating race used in test no. 4093.

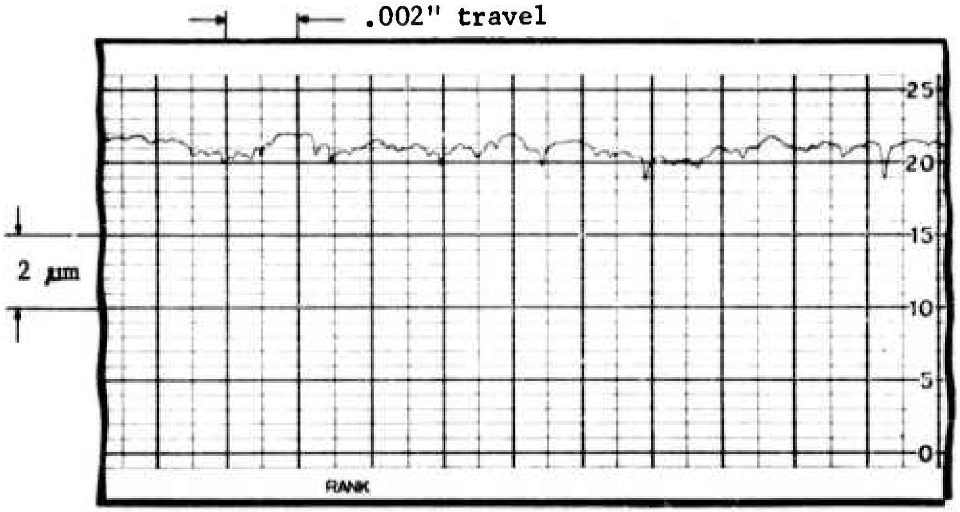


Figure 3.2-5b. A Tally surf of surface of rotating race from test no. 4093 after wearing.

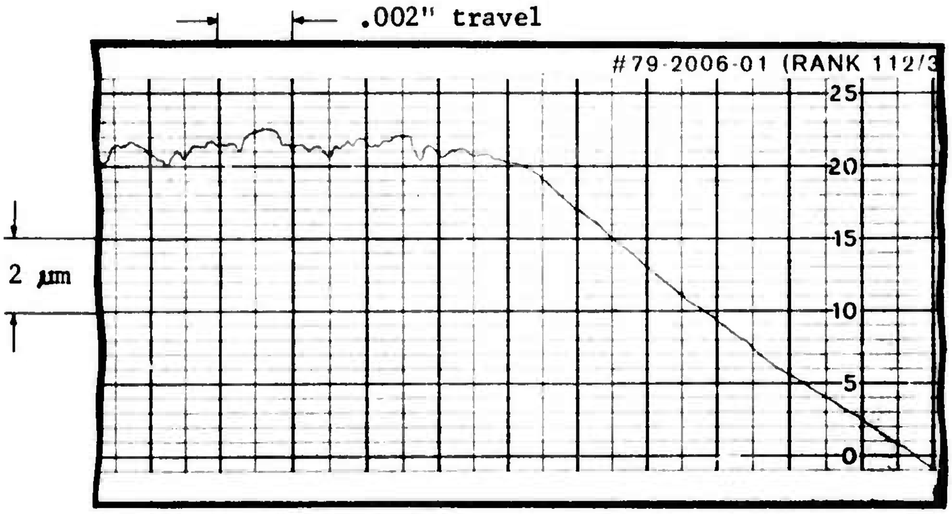


Figure 3.2-5c. A Tally surf trace of the wear surface of the static piece from test no. 4093 after wearing.

