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FINAL REPORT
ON
SCANNING ELECTRON MICROSCOPY STUDY OF
6309 SIZE BEARINGS

JANUARY 31, 1971

Contributors

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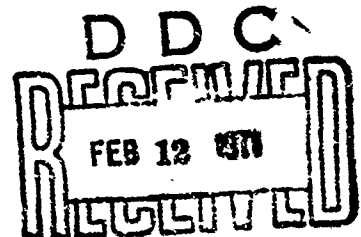
PROJECT LEADER: L. LEONARD U. S. Navy Contract: N00014-70-C-0229
U. S. Navy Project: NR259-055/12-11-69(463)
ESF Report: AL71C002
ESF Code: 6371-0835
ESF Project: 21-12
ESF Reg: 610 119
610 13

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KING OF PRUSSIA, PA.



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AL71C002

SCANNING ELECTRON MICROSCOPY
OF 6309 SIZE BEARINGS

SUMMARY

This report covers a study of 6309 size ball bearings in which the techniques of scanning electron microscopy were employed to follow the details of the very localized surface alterations which occur during running. This work reveals by scanning electron microscopy (SEM) various aspects of bearing surface finishing, the effects of surface morphology upon alterations induced by running, and the fine details of these very localized alterations.

Groups of carburized and through hardened bearings were studied after running in a controlled series of endurance tests designed to evaluate the effects of a range of elastohydrodynamic (EHD) running conditions upon life and surface alterations in general.

The SEM examination has yielded much information indicating that various competitive processes take place on inner ring surfaces as a function of several factors including lubrication, running time, and position relative to the bottom of the ball groove. In evaluating the effects of lubrication conditions on endurance life, the SEM information provides valuable supplemental data to film thickness or h/c calculations.

Surface phenomena observed in this study include pitting, denting, spalling, finger nail marks, plastic deformation and large complex dent-and-pit defects. The latter were a novel type of defect upon which one can postulate a model to account for the small L_{10} lives of some test groups run under high h/c test conditions.

↑
Diagram

-v-

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DETAILS

Introduction

In the interim report (1)* of this current sponsored research program, examples of surface topographical phenomena observed on 6309 size deep groove ball bearings were presented and discussed. The first stages of this investigation clearly demonstrated both the value of the scanning electron microscope (SEM) in bearing studies and the wide ranging nature of surface alterations which occur on bearings run under well lubricated laboratory conditions. Drawing upon the preliminary results, this present report covers a more detailed characterization of bearings tested within a systematic schedule of lubrication, speed and temperature conditions which define the elastohydrodynamic (EHD) parameter of h/σ the ratio of the lubricant film thickness h , to the composite rms asperity height, σ . Both carburized and through hardened grades of steel were studied and differences and similarities were noted.

Background

Early work in rolling contact fatigue concerned itself primarily with failures considered to be of subsurface origin. There is ample metallurgical evidence of subsurface initiated fatigue failures or spalls, and this experimental data is consistent with a failure model attributing spall initiation to the alternating shear stress, which occurs well below the surface, and the stress raising capacity of non-metallic inclusions. With the advent of vacuum processed steels and more extensive research, it was recognized that many rolling contact spalls originate at the surface, and it was shown that surface defects which exist prior to running can initiate failure. There is also evidence that defects which are generated and become apparent only after running can also act as spalling failure nuclei. Accordingly, there exists a strong need for experiments leading to an understanding of the mechanisms of surface initiated spalls. High resolution microscopy techniques are required in order to study the topographical and, metallurgical nature of bearing surfaces and the effects of rolling contact upon them. Light microscopy is severely limited by the very small depth of field obtainable at high

*Numbers in parenthesis refer to references at the end of this report.

magnifications, and replica transmission electron microscope (TEM) techniques, in addition to being very tedious, have many shortcomings particularly since the surface itself is not being directly observed. The introduction of the scanning electron microscope (SEM) has now made it experimentally and economically feasible to study bearing surfaces directly at high magnification and depth of field resolution, and to fully characterize morphology differences. Rather than describe the SEM here, reference is made to the interim report on this project (1) and to the ample literature on SEM⁽²⁻⁸⁾.

Since this is one of the initial projects concerned with applying SEM to bearing failure mechanisms research, its foremost goal was to characterize unrun bearing surfaces and to catalog the effects of rolling contact upon the surface morphology and failure modes. Theories regarding surface asperities and surface microgeometry can then be more critically evaluated along with the relative effects of wear and plastic deformation and surface alterations. Since lubrication conditions critically influence bearing fatigue life and failure mechanisms, a study of the role of lubrication and environmental conditions upon surface alterations was also included. To maximize the results from this program the 6309 size ball bearing inner rings studied were selected from a systematic series of tests conducted under separate SKF Industries projects to monitor the relationship between elastohydrodynamic lubrication conditions and endurance life. The tests are tabulated in Enclosure 1 and explained fully in the foot notes. In the body of this report, the tests groups will be referred to by the prefix to the code number (i.e. I, II, etc.) and by the abbreviated notation used in the "Test Condition" column of the Table (i.e. heavy oil, high speed).

The particular groups investigated here represented a spectrum of different lubrication regimes, with identical tests on two specific heats of steels - one carburized and one through hardened. Calculated values of the lubrication parameter h/σ served as guidelines in selecting these test groups. The tests conducted at high speed (9700 rpm), heavy oil (Mobil DTE Extra Heavy) are standard for SKF evaluation of 6309 size bearings, and the dead weight radial load of 4240 pounds (C/P = 2.15, AFBMA L10 = 10 million revolutions)

is conventional for the bearing industry. The low speed, heavy oil tests were conducted to evaluate the interrelationship of speed and viscosity. By lowering the test temperature the viscosity of oil increased and, in conjunction with the lower speed, yielded essentially the same calculated lubricant film thickness as in the standard tests. The low speed, light oil (Mobil DTE Light) tests were conducted with a lubricant from the same family of paraffinic mineral oils as the heavy oil standard test. The combination of this lighter oil and slow speed led to a calculated h/σ about 7 times less than standard. This calculated reduction was due solely to a change in h since the as-processed surface finish (about 1.5-2.0 microinches AA roughness) was approximately the same for all the bearings. Finally, the grease tests were run in order to evaluate the inner rings running response to conditions under which the oil in the grease, based on calculated h/σ values, should provide equivalent lubrication to the light oil tests. However, when running in the grease it is questionable whether the oil in the grease is completely effective in maintaining an oil film between the rolling elements. Furthermore under grease lubrication there is little of the debris removing flushing action characteristic of the circulating oil tests. Accordingly, the results for the grease tests are of particular interest with regard to both the endurance life behavior and the surface alterations resulting from the rolling contact.

It should be noted that the calculated values of h/σ based on roughness at the start of a test may vary by a factor of 2-3 from measured values due to the current limited state of EHD theory. However, the relative magnitudes among groups is believed to be fairly reliable. For example by employing AC electrical resistivity and capacitance techniques⁽⁹⁾, h/σ for the standard test conditions, i.e. high speed, heavy oil, as well as for the low speed (1500 rpm) heavy oil conditions, was found to be 4.5, while similar measurements for the 1500 RPM, light oil tests yielded a value of $h/\sigma = 3$. No measurements were made for the grease tests. Accordingly, the h/σ values given in Enclosure 1 are useful primarily for the comparison they afford between the several lubrication conditions rather than as absolute values in themselves.

Procedure

To establish standards against which to compare the effects of running upon the surfaces of 6309 size bearing inner rings, unrun surfaces were first analyzed. Specimens from the test groups in Enclosure 1 were then selected for the SEM study. After a preliminary observation of all the inner rings under a 10-20X binocular light microscope, the T.U. (time-up, or unfailed) bearings were selected on the basis of being representative of the individual groups. Since the JSM-U2 Scanning Electron Microscope employed in this investigation could not accommodate an entire inner ring, sections one inch long were cut from these rings. Other sections containing specific defects from both T.U. and spalled bearings were also examined in the SEM in order to achieve an overall impression of the types and magnitude of surface alterations. After the contact area of each ring section was examined in the SEM, micrographs were taken of both representative and of specific features. In order to facilitate the comparison of different surfaces, and different locations in the contact area, series of micrographs were taken at incremental steps transverse to the ball groove. In this manner the surface at the edge of the contact area could be contrasted with that at the bottom of the ball groove for each test group as well as with that of all other groups.

While all the bearings studied will not be discussed, an indication of the variations noted will be given in the discussions. For the evaluation of surface alterations as a function of lubrication conditions, attention was focused primarily on bearings that were still running intact (time-up or T.U.) when testing was suspended after sufficient failures had occurred to determine a statistical group endurance life (L10). In failed bearings, spalling debris was noted to have introduced much denting, gouging and surface deformation, and in many cases this overshadowed the cycle dependent general surface modifications evident on the unfailed races. Individual spalls from most of the test groups were studied in the SEM, and following the time-up data presentation, a brief discussion of spall morphology observations will be given. A comprehensive study of spall morphology was beyond the scope of this investigation.

Since the resolution of details in the SEM is very sensitive to surface topography, owing to the large depth of focus and the fact that the intensity of secondary electrons is enhanced at edges and elevated particles or asperities, any small surface defects are made much more obvious than in the light microscope even at relatively low magnifications, i.e. 100X or less. It is also important to keep in mind that the surface roughnesses being considered here ($2\mu\text{in. AA}$ or less) are very low and that high magnifications are required in order to resolve the fine details of the surface which are superimposed upon the finishing line texture, or "lay", which is visible to the eye. Thus, when magnifications up to 10,000X are used, small defects will appear to be very gross. This presents some difficulty in perspective when comparing the SEM micrographs with surface roughness measurements obtained in the standard manner of tracing a fine diamond stylus across the surface and recording its up and down motion. Since the radius of curvature of the tip of the standard diamond is 0.0005 inches, the radius of the curvature of the diamond tip would be 0.5 inch when looking at details in an SEM micrograph at 1000X. Accordingly, the details seen in the SEM micrographs at high magnifications are in many cases finer scale, higher frequency perturbations on the surface ups and downs measured by the stylus, which could not be expected to respond to all the microgeometry.

In this report only a few representative examples are required to convey the impression of the general surface appearances, however, many individual micrographs of deviations or defects, each a little different, could have been included. This would give much too high a defect population density. Furthermore, by considering what the total area of the ball groove of a 6309 size inner ring would be at 1000 magnifications, it can be seen that it would be very difficult not to find examples of defects. Accordingly, it was standard practice to scan the entire section of each ring placed in the microscope to first get a general feel for the surface morphology and defect population. Then representative micrographs of the general surface as well as defects were taken. When these latter type micrographs are discussed, special effort will be made to specify to what degree or extent such surface defects were noted.

Unrun Inner Ring Surfaces

All the inner rings of the deep groove 6309 size ball bearings studied in this investigation had been surface finished according to SKF Research Laboratory standards for the manufacture of endurance test bearings. The final surface finishing steps involved grinding and honing to about a 1.5 - 2 in. AA roughness, a quality characteristic of aircraft and other precision bearings. It is also standard practice to inspect at 10-20X under a binocular light microscope, all test inner rings after the following etching procedure: etch in 5% nital for 5-30 secs., rinse in H₂O and then alcohol, etch in 10% HCl for 10-20 secs. and finally rinse in H₂O and then alcohol. This etching procedure makes it possible to detect large surface inclusions, as well as the existence of heat treating or grinding defects such as rehardened, burned, cracked or soft areas. Since this etching removes a microscopically thin layer of metal it modifies the as-honed surface both with regard to fine morphology and the very near surface residual stress pattern. From information obtained to date, this etching is neither beneficial nor detrimental to endurance life under standard test conditions.

In Enclosure 2 are SEM micrographs of an unetched-unrun 52100 inner ring. Finishing lines are clearly evident as is the plastic flow of metal over these lines, apparently by the final honing operation. The slightly mottled background appearance in Figure B is from the large primary carbides ordinarily present in this steel. This conclusion is based upon the observations made on an etched section of this same ring (Enclosure 3), as well as on other standard etched 52100 rings. In Figure A of Enclosure 2 there can be seen an inclusion stringer, the center part of which was ground away in the bottom of the ball groove. During scanning, many other inclusions were noted on the surface of this ring and x-ray analysis in the SEM revealed mixed inclusions containing Al, Ca, Mn, and S. On the whole, the surface was relatively free of such inclusions which made those present appear quite obvious. This material had passed inspection for standard quality CVD steel and the observations here would not contradict that. However, what is of major consideration here, is that these deviations do

exist on a well finished bearing and must be taken into account when studying basic surface-initiated fatigue mechanisms and their causes.

A separate section of this unetched 52100 ring was then given the standard BF_3 etch treatment. The upper limits in etching times were used to determine the maximum extent of the etching. As can be seen in Enclosure 3, most, if not all of the plastically flowed metal has been removed, the finishing lines are no longer clearly evident and the carbides now stand out in relief. This is not unexpected since the thin layer of heavily cold worked matrix in the honed surface should be very reactive to the etch, more so than the less deformable carbides. The general appearance of the matrix is feathery, probably as a result of both the martensitic substructure as well as the non-uniformity, on a microscale, of the surface deformation. Finishing or handling nicks and surface inclusions can also be noted in Enclosure 3. In particular, in Figures A, B and C a large sulfide inclusion is evident.

In comparing the etched and unetched sections of the inner ring, the complex surface geometry of the etched piece makes it difficult to estimate how much metal is actually removed. It is obvious that more etching takes place between some of the carbides than between others. On the assumption that the depth of removed metal between carbides is about the order of magnitude of the carbide size, one can estimate about 10^{-6} inch removal. Since it appears that little of the carbide dissolves, the surface roughness measured by a stylus tracking profilometer should change very little with etching. This can be better appreciated by observing Figure C in Enclosure 3 and understanding that at this magnification the radius of the diamond tip of the surface measuring stylus would be 1.5", and thus would be expected to be little affected by the material removed from between the carbides.

Although the AA surface roughness of the carburized bearings was approximately the same (an average value of 1.3 microinches AA) as the 52100 steel, there were definite differences between the surfaces as seen in the SEM. Enclosure 4 contains SEM micrographs of an unrun carburized inner ring in the etched condition. All figures are generally typical of the surface

as a whole. Clearly evident in the micrographs are finishing lines, inclusions and some nicks and dents. Also shown in Enclosure 4 particularly at the higher magnifications, is a very fine substructure. This feathery appearance is again felt to be the result of etching based upon the information in previous micrographs for unetched and etched 52100 rings.

In contrast to the 52100 steel, the etched carburized steel contains no large carbides standing in relief on the surface. The surface had been carburized to about 0.9%C and, for this level carbon and the ~~ESF~~ heat treatment it underwent, there should have been no large primary carbides. In fact none were revealed in metallographic analysis. After a section of the surface was very lightly gold coated to improve resolution, (see Enclosure 4-D) a few little particles were apparent on the surface, but from their distribution they were most likely dirt particles.

In the carburized steel, finishing lines are more evident after etching than they were in the through hardened steel, indicating either that the general depth of lines is deeper or the etching may remove more metal in the heavily worked condition in the finishing lines on the carburized steel. This may be a direct consequence of the absence of the large carbides in the latter steel. The general impression gained from comparing etched 52100 and carburized surfaces is that in the former most of the high spots (asperity tips) on the surface are hard rounded carbides while in the latter, asperities are the general matrix metal. However, since the finishing lines are so narrow, as far as surface roughness measurements are concerned, the stylus would detect little difference between the two steels.

During the analyses of unrun inner ring surfaces, it was found that there was little difference in the quality of surface finish at the bottom of the ball groove as compared to close to the edge of the ball contact area. Enclosure 5 presents a series of SEM micrographs taken at different locations in the ball groove of a 52100 steel inner ring. The finishing lines run with the circumference of the groove (vertically in the micrographs). As can be seen by comparing these micrographs with those in Enclosure 3 this ring had probably experienced shorter times in the etching solutions. While the carbides are

also elevated, as in Enclosure 3, the effect is less pronounced than shown previously. Furthermore in Enclosure 5 there are locations particularly in Figure B where the etch has not completely removed the deformed surface layer. The specific defect at the bottom of the groove, Figure A, probably resulted from handling as it was not typical of the ring as a whole. Micrographs following those in Figure A were obtained by moving the field of view in the SEM in steps of 1 mm (as measured on a straight, horizontal line across the top of the groove), such that the left hand side of each micrograph is furthest from the center of the groove. In all the Figures both finishing lines and carbides are evident and it is plain that the surface, on a fine scale is very nonhomogeneous. However, the region appearing in Figure D, which is beyond the ball contact area, is very similar in topography to that in Figure A. Thus, differences in topography, as a function of location on the tested inner rings, can be interpreted on the basis of the running conditions rather than the initial morphology.

Endurance Tested Inner Ring Surfaces

In order to systematically include and analyze a maximum amount of data in this report, representative SEM micrographs of inner ring races from the bearings run under each of the test conditions noted in Enclosure 1 will first be presented and individually discussed. A brief summary of the observations follows this. Next there is a general discussion of similarities, differences and trends. Significant points are considered in more detail and a series of conclusions developed.

I. 52100 Steel - High Speed, Heavy Oil - 200 M.R.* ($h/\sigma = 14.9$)

As seen in the SEM micrographs of Enclosure 6 there are several obvious changes that running induces on the surface of an inner ring. The carbides that were clearly elevated

*The test group identification used here and in subsequent sections, corresponds to the terminology used in Enclosure 1. The complete test details and procedures are given in Enclosure I and its footnotes and hence are not restated in each test result section.

on the unrun surface have been flattened out, there is a relatively uniform pattern of small pits and there is some denting. Since the load distribution and slide to roll ratio vary across the contact area of the groove, the micrographs were taken at locations 1mm apart, moving from left to right across the groove transverse to the rolling direction which is vertical in the micrographs.

Figure A of enclosure 6 illustrates the appearance at the edge of the contact area where only slight contact had been made. The carbides have been noticeably flattened, there is some shallow pitting and there are some elongated, slightly curved gouges referred to as "horseshoe" or "finger nail" markings. When the specimen was moved 1mm toward the center of the groove, the surface appeared as in Figure B where the carbides are more flattened, and there are more finger nail marks which are more curved than in the previous case. This trend continues as seen in Figure C. Figures D and E represent the center region of the groove approximately between the two Heathcote bands. While the Heathcote bands are often quite obvious to the eye, this is apparently only a light reflectivity effect since no distinct surface morphology differences at the bands could be detected in the SEM for this or any of the other test groups. The finger nail marks which were evident in A, B and C are almost totally lacking in D and E. In Figure E (at the arrows) there are a few short straight gouges which are probably (as will be borne out by later micrographs of other test groups) the same type of marks. Micrographs were also taken of further portions of the contact area as the field of view on the ring was moved from left to right across the groove until the edge of the contact area was reached. Since the details mirrored those in Figures A, B, and C the micrographs are not presented here. The curvature of the finger nail marks, of course, was also reversed as is shown in the sketch in Enclosure 7.

The density of small pits is approximately constant in Figures C-E and the degree of plastic deformation as measured by the flattening of the carbides and smoothing over of the finishing lines is greatest at the bottom of the groove. The general transition of the finger nail marks across the groove is sketched in Enclosure 7. This same type of

configuration was noted in all the test groups. However, the density and severity varied among the groups and this aspect will be discussed further after the data for all the groups has been presented.

The presence of the finger nail marks and their configurations can be explained on the basis of kinematics. Since a ball and the inner ring groove each have a curved contact area and since the rolling axis includes an angle with the surface, the ball must have a spinning motion relative to the ring. This results in a relative sliding between the ball and groove which varies as a function of position along the major axis of the contact ellipse. At a fixed distance from the center of the ball path the sliding component is equal to zero. The loci of these points fall in two bands known as Heathcote bands which run circumferentially around the surface of the ball groove. The magnitude of the sliding component changes sign at each band and increases with distance from the band, reaching a maximum near the edge of the contact area. This spinning of the ball, in combination with an asperity on the ball surface or a debris or dirt particle trapped between the ball and the inner ring surface, causes the finger nail shaped marks on the inner ring. The length and shape of the marks vary with distance from the center of the ball path in a manner consistent with this explanation. In the region between the Heathcote bands, the sliding component is small and almost in the direction of rolling leading to marks which should be relatively short and straight and make it difficult to distinguish them from other surface markings. Furthermore, the plastic deformation of the surface is greatest in this region and this may help mask the appearance of the finger nail marks. Since small pits were always noted on the inner ring surfaces after running, there is an ample supply of particles to interact with the sliding and cause the marks, even if one assumes no extraneous contaminant, which in general are always present.

