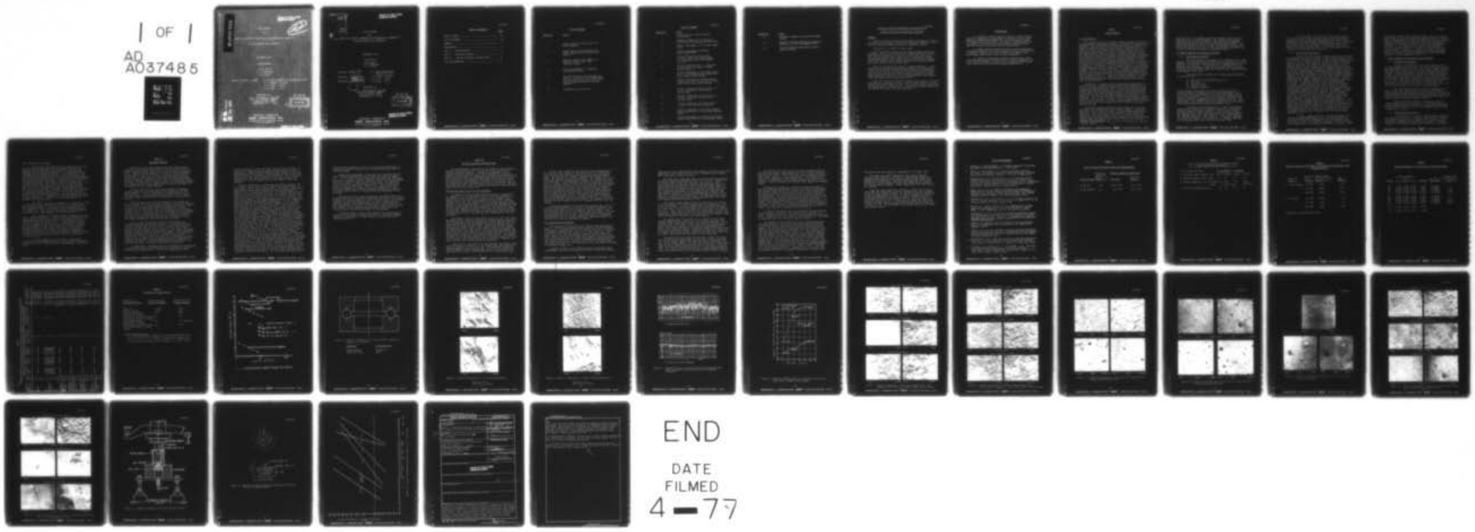
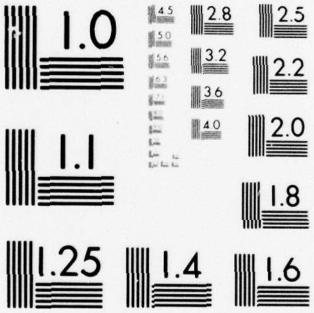
AD-A037 485 SKF INDUSTRIES INC KING OF PRUSSIA PA RESEARCH LAB F/G 13/9
EFFECT OF LAPPING PARAMETERS ON GENERATION OF DAMAGE ON SILICON--ETC(U)
DEC 76 H M DALAL, J W ROSENLIEB, L B SIBLEY N00019-76-C-0147
UNCLASSIFIED AL76T026 NL

| OF |
AD
A037485



END
DATE
FILMED
4 — 77


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3

NW

FINAL REPORT

ON

EFFECT OF LAPPING PARAMETERS ON GENERATION OF DAMAGE ON SILICON NITRIDE BALL SURFACES

DECEMBER, 1976

CONTRIBUTORS

H. M. DALAL
J. W. ROSENLIEB
L. B. SIBLEY

PROJECT LEADER: H. DALAL

U. S. NAVY CONTRACT NO. N00019-76-C-0147
S K F REPORT AL76T026
S K F CODE LC050
S K F REG. 414 2

SUBMITTED TO:

U. S. DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
CODE AIR 310C (JP1)
WASHINGTON, D.C. 20360

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

FINAL REPORT

ON

EFFECT OF LAPPING PARAMETERS ON GENERATION OF DAMAGE ON SILICON NITRIDE BALL SURFACES

DECEMBER, 1976

Contributors

H.M. Dalal
J. W. Rosenlieb
L. B. Sibley

Prepared: Harish M. Dalal

Approved:

Released:

U.S. Navy Contract No.
N00019-76-C-0147

S K F Report AL76T026

S K F Code LC050

S K F Reg. 414 2

SUBMITTED TO:

U. S. DEPARTMENT OF THE NAVY
NAVAL AIR SYSTEMS COMMAND
CODE AIR 310C (JP1)
WASHINGTON, D.C. 20360

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

TABLE OF CONTENTS

	PAGE
LIST OF TABLES	ii
LIST OF FIGURES	iii
SUMMARY	1
CONCLUSIONS	2
PART I - ROUGH LAPPING	3
PART II - POLISHING STUDIES	8
PART III - ROLLING FOUR-BALL FATIGUE TESTS	11
LIST OF REFERENCES	16

LIST OF TABLES

Table No.	Title
1	Data on Abrasive Slurry Used for Rough Lapping
2	Grade NC132 Silicon Nitride Ball Rough Lapping Test Conditions and Results
3	Material Removal Rate (MRR) as a Function of Unit Ball Load (Limited Slurry)
4	Surface Roughness as a Function of Diameter Change
5	Rolling Four-Ball Test Fatigue Life Data on 17.5mm Balls of CVM M50 Steel Baseline and NC 132 Silicon Nitride with Surfaces Finished by Various Methods
6	Estimated L_{10} Life Valves

LIST OF FIGURES

Figure No.	Title
1	Silicon Nitride Element Fatigue Test Results
2	Schematic Drawing of the Grooved Plates Used for Lapping and Polishing
3	Surface Topography of SiC Rough Lapped Balls
4	Surface Topography of Diamond Rough Lapped Balls
5	Talysurf Traces of Grade NC132 Silicon Nitride Ball Rough Lapped at a Unit Ball Load of 44 Newtons (10 lbs.)
6	Material Removal Rate as a Function of Unit Ball Load Using a Single Slurry Charge
7	Surface Topography of SiC Rough Lapped Balls with Increasing Unit Ball Load Using Single Slurry Charge
8	Surface Topography of Diamond Rough Lapped Balls with Increasing Unit Ball Load Using Single Slurry Charge
9	Surface Topography and Structure of an As - Received 17.5mm Silicon Nitride Ball
10	Surface Topography and Structure of an Al_2O_3 Polished 17.5mm Silicon Nitride Ball
11	Surface Topography and Structure of a 7mm Silicon Nitride German Ball
12	Surface Topography of Polished Diamond Rough Lapped Balls (A2-A4) Using Abundant Slurry
13	Surface Topography of Polished SiC Rough Lapped Balls (B2-B4) Using Abundant Slurry

Figure No.	Title
14	Schematic Drawing of Rolling Four-Ball Tester
15	Schematic Drawing Showing the Relative Positions of Test and Support Balls
16	Graph of Maximum Likelihood Analysis of Test Groups

AL76T026

EFFECT OF LAPPING PARAMETERS ON GENERATION OF DAMAGE ON SILICON NITRIDE BALL SURFACES

SUMMARY

This is the Final Report on the Effect of Lapping Parameters on Generation of Damage on Silicon Nitride Ball Surfaces. The work was performed under Contract No. N00019-76-C-0147.