Figure 3.2-5

Figure 3.2-6

Crossed Race Wear Test Machine

Load/Area Relationship

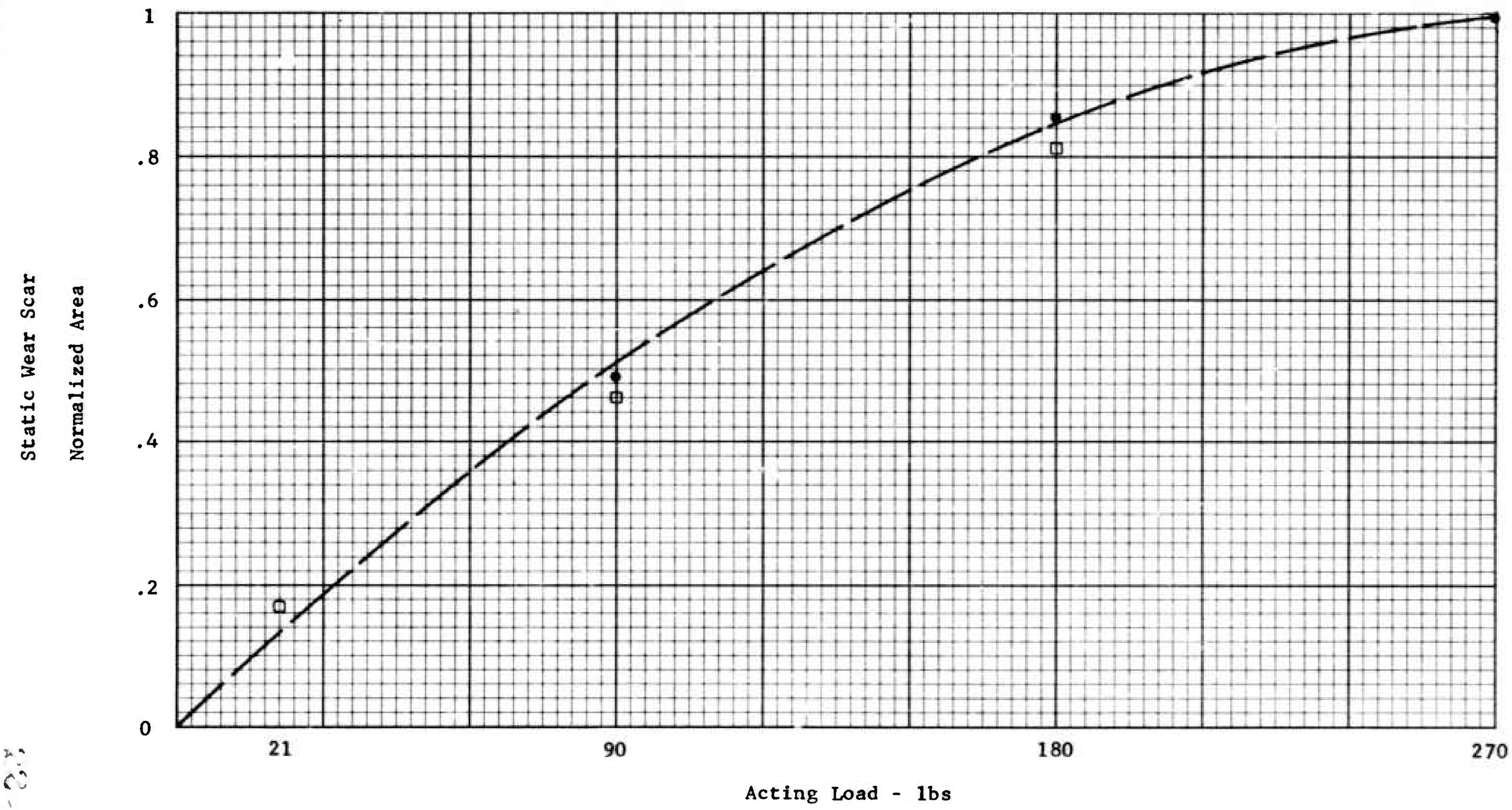


PHOTO NO. 3.2-7 DATE 5/6/74

MAGNIFICATION: 560X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test 4102. Wear scar on the rotating race.

OPERATING HISTORY:

Same as photo 3.2-3

REMARKS: Optical Photomicrograph

Original ground surface at top of photo. The grinding lines have not been completely worn away in the wear track at bottom of photo. Note blue bands thought to be caused by heating.

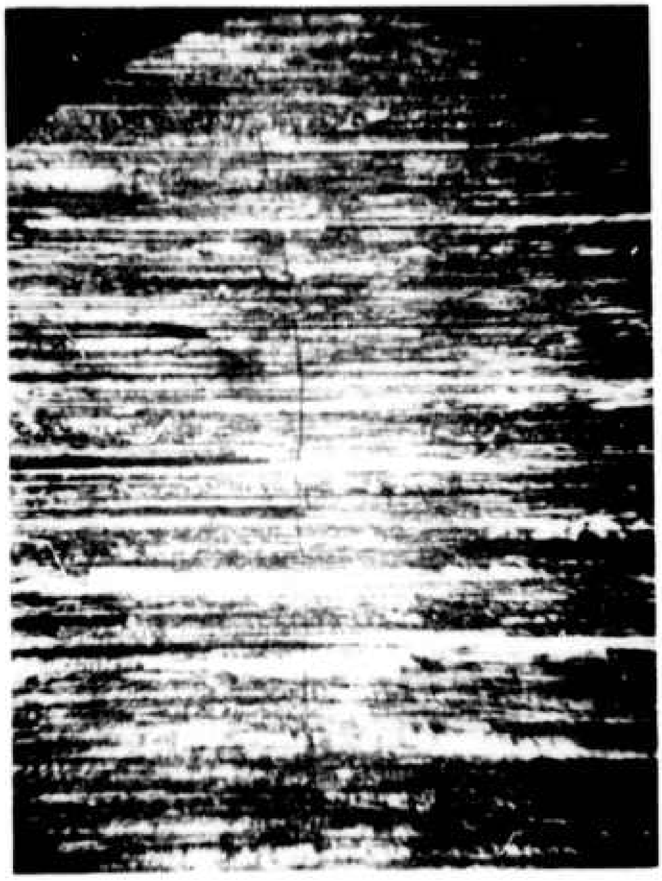


PHOTO NO. 3.2-8 DATE 5/6/74

MAGNIFICATION: 560X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Same as above. Different location on circumference.

OPERATING HISTORY:

Same as above.

REMARKS: Optical Photomicrograph

A diagonal running crack worn over in the wear track.

PHOTO NO. 3.2-9 DATE 4/15/74

MAGNIFICATION: 110X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:

Test No. 4093. Wear scar on the rotating race.

OPERATING HISTORY:

Same as photo 3.2-2

REMARKS: Optical Photomicrograph

Two of general cracks or fissures found in this race at end of test. Surface still contains grooves from original finish grinding. Only the tops have been removed.

3.3 The Development of a Contact Wear Machine

Fatigue particles are those particles most often associated with gear wear. See Figure 18, Appendix 1. The particles are in the form of chunks of steel and usually have flat upper and lower surfaces with the characteristic of a crystal cleavage plane. It has been observed that such particles are seen in connection with heavily loaded gear boxes and they are not associated with simple rubbing systems or rolling bearings. These chunk-like particles have, therefore, been used to identify situations in which gear pitting is involved.

A new wear machine designated the "Contact Wear Machine" was designed to siumlate conditions near the pitch line of gears. The machine was developed so that the generation of such fatigue particles could be studied with low cost test pieces capable of being fabricated from a wide variety of materials. The test pieces employed consist of a small rectangular block of metal, 1/2 inch square x .187 inch wide, called an anvil and a small rod, 1/4 inch diameter x 1 inch long, called a cylinder.

Figure 3.3-1 shows the machine. Figure 3.3-2 is an exploded view. By adjusting the position of the contact surfaces with respect to the pillow block pivot bearing centers, it is possible to obtain a wide variation in the ratio of sliding to rolling motion. The anvil is forced against the wear cylinder by a stack of Bellville washers which may be adjusted to load the contacting surface with a force ranging between 20 and 300 lbs.

Several requests for information on this machine have been received. In view of the interest, a short note is in press. (R.A. White, "A Versatile Contact Wear Machine", Wear, 1974) - Appendix 2.

The series of tests described in the following paragraphs represent the initial use.

As described above the machine can be adjusted to provide a range of rolling and rubbing amplitudes. The first test was carried out with the machine adjusted to provide pure rolling motion, i.e., the wear cylinder did not slide on the surface.

The rolling amplitude was ±0.5 mm at the contact point. The machine was operated at a speed of 200 cycles per minute. The velocity of motion was approximately sinusoidal, having a maximum at the center of 10.5 mm/second.

The wear cylinder and anvil were fabricated from Armco 17-4 PH steel heat treated to H900 (hardness 37 R.C.). The anvil was milled and the cylinder turned without subsequent surface finishing. The surface roughness was estimated as 16 micro inch R.M.S. Microscopic examination showed a smooth bright surface with occasional deeper machining grooves (2 μm). Differences in surface height were generally within ±1 μm except for occasional deeper grooves. The machining direction on the anvil was perpendicular to the long dimension and consequently to the direction of rolling. As the direction of motion of the wear cylinder is perpendicular to the direction of the machining, any further grooving or marking of the surface may be distinguished from the original marks.

At the start of the experiment, the machine was operated for 3,058 cycles with a contact force of nine kilograms. The force was then increased to 123 Kg for the remainder of the experiment.

The lubricant was a polyester oil to specification MIL-L-23699 (Mobil Jet II). The machine was run for periods ranging from 30,000 cycles to 70,000 cycles, the oil was changed after each running period and a Ferrogram was prepared.