The pits in the micrographs in Enclosure 6 are surrounded by glazing (smoothing of the surface by plastic deformation) to some extent. In the bottom of some of the pits there is an indication of the presence of carbides standing above the surface as in the case of the etched surface. If this is so, the pits may have been open to the pre-test etch through small cracks and during initial running the material may have spalled out. This is only speculation at this point since higher magnifications could not clearly resolve the carbides. On the fracture surfaces of large spalls, carbides have never been found to stand out in relief as they do on an etched surface.

II. 52100 - Low Speed, Heavy Oil ($h/\sigma = 17.6$)

There were no time-up bearings in this group for which the L10 life was only 17.5 M.R. The longest life was 82.6 M.R. in contrast to the 200 M.R. time-up achieved by 16 of the 26 bearings in the heavy oil, high speed test.

The surfaces of several inner rings which had spalled were studied in the SEM. The debris from the spalls had caused such extensive denting and marking of the surface that it was difficult to judge which surface alterations had preceeded the spalling failure. However, in Enclosure 8 which illustrates a region between the Heathcote band and the edge of the contact area on an inner ring which failed at 70 M.R., the carbides are plainly evident, indicating that the general deformation of the surface was limited. In comparing this to a similar position in the ball path for the previous group (Figure C, Enclosure 6), there appears to have been less deformation in the low speed test group consistent with both its calculated thicker oil film and its shorter running time.

Since the life data for comparable groups of the 52100 and carburized steels follow the same trends, the discussion of the surfaces for the carburized steel, low speed - heavy oil test group, for which T.U. inners were available should also apply here. Accordingly, no further discussion of the 52100 steel will be given at this point.

III. 52100 - Low Speed, Grease - 54.5 M.R. ($h/\sigma = 2.1$)

SEM micrographs of a bearing from this group are in Enclosure 9. A stepping scan transverse to the ball path similar to case I was carried out. Again, since the surface characteristics were symmetrical about the center of the groove, the micrographs in the Enclosure cover only approximately half the groove. Near the edge of the contact area, Figure A, sufficient deformation took place during the 54.5 M.R. test life to render the carbides unresolvable above the surface. Many large shallow pits, and a multitude of finger nail marks are apparent. Nearer the center of the groove, Figure B, the pits are fewer and smaller and the degree of plastic deformation is greater. In particular, in the high magnification view in Figure B, it is evident that the deformation involved a good deal of metal flow parallel to the surface in addition to the general flattening observed in the high speed - heavy oil tests. The finger nail marks in Figure B are also almost obscured by the plastic deformation. In Figure C near the bottom of the groove, relatively few pits are seen and even at 1000X the surface is almost featureless except for some very small pits and dents. To the eye, this area appears highly burnished, a condition which is common in bearings run at low h/σ values and which is referred to as glazing. From this series of micrographs it can be determined that the degree of plastic deformation is highest at the bottom of the groove and diminishes with distance to the edge of the contact area. However, the extent of pitting goes in an inverse manner. This appears to be a real effect and not a smearing over of pits in the heavily deformed regions of the groove. This is particularly true of the larger pits which, of course, would require a high degree of smearing to be obliterated. The few large pits and dents in Figure D show little signs of such smearing.

IV. 52100 - Low Speed, Light Oil - 99.9 M.R. ($h/\sigma = 2.1$)

The L_{10} life for this test group was not determined accurately, since within the original design of the broad testing program sponsored by SKF, the behavior of this group relative to others had been sufficiently established.

Nevertheless the observations of surface alterations after 100 M.R. do contribute to the overall understanding of the effects of lubrication conditions during running.

Enclosure 10 illustrates the variations in surface appearance as a function of position within the ball groove. The surface in general, shows little pitting, denting or finger nail marks. The plastic deformation, which, as in the previous groups is greatest at the bottom of the groove, (Figure D) appears to be limited to a thinner layer of the surface than the previous groups. The basis for this statement is the fact that the lower areas in the surface are accentuated by elevated carbides, as is characteristic of the unrun state previously discussed. This is illustrated in Figure E of Enclosure 10 and also in a more pronounced fashion in Figure F which contains micrographs of another T.U. bearing from this group run for the same number of revolutions. (The coloration differences on the surface resulted from lubricant degradation products which were not removed from the surface in the process used to clean the bearing prior to examination in the SEM. Such a surface film can modify electron charge build up on the surface and can also affect the scattering efficiency of secondary electrons from the metal surface leading to the coloration differences noted.)

The major characteristic of this bearing group is that the surfaces show few pits, and as a result of running appear to have a better topography in that the asperities have been uniformly flattened without excessive plastic deformation and glazing. The running times for this group were 100 M.R. as compared to 200 M.R. for group I and thus it is difficult to assess whether the L_{10} life of this group would equal that of the high speed - heavy oil test group or whether further surface deformation would occur to obliterate remaining traces of the original surface. Nevertheless, the long running times of the group compared to the other 52100 groups in Enclosure 1 are consistent with the surface observations in the SEM and indicate that the lubrication conditions were conducive to avoiding surface initiated failures.

V. Carburized Steel - High Speed, Heavy Oil - 400 M.R. ($h/\sigma = 14.9$)

As seen in the scanning micrographs in Enclosure 11 the surface characteristics after running depend on the location within the groove. Finger nail marks are most pronounced at the top of the contact area of the groove while plastic deformation is most obvious at the bottom of the groove. In contrast to the previous 52100 steel groups, the degree of denting was more severe in this group and the density of pits more numerous particularly at the bottom of the groove (compare Figure E, Enclosure 11 with Figure E of Enclosure 6). The longer running time of 400 M.R. may account for some or all of this difference. However, this long running time did not lead to the finishing lines being completely flowed over by the plastic deformation. The noticeable folding over of metal into the finishing lines indicates that plastic flattening of the higher spots (asperities) and not a wearing away of the surface is responsible for the improved smoothness of the surface evident both to the eye, in the form of luster, and in the SEM micrographs as true surface topography modification. As exhibited in Enclosure 11 there is a broad range in the sizes of the dents, with many dents being larger than the pits. This indicates that while some of the denting may have arisen from the pitting debris many dents must have been caused by dirt carried by the oil or possibly from wear or spall particles from the ball cage, the outer ring, or the balls. Since the oil circulation system had a 25 micron filter, dents equal to or smaller in diameter than this size could have been caused by debris continuously recirculated by the oil. At 1000X a 25 micron size dent would measure 25mm, which is larger than any of the dents visible in the micrographs. Of course it should not be expected that a debris particle would leave an imprint equal to its full size. All of the dents observed would fall within a size range consistent with their being caused by debris.

VI. Carburized - Low Speed, Heavy Oil - 49.9 M.R.(h/σ = 17.6)

As presented in the scanning micrographs in Enclosure 12, the time-up bearings from this group showed fewer general indications of having experienced running than any of the other test conditions. The number of pits, dents, and finger nail scratches in Enclosure 12 is low, and the degree of plastic deformation was minimal as shown by the fact that the finishing lines are clearly evident at all locations in the ball path. Of course, the running times were much shorter than for the high speed - heavy oil tests, which may account for much of the difference. However, past studies on the run-in phenomenon, based on measuring asperity interactions by electrical conductivity and capacitance techniques, have shown that the bulk of the asperity interaction indications occur well before 50 M.R. in high speed - heavy oil. Thus it would appear that some of the difference in surface deformation between the high and low speed heavy oil tests may be due to the lubrication conditions and not only to the difference in the number of cycles.

The low density of finger nail scratches in this group is consistent with the absence of debris from pits. However, the calculated thicker oil film separating the rolling elements certainly could have played a role in reducing the effectiveness of surface asperities and dirt in the oil in producing the scratches.

Under the 10X light microscope and also by eye, a few large, shallow, surface defects, were found at various locations in the ball groove of the time-up bearings. Some representative scanning micrographs are presented in Enclosure 13.

Within the defects, the surface material looks as if it had been moved by a denting or, in some areas, a plowing operation. With further running, there apparently was a mashing down of the higher spots which in turn leads to high glazing. Such glazing around defects can lead to cracking as has been reported in past reports (10-13) and as seen in Enclosure 14 which shows cracking in the glazed area around a similar type pit on the surface of a 52100 steel unfailed inner ring from the low speed light oil group.

In the bearings from this carburized low speed - heavy oil group no evidence of cracking in conjunction with the defects was found. However, it is reasonable to assume the low life of the group is associated with them, especially since the general surface appearance indicates little signs of running other than these defects. With further running, cracks could very well initiate in the glazed region, as in Enclosure 14. Further discussion of this will be presented in a later section.

Enclosure 15 shows similar shallow defects found in the low speed heavy oil group of bearings made of 52100 steel, all of which had spalling failures as mentioned previously. The edges of some of these defects, such as the one shown in Figure C of Enclosure 15, were raised above the original surface plane whereas others appeared as if subsequent running after initial defect formation had apparently mashed down these edges.

VII. Carburized - Low Speed, Grease 49.9 M.R. ($h/\sigma = 2.1$)

Scanning micrographs of the surface appear in Enclosure 16. The extensive shallow pits near the edge of the ball contact region (Fig. A) and the finger nail marks are similar in appearance and number to those in the 52100 steel bearing run under the same conditions. The denting and the plastic moving around the surface metal (Figures B, C and D) is significantly more pronounced than in the 52100 steel. There also is a high density of apparent finger nail marks in the bottom of the ball groove in contrast to the extreme smoothness or glazing that was noted in the 52100 steel (Figure D, Enclosure 9). The marks which occur as relatively broad, almost rectangular indentations or gouges are superimposed on the plastic deformation effects as shown in Figure D of Enclosure 16. The high degree of deformation and denting makes it difficult to evaluate the true extent of pitting in the bottom of the ball groove. However, at this location it is possible to note the absence of the extensive pitting that is seen at the edge of the contact area of the groove and also to find more evidence of pitting than in the 52100 steel.

VIII. Carburized - Low Speed, Light Oil - 199.9 M.R. ($h/\sigma = 2.1$)

The testing of this group was not complete, but several bearings had reached the T.U. of 200 M.R. One of these was available for sectioning for study in the SEM. The series of micrographs representing the different locations in the contact area appear in Enclosure 17. There are fewer finger nail marks and dents on this inner ring than on the carburized, high speed - heavy oil tests. The longer running times of the latter tests may account for some or all of this difference.

AL71C002

The fine details of the plastic deformation, which was greatest at the bottom of the groove, indicate a greater severity of flow of surface metal in this carburized ring as compared to the corresponding 52100 test group (99.9 M.R., Enclosure 10). The asperity interaction of the contact surfaces should not be expected to be as great during the additional running time from 100 to 200 M.R. as during the first 100 million cycles, since the majority of contacts flatten early in the running. Accordingly, some of the more extensive deformation in the carburized group can be attributed to the nature of this steel as compared with the 52100 steel. This will be considered in more detail in the general discussion later.

The density of small pits is similar for both the carburized and 52100 steel light oil groups, but in the carburized inner rings there were many indications of larger pits and incipient spalls as shown by Enclosure 17. The pits in Figure E are apparently associated with inclusions; those in Figures C, D and F may have originated at inclusions also, but positive identification of inclusions was not obtained. Since only one ring was studied it is not certain that these pits are typical of the entire group. However, since such pronounced surface defects were not found on any of the high speed - heavy oil test rings of this same carburized steel after 400 M.R., it is felt that this finding indicates the superiority of the lubrication conditions in the high speed test, consistent with the calculated h/σ values.

SUMMARY OF OBSERVATIONS OF TIME-UP INNER RINGSI. 52100 - High Speed, Heavy Oil - 200 M.R.*

- 1) A few large shallow pits exist near the top of the ball path.
- 2) Elevated carbides are still visible after 200 M.R.
- 3) The carbides and the surface in general have been plastically deformed; the carbides appear closer together than on the unrun surface.
- 4) The degree of plastic deformation was greatest at the bottom of the ball path. There are small pits and a few dents near the bottom of the groove.
- 5) The "finger nail" marks or scratches are longest at the edge of the ball path and become much less apparent in the area between the Heathcote bands. (See the sketch in Enclosure 7.) This distribution of the scratches is essentially the same for all the test conditions.

II. 52100 - Low Speed, Heavy Oil

There were no time-up inner rings in this group. Spalling debris obliterated the surface detail characteristics of the time-up life prior to spalling.

III. 52100 - Low Speed Grease - 54.5 M.R.

- 1) The shallow pits at the edge of the contact area are the largest and most numerous observed in all the lubrication conditions.

*See Enclosure 1 for full details of test conditions.

AL71C002

- 2) Plastic deformation and glazing are greatest at the bottom of the groove where there is little pitting. No carbides are resolvable in this area.
- 3) Denting in the ball groove is not obvious - high plastic deformation may mask it.
- 4) The finger nail scratches occur in common with all bearings; they are more numerous than in I.

IV. 52100 - Low Speed, Light Oil - 99.9 M.R.

- 1) The pitting at the top of the ball path is similar in severity to I; and, as in III, there is more pitting at the top of the contact area than in the bottom of the groove.
- 2) There is high glazing at the bottom of the groove, but unlike the grease lubricated group (III) finishing lines can still be resolved. A few carbides, particularly in depressed areas of the surface, are resolvable. The plastic deformation is apparently limited to a shallower surface layer than in cases I and III.
- 3) Denting is not pronounced.
- 4) The finger nail marks are similar to I.

V. Carburized - High Speed, Heavy Oil - 400 M.R.

- 1) Some of the pits at the top of ball path are larger and shallower than in the bottom of the groove.
- 2) Finishing lines at all locations in the groove are still readily resolvable after 400 M.R.
- 3) The surface has been plastically deformed as evidenced by the flow of metal over the finishing lines. Much more denting is apparent than in corresponding 52100 steel group.

- 4) Plastic deformation is greatest at the bottom of the groove. There are small pits and many dents of various sizes at the bottom of the groove.
- 5) There are many finger nail scratches - more than in the 52100 groups. This may be due to longer running times. In the center of the groove the marks are short and relatively broad.

VI. Carburized - Low Speed, Heavy Oil - 49.9 M.R.

- 1) This group of bearings showed the least overall surface damage in terms of pits, dents and plastic deformation of all the test conditions.
- 2) A few relatively large, shallow multi-fragment pit and dent groupings on the surfaces of T.U. inner rings from this group were obvious to the eye or in the light microscope.
- 3) The finishing lines were only slightly altered by plastic deformation; some furrows were made particularly obvious since glazing occurred primarily around deeper finishing marks and the few defect groups which occurred.
- 4) While the plastic deformation was greatest at the bottom of the groove, many details of the original surface are still obvious.
- 5) There are few finger nail scratches evident; this may be the effect of the low density of pits or the thicker (calculated) oil film.

VII. Carburized - Low Speed Grease - 49.9 M.R.

- 1) There was heavy pitting near the edge of the contact area, very much like III. (52100, grease lubricated).
- 2) There was much mashing around of the surface metal particularly at the bottom of the groove.
- 3) There was much more pitting and denting than in III and over most of the contact area the finishing marks were obliterated.

- 4) There are many apparent finger nail markings at the bottom of the groove. They appear as short, stubby straight indentations superimposed upon the plastic deformation effect on the surface.

VIII. Carburized - Low Speed, Light Oil - 200 M.R.

- 1) Shallow pits occurred in all regions of the contact area, although the large multi-fragment pit and dent groupings found in VI were not evident.
- 2) The degree of surface deformation was greatest at the bottom of the groove and was greater than for the corresponding 52100 steel group (IV) but similar to the high speed - heavy oil carburized group (V).
- 3) There were more large pits than for groups IV and V and many of the pits appeared to be incipient spalls.
- 4) There were slightly fewer finger nail marks than group V but a comparable number to group IV.

DISCUSSION

Plastic Deformation and Denting of Surfaces

In the observations of bearing surfaces presented previously, plastic deformation was always a factor in the topography modifications. The results of the deformation have been demonstrated in the scanning micrographs and mechanisms by which this deformation occurs will now be considered. If two metal surfaces are pressed together such that high spots (asperities) on either or both surfaces make contact with the other surface, the load will be carried by small areas resulting in very high stresses leading to both elastic and plastic deformation of the asperities. The high spots can then plastically flatten out until an increase in contact surface leads to a decrease in stress and an end to the plastic deformation. If there were no lubricating film separating the surfaces during rolling contact, surface deformation should occur in the above manner. In the presence of a thin lubricant film deformation could still occur. Those asperities which penetrate the film would be deformed as described. Since a particular area on a ball continuously changes the position where it contacts the inner ring, various asperities on both surfaces could continue to interact even after long running time. However, the probability of such interaction should decrease with running. Electrical measurements of contacts between the elements in a bearing indicate that the above is a valid model of the run-in of a bearing (14, 15).

Once a full film has been established there remains several ways in which the surfaces can continue to deform. The debris particles which can flow through the 25 micron size oil filter are large compared to the oil film thickness. (For an $h/\sigma = 15$ and a 1.5 μ in surface roughness, the film thickness would be about 0.8 micron). The occasional debris particles (metallic or non-metallic) can get trapped between the contact surfaces and in the highly loaded bearing tests in this investigation help cause further deformation of the surfaces.

With a full film and no debris, there can always be small increments of non-reversible strain accumulated with each cycle since the microyield point of metals is well below the macro or engineering yield stress. The formation of the white or light etching areas of structurally altered metal below the race way (12) is another example of deformation accumulated in small increments over a large number of loading cycles. Since the SEM results indicate surface deformation progresses with running, it appears very likely that accumulation of microplastic increments is responsible for surface deformation after long running times. The observed flattening of the elevated carbides in the 52100 steel during running can be explained by a combination of the mechanisms described above. Likewise one can explain the small degree of surface deformation under the relatively thicker film in the low speed, heavy oil tests as compared to the other test conditions. Furthermore a general improvement in surface topography by deformation in the high speed - heavy oil and low speed - light oil tests can occur without excessive true asperity interactions between the metal surface themselves. This type of deformation may be beneficial to some extent and this topic is discussed further in the next section which considers the correlation of life data, calculated h/σ values and observed surface topographies.

The SEM micrographs illustrated that plastic deformation was greatest at the bottom of the ball groove and that the density of micropits was generally lowest at this location, indicating that uniform deformation may delay or preclude micropitting. In the case of the low-speed heavy oil (thick film) tests there was little plastic deformation and the few surface defects that formed were large and visible to the eye or under low power light microscopy. (See Enclosure 13). These were found in all locations within the contact area

and were similar in size to the largest defects of the other test groups found near the unrun edge of the contact area where the deformation was the least. In the case of the low speed - heavy oil carburized inners, the defects, as discussed previously, had many aspects of both pits and dents indicating some external factors, such as debris of some multifragmented type, must be taken into account in addition to deformation. In the grease lubricated bearings the large pits were particularly pronounced at the edge of the path which was the only location where deformation had not completely mashed over the original surface characteristics.

That these multifragmented dented defects did not seem to appear at the bottom of the grooves in any test groups other than the low speed - heavy oil groups can be explained with several conjectures. In the high speed - heavy oil tests the combined lower viscosity and higher speed would serve to produce a greater flushing action of sweeping debris out of the contact area in front of a ball in the load zone. In the low speed - light oil tests the lower viscosity might preclude debris entrainment whereas the high viscosity oil might help trap debris particles. In addition, the light oil used in the tests was supplied from a different system than used in the heavy oil tests and was set up for this particular test program. The oil was new and hence there very well may have been less debris being generated in this system than in the heavy oil system which contained oil that had been in use for a greater period of time. Of course, further work would be necessary to evaluate these postulations but at present they provide a framework within which to develop the direction of future investigations.

Endurance Life Dependency on Lubrication

The very close similarity between the ranking of L_{10} lives of corresponding test groups of the two test steels indicates that the surface initiated failure behavior was strongly controlled by the lubrication conditions, in spite of the widely different matrix microstructure, inclusion characteristics and residual stress pattern for the two different steels. The general similarity of the surfaces of corresponding groups after running further supports this theory.