The report is written in three parts.

Part I presents results of two rough lapping experiments conducted using 44 μm SiC and 15 μm diamond abrasives in free and controlled quantities and with various unit ball loads. The results indicate that, under the test conditions chosen, diamond generates a more uniform finer surface finish compared to the SiC and provides a larger increase in material removal rate with increase in unit ball load.

Part II discusses the results of Al_2O_3 polishing. It was found that by using the developed procedures silicon nitride balls can be polished to meet surface roughness specification of 0.01 μm AA for aircraft quality balls. It was also found that the more uniform and finer surface generated by *diamond* rough lapping is polished to the required quality more readily than the rougher surface generated by SiC.

Part III discusses four-ball fatigue test results of silicon nitride balls produced in Parts I and II tested against vacuum melted M-50 steel support balls. The results clearly demonstrate the improvement in fatigue life of the silicon nitride balls due to the use of proper finishing procedures.

CONCLUSIONS

1. Rolling - contact fatigue tests of silicon nitride balls show substantial improvement in fatigue life of rough-lapped or lapped and polished balls over as-received balls. The lapped and polished balls are shown by scanning electron microscopy to be free of the microscopic surface cracking observed on the as-received silicon nitride balls.

2. Rough lapping experiments show a clear superiority of diamond abrasive over silicon carbide abrasive in efficiency of material removal in silicon nitride ball lapping while maintaining consistently lower surface roughness.

3. Alumina polishing of silicon nitride balls after rough lapping produced the desired low surface roughness with less material removal required with the diamond rough lapped balls than with silicon carbide rough lapped balls.

PART I

ROUGH LAPPING

1.1 Introduction

The reliability of hot pressed silicon nitride for critical rolling-bearing components depends on the ability to manufacture components from this material without generating material or finishing induced defects in the process. Material defects are known to affect the fatigue life of bearing steels (1)*, and significant improvement in critical aircraft applications has been demonstrated through the use of vacuum processed steels and improved processing techniques and quality control procedures. The greater brittleness of silicon nitride compared to bearing steels increases the importance of producing components with even fewer and less severe strength degrading flaws. Material defects such as porosity, non-uniform density and tramp impurities or foreign inclusions are obviously deleterious to its fatigue performance. In addition, poor grinding procedures can generate strength degrading flaws in glasses and ceramics leading to poor strength (2,3) or fatigue life (4,5). Rolling contact fatigue testing (4,6,7,8) of hot pressed silicon nitride, summarized in Figure 1, has demonstrated that the material equals the rolling contact fatigue life of a good quality bearing steel (1) and at times greatly exceeds it. There is further evidence (4,5,9) that finishing procedures significantly influence the fatigue life of this material.

Presently, a significant design-effective application of silicon nitride in rolling contact applications appears to be as balls in high-speed ball bearings to reduce the centrifugal loading and improve fatigue life. A lower heat generation of steel-silicon nitride bearings compared to all steel bearings (9,10) makes this material additionally important where heat generation as well as centrifugal loading, is critical to performance. The purpose of this research and development program, therefore, was to study the effect of ball rough lapping parameters on the severity of surface damage generated and its effect on fatigue life of balls made from NC 132 grade hot pressed silicon nitride.

Two rough lapping experiments were conducted. The first experiment was conducted with an abundant supply of abrasive particles such as would be used in a production manufacturing operation. This was done to duplicate an actual production process in which the average size of the abrasive particles contacting the silicon nitride ball surface is not significantly smaller than the starting size towards the end of the rough

---

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

lapping cycle. The damage generation tendency of the abrasive type and size was thus evaluated. The second rough lapping experiment was conducted using a fixed quantity of abrasive slurry sufficient to just fill the lapping plate grooves. This permitted evaluation of the response of the abrasive particles to increasing unit ball loads. The experimental conditions and results of the above studies are presented below.

1.2 Rough Lapping with Abundant Abrasive

1.2.1 Experimental Approach

The rough lapping experiments were conducted on 17.5 mm diameter silicon nitride balls made from hot pressed NC 132 grade material. A precision single groove ball lapping machine was used for this purpose. A lever arm with a leverage of 5:1 was added to the dead weight system on the spindle of the machine to permit the variation of unit ball load for any number of balls being lapped at one time.

The significant variables of a rough lapping operation are listed below:

a) grit type (SiC,diamond,Al_2O_3 etc.)
b) grit size
c) unit ball load
d) lapping speed
e) coolant chemistry

In the present investigation constant lapping speed and coolant chemistry (mineral base oil) were maintained. Two grit types (SiC and diamond) and two unit ball loads (44 and 111 N) were evaluated. A 45μm size SiC grit, conventionally used for rough ball lapping and 15μm diamond were used. The smaller grit size diamond was chosen to account for the lesser friability of the diamond particles compared to the SiC particles which break down during the production cycle.

The rough lapping operation on a small experimental single groove machine, was conducted using a set of grooved Meehanite lapping plates (Figure 2). The abrasive slurry was contained in a small tank surrounding the lapping plates. The lapping plates were kept immersed in the slurry during the lapping operation. The slurry was continuously agitated to prevent the abrasive from settling. A separate tank and set of lapping plates were used for each grit type.

A set of twelve 17.5 mm balls were rough lapped at 44N (10 lbs.) unit ball load with each of the two abrasives. A detailed study on the polishing response of these rough lapped balls was subsequently conducted,(Part II) to establish the change in surface roughness with material removal by Al_2O_3 polishing. At the higher unit load of 111N (25 lbs.) the set size was reduced to six. A polishing study was not conducted on these two sets of balls.