The initial Ferrograms showed extremely low wear as would be expected from pure rolling. The Ferrogram prepared from the oil taken from the test period, 168,000 cycles contained an abundance of spheres.

Ferrogram 2938 made from 4 cc of oil contained approximately 750 spheres ranging in diameter from 1 to 10 μm. As the reservoir contained 10 cc of oil, the total number of spheres generated was approximately 1,875. However, the oil sample examined after an additional 61,000 cycles contained no spheres.

Ferrogram 2938 also contained several large fatigue chunks, typical of the spalls associated with gear wear. It is hypothesized that the upper surface of the crack generating the spheres spalled off during the run ending at 238,000 cycles.

The anvil was removed from the machine at the end of 299,000 cycles and examined in an incident light microscope. The wear anvil was not cleaned, the oil merely being drained from the surface. The original machining grooves were visible indicating that sliding was negligible. However, unusual strings of dark pits were observed. See Figure 3.3-3.

The majority of these pits were arranged in straight lines parallel with the direction of motion. Often the density of the pits increased near a perpendicular scratch such as might be caused by an original machine mark. The spacing of the pits was unusually uniform, about 1 1/2 μm apart. Often parallel strings were seen side by side.

In some places the pits appeared in curved lines constituting a network somewhat like a railroad yard from the air, i.e., the curves followed parallel courses, Figure 3.3-4. The anvil was also examined with a scanning electron microscope. Typical lines of such pits are shown in the Scanning electron micrographs, Figures 3.3-5 through 3.3-8.

One theory is that these pits may be etch pits where edge dislocations intercept the surface. Presumably, the environmental conditions were such that the pits could be produced by surface attack. While the pits can be clearly seen with an S.E.M., they are much easier found with an optical instrument. This fact may imply that the pits are filled with a solid such as Fe_3O_4, prior to being removed by the cleaning of the specimen for the S.E.M. viewing. The region where the etch pit networks are seen tend to be high regions in the form of rectangular areas about 15 μm x 20 μm.

When the wear machine is set to slide and roll simultaneously, the pits are not generated, possibly because they are obliterated by smearing due to rubbing action.

Black marks suggestive of these pits are seen in many wear particles, particularly those from the shear mixed layer. It is possible that particles from the shear mixed layer may be etched by the environment. The exposed surface may likewise be attacked to decorate dislocations.

In view of the unexpected discovery of these pits, the previous experiment was repeated under the same conditions, but the test was not interrupted to change oil until 300,000 cycles had been reached. The specimen surfaces contained almost identical displays of pits. A Ferrogram prepared from the oil contained no spheres.

In another test, specimens of EN-8 (SAE 1040) steel heat treated to a hardness of 36 R.C. were run under the same conditions as reported above. Again the oil was changed and Ferrograms were prepared at intervals ranging from 53,000 to 74,000 cycles. Examination of the anvil at the end of 306,000 cycles showed a spall approximately 800 by 400 μm. The spall had a very flat bottom which averaged 58 μm below the original surface.

The surfaces of the test pieces were blasted with aluminum oxide to remove the scale formed during heat treatment resulting in surface of random irregularities of a few microns in extent. Even after running for 306,000 cycles the surfaces were still irregular. No long strings of dislocation pits evident in the test of the Armco 17-4 steel were found on these samples.

This test indicated that the SAE-1040 steel is more prone to fatigue spalling than the Armco 17-4 steel. Also, the contact wear machine produced the same type of pitting associated with heavily loaded gears.

A repeat of this test with SAE-1040 steel heat treated to a hardness of 47 R.C. produced a similar spall in approximately the same location on the anvil in 300,000 cycles.