As stated earlier, the bearing groups studied were run under the various speed and lubricant conditions in order to achieve experimental data upon which to extend the elastohydrodynamic lubrication theory of bearing life. According to this theory, bearing endurance life should be a direct function of several lubrication factors including the parameter h/σ , especially in the range ($h/\sigma < 3$) where significant surface asperity interaction occurs. The L10 and calculated h/σ data in Enclosure I reveals that for both the heavy oil - low speed and light oil - low speed tests factors in addition to the film thickness/roughness ratio, as calculated, interacted to define life. This is true for both the 52100 and carburized steels. However, the measured h/σ for the low speed - light oil tests was higher than calculated, indicating an ability of this oil to generate thick EHD films (perhaps due to unknown non-Newtonian effects and the lack of significant thermal and starvation effects). Since this measured $h/\sigma = 3$, it is not surprising that no drastic reduction in life below that for the high speed - heavy oil conditions, for which the measured $h/\sigma = 4$, was found.

The low speed, heavy oil test conditions were characterized by a higher calculated h/σ but an L10 life of 5 to 20 times smaller than the high speed tests with the same oil. Reduced churning at the low speed led to a lower running temperature and hence to a higher viscosity and film thickness. Even if measured h/σ values rather than calculated values are used (measured $h/\sigma = 4.5$ for both conditions), they do not account for the large difference in the L10 lives of the low speed and high speed heavy oil test groups for each steel.

The surface topography noted in the scanning micrographs described previously does indicate that a thick film did exist in the carburized, and most likely in the 52100, low speed, heavy oil tests. The least surface plastic deformation of all the tests was noted for this condition. The fact that the running time was low does not seem to account for all this difference as was discussed previously. Likewise, there was very little pitting, finger nail marks, or classical debris denting, although these were the only groups on which few large multifragmented dents were all over the tracks, especially in the critical high pressure region at the bottom of the ring grooves. In short the surfaces of the time-up bearings were

closest to looking like they had not experienced running, except for these unique few multifragment dents. Yet, the L_{10} lives of the heavy oil-low speed groups were essentially the same as that for the grease lubricated inner rings which showed the most pronounced surface damage and were expected to have a low L_{10} life. The multifragment dents, therefore, must have been influential in reducing life.

SEM observations on the run bearings given previously can assist in the evaluation of the test results, particularly if they can provide some insight into the actual steps leading to ball initiation. Accordingly, in the following discussion an attempt is made to apply the available data in proposing self consistent models explaining the life data.

The high L_{10} life of the low speed, light oil test groups can be accounted for on the basis of several arguments. The measured value of h/σ for the light oil tests was about 3 compared to a value of about 4.5 for the high speed - heavy oil tests, indicating essentially just as good lubricating conditions between the two sets of groups than indicated by the calculated h/σ values in Enclosure I. Thus the light oil conditions apparently provided sufficiently good lubrication to prevent surface initiated failures long enough, that eventually subsurface initiated or furrow initiated fatigue became the dominant failure modes. In that case little difference in L_{10} life would be expected between the high speed - heavy oil and low speed - light oil tests. However, on long lived time-up bearings it should be expected that differences in the lubrication conditions should become manifest by observing the surface alterations. In fact the SEM micrographs support this postulation.

The plastic deformation of the surface in the high speed, heavy oil tests after 200 M.R. was more pronounced than for the low speed, light oil 52100 tests after 100 M.R. (Enclosure 6 vs Enclosure 10) indicating the longer running time in the former case more than offset the effects of the slightly poorer lubrication in the latter case. However, when comparing the surfaces of the carburized steel after 400 M.R. under high speed - heavy oil conditions and 200 M.R. under low speed - light oil conditions (Enclosure 11 versus 17), it becomes quite apparent that after these longer running times, the poorer lubrication condition can make itself manifest. The

carburized, light oil test inner ring showed significant deterioration of the surface, particularly in the form of pits containing cracking.

It would be interesting to continue the testing of the light oil groups to determine if the trend noted for the carburized steel is repeated in the 52100 steel and also to see if the carburized steel could achieve the 400 M.R. time-up life of the high speed - heavy oil group. It would seem that the pitting and cracking, if representative of the carburized light oil test group, should preclude this.

In the grease lubricated bearings, the high surface deformation noted in both steels and the extensive denting in the carburized steel indicate the ineffectiveness of the lubricant system in separating the contact surfaces and removing debris from the bearing. The heavy deformation or glazing essentially exhausts the metal's ductility or ability to deform further and hence can lead to crack initiation. Such cracking has been often noted in the glazed regions around defects as shown in Enclosure 14-A.

The short lives of the low speed - heavy oil test groups are the hardest to explain especially since the absence of extensive general pitting, surface deformation or finger nail marks indicates that the oil film probably did separate the surface efficiently. While surface plastic deformation may be beneficial to life it is not reasonable that the apparent limited deformation in these groups should totally account for the short lives. It is more likely that the large multi-fragment defects shown in Enclosure 13 are intimately involved in the failure mechanism. As discussed previously these defects may arise from debris interaction with high viscosity effects in the oil. While there is little doubt that such extensive defects as seen in Enclosure 13 can lead to spalling from heavily glazed areas near their edges, further work will be necessary to show conclusively that the defects lead directly to spall initiation.

The Effects of Etching on Endurance Life

As stated early in this report it is standard SKF practice to visually inspect all test inner rings prior to testing. To facilitate the detection of defects a chemical etching procedure which removes some surface metal is employed. Comparison endurance tests under high speed - heavy oil conditions in the SKF Laboratory both with and without this etch have not shown any significant effect of the etching on endurance life. No such comparative test results exist under poorer lubrication conditions. There is, however, evidence in the literature (17) in which an improved rolling contact life was shown to result from electrolytic removal of a surface layer.

In many of the surface defects found after running, intergranular facets were noted, as seen in the few examples in Enclosure 18. These facets may have been the result of brittle fracture stemming from hydrogen pickup during the etching procedure, although it was not shown they are limited to etched parts. Embrittlement due to acid pickling is documented in the literature (for example see Reference 19). Since it also has been shown that a cold worked steel is particularly sensitive to such embrittlement, the non-uniformly deformed layer in the as-honed inner rings would certainly be susceptible to hydrogen pickup and localized brittle cracking as seen in Enclosure 20.

Finger Nail Marks

These marks, which appeared to varying extents on all bearing inner rings studied, can be explained on the basis of the kinematics of the ball and groove in conjunction with surface asperities on, or (less likely) debris between, the contact surfaces.

The extent of the finger nail scratches for any particular test is a function of the number of revolutions. With increasing running time (comparing the time-up 5210C and carburized rings under heavy oil, high speed conditions) the number of pits and marks both increased. In the grease lubricated bearings in which there was more pitting at the edge of the contact surface and in which the debris was not flushed out of the

bearing as in the tests in circulating oil, the number of finger nail marks was very high. For the tests run at low speed with both light and heavy oil, the time-up bearings exhibited relatively few finger nail marks. In the case of the light oil the lubricant film thickness, even though calculated to be relatively small, was actually measured to be large enough to provide substantial separation of the surfaces. Therefore, it is reasonable to expect the relatively few marks observed. It is also reasonable that the new oil in the light oil lubricant circulating system had less debris accumulation than the older heavy oil and this helps to account for the small number of marks. In the case of the low speed - heavy oil groups the thicker film, the low density of pits and the short running time can all contribute to the few finger nail marks. Since it is hard to imagine debris large enough to bridge the film leaving such sharp marks as those observed, it is likely that these marks are caused by surface asperity interactions.

While the marks correlate with the degree of surface pitting, they in themselves do not appear to affect endurance life. There was no evidence to indicate that surface failures or pitting originate at the marks. This is to be expected since the marks are generally less pronounced defects than those introduced during finishing. As can be seen in a number of the enclosures showing bearings with long running times, some of the marks have their edges plastically folded over in much the same manner as the original finishing lines.

Spall Characteristics

This program was primarily concerned with correlating surface alterations induced by running with endurance life and lubrication conditions. In the course of studying the surfaces, a few spalling failures were also observed in an effort to determine if spall initiation can be documented using the high depth resolution and magnification capabilities of the SEM. Enclosure 19 contains an example of a spall which was apparently initiated at the pit at the entrance end of the spall. Although the lower half (exit end of the spall) is not included here it is readily apparent that the spall is composed of many segments which exhibit a range of

morphological characteristics. A region in the center has clam shell markings characteristic of fatigue but there is no evidence to indicate that this was the initiation point of the spall as a whole. The extensive surface cracking evident at the entrance end of the spall was also present at the exit end as well and was also characteristic of other spalls showing that spall propagation proceeds both in and opposite to the rolling direction. Enclosure 20 contains micrographs of a metallographically polished cross section of the spall in Enclosure 19. The pronounced branching of the cracks in Figures A and C is very evident and it can be seen that several pieces of metal in the spall are about to flake off. The fact that spalls form in small fragments and that these fragments do not drop off in a single step of crack growth indicates that the crack propagation is not catastrophic and also explains why most of the surface at the spall bottom is very smooth and relatively featureless. The individual fracture faces undergo extensive rubbing against each other prior to the piece flaking out. This is also true of the bottom of the spall at its entrance end where there is a backward undercutting of the groove surface. This would certainly preclude the balls directly causing the smoothing by contacting the fracture surface after the material spalled out. In Figure 20-B it is readily apparent that each time the ball passes over the entrance of the spall it would press down the metal in the process of flaking out. The cantilever action would cause much rubbing and would obliterate the details of the fracture characteristics and crack growth.

In most of the spalls studied the propagation in the running direction was generally greater than in the opposite direction. The cracking at the entrance to the spall makes it difficult to assess whether pit or dent occurrences at the entrance initiated the spall or were formed subsequent to spall formation. This, of course, in many cases precludes establishing the spall origin.

CONCLUSIONS

Based on the foregoing discussions on the plastic deformation of the bearing surfaces and the interpretation of the scanning micrographs it is possible to arrive at some conclusions concerning lubrication and bearing endurance life. While further research is necessary to confirm some aspects of these conclusions, it is felt that in their present form they provide a framework for understanding failure as influenced by lubrication and also serve as a guide in designing future research.

- 1) The strong dependency of L_{10} endurance life upon lubrication conditions (h/σ parameter) in a given steel is indicative of surface initiated fatigue failures.
- 2) The alterations which occur on the contact surface of 6309 size inner rings are a function of a number of factors including lubrication, running time, type of steel, and relative position in the ball groove. The nature and extent of the alterations can in most cases be correlated with the endurance life of each test group.
- 3) Endurance life is not solely a function of the h/σ parameter, either calculated or measured. In greased tests, debris action is a detrimental factor; in some low speed-high viscosity tests, an anomalously short life was noted which is probably explicable by unusual multifragment dents existing on the run surfaces.
- 4) The variation in the surface modifications as a function of position across the ball contact area is due to kinematics (sliding) and not to an initial characteristic of the surface.

- 5) Micropitting of inner ring surfaces is a general phenomenon occurring under a variety of lubrication conditions, including those that are considered full film conditions. The density of the pits is a function of the degree of plastic deformation of the surface and position within the ball groove. The pits do not preclude long life. However, after long running times there is evidence of cracking within the pits and cracking in the glazed areas around the larger pits which can lead to spalling failure.
- 6) Plastic deformation of the surface layer of a bearing inner ring occurs under full film lubrication regimes as well as under marginal conditions. When this deformation is not excessive, it does not preclude long life and in fact may conceivably be beneficial to life through geometrical improvement of the surface and through introduction of desirable compressive residual stresses on the surface.
- 7) In the limited range of tests studied, no significant differences in life or pronounced differences in surface alterations were found between the carburized steel and the through hardened 52100 steel in any of the lubrication conditions. The elevated carbides in the etched 52100 steel parts may have contributed to the lesser degree of surface denting and plastic deformation compared to corresponding tests with carburized steel.
- 8) Spall morphology is very complex. There are a series of cracks involved in spall propagation and there is much evidence of rubbing of fracture surfaces indicating crack propagation involves many loading cycles. Spalls clearly propagate both in and opposite to the direction of running.

F-410A R 100

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ENCLOSURE I

6309 BEARING TEST DATA

Code	Steel (1)	Test (2) Conditions	L ₁₀ Life M.R.	Calculated EHD Parameter h/ (3)	Lubricant	Speed RPM	Temp. °C (4)	No. of Brigs. in Test Group	FAILURES		
									Inner Ring	Outer Ring	Ball
I-9581	52100 CVD	High Speed Heavy Oil	89	14.9	Mobil DTE Extra Heavy (7)	9700	95-105	26	6	0	4
II-9589	52100 CVD	Low Speed Heavy Oil	17.5	17.6	Mobil DTE Extra Heavy (8)	1500	45-55	18	10	6	
III-217-1	52100 CVD	Low Speed Grease	9	2.1	Shell Alvania 2 (9)	1500	70-120	20	12	0	3
IV-217-2	52100 CVD	Low Speed Light Oil	>34(5)	2.1	Mobil DTE Light (10)	1500	74-84	14	0	0	4
V-9584	Carb. 8620 CVM	High Speed Heavy Oil	161.5	14.9	Mobil DTE Extra Heavy (7)	9700	95-105	20	5	2	1
VI-9585	Carb. 8620 CVM	Low Speed Heavy Oil	7.9	17.6	Mobil DTE Extra Heavy (8)	1500	45-55	13	2	2	0
VII-9586	Carb. 8620 CVM	Low Speed Grease	14.3	2.1	Shell Alvania 2 (11)	1500	70-120	15	4	0	0
VIII-9590	Carb. 8620 CVM	Low Speed Light Oil	137(6)	2.1	Mobil DTE Light (10)	1500	74-84	15	3(6)	-	-

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ENCLOSURE 1 (Continued)

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Notes:

- 1) All inner rings of the 52100 through hardened steel were from the same heat and were heat treated identically to a final hardness of $R_c 59$.

Similarly, all the carburized 8620 inner rings were from the same heat of steel, heat treated to a final hardness of $61R_c$.

The outer rings and balls, not being the test elements in this series of tests, were taken from standard stock manufactured from 52100 CVD steel. The balls had a hardness of $62-63R_c$ while the outer ring hardness was $59-61R_c$.

- 2) The test conditions listed in this column are broad classifications primarily for identifying bearings discussed in the body of the report. More details are given in the following columns.

Endurance testing was conducted on SKF Industries high speed R2 test machines under a dead weight radial load of 4240 lbs. ($C/P = 2.15$, AFBMA, $L_{10} = 10$ mill revs). For oil lubrication, the rate of the oil flow and auxiliary heating were controlled to maintain the temperature within test limits.

- 3) The elastohydrodynamic (EHD) parameter primarily reflects the lubrication conditions of the test since the surface finish was approximately 1.5 microinches AA for all the test inner rings. The calculation of h/σ is based upon the measured surface roughness, σ , and a lubricant film thickness, h , which is calculated using speed, temperature and lubricant viscosity data according to the theory of Grubin (16).
- 4) Temperatures were monitored on the outer ring of each bearing. The test machines are programmed to stop if the temperature goes beyond specified limits.

F-406A R 100

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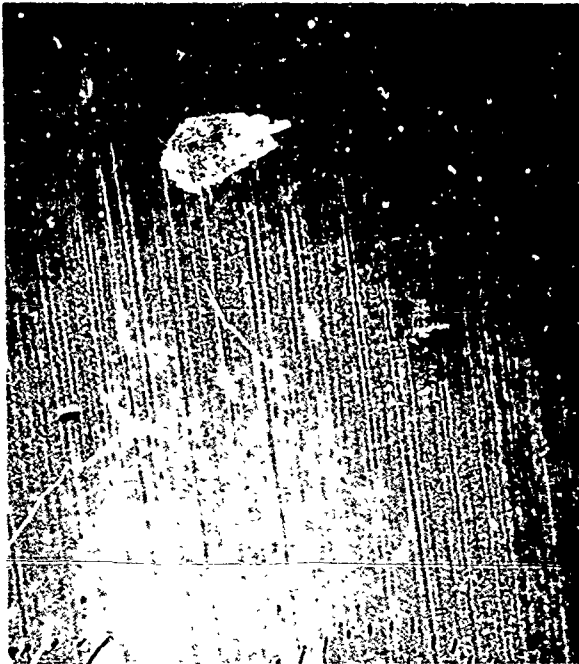
ENCLOSURE 1 (Continued)

- 5) Tests were suspended with no inner ring failures after 99.9 million revolutions. Since four bearings failed due to balls spalling, the figure in the table represents an estimate of the minimum life of an inner ring in the absence of other bearing element failures.
- 6) Tests are not yet complete; the L_{10} life is an estimate based on three inner ring failures which have occurred, the earliest at 106 million revolutions.
- 7) Bearings were splash lubricated with oil from a central lubrication system. The oil was continuously circulated through a 25 micron filter and the flow rate was regulated to maintain the desired test temperature. Groups I and V were run according to the standard SKF endurance test conditions, under which extensive data on particular heats of steels or heat treatments have been accumulated.
- 8) The lubrication system was the same as 7.
- 9) The bearings had no seals and were recharged by holding a wick with a supply of the grease against the face of the bearing while it was running. This procedure was carried out every 8 hours.
- 10) The oil was filtered and fed to the bearings in the same manner as the heavy oil in 7. However, a separate oil system was used for this lighter oil. The oil was heated slightly to maintain the outer ring test temperature.
- 11) The lubrication procedures were the same as in 9 except the bearings were regreased after every 24 hours of running.