1.2.2 Results and Discussion

The data on the SiC and diamond slurries used in this investigation is shown in Table 1. The concentrations of the two abrasives chosen are typical of those used in manufacturing practice. It is significant in considering processing costs that the number of SiC particles per cc of slurry is approximately four times the number of diamond particles per cc. Material removal rates, measured as a change in the diameter of the balls per hour, and surface roughness produced by each of the four rough lapping experiments are presented in Table 2. The results indicate that at the conventional rough lapping load of 44N/ball the material removal rate produced by diamond (36μm/hr) is only marginally less than that of SiC (40μm/hr), inspite of the higher concentration of the latter. On the other hand the surface roughness of the diamond lapped balls (0.1μm AA) is superior to that of the SiC lapped balls (0.4μm AA). Increasing the unit ball load to 111N leads to greater increase in material removal rate for diamond (36 to 50μm/hr) compared to SiC (40 to 42μm/hr) while still maintaining a superior surface finish. The greater increase in material removal rate with load for the diamond abrasive is consistent with the lower friability of the diamond particles. In the case of the balls lapped at the higher load, the variation in spot-to-spot surface roughness was also measured. It was found that, when computed as a percent of the average value, the variation is greater (~26%) for SiC than for diamond (~17%) rough lapped balls. It is noted that the surface roughness of the SiC and diamond rough lapped balls are in the same ratio as their particle sizes indicating that while the SiC may breakdown in size during the lapping cycle, the initial size, needed to provide a reasonable cutting rate, determines the resulting surface characteristics.

A visual comparison of the surface topographies of SiC and diamond rough lapped balls, at 44N/ball load, is obtained by comparing scanning electron micrographs shown in Figures 3 and 4. The greater roughness of the SiC lapped balls compared to the diamond lapped balls is evident. This is further illustrated by Talysurf traces shown in Figure 5. Close study of the 5000X photomicrographs reveals a difference in the mechanism of material removal by the two abrasives. Material removal by SiC appears to take place largely by a rubbing action producing a flat chip of the type indicated in Figure 3. The clean cutting action of the diamond abrasive, on the other hand, is evident from the surface scratch shown in Figure 4. Increasing the unit ball load does not cause a significant change in surface topography with either abrasive as evidenced by the relatively minor change in surface roughness (Table 2).

1.3 Rough Lapping with Limited Abrasive Supply

1.3.1 Experimental Approach

The basic experimental set up and slurries used for this purpose were the same. The main difference is that each experiment used a set of 3 balls with a single charge of abrasive slurry sufficient to fill the lapping plate groove. The balls were spaced equally around the groove by means of a cage. A rubber finger was designed to scrape the bottom of the groove in front of each ball to stir up the slurry and minimize settling of the abrasive during the brief period of the test. Tests were conducted using unit ball loads of 44, 111 and 222N (10,25 and 50 lbs.) with each of the abrasives. A fresh batch of abrasive slurry and a new set of silicon nitride balls was used for each experiment.

The cycle time selected for these expirments was 2 hours. This short time period was chosen to facilitate interpreting and comparing test data for the two abrasives by minimizing the effect of settling rate differences of the two abrasives due to the difference in their particle shape and density and the absence of good stirring.

Material removal rate was measured in terms of weight change using a microbalance. The weight change per hour per ball was then converted to an equivalent reduction in diameter per hour for the 17.5 mm diameter balls, using a density of 3.2 g/cc.

1.3.2 Results and Discussion

The results of the second rough lapping experiments are presented in Table 3. Material removal rate in terms of diameter change per hour (μm/hr) as a function of unit ball load is graphically presented in Figure 6. Surface roughness of the balls produced with each unit ball load is also included on the graph.

The results show that material removal rate for the diamond abrasive increases almost linearly at the lower unit ball loads after which it seems to be leveling off. Some decrease in material removal rate is expected from the breakdown of the diamond particles. A second cause of the leveling off may be due to the fact that at the higher unit ball loads the diamond particles are pushed into the Meehanite plate and made less effective. In the case of SiC abrasive, the material removal rate shows a gradual increase with increasing unit ball load without signs of leveling off. The slightly upward slope may be due to the increasing breakdown rate of the SiC particles under increasing pressure. This leads to an increase in contact area between the silicon nitride ball surface and the abrasive particles resulting in an increased material removal rate. In the case of SiC, embedding of the abrasive particles into the Meehanite plate is less significant. Regardless of the reasons for the shape of these curves, it is obvious that diamond lapping is superior for removal rate.

The change in surface roughness as a function of load is found to have an opposite trend for the two abrasives. While surface roughness decreases with increasing load for the diamond abrasive, it increases with increasing load for SiC (Figure 6). This finding also clearly favors diamond as an abrasive for rough lapping silicon nitride balls.

The combination of highest material removal rate and lowest surface roughness of diamond rough lapped balls offers a good potential for developing a cost effective silicon nitride ball manufacturing process. Optimization, however, is not as simple as stated above. A high material removal rate which implies short cycle time can lead to excessive out-of-roundness of the rough lapped balls which would be extremely difficult and costly to correct in subsequent polishing operations. Of course the danger of generating surface microcracks with increasing unit ball load due to the low friability of diamond grit must also be considered as a limiting factor.

A visual comparison of the surface topography produced with increasing unit ball loads by the two abrasives is provided by the scanning electron micrographs in Figures 7 and 8.

PART II

POLISHING STUDIES

Polishing is the final stage in the ball manufacturing operation in which the surface finish of the balls, and to a limited extent roundness and size, is improved to the required level. Based on prior endurance testing, a surface roughness better than 0.01 μm AA (0.4μ in.) is desired on the silicon nitride balls. This was achieved by using E-330 grade Al_2O_3 produced by Norton Company, in the final polishing operations. It has an average particle size of 5 μm. In the present study, polishing was also used to remove selectively increasing amounts of surface layer on rough lapped balls to assess the depth of the potential rough lapping damage.

For polishing purposes, the grooved Meehanite lapping plates (Figure 2) were replaced by brass plates of the same configuration. A slurry containing 10 weight percent (w/o) Al_2O_3 was used. The same mineral-base carrier oil as used in the rough lapping experiments, was employed in the polishing slurry.

Since the main objective of polishing is to produce as fine a surface finish as possible, improved results are obtained if the surfaces of as-machined brass plates are "run-in" prior to their use in polishing. This was achieved by running finished 17.5 mm M50 steel balls in the grooves for six hours without slurry. The run-in was then continued for an additional 20 hours with the polishing slurry. At the end of this period, the plates were cleaned and the surfaces examined to ensure that all tool marks were removed and that the groove surface was smooth, indicating even contact with the balls.