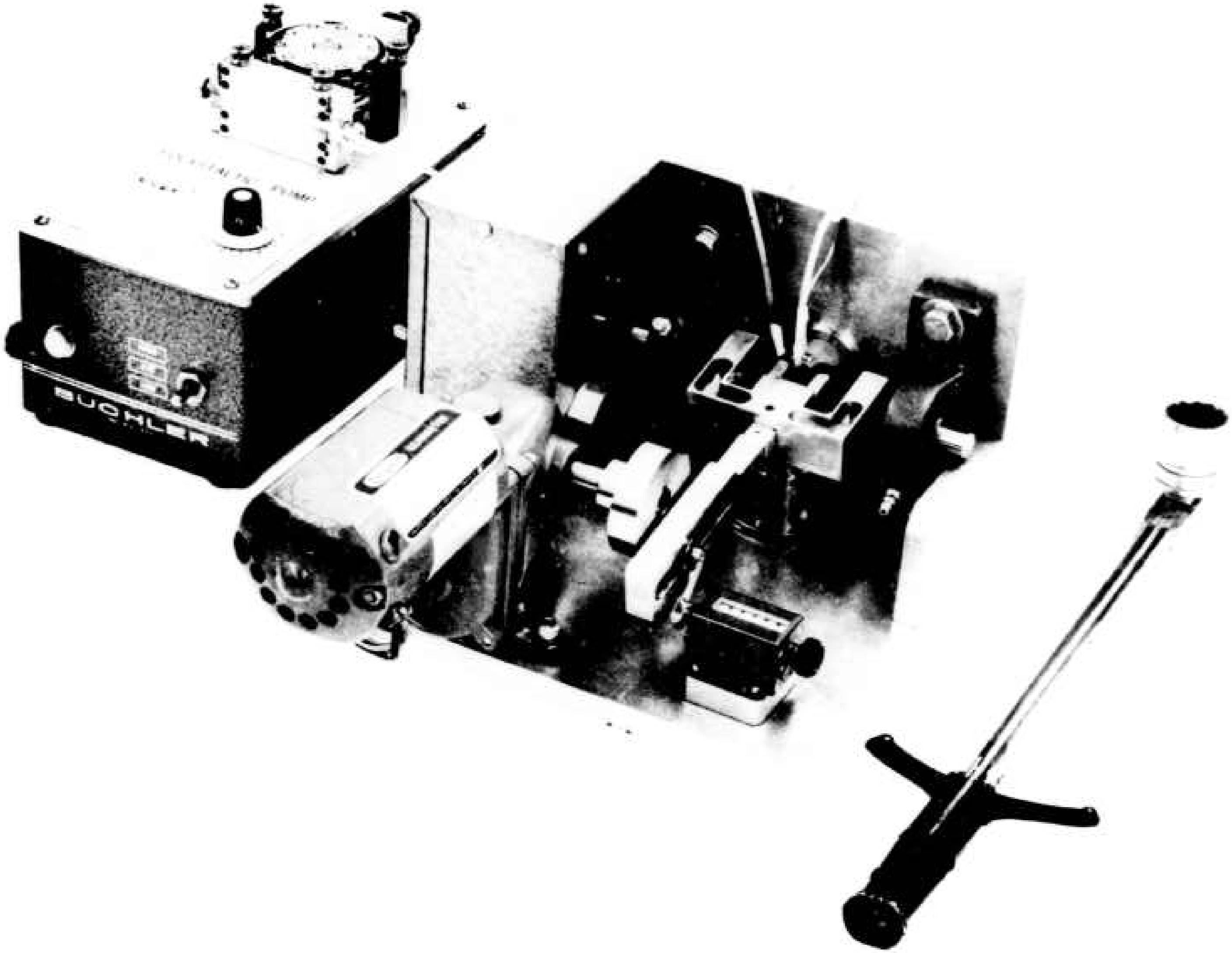


FIGURE 3.3-1 CONTACT WEAR MACHINE

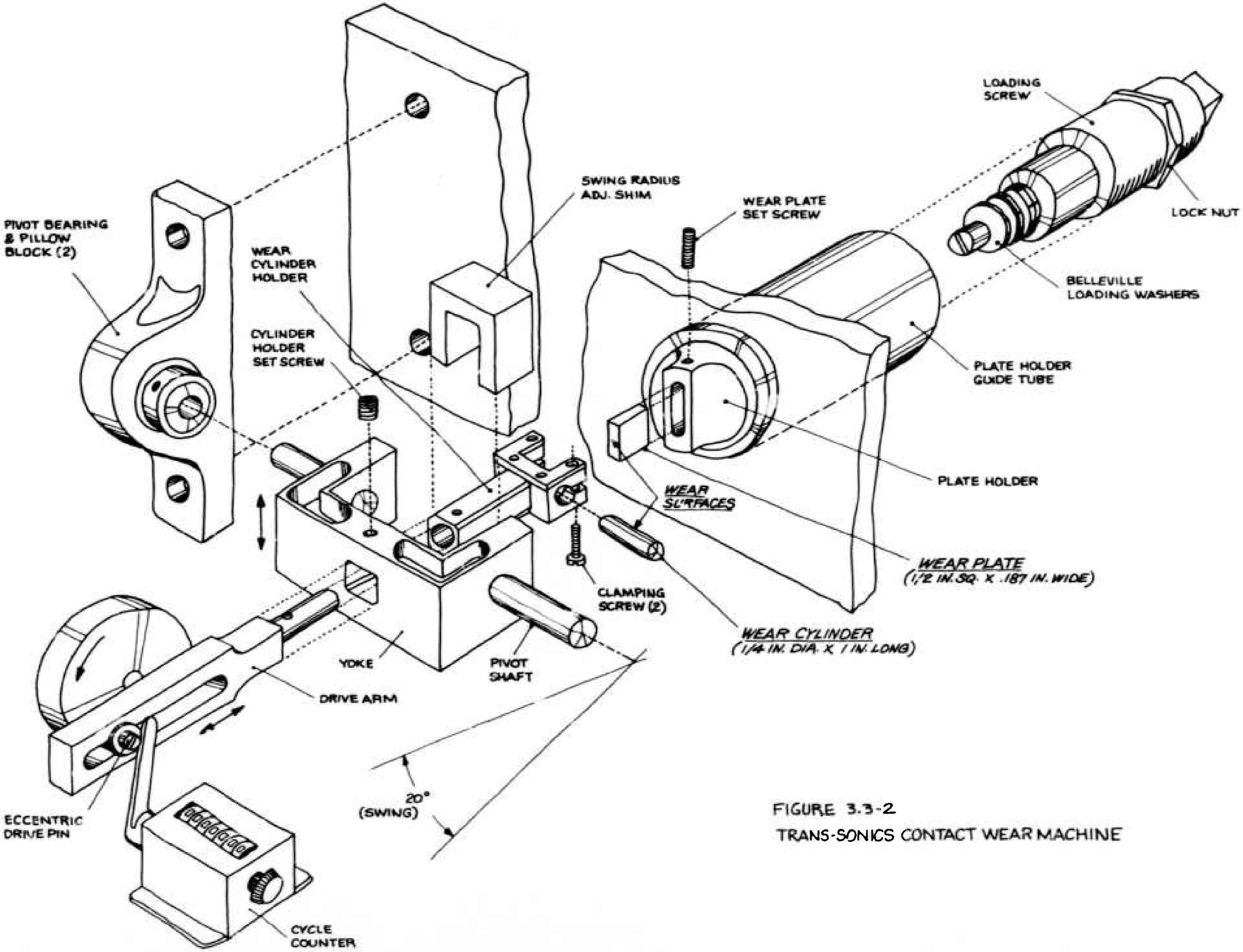


FIGURE 3.3-2

TRANS-SONICS CONTACT WEAR MACHINE

PHOTO NO. 3.3-3 **DATE** JULY 74

MAGNIFICATION: 1120X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c 37
±0.5mm Rolling Amplitude
No Rubbing Motion.

OPERATING HISTORY:

299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L 23699 (Mobil Jet II)

REMARKS:

Optical photomicrograph of strings of dark pits running parallel with the direction of rolling motion.

PHOTO NO. 3.3-4 **DATE** JULY 74

MAGNIFICATION: 1120X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c 37
±0.5mm Rolling Amplitude
No Rubbing Motion

OPERATING HISTORY:

299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L-23699 (Mobil Jet II)

REMARKS:

Optical photomicrograph of dark pit network. Note parallel curved strings.

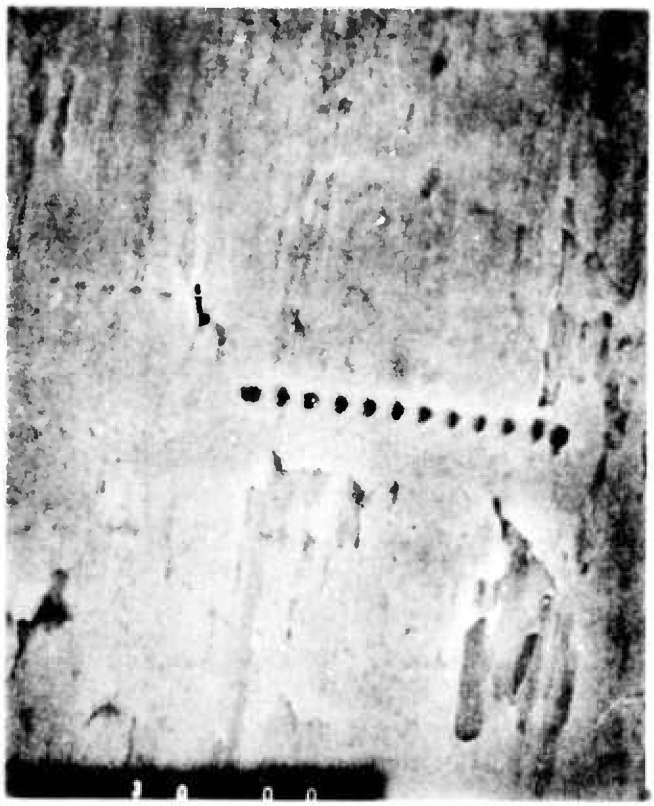


PHOTO NO. 3.3-5 **DATE** JULY 74

MAGNIFICATION: 3000X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c37
±0.5mm Rolling Amplitude
No Rubbing Motion

OPERATING HISTORY:
299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L-23699 (Mobil Jet II)

REMARKS:

S.E.M. photomicrograph showing typical lines of pits. Note triangular shape of pits.