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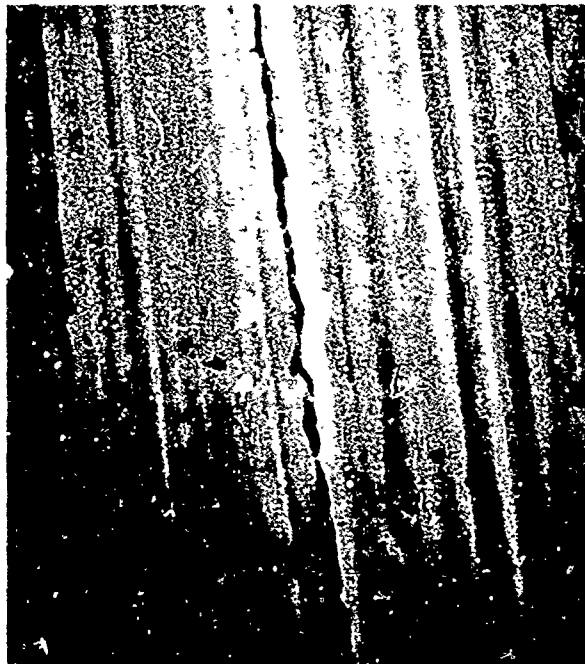
ENCLOSURE 2

CONTACT SURFACE OF UNRUN (UNETCHED) 52100 STEEL



400X

A. General surface appearance.
Note inclusion stringer.



5000X

B. Finishing line partially
smeared over in honing operation.

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ENCLOSURE 3

CONTACT SURFACE OF UNRUN (ETCHED) 52100 STEEL



300X

A. General surface appearance. Note carbides in relief and large inclusion.



1000X

B. Higher magnification of the center region of A.

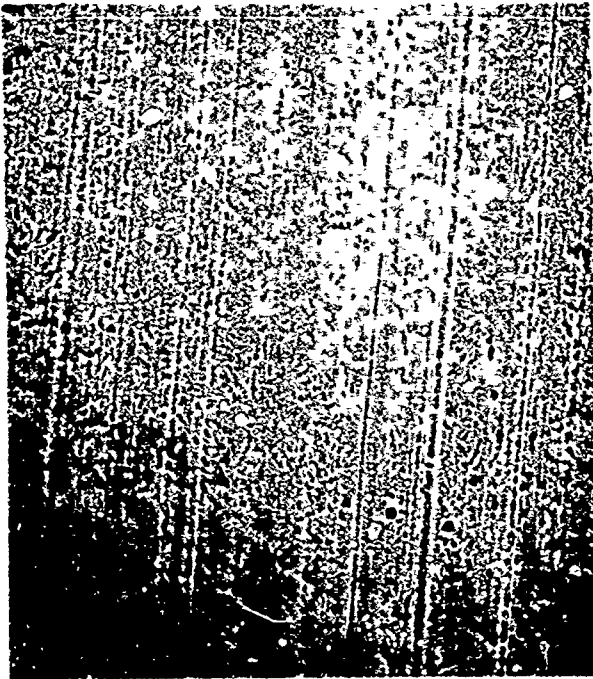


3000X

C. Higher magnification of the center region of B. Note finishing marks in inclusion and etching out around it.

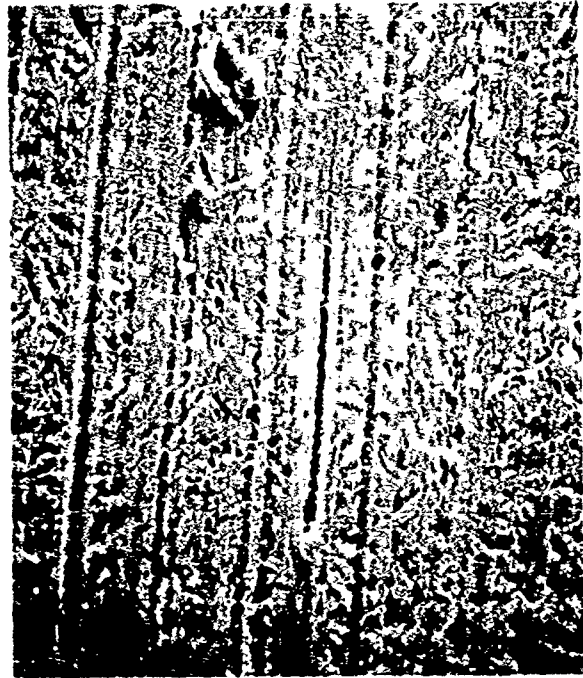
RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 4

CONTACT SURFACE OF UNRUN (ETCHED) (CARBURIZED STEEL

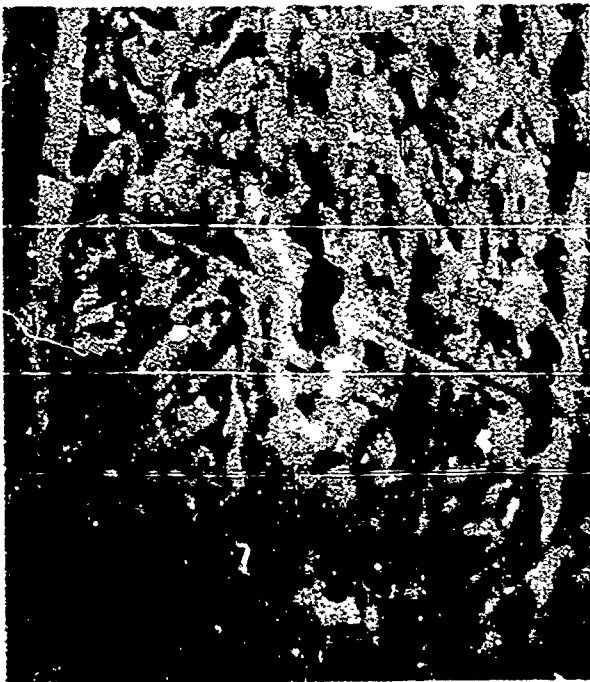
1000X

A. General appearance.
Note inclusion stringer.



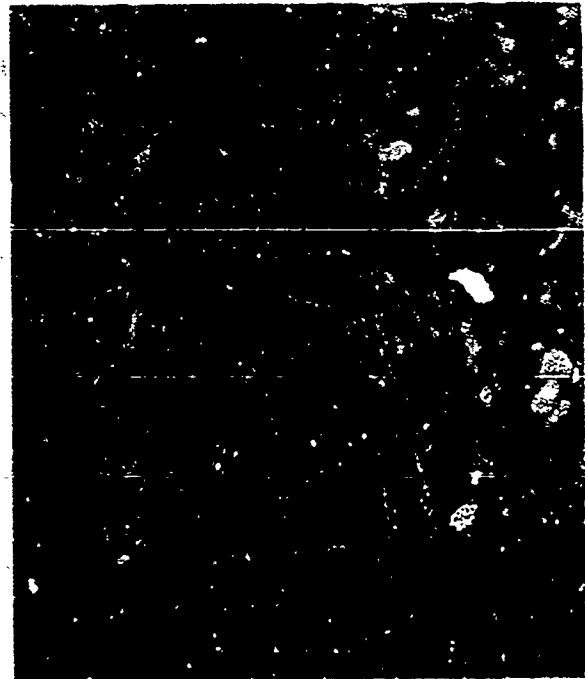
2000X

B. Several nicks and furrows.



6000X

C. General surface appearance.
Several inclusions have been
pulled out.

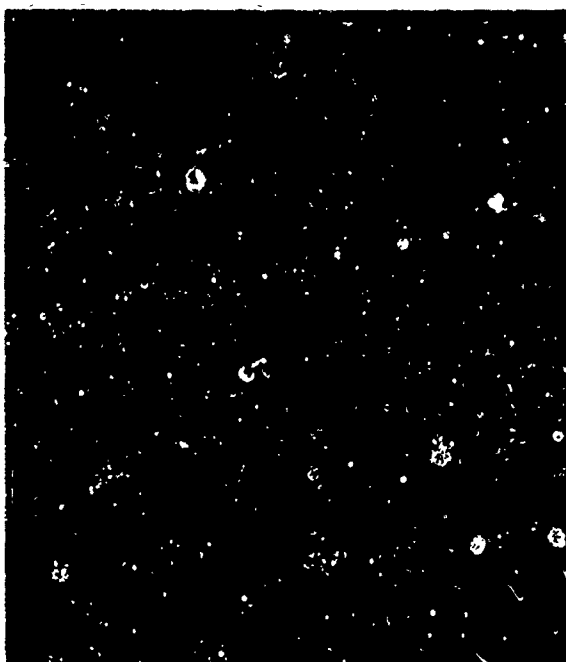


10,000X

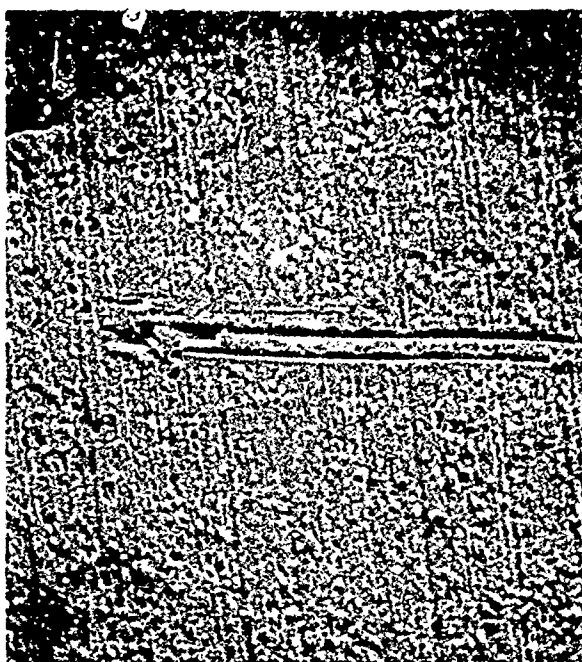
D. General surface appearance.
(Gold coated).

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ENCLOSURE 5

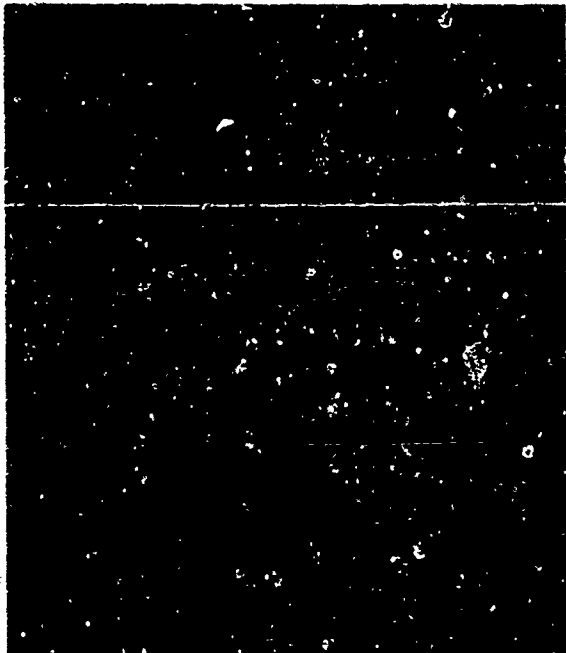
CONTACT SURFACE OF UNRUN (ETCHED) 52100 STEEL

300X

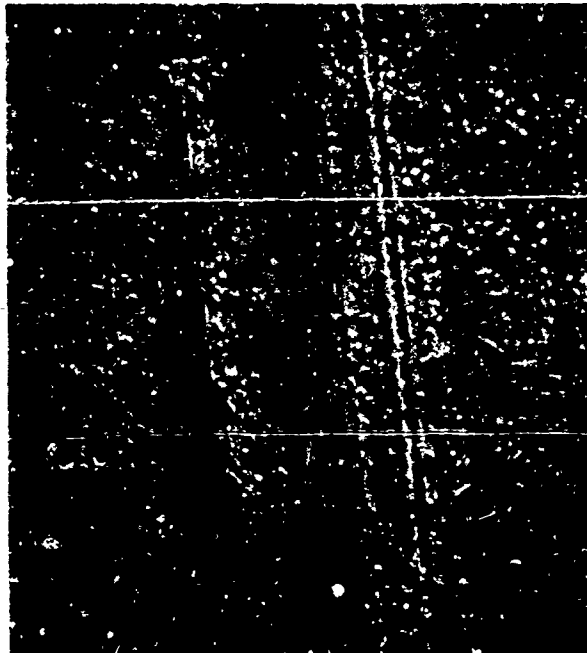


1000X

A. Bottom of the ball groove. The defect probably resulted from handling and was not typical of the surface in general.



300X

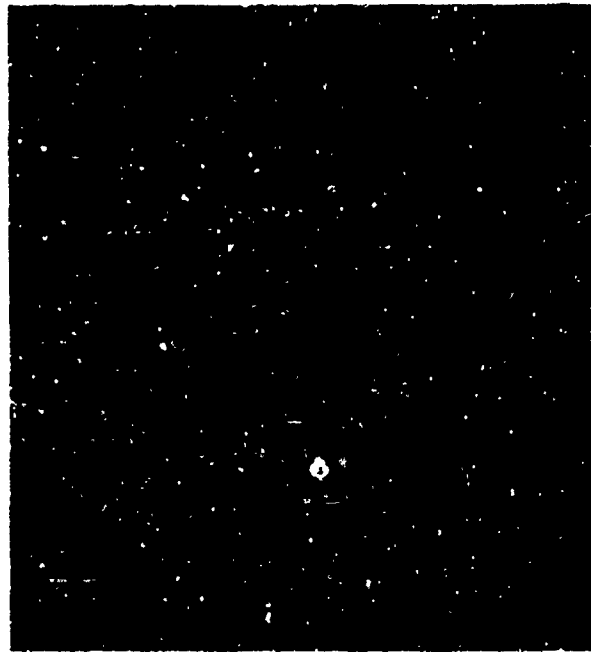
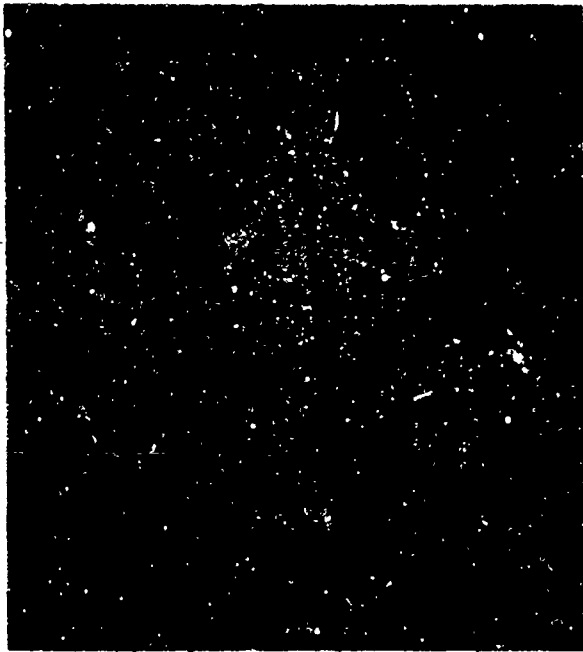


1000X

B. Area on ball groove 1 mm away from A. Note smeared metal not removed by the etch.

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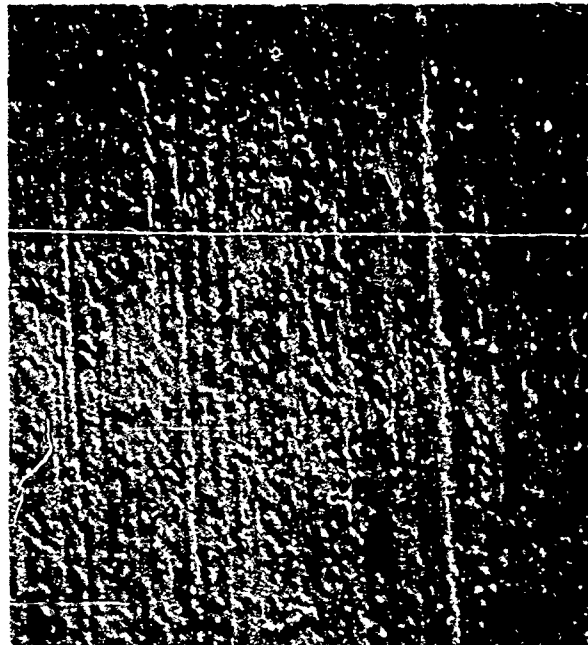
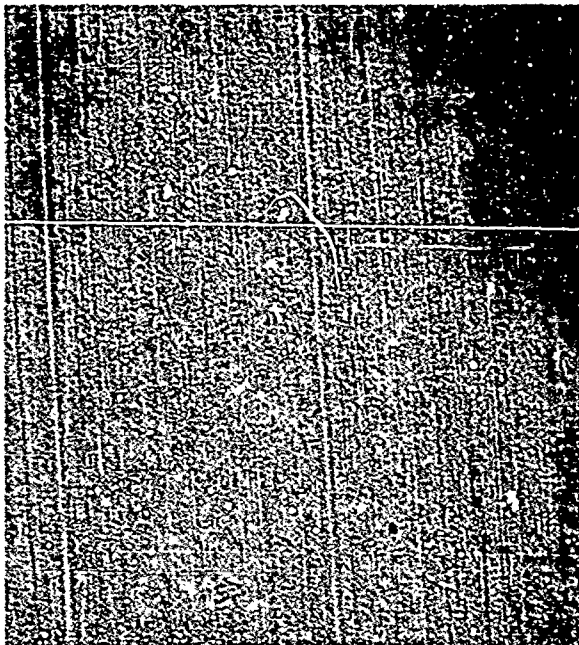
ENCLOSURE 5 (Continued)



300X

1000X

C. Area in ball groove 1 mm from B toward the edge of the contact area.



300X

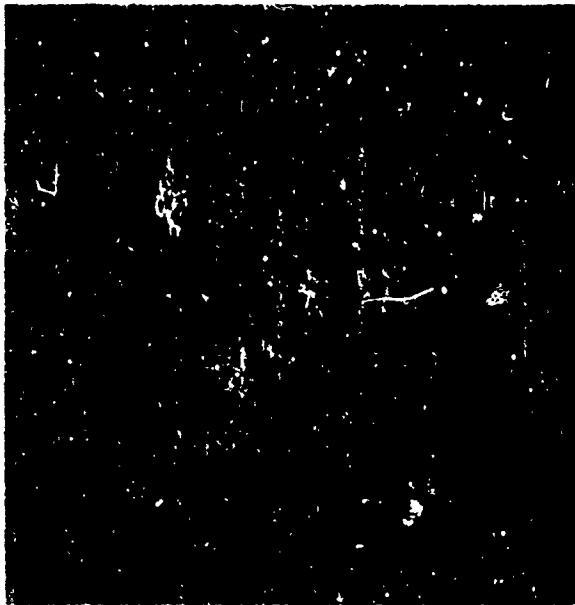
1000X

D. Area in ball groove 2 mm from C. This region is beyond the limit of normal ball contact.

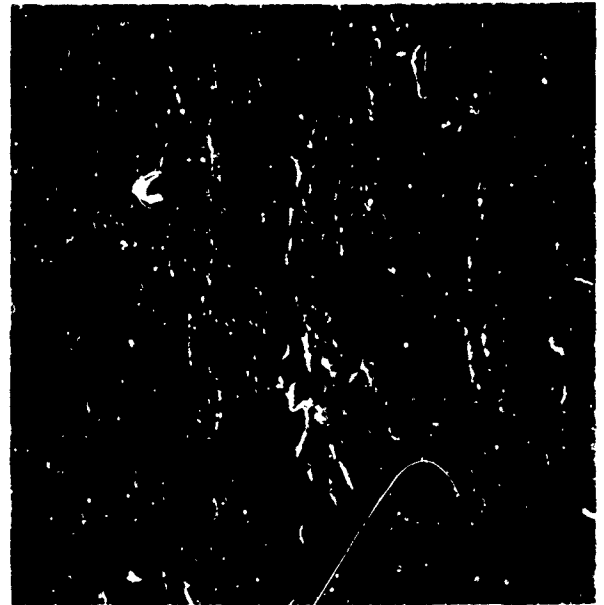
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ENCLOSURE 6

CONTACT SURFACE OF 52100 STEEL AFTER 200 M.R. - HIGH SPEED - HEAVY OIL

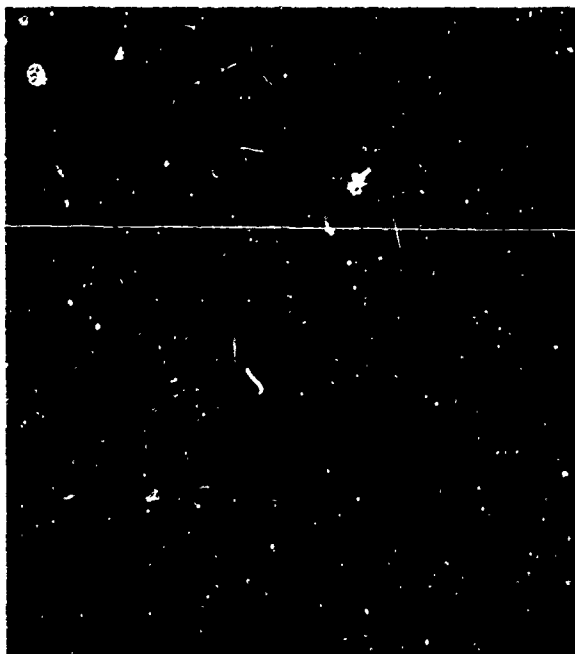


300X

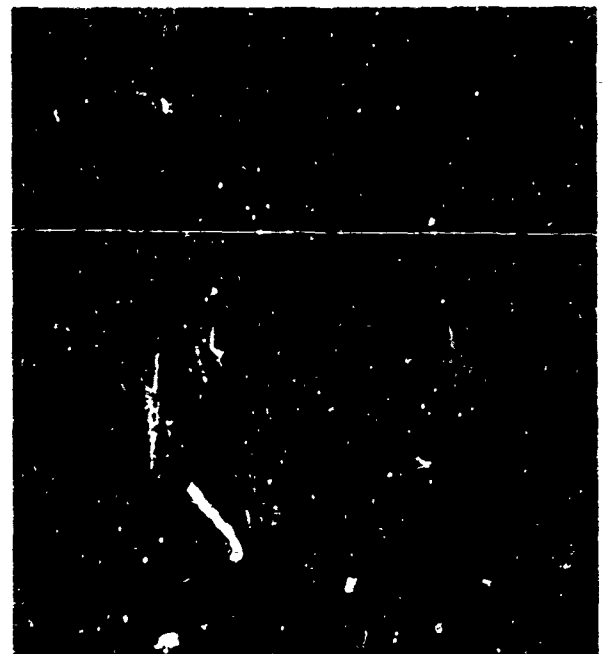


1000X

A. Region at edge of contact area.



300X

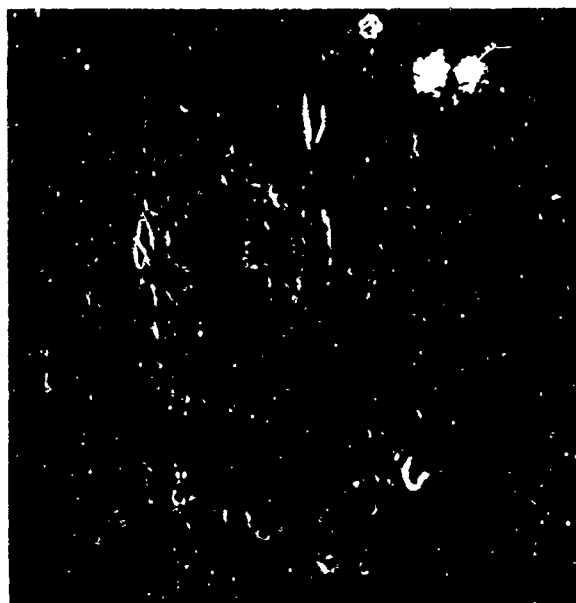
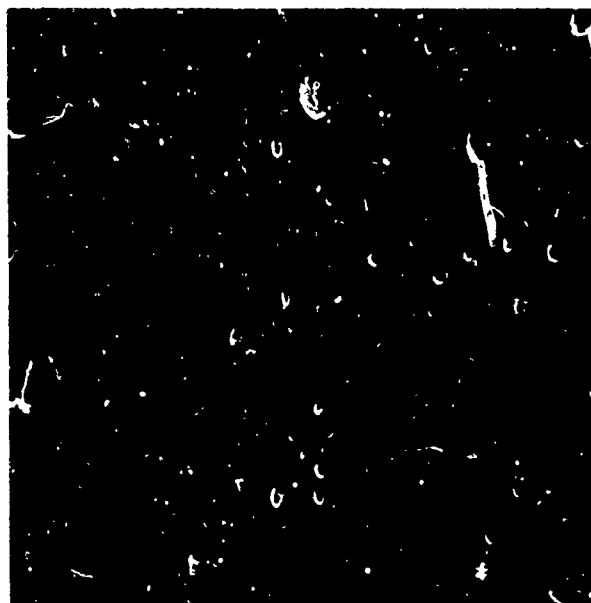