A set of six as-received silicon nitride balls were polished using the run-in brass plates. A polishing cycle of 20 hours improved the surface finish of the as-received balls from 0.02 μm AA (0.8μ in. AA) to 0.01 μm AA (0.4μ in. AA). Absence of visible marks on the surfaces of the balls indicated that the groove surfaces were properly run-in. SEM examination further revealed that the surface topography was quite acceptable being similar to that of a 7 mm ball received from Germany (9). A longer term polishing (up to 40 hours) produced silicon nitride balls having a measured surface roughness of 0.008 μm AA, which is only insignificantly better than the 20 hour lap and which is probably smoother than required.

For comparison, scanning electron micrographs of as-received, Al_2O_3 polished, and 7 mm German ball are presented in Figures 9, 10 and 11, respectively. The surface topography of the as-received ball is seen to be more pitted than the other two balls, as revealed in the secondary emission (SE) electron micrographs. Back-scattered electron (BSE) images of the same surfaces reveal the presence of microcracks on the as-received ball surface, not seen on the other two balls. The structural similarity of the Al_2O_3 polished 17.5 mm ball and the 7 mm German ball is also evident from the BSE images of the ball surfaces.

Having established an acceptable polishing procedure, the run-in brass plates were used to conduct polishing studies on the diamond and SiC rough lapped balls. Out of the twelve rough lapped balls, three were retained for SEM and Metrological studies and for evaluating the severity of rough lapping surface damage by four-ball fatigue testing. The polishing studies were conducted on the remaining nine balls. In order to measure the rate of polishing of the rough lapped balls, the remaining nine balls were loaded in the lapping machine as one set. Change in surface roughness was monitored continually. A set of three balls was removed after the surface roughness was reduced to approximately 0.05, 0.015 and 0.005 μm AA. The three balls were retained for SEM examination of the surfaces and to determine the material removal (diameter change) that occurred in decreasing the initial surface roughness to the given value. The relationship between diameter change and surface roughness is presented in Table 4. In the case of finished balls produced from the diamond rough lapped balls (A4), a diameter reduction of 4.83 μm was required to reduce the initial surface roughness (0.095 μm AA) to the desired final value of 0.01 μm AA or less on the finished ball. The three surface roughness readings on the A4 balls indicate very little variation in surface roughness from spot-to-spot. In the case of finished balls produced from the SiC rough lapped balls (B4), it was necessary to reduce the diameter by 22.83 μm to bring the surface roughness down to a level less than 0.01 μm AA. The three surface roughness values reported on the B4 balls indicate a greater spot-to-spot variation compared to the diamond rough lapped balls. This indicates the presence of some non-cleaned-up areas on the finished balls which is confirmed by SEM photomicrographs of the surfaces discussed later. It must be pointed out that although there is a spot-to-spot variation in surface roughness of the B4 balls, the highest surface roughness value (0.011 μm AA) does meet the desired maximum limit. A few short or narrow residual scratches will not normally be detected in surface finish readings and, therefore, an additional description of surface characterization besides AA finish is necessary. The detection and rejection of residual deep scratches or pits is of particular importance to attain the required fatigue life of brittle materials such as silicon nitride.

Comparative photographs of the partially polished and finished A(A2-A4) and B(B2-B4) series balls are shown in Figure 12. It is clear from the polishing rate data that polishing proceeds by removing a greater amount of material from the higher spots and a smaller amount at the lower spots. The polishing of the high spots is particularly evident from the SEM micrographs of the B-series balls (Figure 13). Since the B-series balls are rougher initially, this is in agreement with the previous finding that a greater diameter reduction is required to produce the B4 balls of finished quality comparable to the A4 balls.

The results of the rough lapping and polishing studies reported above clearly indicate a preference for the use of diamond abrasive for rough lapping of silicon nitride balls. The surface roughness of the rough lapped balls is lower, requiring less material removal to produce finished balls. This potential of the diamond abrasive can only be realized if the silicon nitride ball surface is not damaged causing severe reduction in the rolling contact fatigue performance of the material.

A selected group of balls were four-ball fatigue tested to evaluate the severity of damage generated by the rough lapping operation. The results of these tests are presented and discussed in PART III.

PART III

ROLLING FOUR-BALL FATIGUE TESTS

The experimental evaluation of the effect of the finishing process on the fatigue life of Si_3N_4 balls was performed on rolling four-ball testers. Testing was performed on five groups of NC132-type Si_3N_4 balls each finished by a different process and one group of consumable-electrode vacuum melted (CVM) M-50 steel balls with six specimens being tested in each group. The test series was designed to determine the relative effects of variations in the finishing processes on the fatigue life of the Si_3N_4 balls and a comparison of the lives with that obtained from CVM M-50 steel balls (a standard aerospace bearing material), which were used as a base line.

Rolling Four-Ball Tester & Test Procedure

A schematic of the rolling four-ball tester is presented in Figure 14. In the four-ball tester, the test specimen, i.e., the spindle ball, is held in a vertical arbor against three support balls which orbit the spindle axis on a ball raceway machined in a cup. The spindle ball is fixed in position with respect to the rotating arbor by a spring loader/plunger pressed against a flat surface ground on the top of the spindle ball and the friction between the cone machined in the end of the arbor and the ball spherical surface. Two flats are machined on each spindle ball diametrically opposite each other; thus, each ball is tested twice, i.e., the two ends are considered as two test specimens.

The support balls are positioned in the cup race 120° apart and held in this relative position by a brass cage or separator. The positioning of the cup concentric with the spindle axis insures equal loading of the support balls and identical Hertzian stress at the three contact points between the spindle (test) ball and the support balls. The contact angle of the assembly is controlled by the race design in the cup and the support and test ball sizes, see Figure 15. The load, which determines the Hertz stress at the contact points between the balls, is applied through the spindle by a dead weight lever system. The spindle is driven by a constant speed DC motor through a pulley and belt drive system. The spindle speed can be varied by changing the ratio of the driver to driven pulley diameters.

Lubrication is provided by a once-through, drip-feed system which provides oil directly to the spindle ball and maintains a copious quantity of oil in the cup. A vibraswitch mounted on the cup support table automatically turns the drive motor off and stops the testing at the initiation of a spalling failure.

Prior to the initiation of each test, the concentricity of the cup race with respect to the spindle axis was determined with the operating load applied and any necessary adjustments made. The cup race was visually examined for damage, and if damage was present the cup was replaced. The spindle ball, test balls and cup were cleaned before assembly and coated with the test lubricant. After assembly and prior to starting the drive motor, a copious supply of test oil was injected onto the spindle ball and allowed to drain from the bottom of the cup while the spindle was rotated by hand. This was performed to prevent wear at startup and flush any dirt from the assembly which may have inadvertently been introduced. Each test was performed until a spall or wear failure occurred on the spindle ball or to a pre-established time up. Following each motor stoppage due to the vibraswitch, all balls were inspected. If the test ball had failed the test was terminated. If a support ball had failed, all three support balls were replaced and the test continued.