PHOTO NO. 3.3.6 **DATE** JULY 74

MAGNIFICATION: 3000X

LOCATION ON
FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c37
±0.5mm Rolling Amplitude
No Rubbing Motion

OPERATING HISTORY:
299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L-23699 (Mobil Jet II)

REMARKS:

S.E.M. photomicrograph showing parallel strings and parallel curved strings.

PHOTO NO. 3.3-7 **DATE** JULY 74

MAGNIFICATION: 3000X

LOCATION ON FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c37
±0.5mm Rolling Amplitude
No Rubbing Motion

OPERATING HISTORY:
299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L-23699 (Mobil Jet II)

REMARKS:

S.E.M. photomicrograph showing network of pits.

PHOTO NO. 3.3-8 **DATE** JULY 74

MAGNIFICATION: 3000X

LOCATION ON FERROGRAM: N.A.

SAMPLE IDENTIFICATION:
Test No. 4140
Wear Anvil
Armco 17-4 PH Cond H900 R_c37
±0.5mm Rolling Amplitude
No Rubbing Motion

OPERATING HISTORY:
299,000 cycles at 200 R.P.M.
123 Kg force
Lubricant=MIL-L-23699 (Mobil Jet II)

REMARKS:

S.E.M. photomicrograph showing typical arrangement of pits near a machined groove. Note thin (white) metal extruded over machined groove.

4.0 CONCLUSIONS

1. Conventional fatigue failure whereby cracks propogate by cyclic stressing does not produce spherical particles. Thus spherical particles appear to be characteristic of rolling contact fatigue. Therefore, they are indicative of fatigue cracks in rolling bearing and gear surfaces.

2. Dark metallo oxide particles are not generated when soft steel slides on similarly soft metal.

3. Metallo oxide particles are not generated when hard steels slide on hard steels if the contact pressure is below a certain threshold value.

4. Dark metallo particles are generated when strong steels slide with respect to each other under heavy load.

5. Thin straight strip-like particles formed from the shear mixed layer are generated as cornices on the top of parallel grinding marks. Their strip-like shape is characteristic of the initial wear or "running-in" of ground surfaces.

6. Normal non-destructive sliding often results in the generation of flat, shiny bright particles which are very thin. These flakes may be taken as symptomatic of benign wear. They are normal on all machines.

7. Under some wearing conditions one steel surface can become very smooth, almost of optical quality, while the opposing rubbing surface may retain its initial roughness. The smooth surface is composed of a shear mixed layer, thought to have very small crystallite size (300 Å). The generation of such a smooth layer involves the flow of surface metal in a temporarily super plastic form.

   The study of this smooth layer and the particles from such a layer appear to be fundamental to the understanding of normal benign sliding wear and the clarification of wear theories.

8. Particles in the form of tiny chunks of steel having typical dimensions of 10 µm x 20 µm x 5 um with flat surfaces like cleavage planes, are characteristic of surface failure caused by spalling under heavily loaded contact. A low velocity high contact force rolling motion is conducive to their generation.

   The pits from which these particles spall, tend to have vertical sides and flat bottoms, characteristic of pitting of gears.

9. Lines of micron size pits are found on the surface of some steel parts that have been subjected to high force reciprocating rolling motions. It has been postulated that these lines are a series of dislocation etch pits revealed by lubricant attack. The extent of the lines of pits may reveal the range of surface crystalline order.

10. During the examination of a number of Ferrograms prepared as part of this program, it has been established that there is a considerable variation in the performance of lubricants formulated by different manufacturers to the same specific military specification. For example, wear rates ranging over an order of magnitude have been observed with different supplies of oils to MIL-L-23699, a controlling specification for jet lubricants.

    An investigation of the cuase of these variations has revealed that there is a marked difference in behavior of these lubricants under service conditions. Some of the oils generate copious quantities of a gel-like polymer which manifests itself by deposits on or near contacting surfaces, changes in the lubricant characteristics, and the morphology and behavior of particles contained in the oil.

The polymer produced by the lubricant as a result of the friction and wear processes becomes embedded with wear particles. Consequently these polymers are recovered on the Ferrograms even though the volume of polymer may be a small fraction of one part per million when related to the volume of oil. These polymers can significantly influence the subsequent behavior of the wearing surfaces because they are produced at the wearing point and often separate the wearing surfaces.

This aspect of the use of Ferrography to follow the generation of friction polymer under service conditions, can provide information leading to improvements in lubrication function and reliability. The next report will contain information and photomicrographs of a variety of polymers which have been discovered on Ferrograms as a result of selecting various lubricants.