1000X

B. Region 1 mm away from A toward bottom of groove. Note finger nail marks and flattening of carbides.

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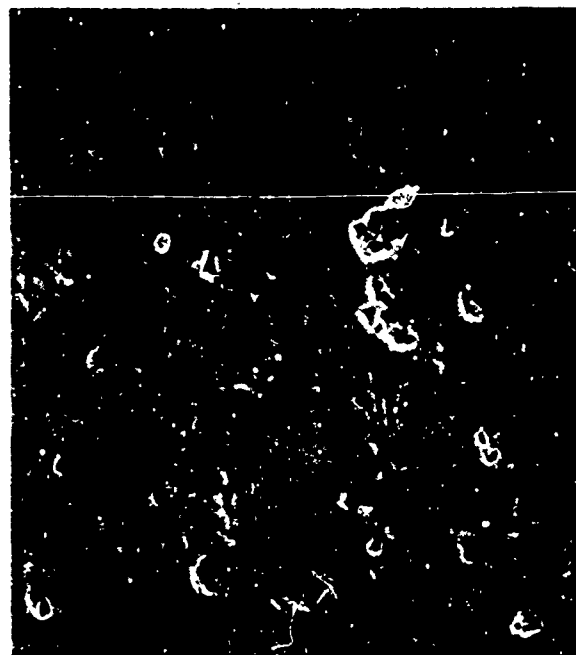
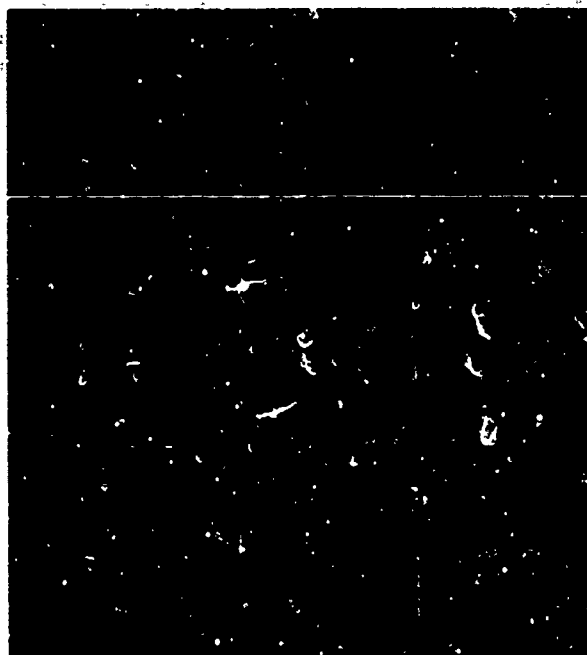
ENCLOSURE 6 (Continued)



300X

1000X

C. Region 1 mm away from B toward bottom of groove.



300X

1000X

D. Region 1 mm away from C toward bottom of groove.

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ENCLOSURE 6 (Continued)



300X

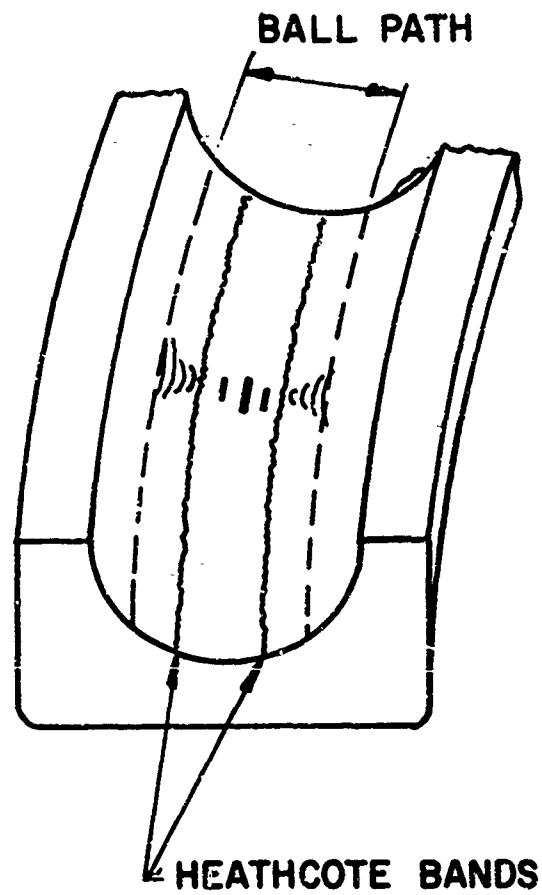
1000X

- E. Region 1 mm away from D, approximately at the bottom of the ball groove. Arrows point to what are believed to be finger nail marks.

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ENCLOSURE 7

SKETCH OF INNER RING BALL GROOVE SHOWING DISTRIBUTION
AND SHAPE OF FINGER NAIL MARKS

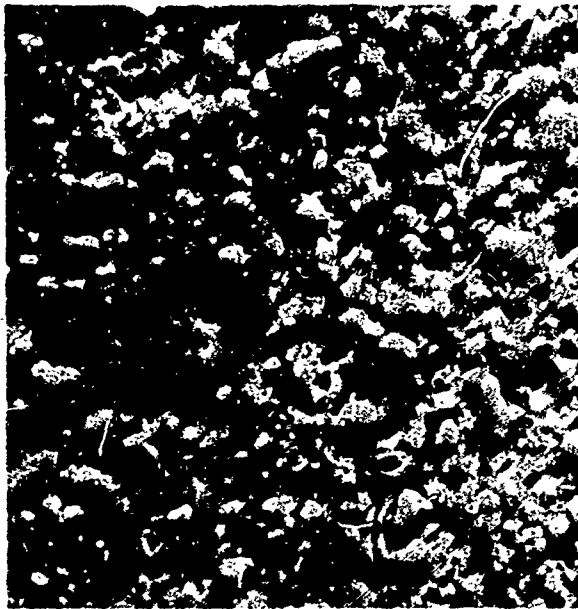


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ENCLOSURE 8

CONTACT SURFACE OF 52100 STEEL AFTER 70 M.R. (SPALLIED) -
LOW SPEED - HEAVY OIL



1000X

Region between Heathcote band and edge of contact area.
Note the limited flattening of the carbides.

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ENCLOSURE 9

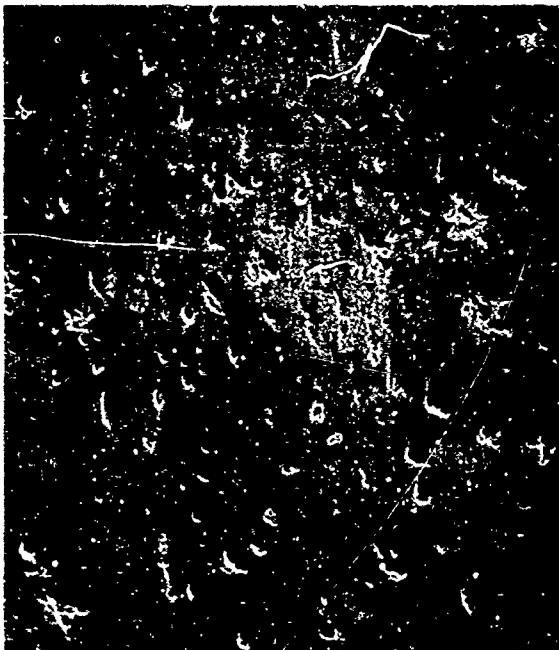
CONTACT AREA OF 52100 STEEL AFTER 54.5 M.R. - LOW SPEED - GREASE

300X

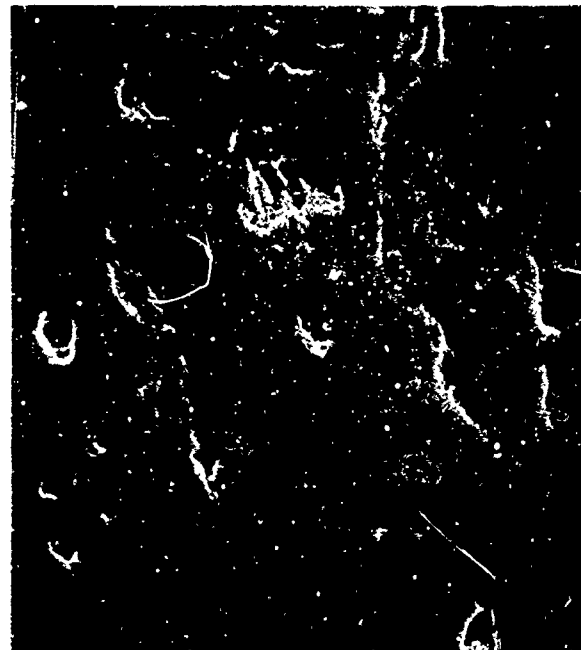


1000X

- A. Region near edge of contact. Note finger nail marks, large, shallow pits and absence of elevated carbides.



300X

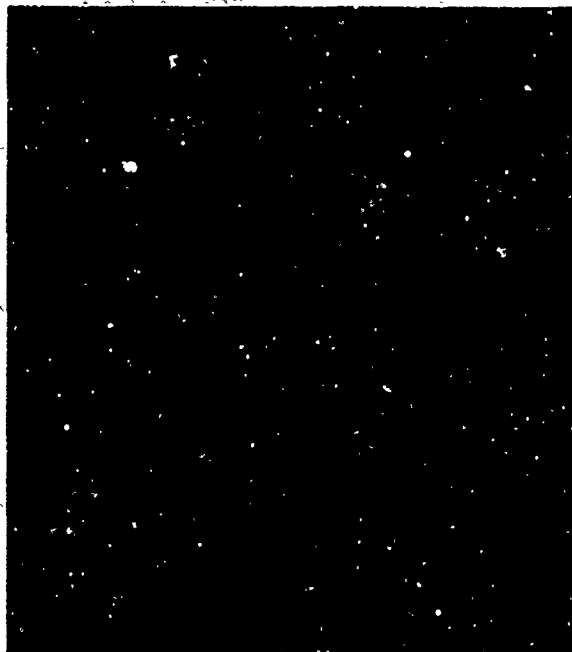


1000X

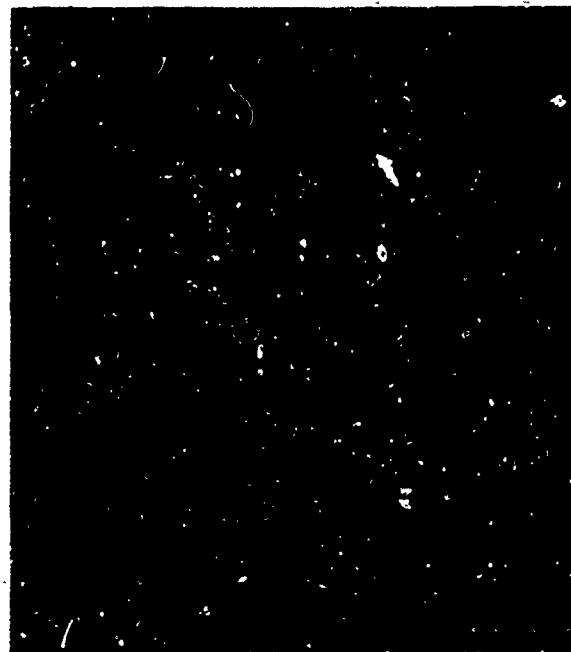
- B. Region 1 mm away from A toward the bottom of the groove. Note plastic deformation of the surface.

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ENCLOSURE 9 (Continued)



300X

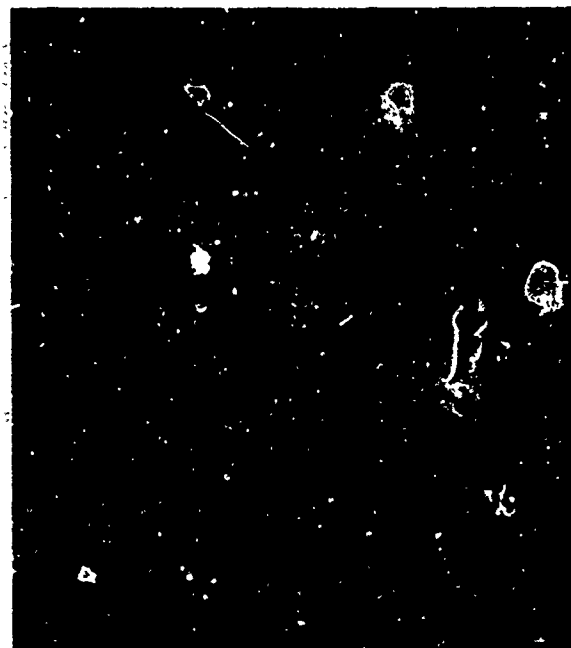


1000X

C. Region 1 mm away from B toward the bottom of the groove.



300X



1000X

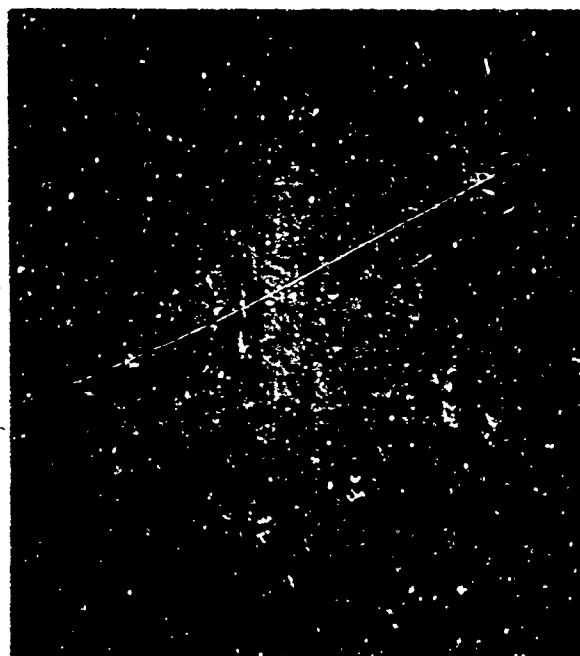
D. Region 1 mm away from C, approximately at bottom of groove.
Note what appear to be finger nail marks at arrows.

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AL71C002

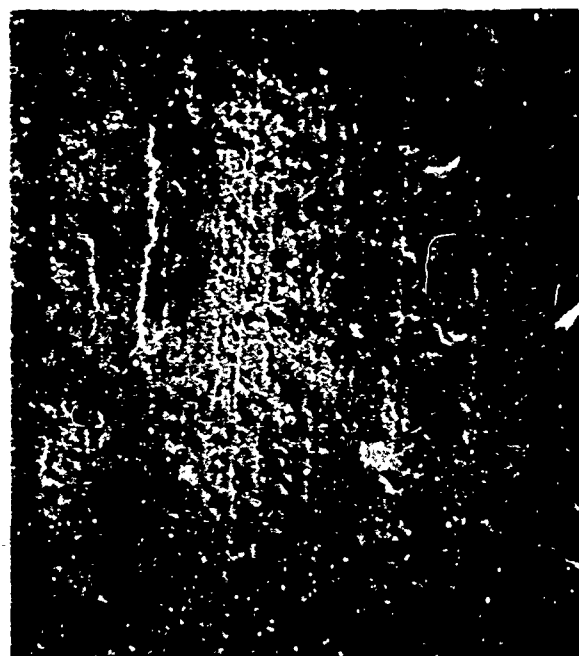
ENCLOSURE 1C

CONTACT SURFACE OF 52100 STEEL AFTER 99.9 M.R. - LOW SPEED - LIGHT OIL

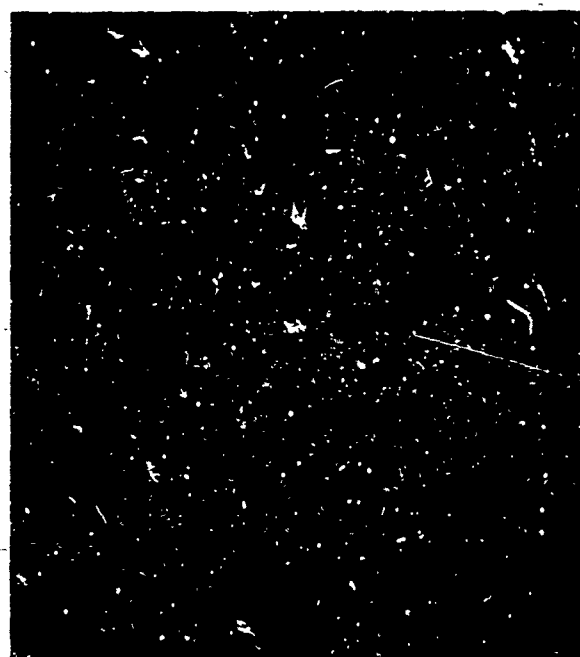


300X

A. Region near edge of contact area.



1000X



300X

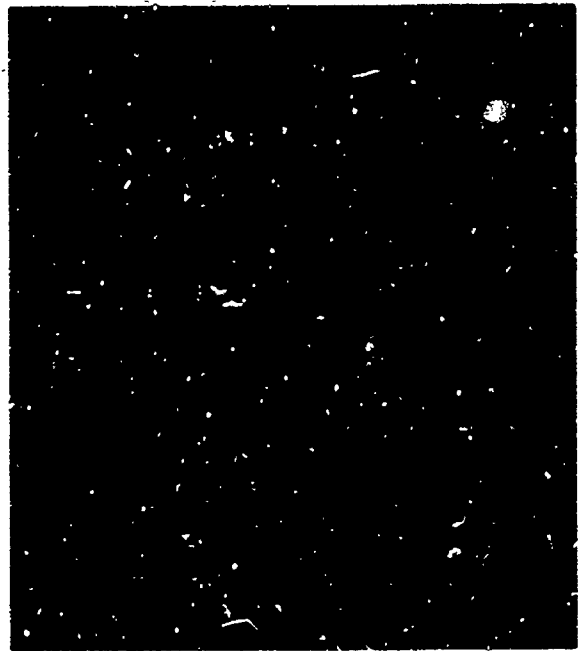
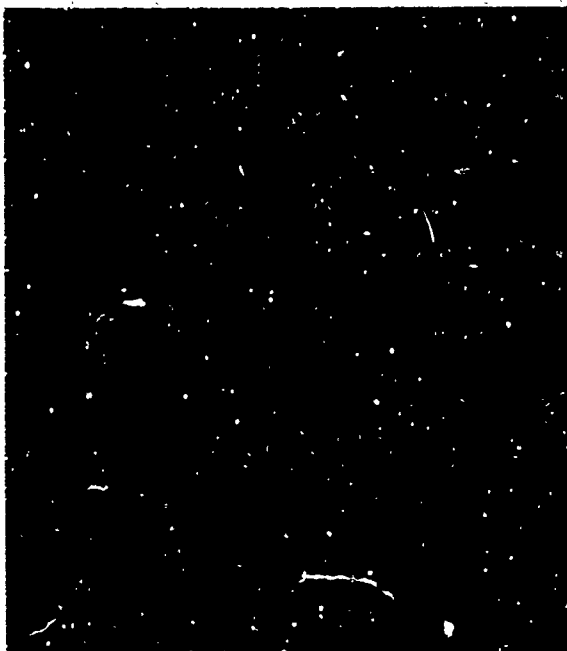
B. Region 1 mm away from A toward the bottom of the groove.