A lubricant meeting MIL-L-23699 specification was used in all tests and supplied at a rate of 3-6 drops per minute. The spindle balls were 17.5 mm in diameter and the support balls were aircraft quality 12.7 mm diameter CVM M-50 steel. The cups were machined from 52100 steel. The spindle ball material and finishing process, the spindle speed and load, the calculated maximum Hertz stress, and the calculated Lundberg-Palmgren L_{10} life for each test is presented in Table 5.

Test Results and Discussion

The results of rolling four ball testing are summarized in Table 5. The M-50 steel balls were tested at 5200 rpm spindle speed under a spindle load of 1277 Newtons (287 lbs.) calculated to produce a maximum Hertz stress of 4.7 GPa (680 ksi). This stress level was selected based on previous 52100 steel ball test results. It was the maximum stress found with 52100 steel balls (thus minimizing test time) that would not cause excessive loss in fatigue life due to plastic deformation and grooving of the contact track (11). Even so, the life of CVM 52100 steel balls was less than half the theoretical life calculated according to Lundberg-Palmgren (1).

As seen in Table 5, the CVM M-50 balls tested also lived considerably less than the theoretical life to spalling failure.

This result is not unexpected for the higher alloy M-50 tool steel compared to 52100 steel in this type of element tester running under high Hertz contact stresses.

The first test conducted with a NC 132 silicon nitride ball of current domestic manufacture under the same test conditions lived many times longer than the M-50 steel balls. Since the accumulation of spalling failure life data under this test condition would proceed very slowly, and since other investigators have run the harder silicon nitride at higher Hertz contact stresses successfully (7,8), both the test load and the test speed were increased for subsequent tests (spindle load-1480 Newtons (333 lbs.), calculated maximum Hertz stress-5.5 GPa (800 ksi), spindle speed 10,000 rpm). The fatigue life of all domestic silicon nitride balls tested exceeded about two times the Lundberg-Palmgren theoretical life.

The diamond rough lapped silicon nitride balls (A1 balls), using an average 10 lb./ball lapping load, (see Sections I and II of this report), ran even longer than the domestic silicon nitride balls, all of them exceeding 14 to 30 times the theoretical life. Also, half of them were still unfailed at the end of the tests. These results indicate that substantial fatigue life degradating flaws must exist on the surface of the domestic balls which are removed effectively by rough lapping.

All except one of the third set of silicon nitride balls tested, diamond rough lapped with 10 lbs./ball load and then polished with Al_2O_3, had a longer life than the domestic silicon nitride balls. The initial two tracks tested, had relatively short life values compared to the diamond rough-lapped only balls. This suggests that the Al_2O_3 polishing may be detrimental to fatigue life of the Si_3N_4. However, the high life values of the final four tracks tested could indicate that the results may be normal scatter and not the effect of the polishing.

The fourth set of silicon nitride balls tested (A'1 balls), were diamond rough lapped with a 25 lb./ball load to determine if a faster rough lapping rate would produce a deleterious effect on the fatigue life. The test life values were even greater than the balls diamond rough lapped with 10 lb./ball. The one spall that occurred before time up was 14 times the theoretical life. All other tracks tested ran for a period greater than 26 times the theoretical life to spalling failure without spalling.

The fifth set of silicon nitride balls tested (B4 balls) were silicon carbide rough lapped with a 10 lb./ball load and polished with Al_2O_3. The initial two tracks tested resulted in life values similar to those obtained with the domestic Si_3N_4 balls which suggested no improvement due to the refinishing. However, the remaining four tracks evaluated resulted in lives similar to those obtained with diamond rough lapped and polished balls.

Although all methods of finishing evaluated resulted in greatly improving the fatigue life of the domestic Si_3N_4 balls, the greatest improvement was obtained with rough lapped balls. The surface finish on these balls, however, do not meet the desired surface finish and would not be considered useable in an application. The test data from each group of balls tested was statistically evaluated using the maximum likelihood technique for determining the L_{10} estimated fatigue life of the group. This method of evaluation is standard in calculating bearing life and provides a comprehensive approach to comparing life data. The results of these calculations are presented in Table 6 and shown as a Weibull plot in Figure 16.

It must be recognized that the estimated L_{10} life results based on small test groups are particularly sensitive to a single failure if there is wide scatter in individual test life data. Therefore, the life estimates obtained must be considered as indicators of life and not as precise values.

The results of the estimated L_{10} life calculations show that all groups of silicon nitride balls tested had greater estimated L_{10} life values that the baseline M-50 steel ball group. The lowest life of Si_3N_4 balls was obtained with the domestic balls which had an estimated L_{10} life slightly better than the calculated theoretical life of 7 X 10^6 revolutions. The two groups of balls rough lapped with a diamond compound had the longest lives. One group was lapped with an average load of 10 lb./ball and the other with 25 lb./ball, and has estimated L_{10} life values of 116 and 162.7 x 10^6 revolutions, respectively. The two lapped and polished ball groups, each lapped with a 10 lb./ball load but one with a diamond compound and the other with silicon carbide compound before polishing with Al_2O_3, had estimated L_{10} life values of 36.7 X 10^6 and 13.8 X 10^6 revolutions each. Although these two groups have an improved life over the domestic Si_3N_4 balls, there is an indication that the lapping is detrimental to fatigue life.

The lower life value obtained by the silicon carbide lapped and polished balls relative to the diamond lapped and polished balls suggests that silicon carbide rough lapping may degrade the fatigue life. Further substantiation of this observation was not established since the rough surface produced by silicon carbide lapping alone rendered the ball impractical for testing.

Since the steel balls were tested at a lower Hertz stress value than the Si_3N_4 balls a direct comparison of the estimated L_{10} life values cannot be made. To obtain a relative evaluation of the two materials the ratios of their estimated L_{10} life to calculated theoretical life must be made. The M-50 ratio is 0.112 and the ratio of the lowest L_{10} life value for the Si_3N_4 (domestic Si_3N_4) is 1.07. A comparison of these two values indicates that the domestic Si_3N_4 out performed the M-50 steel by a factor of 9.5. The refinished Si_3N_4 groups have an even higher improvement factor.