APPENDIX 1

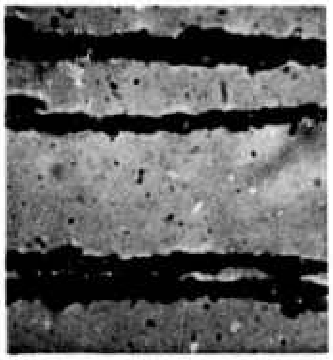
FERROGRAPHIC OIL ANALYSIS

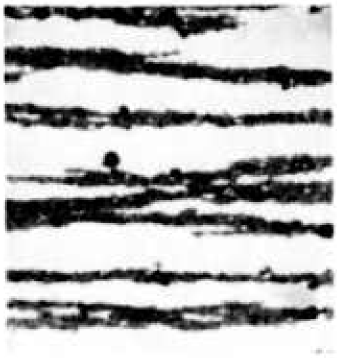
DESCRIPTION OF PARTICLES

FIGURES 1 THRU 40

FERROGRAPHIC OIL ANALYSIS

Photomicrographs of typical wear particles on Ferrograms


1 — 25 m —

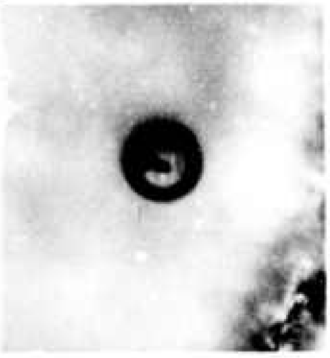

2 — 25 m —


3 — 25 m —


4 — 5 m —

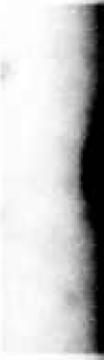

5


9 — 50 m —


10 — 30 m —


11 — 25 m —


12 — 10 m —

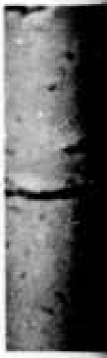

13


17 — 25 m —

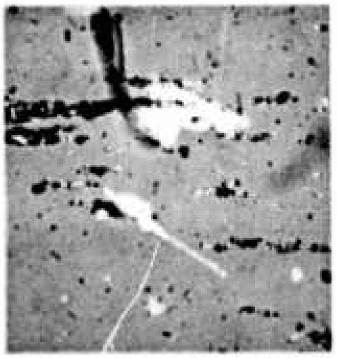

18 — 100 m —


19 — 25 m —


20 — 50 m —


21


25 — 50 m —


26 — 25 m —


27 — 50 m —

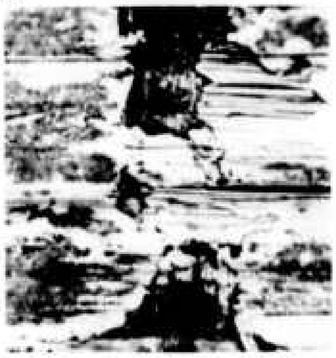

28 — 25 m —


29


33 — 50 m —


34 — 30 m —


35 — 25 m —


36 — 50 m —


37


5

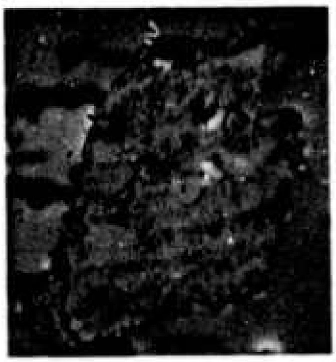

6


7


8


13

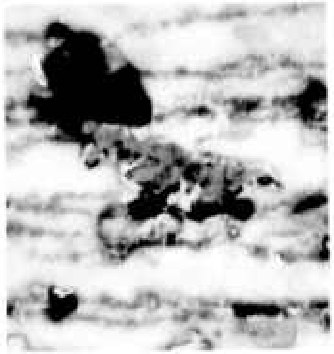

14


15


16

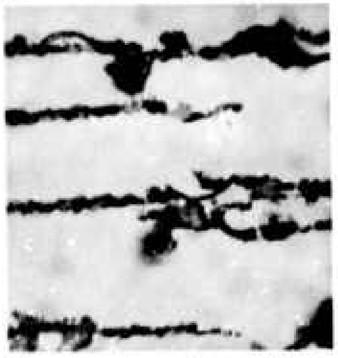

21


22


23


24


29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37


38


39


40

Description of Particles

The particles shown on the preceding page are described below. Black and white photographs were taken with scanning electron microscopes and we wish to acknowledge the courtesy of the following organizations in supplying these photographs.

Figure 4 - Coates & Welter, Sunnyvale, California
Figure 9 - National Bureau of Standards, Washington, D.C.
Figure 12- JEOL, Medford, Massachusetts

Figures 1 through 3 are Bichromatic photomicrographs of normal rubbing wear particles. The particles are from a Beilby layer on the surface of the metal. The Beilby layer has only short range crystalline order. This layer exhibits super ductility during formation and covers over the original machining marks and crevices. After repeated cycles the layer fatigues and little flakes strip off. The flakes are typically 0.75 to 1μm in thickness if the material is steel. Softer metals often develop much thicker Beilby layers.

The particles are precipitated into chains by the lines of force of the magnetic field of the Ferrograph. Figure 36 shows a Beilby layer in the process of formation. It is this layer that contributes most of the wear particles when a machine is running normally.

Figure 4 is a scanning electron photomicrograph of rubbing wear particles. Note the thin flake-like characteristics of these particles. Before wear particles could be recovered by means of Ferrography, it was generally thought that surfaces wore by the interactions of asperities. The asperities were often spoken of as little hills. The theory stated that as the asperities touched each other they adhered and a piece of the asperity was broken away, resulting in roughly hemispherical particles. Investigations using Ferrography have shown that most sliding wear is caused by the exfoliation or flaking off of the Beilby layer.

Figures 5, 6, 7 and 8. These figures show various examples of cutting wear particles. Cutting wear occurs when a part of one surface penetrates another to act like a tiny lathe tool. Occasionally cutting wear is caused by an abrasive particle which becomes imbedded in a softer material to form a small cutting tool. Under these conditions it is known as abrasive wear. However, cutting wear often occurs when there is no abrasive in the oil. A large number of cutting wear particles is a harbinger of failure.

Figures 9, 10, 11 and 12 are examples of steel microspheres which were generated in microscopic cracks in ball or roller bearing races and balls.

Figure 9 is a scanning electron microscope photograph of spheres attached to the bottom of a tiny spall region on a bearing ball. It is signficant to note that the surface of this spall is covered with smooth

42

flakes of Beilby layer, indicating that prior to spalling the motion of the crack polished the inside surface. A surface crack begins at a tiny dent in the surface and grows downward at a small angle until it reaches the depth of maximum Hertzian pressure, a few micrometers below the surface. At this point, the crack progresses parallel with the surface in the direction of rolling. As the balls roll over the crack, the crack tends to be sealed and high pressures in the order of the Hertzian pressure are generated in the oil within the crack. This causes the viscosity of the oil to rise until the oil takes on the properties of a semi-solid. One hypothesis is that the oil becomes sufficiently solid to polish the inside surface of the crack as the bearing balls repeatedly roll over the crack. Another hypothesis is that the upper side of the crack is stretched relative to the lower part as each ball rolls over it. This motion polishes the inside surface of the crack.

Figure 10 is an optical view of the large spherical particle in Figure 9. In this case, white light was used to illuminate the field of view from the top. Note the image of the tip of a ball point pen on the sphere. When an object is placed at an appropriate point in the microscope, opaque spherical particles will image the object whereas particles of other shapes will not. This property is used as a test to confirm that particles that look like spheres are indeed spherical.

Figure 11 is an example of spherical particles from the lubricating oil in a jet engine. A bearing failed a short time after this sample was taken.