1000X

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ENCLOSURE 10 (Continued)



C. Region 1 mm away from B toward the bottom of the groove.



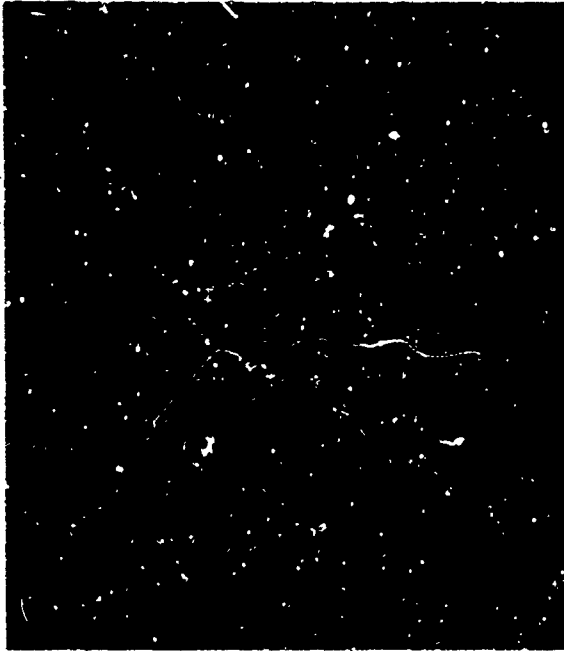
300X

1900X

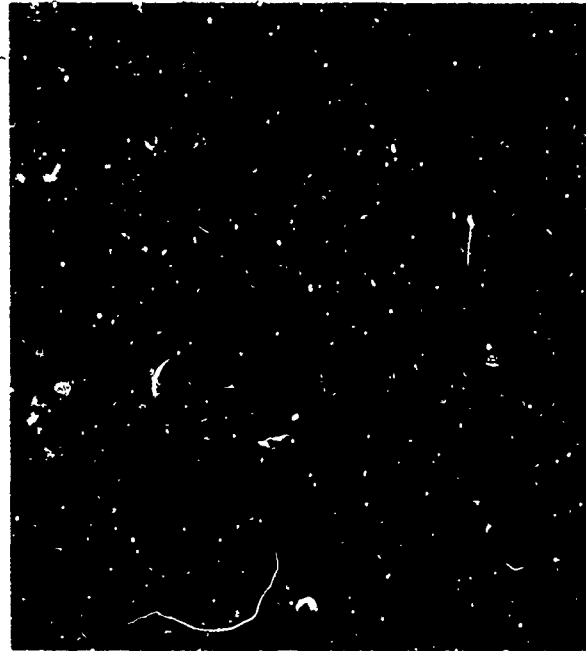
D. Region 1 mm away from C approximately at the bottom of the groove.

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ENCLOSURE 10 (Continued)



300X



1000X

E. Region 1 mm away from D moving away from the bottom of the groove. Note the hard of resolvable carbides.



300X

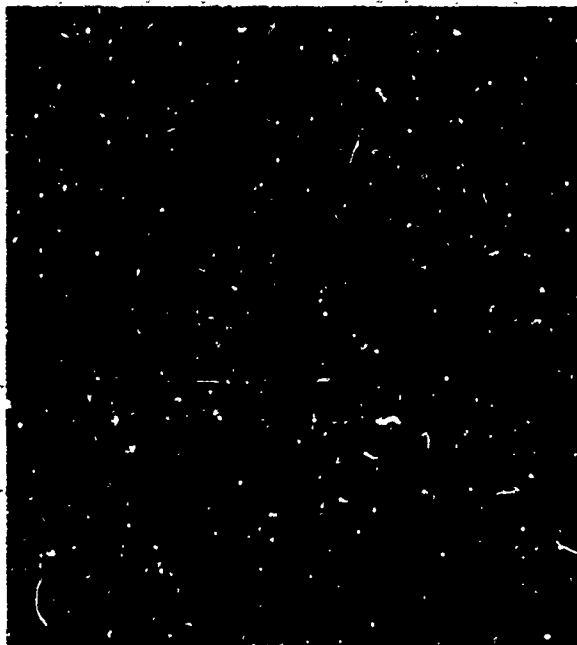


1000X

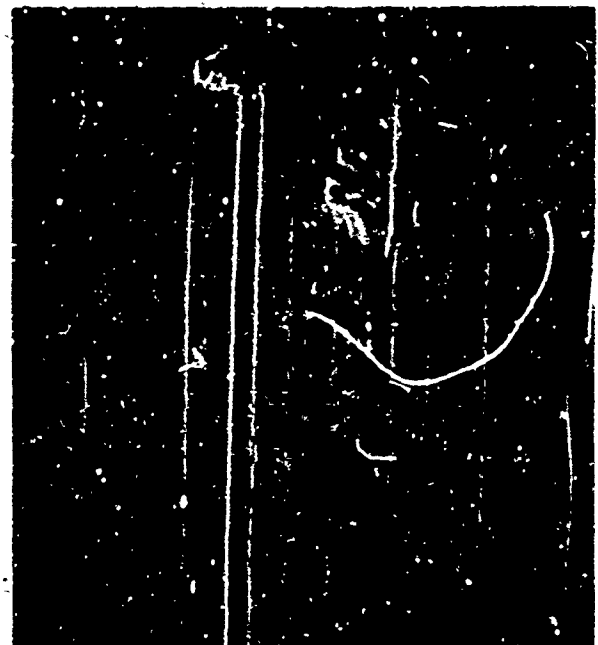
F. Region near the bottom of the ball groove for an inner ring with same history as in Figures A-E. Note the well defined band of carbides as in Figure E.

ENCLOSURE 11

CONTACT SURFACE OF CARBURIZED STEEL AFTER 400 M.R. -
HIGH SPEED - HEAVY OIL



300X



1000X

A. Region near edge of contact area.



300X



1000X

B. Region 1 mm away from A toward the bottom of the groove.
Note large number of finger nail marks.

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ENCLOSURE 11 (Continued)



300X

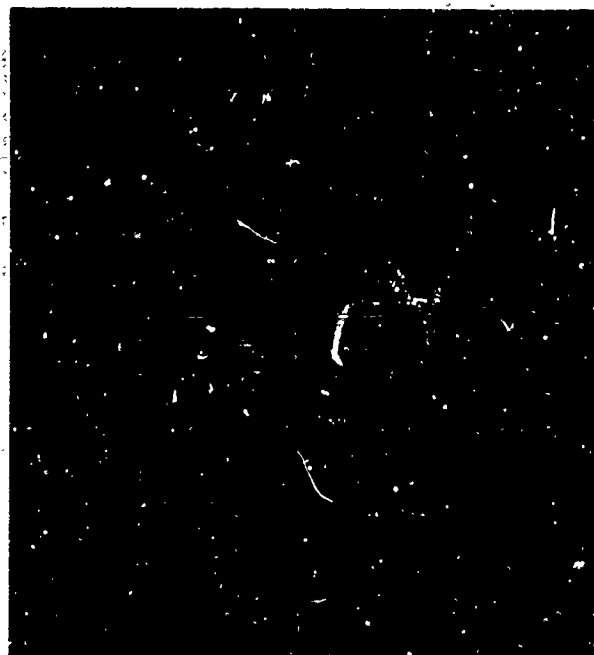


1000X

C. Region 1 mm away from B toward the bottom of the groove.



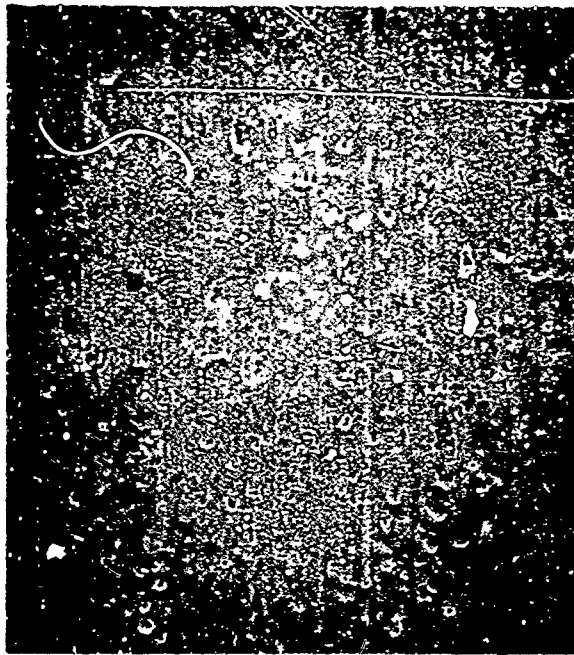
300X



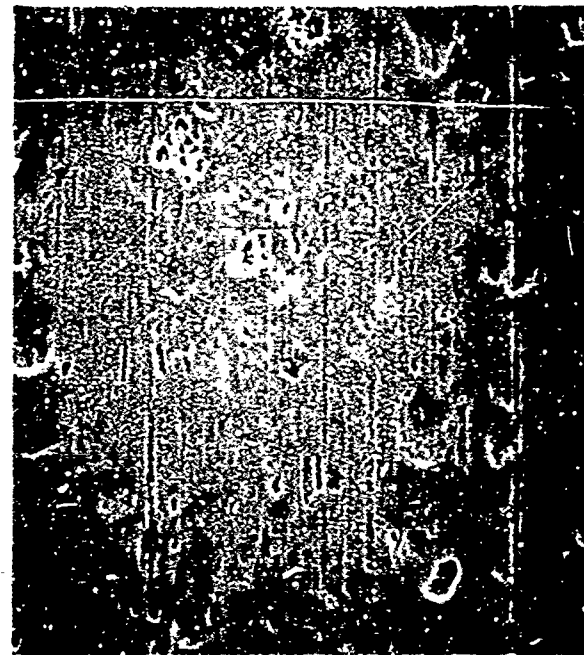
1000X

D. Region 1 mm away from C toward the bottom of the groove.
Note the high degree of denting.

ENCLOSURE 11 (Continued)



300X

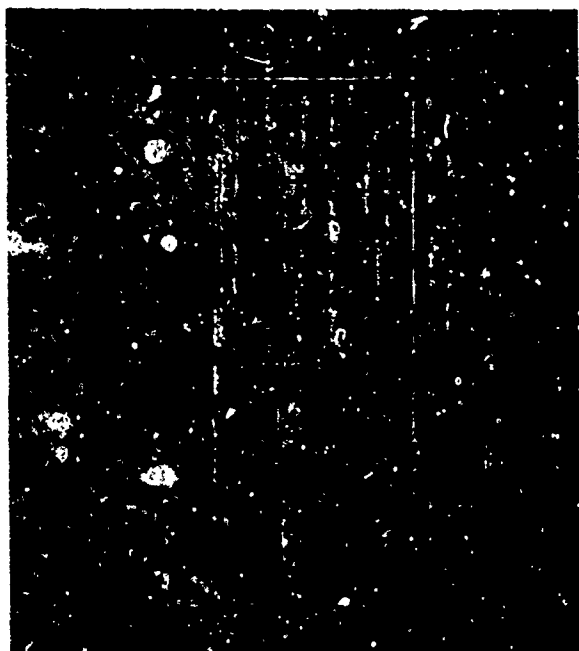


1000X

- E. Region 1 mm away from D, approximately at the bottom of the groove. Note the finger nail marks and heavy denting.

ENCLOSURE 12

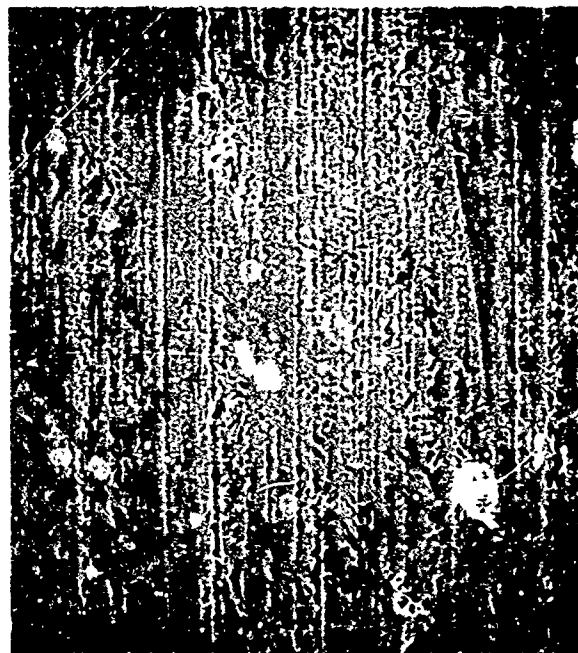
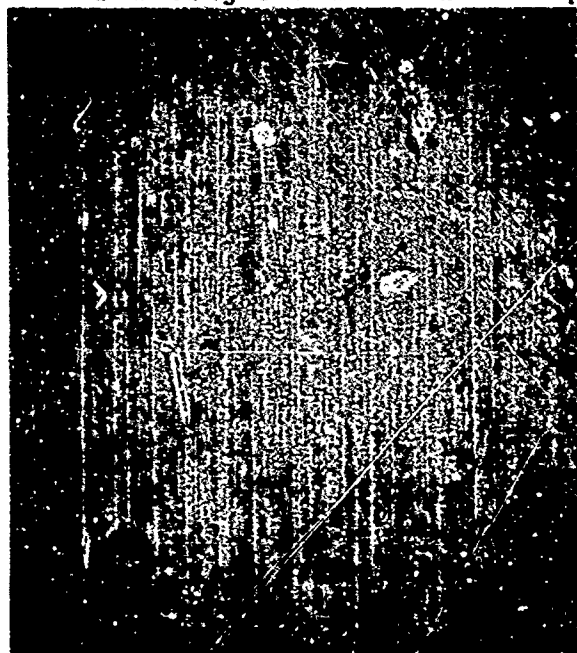
CONTACT SURFACE OF CARBURIZED STEEL AFTER 49.9 M.P.
LOW SPEED - HEAVY OIL



300X

1000X

A. Region near the edge of the contact area. Note only a few finger nail marks are present.



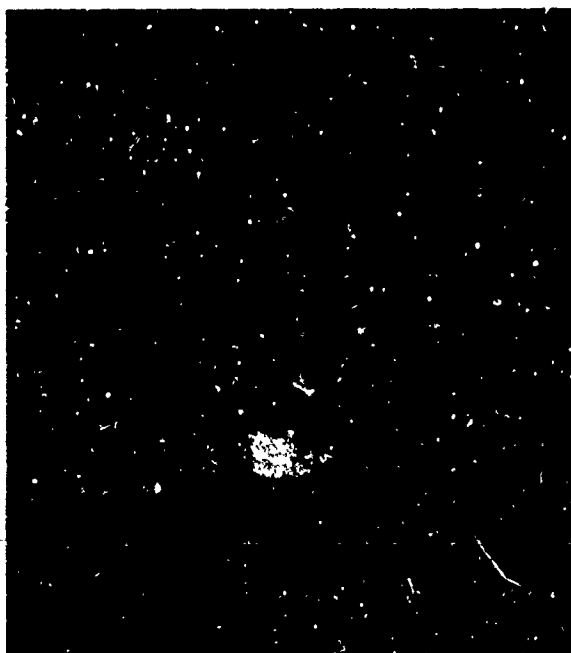
300X

1000X

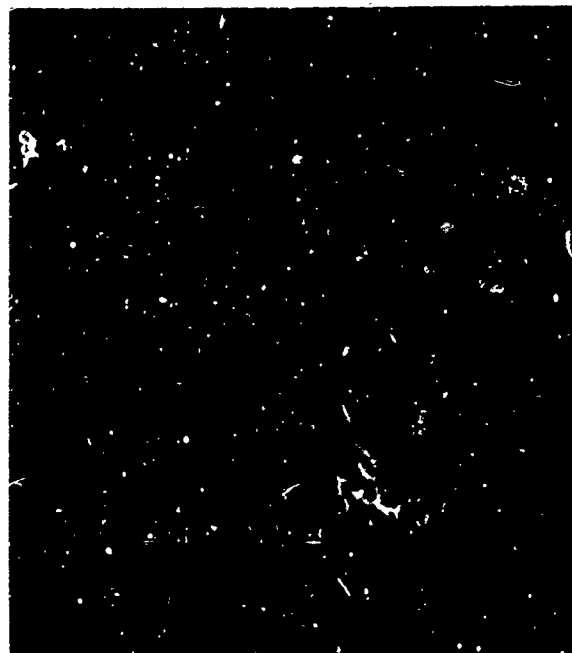
B. Region 1 mm away from A toward the bottom of the groove.

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ENCLOSURE 12 (Continued)