LIST OF REFERENCES

1. Lundberg, G. and Palmgren, A., "Dynamic Capacity of Rolling Bearings," Acta Polytechnica No. 196 (1947).
2. Huerta, M. and Malkin, S., "Grinding of Glass: Surface Structure and Fracture Strength", ASME Proceedings, General Engineering Conference, Paper No. 75-Prod. 2 (May 1975).
3. Baumgartner, H. R. and Wheildon, W. M., "Rolling Contact Fatigue Performance of Hot-Pressed Silicon Nitride Versus Surface Preparation Techniques", Proceedings of the "Symposium on Surfaces and Interfaces of Glass and Ceramics", Alfred University, Alfred, New York (August 1973).
4. Dalal, H. M., et al, "Effect of Surface and Mechanical Properties on Silicon Nitride Bearing Element Performance," SKF Report No. AL75T002, Final Report on Naval Air Systems Command, Contract N00019-74-C-0168 (February, 1975).
5. Baumgartner, H.R., and Cowley, P.E., "Finishing Techniques for Silicon Nitride Bearings", Final Report No. AMMRC CTR 76-5 on Contract DAAG46-74-C-0055 (March 1976).
6. Parker, R. J. and Zaretsky, E. V., "Fatigue Life of High Speed Ball Bearings with Silicon Nitride Balls," Trans. ASME, J. Lub. Technology, 97 (3), pp. 350-357 (1975).
7. Baumgartner, H. R., "Evaluation of Rolling Bearings Containing Hot-Pressed Silicon Nitride Rolling Elements," Second Army Materials Science Conference on Ceramics for High Performance Applications, Hyannic (1973).
8. Valori, R., "Rolling Contact Fatigue of Silicon Nitride," Naval Air Propulsion Test Center Report No. NAPTC-PE-42 (August, 1974).
9. Dalal, H. M., et al, "Surface Endurance and Lubrication of Silicon Nitride Ball Bearings," Final Report on U.S. Department of the Navy Contract No. N00019-75-C-0216, SKF Report AL75T030 (December, 1975).
10. Reddecliff, J. M., "Silicon Nitride Ball Bearing Demonstration Test," Pratt & Whitney Aircraft Report No. FR-6995, Final Report on NAPTC Contract N00140-75-C-0382 (May 1975).
11. Tallian, T. E., McCool, J. I., and Sibley, L. B., "Partial Elastohydrodynamic Lubrication of Rolling Contacts," Symposium on Elastohydrodynamic Lubrication, Paper No. 14, Inst. Mech. Engrs., London (1965).

TABLE 1

Data on Abrasive Slurry Used for Rough Lapping

	Abrasive Type	Percent by Weight of Abrasive in Slurry	Approx. number of Particles Per gram	Approx. number of Particles Per CC of Slurry
1.	44 μm SiC	40	3.27×10^6	1.18×10^6
2.	15 μm Diamond	0.4	85×10^6	0.31×10^6

TABLE 2

Grade NC132 Silicon Nitride Ball Rough Lapping Test Conditions and Results

1. Grit Size and Type:	15 µm Diamond		44 µm SiC	
2. Unit Ball Load, Newtons (lbs)	44(10)	111(25)	44(10)	111(25)
3. Material Removal Rate, µm/hr	36	50	40	42
4. Surface Roughness, µm AA average	0.1	0.09	0.4	0.46
range	--	0.084-0.099	--	0.41-0.53
5. Ball Group Identification	A1	A'1	B1	B'1

TABLE 3

Material Removal Rate (MRR) as a Function of Unit Ball Load (Limited Slurry)

	Abrasive Type	Unit ball Load N (lbs.)	Weight change per ball per hr. (g/hr.)	MRR* (μm/hr.)
1.	15 μm diamond	44 (10)	0.020	13.1
		111 (25)	0.049	31.3
		222 (50)	0.059	38.5
2.	44 μm SiC	44 (10)	0.008	5.2
		111 (25)	0.012	7.8
		222 (50)	0.021	13.7

*Reduction in diameter/ball/hour

TABLE 4

Surface Roughness as a Function of Diameter Change

Group	Surface Roughness (μm AA) 1	2	3	Average	Av. Dia. of Ball (mm)	Dia.Reduction by Polishing (μm)
A1	0.103	0.088	0.093	0.095	17.22298	-
A2	0.035	0.055	0.043	0.045	17.22247	0.51
A3	0.011	0.013	0.016	0.013	17.21866	4.32
A4	0.005	0.004	0.004	0.004	17.21815	4.83
B1	0.600	0.550	0.625	0.600	17.23238	-
B2	0.045	0.073	0.058	0.058	17.22425	8.13
B3	0.015	0.018	0.016	0.016	17.22374	8.64
B4	0.005	0.011	0.005	0.007	17.20952	22.86
A'1	0.148	0.138	0.130	0.138	-	-
B'1	0.400	0.425	0.375	0.400	-	-

TABLE 5

ROLLING FOUR-BALL TEST FATIGUE LIFE DATA ON 17.5mm BALLS OF CVM M50 STEEL BASELINE and NC 132 SILICON NITRIDE WITH SURFACES FINISHED by VARIOUS METHODS

Spindle Ball Material	Ball Track No.	Spindle Speed, rpm	Spindle Load, N/lbs.	Max. Hertz Stress, GPa/ksi	No. of CVM M50 Steel Support Ball Set Failures	Lundberg-Palmgren Computed L_{10} Life 10^6 revs.	Test Life, 10^6 revs.	Spindle Ball Condition After Test
M50	4A	5,200	1277/287	4.7/680	0	29	20.2	Spalled
	6				0		3.2	Spalled
	6A				1		26.0	Spalled
	7				0		11.0	Spalled
	7A				0		7.1	Spalled
	9A				0		11.7	Spalled
Domestic Si_3N_4	1	5,200	909/204	4.7/680	2	30	117.3	Spalled
	1A	10,000	1480/333	5.5/800	1	7	12.0	Spalled
	2	10,000	1480/333	5.5/800	0	7	66.6	Spalled
	2A	10,000	1480/333	5.5/800	0	7	24.6	Spalled
	3	10,000	1480/333	5.5/800	1	7	41.5	Spalled
	3A	10,000	1480/333	5.5/800	2	7	18.3	Spalled
Diamond Lapped (10#/ball) Si_3N_4	A1-1	10,000	1480/333	5.5/800	5	7	211.2	Spalled
	A1-1A				1		133.2	Unfailed
	A1-2				3		184.2	Spalled
	A1-2A				3		138.0	Unfailed
	A1-3				2		100.8	Spalled
	A1-3A				2		143.4	Unfailed
Diamond Lapped (10#/ball) &Polished Si_3N_4	A4-1	10,000	1480/333	5.5/680	2	7	52.2	Spalled
	A4-1A				3		75.0	Spalled
	A4-3				3		163.8	Spalled
	A4-3A				2		204.0	Unfailed
	A2-1				5		217.8	Unfailed
	A2-2A				2		126.6	Unfailed
Diamond Lapped (25#/ball) Si_3N_4	A'1-1	10,000	1480/333	5.5/680	1	7	190.8	Unfailed
	A'1-1A				1		183.6	Unfailed
	A'1-2				3		183.0	Unfailed
	A'1-2A				1		182.4	Unfailed
	A'1-3				3		102.0	Spalled
	A'1-3A				3		183.6	Unfailed
SiC Lapped (10#/ball) &Polished Si_3N_4	B4-1	10,000	1480/333	5.5/680	2	7	25.2	Spalled
	B4-1A				3		26.4	Spalled
	B4-2				4		179.4	Spalled
	B4-2A				1		184.2	Unfailed
	B4-3				2		225.6	Unfailed
	B4-3A				2		130.8	Spalled