32a

Figure 12 is a scanning electron micrograph showing a spherical particle from oil of a modern jet engine that had developed a bearing failure. Such spherical particles are generated in enormous numbers. Often a bearing will generate 500,000 to 1 million spherical particles. In one case, a single ball generated an estimated 6.7 million particles.

Figure 13 is an example of a sphere which is not composed of metal. This sphere is composed of a polymer of constituents of the oil. Such plastic spheres may be distinguished from metal spheres by their translucence.

In order to provide additional evidence as to the material of the sphere in Figure 13 the Ferrogram was heated to 625°F. At this temperature, the sphere melted and deposited metallic wear particles on t[illegible]ogram substrate. Figure 14 shows what is left upon melting of the sphere. The melted polymers spread out over a larger area and could easily be observed by the use of interference contrast microscopy.

Figure 15 shows a large laminar particle. This type of particle is formed from the Beilby layer and usually has holes. Laminar particles are generated most often by ball or roller bearings but can sometimes be produced by gears. The combination of high unit pressures and sliding possibly combined with rolling, seems to be necessary for the formation of these particles. When laminar particles are seen in combination with spherical particles such as those shown in Figures 9, 10, 11 and 12, along with sharp cornered Beilby particles as shown in Figure 16, it is an indication of bearing fatigue which will probably result in bearing failure. A few spherical particles are not ordinarily considered significant. But if a Ferrogram contains several dozen spheres and if the particles of Figures 15 and 16 are seen, it is generally an indication that a rolling bearing failure has occurred or is in the process of occurring. These particles sometimes appear 100 or more hours before a catastrophic failure is observed.

Figures 17 and 18 are examples of fatigue particles which have spalled from the face of gears. It appears that the gears develop a system of cracks perpendicular to the surface and close to the pitch line. When the cracks are deep enough, pieces spall out to form small chunky particles as are illustrated here. These particles often show many details on their surface and are notable for the fact that their thickness, width, and length are of the same order of magnitude.

Figures 19 and 20 are examples of corrosive wear. The oil in this case has become incompatible with the wear particles and presumably with the wearing surface. The particles were, therefore, converted to compounds, possibly a chloride or an oxide. In the Bichromatic microscope when using red and green illumination, compounds appear green and free metal particles appear red. It has been observed that polyester oils often become corrosive if incompatible gasket materials are used in the lubrication system. For example, if neoprene is accidentally introduced into the system, possibly by mistaking a neoprene gasket for a Buna N gasket the result can be as shown in Figure 19.

Figures 21 through 24 are examples of severe wear particles. Such particles are generated in great numbers when a machine is failing and one part is adhering to another with sufficient adhesion to be classified as galling. Such particles often have a bent or split appearance as evidenced by lines on their surfaces. As in the case of all major categories, one or two such particles would not be considered significant but the presence of dozens of such particles is almost invariably a forerunner of failure.

Figure 21. It will be noted that the severe wear particle in Figure 21 is much larger than the underlying rubbing wear particles which in this photograph are slightly out of focus because they lie below the larger particle. Also the larger particle is not oriented parallel with the lines of magnitude force. These facts are evidence that the particle is not steel and is of a non-ferrous material. Very often when such particles are observed, it is possible to identify the material by switching to white reflected light in which case it may be found that the particle is bronze and appears yellow, or the particle may be aluminum and in such a case will be extremely bright.

Figure 22 is an example of a severe wear particle obtained from the lubricating oil of a failing jet engine. In this case, a gear had become loose on its shaft and was rotating back and forth on the shaft constrained by a pin. The rotation caused galling and resulted in much wear material including the particle shown. It will be observed that there is a pair of small appendages, or legs, at the top of the particle and also a pair of appendages at the bottom. It is believed that these appendages are caused by the necking down of the metal as the particle is yanked from the underlying body of metal in the manner of a tensil specimen. In one case, a particle was discovered in which the outside surface was visible on top of a region with conchoidal fracture leading down below the surface with the appendages at the bottom. It appears that strong adhesion is necessary in order to create such particles.

Figures 23 and 24 are other examples of severe wear particles. It will be noted that the structure of the particles shows evidence of tearing or flow and it is this characteristic combined with the large size of the particles which is of note.

Figure 25 shows large bronze particles as viewed in white reflected light associated with strings of rubbing wear particles. Note the small black pebble-like particles that are incorporated in the strings of Beilby particles. These particles are composed of Fe_3O_4 and dissolved iron. They are usually associated with hard steels. The bronze particles are pieces of ball bearing separator which had failed by cracking and expanding due to centrifugal force. The separator in contact with the ball generated the large non-ferrous particles. These particles precipitated because minute quantities of steel are deposited on their surface making them weakly magnetic. The presence of the steel can be demonstrated by heating the Ferrogram to $625^{\circ}F$ for 90 seconds. In this case, the steel particles including the steel deposited on the bronze will turn blue whereas the bronze itself turns a dark golden color.

Figures 26, 27 and 28 are examples of non-ferrous particles which are deposited as a result of wearing against steel. Any system involving steel rubbing against a non-ferrous material can generate such particles.

Figures 29, 30, 31 and 32 are examples of rubbing wear particles generated by ball bearing systems. They sometimes exhibit large quantities of Fe_3O_4, magnetitie, which appears in the form of black pebbles. The presence of these black pebble-like particles is considered an indicator of the wearing of hard steels and, therefore, suggests such mechanical parts as gear teeth and ball bearing balls and races. Such particles are not always generated as a result of the wear of hard steels and the conditions necessary to develop the particles is now being investigated. It appears, however, that rolling bearings generally develop such particles.

Figure 33. Occasionally the lubricant of a machine will show high iron content as determined spectometrically. When a Ferrogram is made it is sometimes found that the iron is not in the form of wear particles but in the form of the red iron oxide, Fe_2O_3, that is rust. This figure shows such particles as viewed with reflected polarized light and a crossed analyzer. The light enters the particles, bounces around, and the direction of polarization is modified. Therefore, the light from the particles is able to pass through the analyzer. The light from the background is blocked by the crossed analyzer. In this way the colors of oxide and similar compounds can be viewed. Oil samples from marine machinery often show large quantities of oxide, sometimes with virtually no free

metal wear particles. When this occurs, it is an indication that the machine has rusted, possible because the oil has become contaminated with water. The remedy is to check the gaskets to find leaks and replace the oil. If, on the other hand, little oxide and large quantities of free metal wear particles were found, it would be an indication that the machine was failing and disassembly might be indicated. Here an examination of the particles determines the nature of the remedial action.