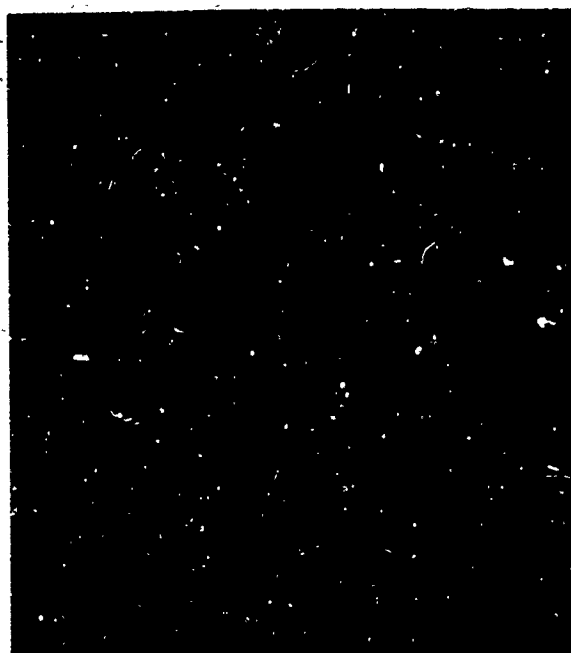


300X

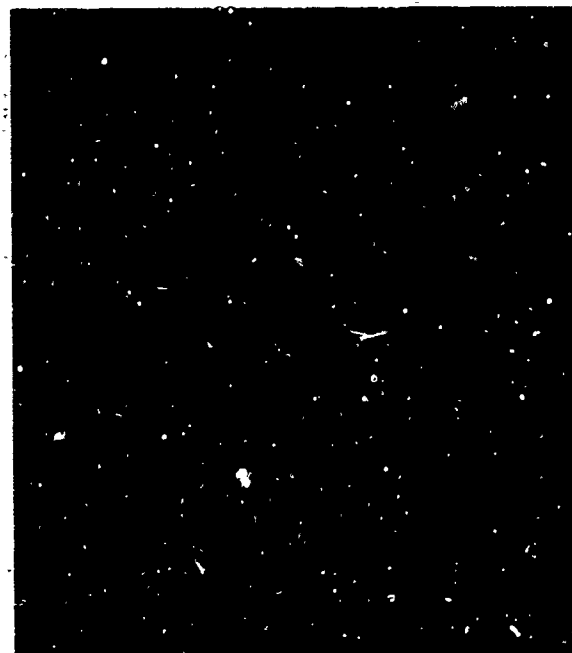


1000X

C. Region 1 mm away from B toward the bottom of the groove.



300X

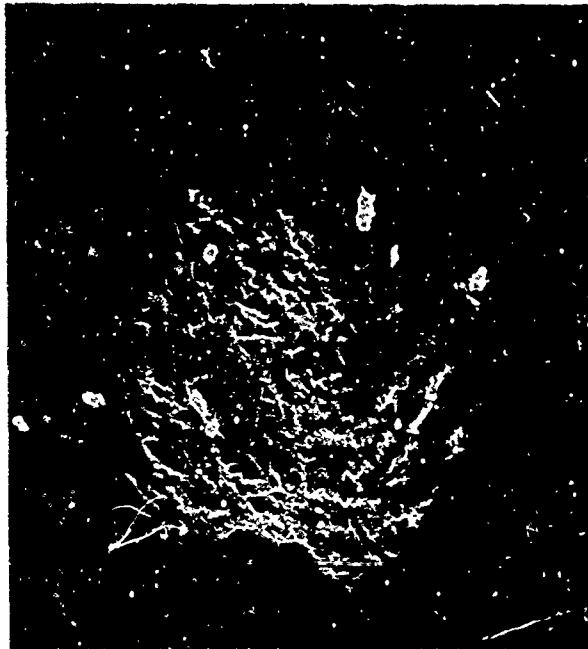


1000X

D. Region 1 mm away from C, approximately at the bottom of the ball groove.

ENCLOSURE 13

SURFACE DEFECTS ON CONTACT SURFACE OF CARBURIZED STEEL AFTER 49.9 M.R. T.U.
LOW SPEED - HEAVY OIL

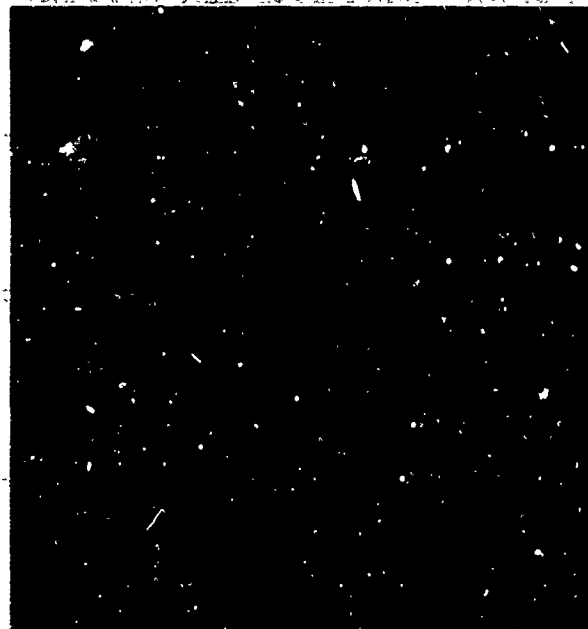


300X

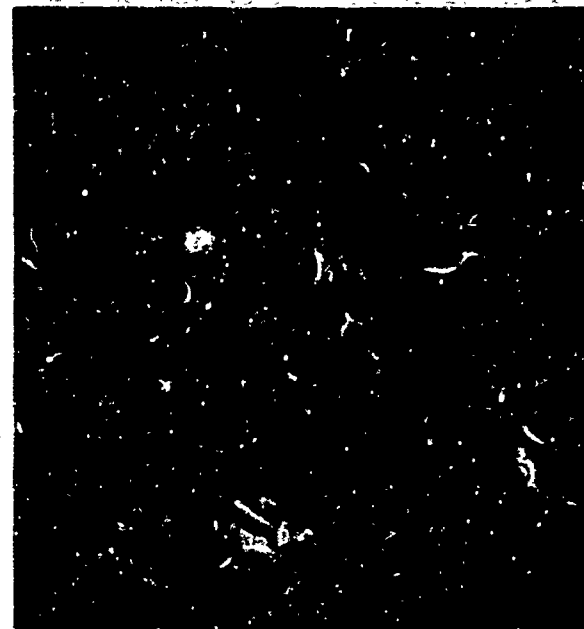


1000X

- A. Defect near the bottom of the ball groove. The presence of what appear to be finishing lines within the defect indicate its shallowness. (The dark streaks in the 300X micrograph resulted from handling after the surface had been lightly gold coated to improve resolution).



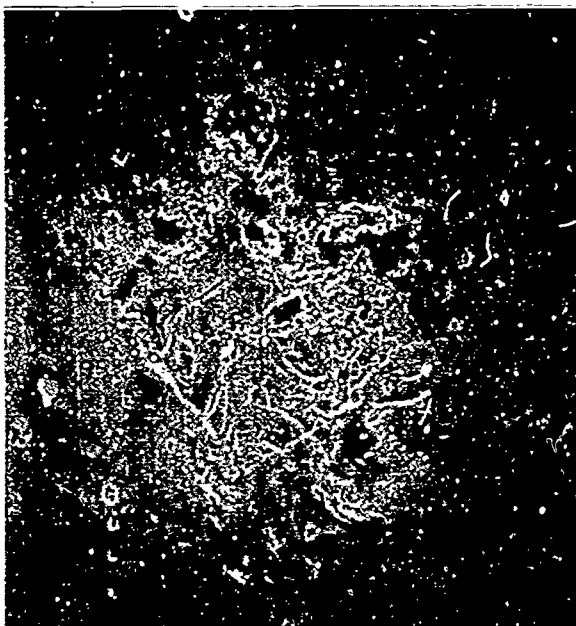
300X



1000X

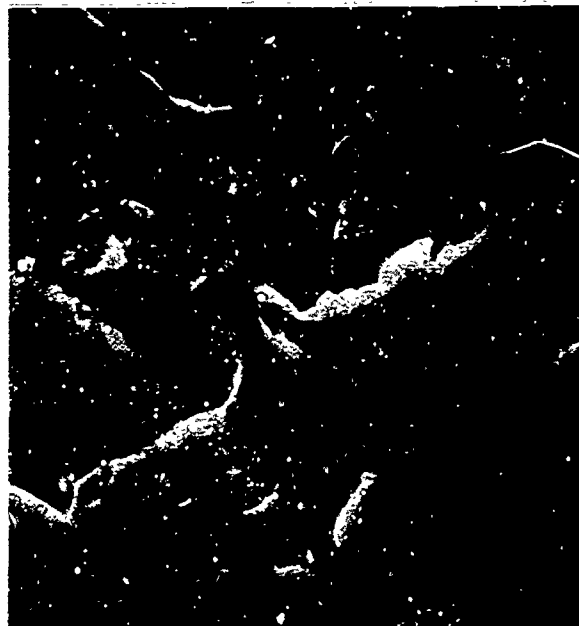
- B. Extensive, shallow defect region near bottom of the ball groove. Both gouging and mashing of the surface are evident.

ENCLOSURE 13 (Continued)



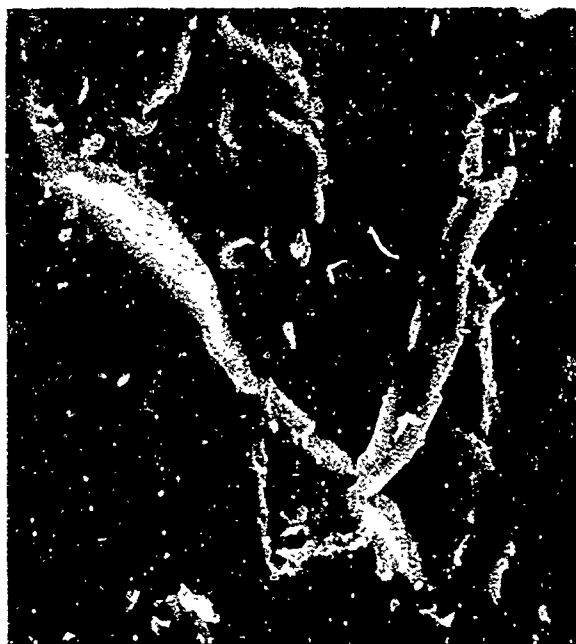
500X

C. Surface defect with several different characteristics



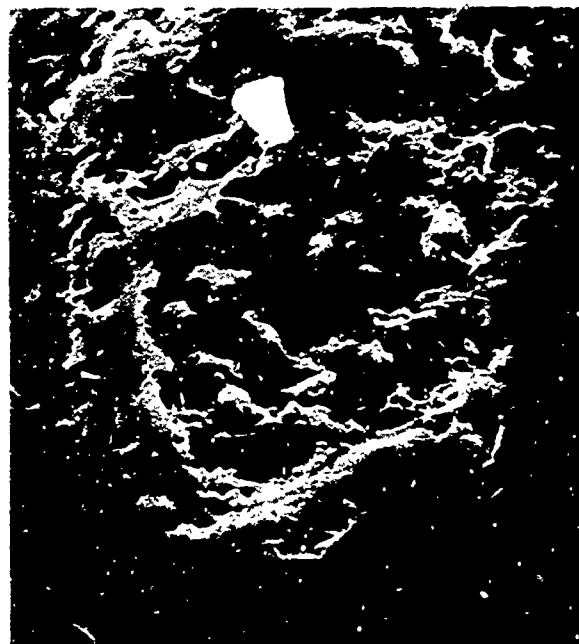
3000X

D. Higher magnification of lower right hand region of C.



3000X

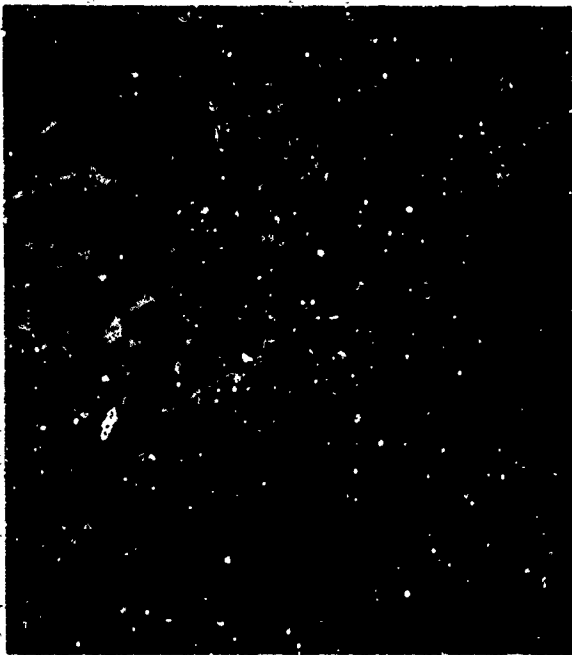
E. Higher magnification of lower left hand region of defect grouping in C.



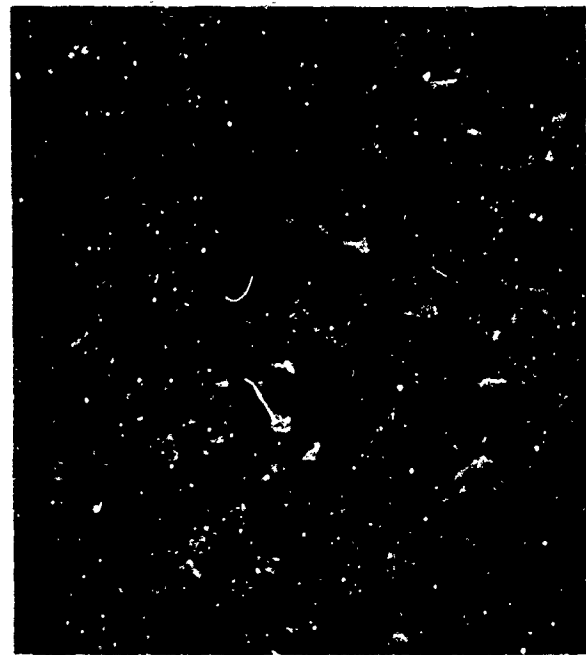
3000X

F. Higher magnification of top center region of C (Specimen was gold coated to improve resolution. Micrograph is rotated 180° relative to C). Note apparent intergranular facets.

ENCLOSURE 13 (Continued)

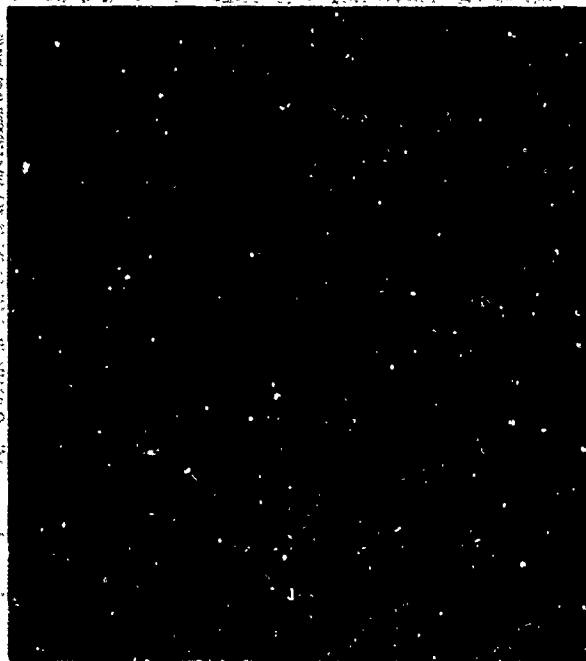


300X



3000X

- G. Surface defect near Heathcote band. Note the extensive flattening of what appear to be pieces of metal within the defect.



- H. Another example of the large complex defects which occur in all regions of the ball groove.

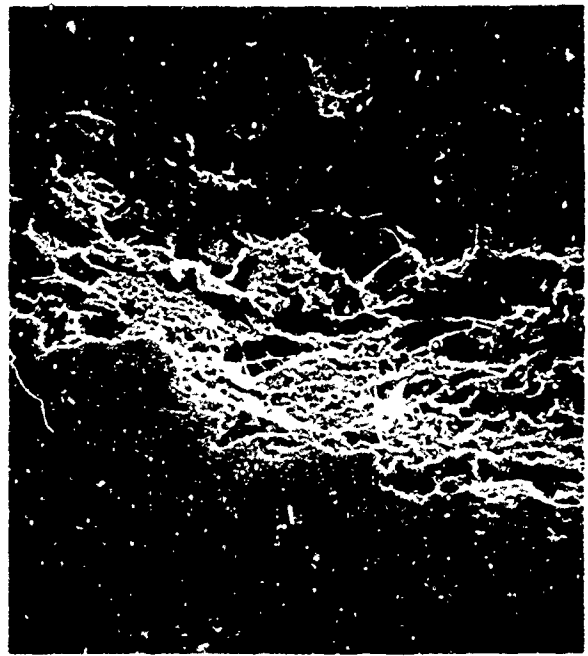
RESEARCH LABORATORY **EKF** INDUSTRIES, INC.

ENCLOSURE 14

LARGE SURFACE DEFECTS ON S2100 STEEL AFTER 99.9 M.R. (T.U.)
LOW SPEED - LIGHT OIL

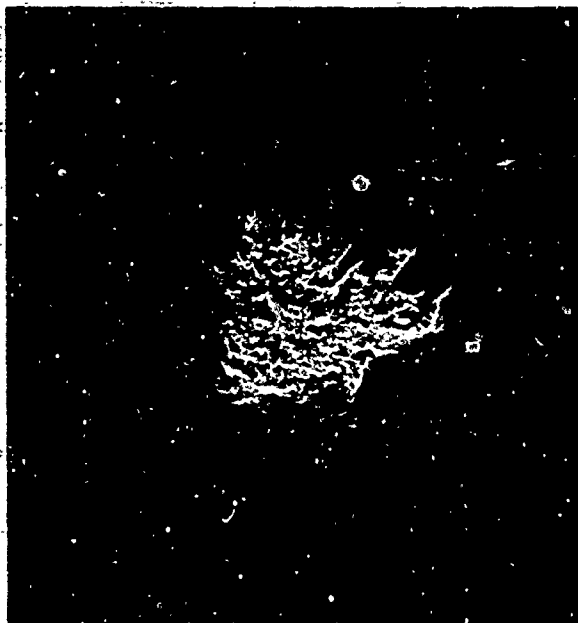


180X



600X

- A. Large defect between Heathcote band and the edge of the contact area. Note cracking in glazed area at lower right hand side of the low magnification micrograph.



180X



600X

- B. Large defect near edge of contact area. Note apparent cracking at lower edge of defect.

RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 15

DEFECTS ON THE CONTACT SURFACE OF 52100 STEEL - LOW SPEED - HEAVY OIL

600X



B. 1000X

- A. Two defects located near the bottom of the ball groove in an inner ring which spalled elsewhere on the ring after 46.1 M.R. The surface had many of these shallow defects. The glazing is an indication that the defects existed prior to the spalling.



1000X



4000X

- C. Large surface defect near the bottom of the ball groove on an inner ring which spalled elsewhere after 70 M.R. The absence of extensive glazing or mashing down of the elevated regions indicates that the spall debris may have played a role in forming the defect.

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ENCLOSURE 16

CONTACT SURFACE OF CARBURIZED STEEL AFTER 49.9 M.R. -
LOW SPEED - GREASE

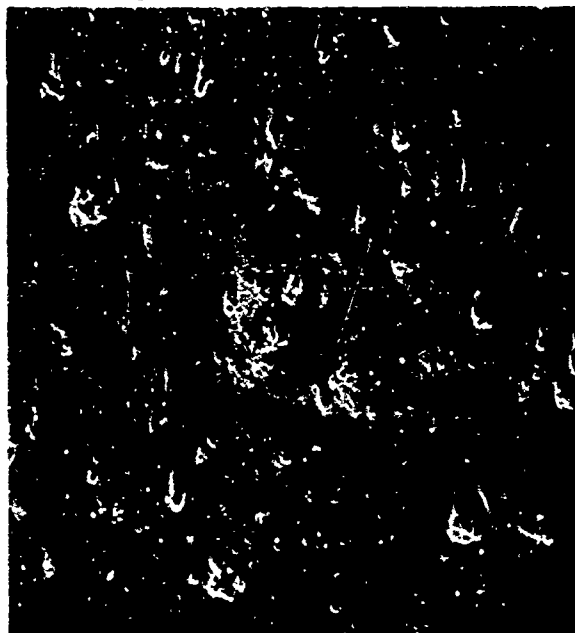


300X



1000X

A. Region near the edge of the contact area.



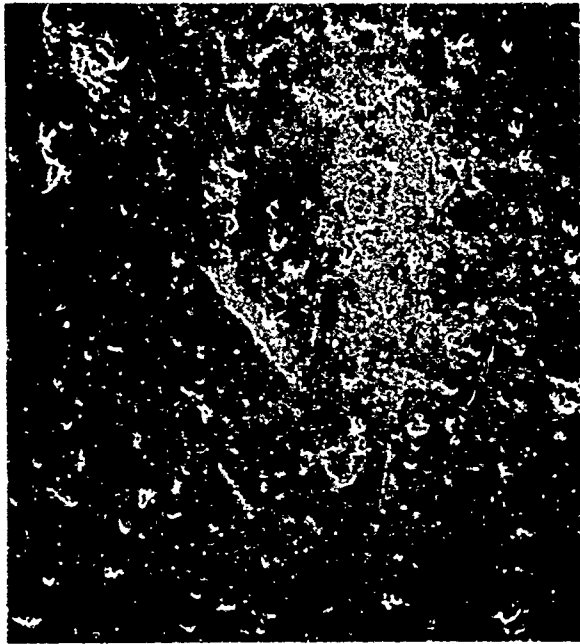
300X



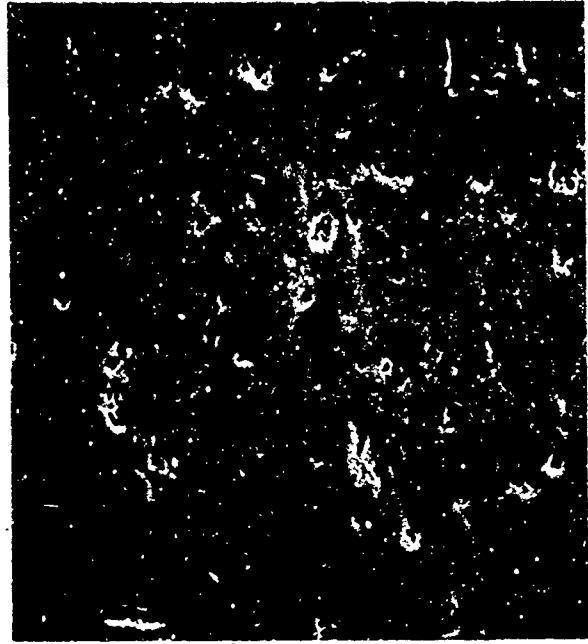
1000X

B. Region 1 mm away from A toward the bottom of the groove.
Note the large shallow defects.

ENCLOSURE 16 (Continued)

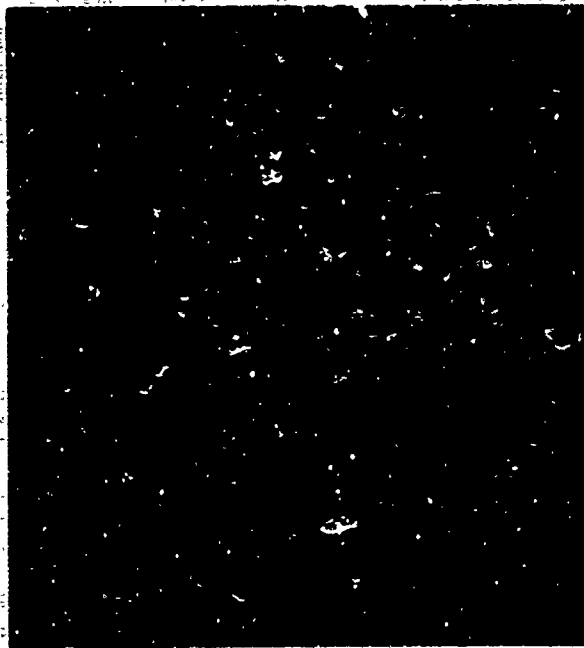


300X



1000X

- C. Region 1 mm from B. The field of view was shifted slightly in the high magnification micrograph to show the general surface details rather than just the very large dent seen in the lower magnification view.