Figure 34 is a view in reflected polarized light with a crossed analyzer of iron oxide particles in the presence of a large number of normal Beilby rubbing wear particles. Since the numerical aperture of the microscope was high, the steel rubbing wear particles do not appear black but rather a steely gray. This is an example where the wear is principally rubbing wear and only a small amount of oxide is present. Occasionally, a new machine willproduce a high iron content in the oil but it will be seen that the particles are principally of oxide. Most often the high iron content will clear up with continued running as the surface rust which formed during the machine's manufacture and exposure to air is worn away.

Figure 35 is an example of a Ferrogram which has been placed on a hot plate at 625°F for a period of 90 seconds. Such a Ferrogram cools in 2 or 3 seconds after removal and can be immediately examined in the Bichromatic microscope. It will be noted that the steel rubbing wear particles appear blue. This is caused by a layer of oxide on the surface of the steel. This oxide which has an exceedingly high index refraction and may, therefore, be quite thin and still be 0.25 wavelengths thick for red light. The red light of the spectrum is, therefore, obliterated by cancellation of the reflection from the top surface of the oxide with the reflection from the metal below. The absence of red causes the blue color. Other metals do not turn blue under the same conditions. The large white particle is an aluminum particle which was so bright as to overexpose the film. Note that the aluminum particle is much larger than the steel particles as would be expected since aluminum is non-magnetic. The particle was apparently deposited as a result of having rubbed against steel. It will also be noted that the principal axis of the particle is not aligned with the magnetic lines of force, thus serving as another indication that the material of this particle is non-magnetic.

Figure 36 is a view of a partial Beilby layer formed on a cold rolled steel part. This is typical of the condition of a surface before a part has completely worn in.

Figure 37 was taken by interference contrast microscopy. This figure shows the worn surface of a bearing ball which was held stationary against a rotating disc. As a result, a Beilby layer was formed on the ball. The direction of motion of the opposing surface was from left to right so that the line running from the middle bottom to the left upper part of the photograph represents the end of the rubbing zone. In such a micrograph the vertical dimension is greatly amplified by virtue of the interference contrast technique and a small fraction of a micron change in level is clearly visible. It will be noted that Beilby material flows

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and that the Beilby layer has significant thickness along the exit line. However, even in this case, the underlying ridges of the polished bearing (polish is also Beilby material) is not completely obliterated.

Figure 38 is an example of a very large non-ferrous Beilby particle. Such particles occur occasionally when non-ferrous and ferrous systems rub against each other. This particle differs from the aluminum particle of Figure 35 in that it is in the order of 1 um thick and is, therefore, considered Beilby material.

Figure 39 is an example of two large non-metallic particles. The same particles as viewed in a scanning electron microscope are shown in Figure 40. Since the particles were coated with evaporated gold to make the substrate conducting, there is no way to tell that the particles are not metal. For this reason, carbon coatings are preferred if Ferrograms are to be examined by an SEM.

APPENDIX 2

A VERSATILE CONTACT WEAR MACHINE

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In conjunction with the development of Ferrography (References 1-3) as a diagnostic tool for industrial trouble shooting and the prevention of failure in service of critical machinery, it is essential to accumulate accurate information of the mechanisms of wear and the characteristic debris produced by such mechanisms.

Wear is a complex process and different forms of wear may occur simultaneously, thus the debris produced by sophisticated machinery under arduous service conditions may be complex in nature. A simple versatile test rig was considered necessary to allow the study of characteristic debris produced by various contact conditions and to relate this debris to the operative mechanisms during wear initiation and wear progress towards component failure.

The use of simple specimens readily manufactured from a wide variety of materials and a lubricating system adaptable to close control and sampling for Ferrography were desirable. To allow a clear insight into the mechanisms of surface failure, the characteristics of the debris produced and the factors controlling surface failure, the means of assessing in turn, significant variables were essential.

Figure 1 (*) shows an exploded view of the wear machine. The primary objective was to simulate in simple form the contact conditions experienced in heavily loaded slow speed gear systems. The test configuration consists of a small rectangular wear plate, 1/2 inch square x .187 inch wide and a mating cylinder, 1/4 inch diameter x 1 inch long. The wear plate is held

*See Figure 3.3-2

against the cylinder with a force determined by a stack of Bellville washers which may be adjusted to load the control surface with a force up to 300 lbs. A wide variation in the ratio of sliding to rolling motion can be achieved by adjustment of the position of the contact surfaces with respect to the pillow blocks pivot bearing centers. The cylinder is rocked back and forth by the eccentric drive through a variable speed electric motor. The oil reservoir, in the form of a disposable bottle is positioned below the specimens and the lubricant from the bottle is fed at a controlled rate over the contact by a peristaltic pump and drains back into the bottle.

Figure 2 (*) shows the experimental set-up. Preliminary tests were run with the machine adjusted to provide conditions of pure rolling with an amplitude of ±0.5 mm at the contact point at a speed of 200 cycles per minute. The specimens were fabricated from Armco 17-4 precipitation hardening stainless steel heat treated to a hardness of 37 R.C. The wear plate was milled and the cylinder turned; the surface roughness was approximately 16 u in RMS. Using a polyester lubricant to specification MIL-L-23699, the machine was run for periods ranging from 30,000 to 70,000 cycles under a load of 123 Kg. The lubricant was changed after each running period and a Ferrogram prepared. Following a run-in period the initial Ferrograms revealed extremely low wear as would be expected from pure rolling. The particles were generally in the form of fine particles, mainly oxides. After 168,000 cycles some spherical particles were present. These increased in number as the test proceeded to 240,000 cycles when some large pieces of metal indicative of fatigue spalls were present. From this point in the test until it was concluded after 300,000 cycles no spherical particles were observed. Repeat tests produced no spherical particles or fatigue chunks so it was concluded that the spherical particles were indicative of a propagating

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*See Figure 3.3-1

fatigue crack (Reference 4) and disappeared with the appearance of fatigue chunks which removed the crack.

Further tests have been carried out with specimens of conventional C.Mn. gear steel at various hardness levels under the same conditions and under conditions of mixed sliding and rolling. Ferrograms taken during these tests correlated generally with those from gear systems in service in that initially considerable miscellaneous shaped particles are produced. Then following run-in a steady state condition exists which produces small quantities of thin plate-like particles prior to impending failure when particle size and density increase rapidly.

It may be concluded that the machine simulates practical contact conditions, wear mechanisms and associated characteristic wear particles and offers many experimental advantages for the study of such phenomenon. A full report of the work will be published in due course.

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R. A. White obtained his Bachelor of Science degree in Mechanical Engineering at Worcester Polytechnic Institute in 1957 and is working for his external M. Science degree. Before joining Trans-Sonics, Inc. as a Senior Mechanical Engineer, he had wide industrial experience on helicopters, optical instruments and computors. He is currently involved in advance design and development work.