300X



1000X

- D. Region 1 mm from B approximately at the bottom of the groove. Note the extensive plastic deformation, denting and finger nail marks.

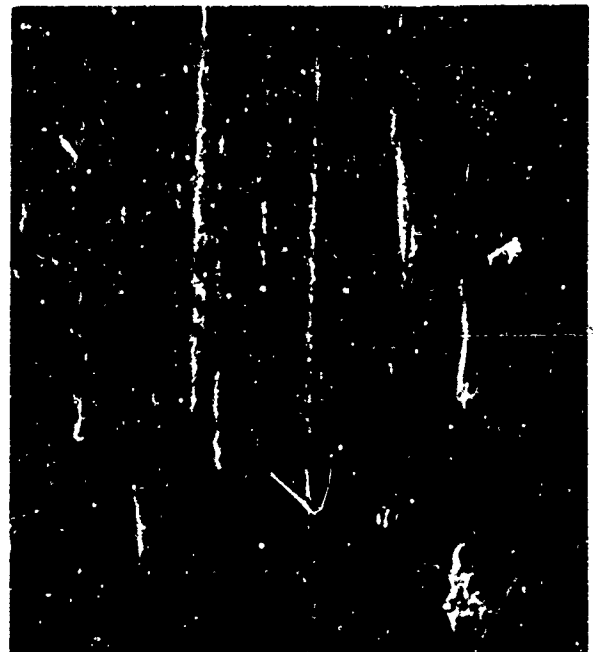
RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 17

CONTACT SURFACE OF CARBURIZED STEEL AFTER 199.9 M.R.
LOW SPEED - LIGHT OIL



300X



1000X

A. Region near edge of contact area.



300X

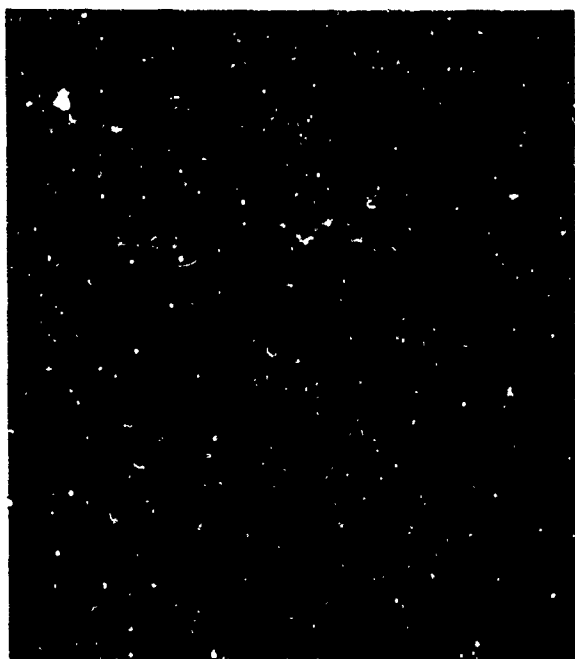


1000X

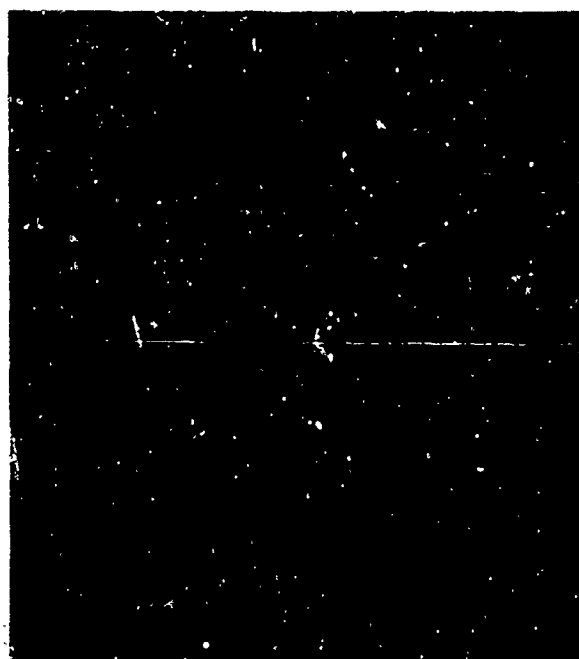
B. Region 1 mm from A toward the bottom of the ball groove.

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ENCLOSURE 17 (Continued)

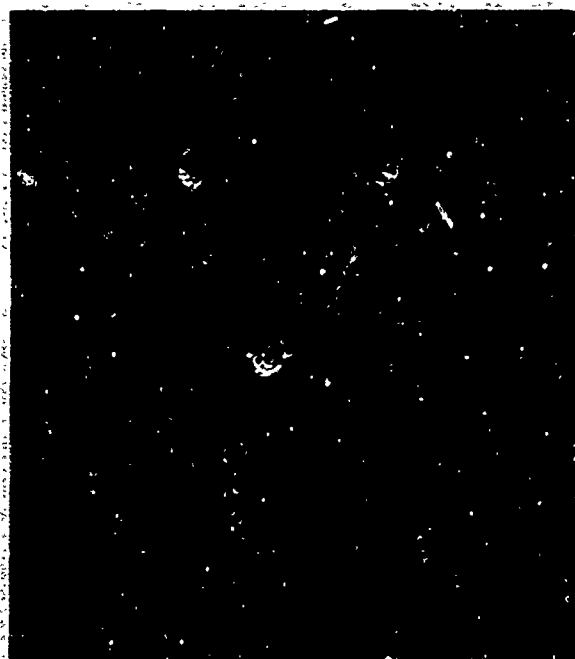


300X



1000X

C. Region 1 mm from B toward the bottom of the ball groove.



300X

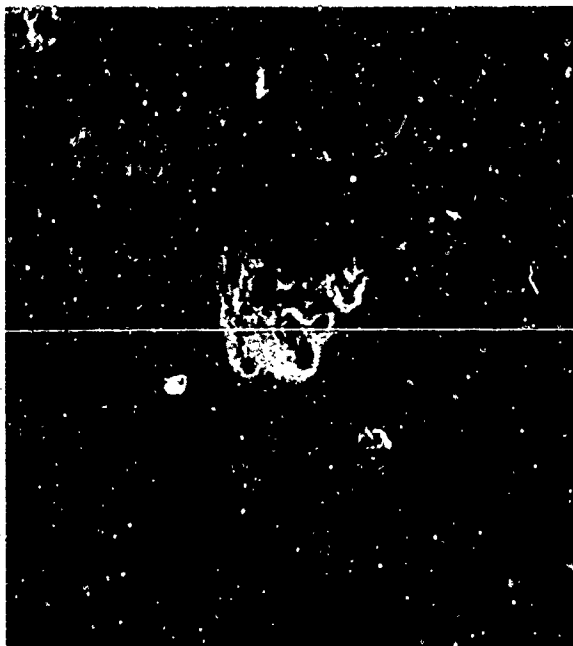


1000X

D. Region 1 mm from C, approximately at the bottom of the ball groove. Note the cracking within the large pit.

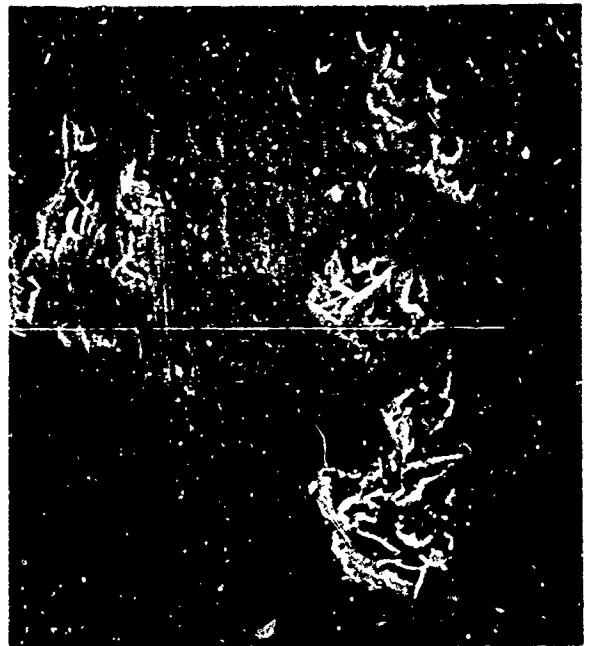
RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 17 (Continued)



E.

1000X



F.

1000X

Cracking within pits near the bottom of the ball groove. There were many examples of such defects on this inner ring.



300X



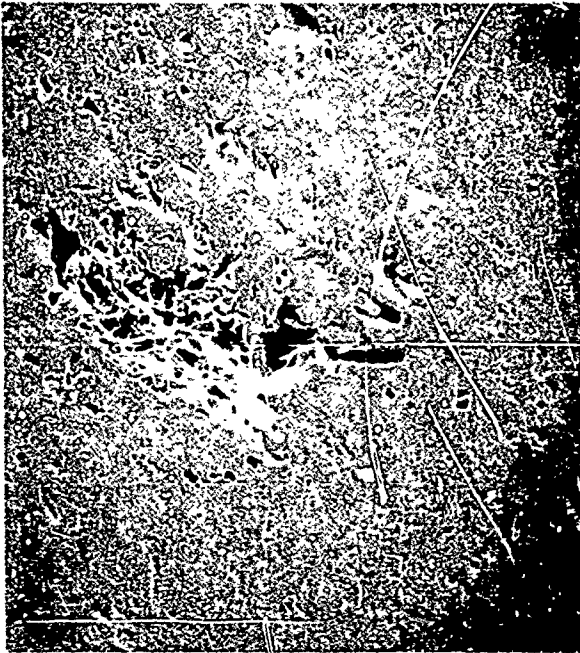
1000X

G. Cracking near bottom of the groove apparently associated with inclusion stringers.

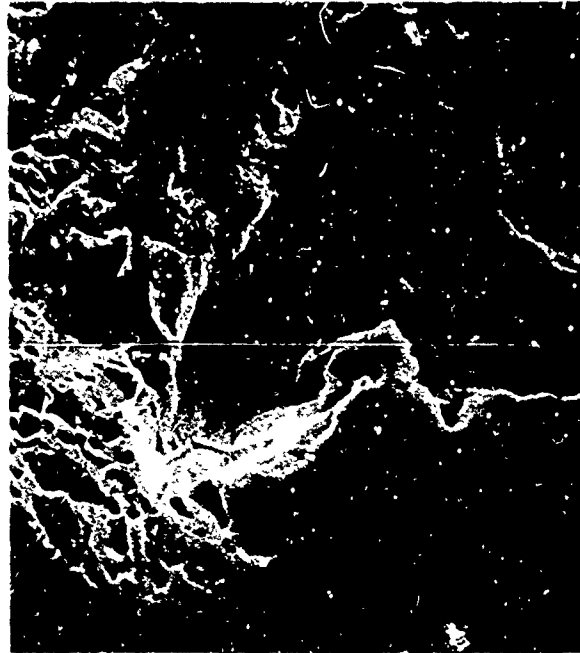
RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 18

EXAMPLES OF INTERGRANULAR FACETS ON SURFACE DEFECTS
NOTED AFTER RUNNING



A. 300X



B. 1000X

Defect between Heathcote band and edge of contact in
T. U. (49.9 M.R.) carburized steel - low speed - grease.



3000X

C. Higher magnification of B.

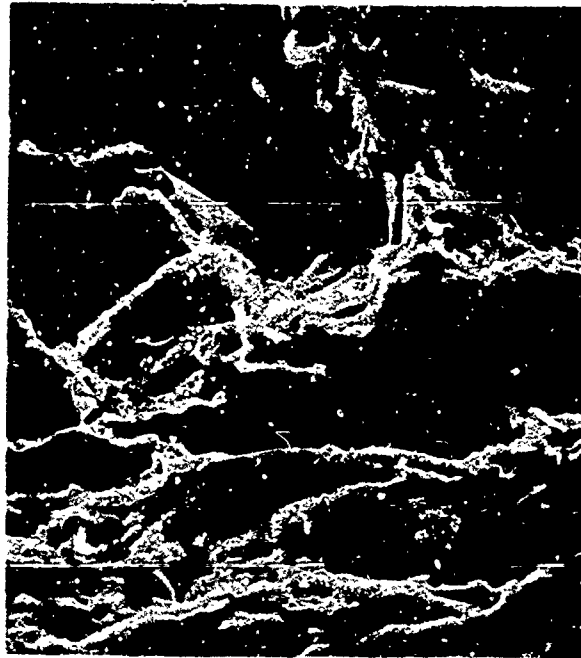


1800X

D. Defect near edge of contact area
in T.U. (400 M.R.) carburized
steel - high speed - heavy oil.

AL71C002

ENCLOSURE 18 (Continued)



1800X

E. Higher magnification of defect
in Enclosure 14, Figure A.

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AL71C002

ENCLOSURE 19

PORTION OF A SPALL ON THE CONTACT SURFACE OF 52100 STEEL (12.4 M.R.) - HIGH SPEED - HEAVY OIL



Rolling Direction
→ 40X

RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

Bottom of Spall

Ball Direction

AL71C002

ENCLOSURE 20

POLISHED CROSS-SECTION OF SPALL FROM ENCLOSURE 19



1000X

A. Cracking at exit end of spall. Note the extensive branching of the cracks.

RESEARCH LABORATORY BKF INDUSTRIES, INC.

ENCLOSURE 20 (Continued)

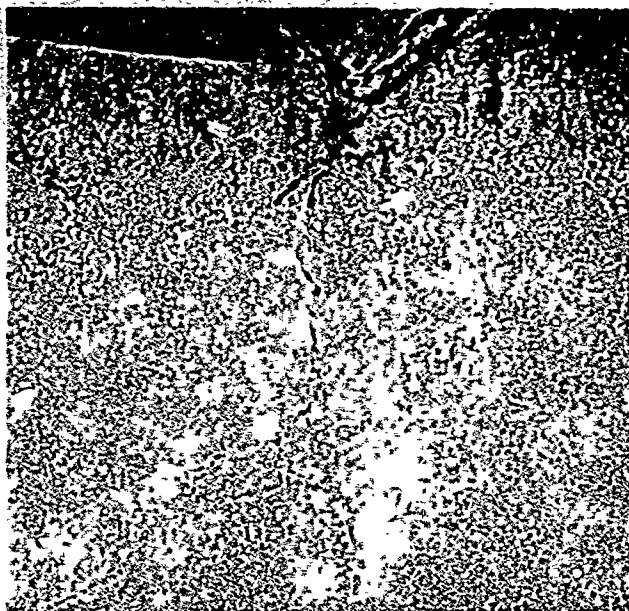


125X

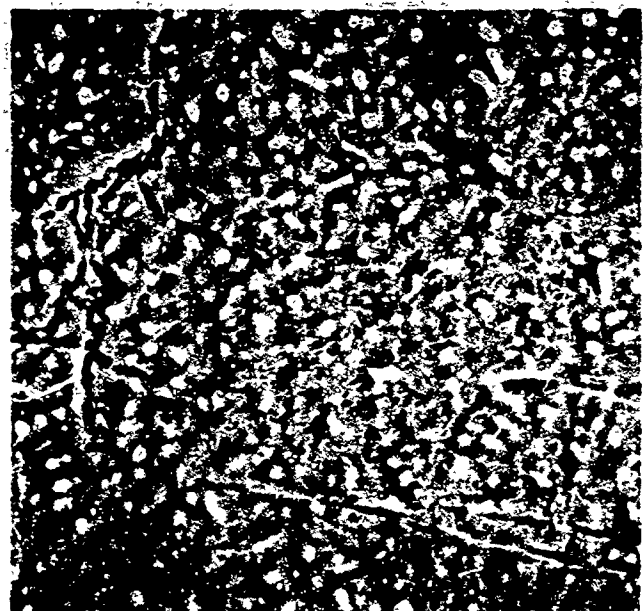


300X

B. Cracking at entrance end of spall. Crack is growing opposite to the direction of rolling.



600X



2000X

C. Cracking extending from the bottom of the spall. Extensive branching is evident.

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DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) B & P Industries, Inc. (Research Lab.) 1100 First Avenue King of Prussia, Pa. 19406		2a. REPORT SECURITY CLASSIFICATION None
		2b. GROUP
3. REPORT TITLE Final Report on Scanning Electron Microscopy of 6309 Size Bearings		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)		
5. AUTHOR(S) (Last name, first name, initial) Leonard, Laurence Cotellesse, Gerald Erhardt, Karl		
6. REPORT DATE January 31, 1971	7a. TOTAL NO. OF PAGES 79	7b. NO. OF REFS 19
8a. CONTRACT OR GRANT NO. N00014-70-C-0229	9a. ORIGINATOR'S REPORT NUMBER(S) AL71C002	
A. PROJECT NO. NR259-055/12-11-69 (463)	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c.		
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13. ABSTRACT THIS REPORT COVERS A STUDY OF 6309 SIZE BALL BEARINGS IN WHICH THE TECHNIQUES OF SCANNING ELECTRON MICROSCOPY WERE EMPLOYED TO FOLLOW THE DETAILS OF THE VERY LOCALIZED SURFACE ALTERATIONS WHICH OCCUR DURING RUNNING. THIS WORK REVEALS BY SCANNING ELECTRON MICROSCOPY (SEM) VARIOUS ASPECTS OF BEARING SURFACE FINISHING, THE EFFECTS OF SURFACE MORPHOLOGY UPON ALTERATIONS INDUCED BY RUNNING, AND THE FINE DETAILS OF THESE VERY LOCALIZED ALTERATIONS. GROUPS OF CARBURIZED AND THROUGH HARDENED BEARINGS WERE STUDIED AFTER RUNNING IN A CONTROLLED SERIES OF ENDURANCE TESTS DESIGNED TO EVALUATE THE EFFECTS OF A RANGE OF ELASTOHYDRODYNAMIC (EHD) RUNNING CONDITIONS UPON LIFE AND SURFACE ALTERATIONS IN GENERAL. THE SEM EXAMINATION HAS YIELDED MUCH INFORMATION INDICATING THAT VARIOUS COMPETITIVE PROCESSES TAKE PLACE ON INNER RING SURFACES AS A FUNCTION OF SEVERAL FACTORS INCLUDING LUBRICATION, RUNNING TIME, AND POSITION RELATIVE TO THE BOTTOM OF THE BALL GROOVE. IN EVALUATING THE EFFECTS OF LUBRICATION CONDITIONS ON ENDURANCE LIFE, THE SEM INFORMATION PROVIDES VALUABLE SUPPLEMENTAL DATA TO FILM THICKNESS OR W/F CALCULATIONS. SURFACE PHENOMENA OBSERVED IN THIS STUDY INCLUDE PITTING, DENTING, SPALLING, FINGER NAIL MARKS, PLASTIC DEFORMATION AND LARGE COMPLEX DENT-AND-PIT DEFECTS. THE LATTER WERE A NOVEL TYPE OF DEFECT UPON WHICH ONE CAN POSTULATE A MODEL TO ACCOUNT FOR THE SMALL L_{10} LIVES OF SOME TEST GROUPS RUN UNDER HIGH W/F TEST CONDITIONS.		

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