TABLE 6

Estimated L_{10} Life Valves

Material and Finishing Process	Median Unbiased L_{10} Life Estimate	Median Unbiased Slope Estimate
M-50 Steel	3.24*	1.48
Domestic Si_3N_4	7.55	1.40
Si_3N_4 Rough Lapped (Diamond-10 lb/ball)	116.3	3.36
Si_3N_4 Rough Lapped-Polished (Diamond-10 lb/ball - Al_2O_3)	36.7	0.91
Si_3N_4 Rough Lapped (Diamond-25 lb/ball)	162.7	1.6 (imposed)
Si_3N_4 Rough Lapped-Polished (Silicon Carbide 10 lb/ball Al_2O_3)	13.8	0.75

---

* The Lundberg-Palmgren computed L_{10} life for the M-50 steel ball test load is 29 x 10^6revs., whereas the computed L_{10} life for all the silicon nitride groups is 7 x 10^6 revs.

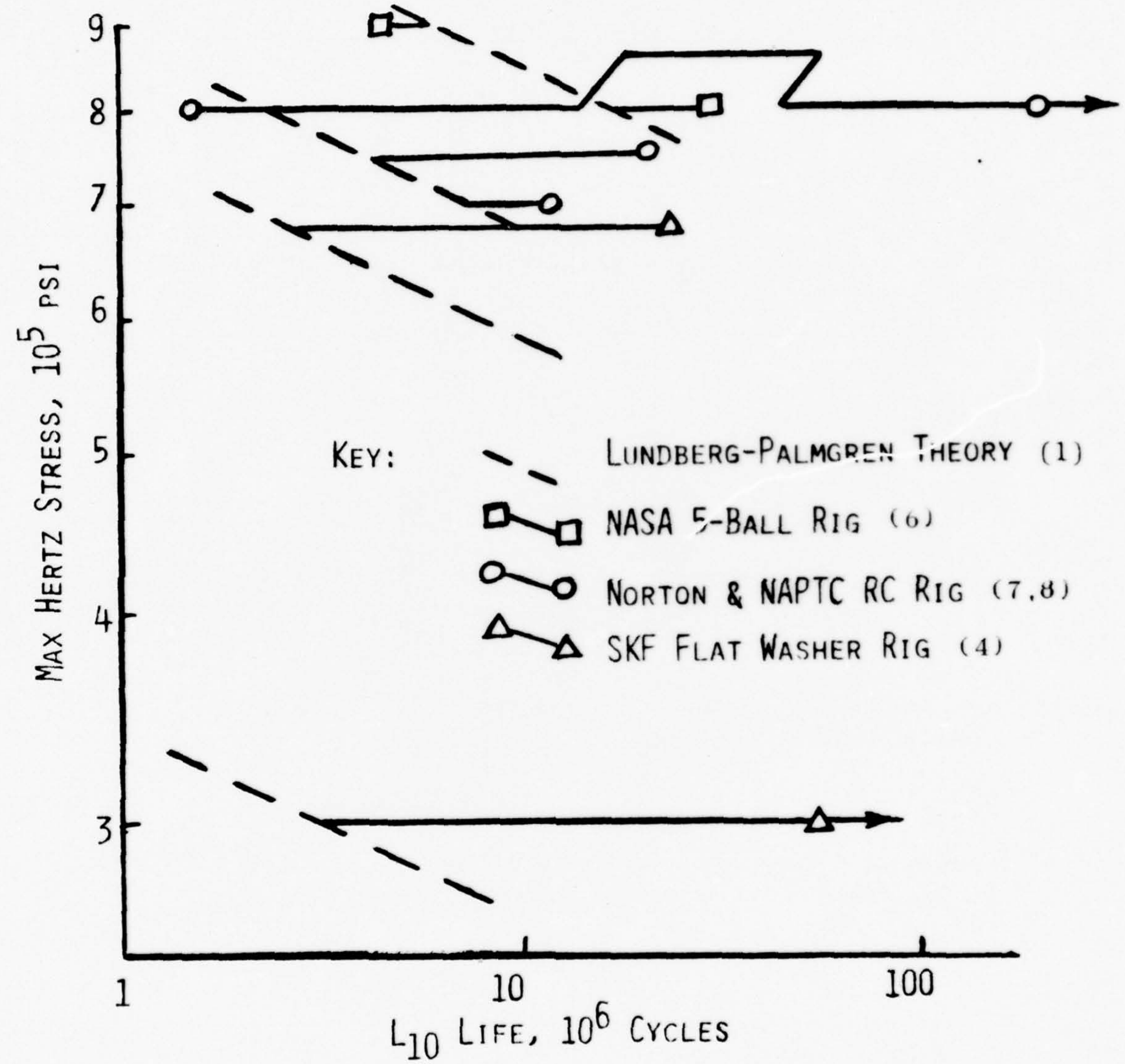


Fig. 1. SILICON NITRIDE ELEMENT FATIGUE TEST RESULTS

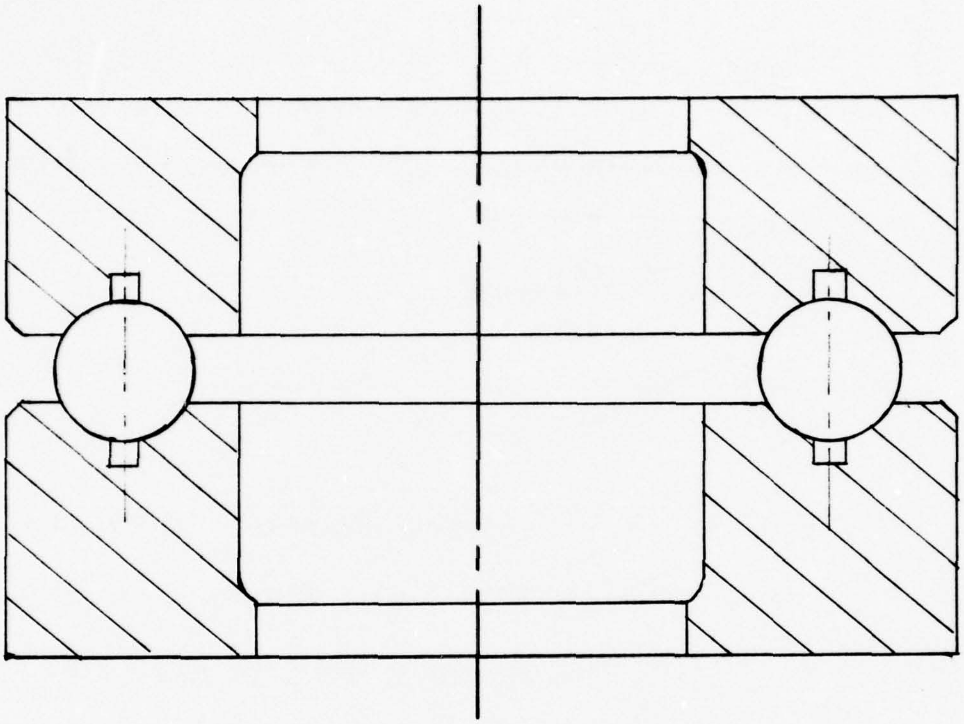
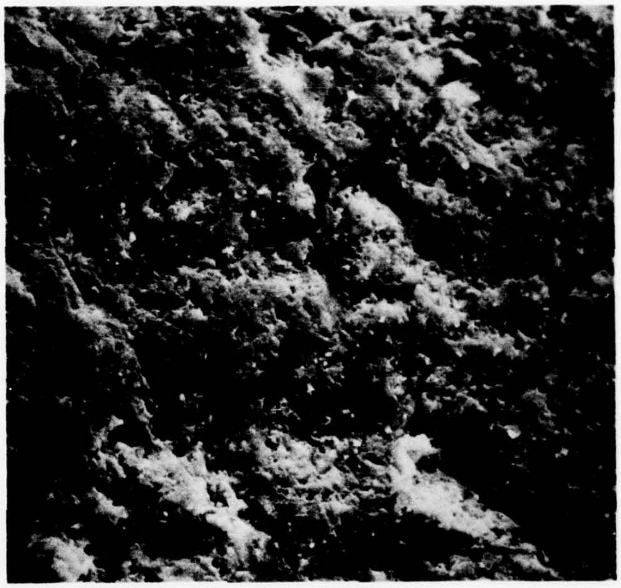
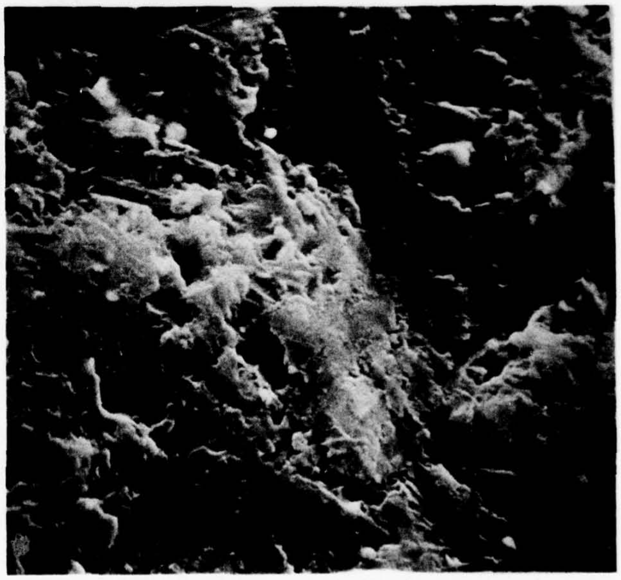


Figure 2. Schematic Drawing of the Grooved Plates Used for Lapping and Polishing

Operation	Plate Material
Rough Lapping	Meehanite
Al_2O_3 Polishing	Brass



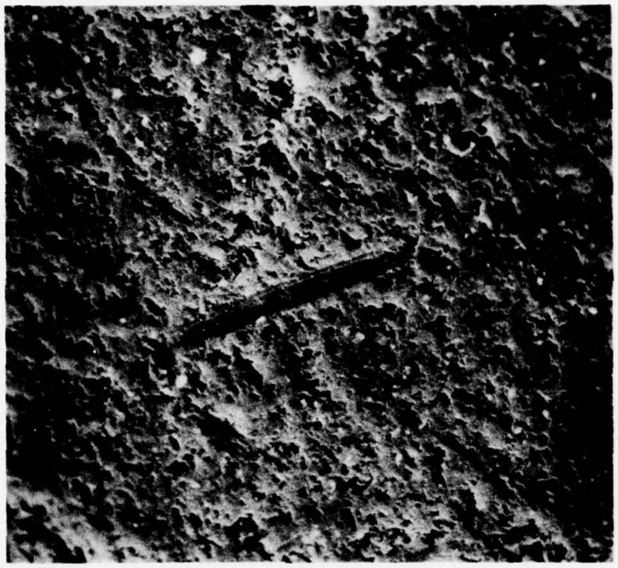
5515 1000X



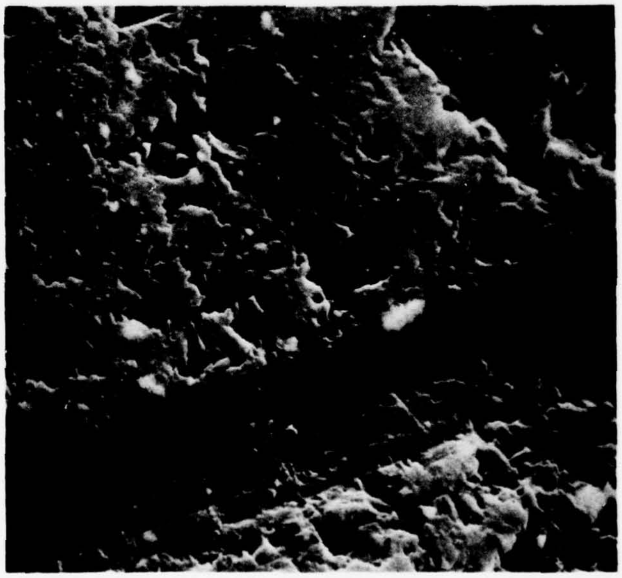
5516 5000X

Figure 3. Surface Topography of SiC Rough Lapped Balls

Abundant Slurry
44 N (10 lbs.)/Ball



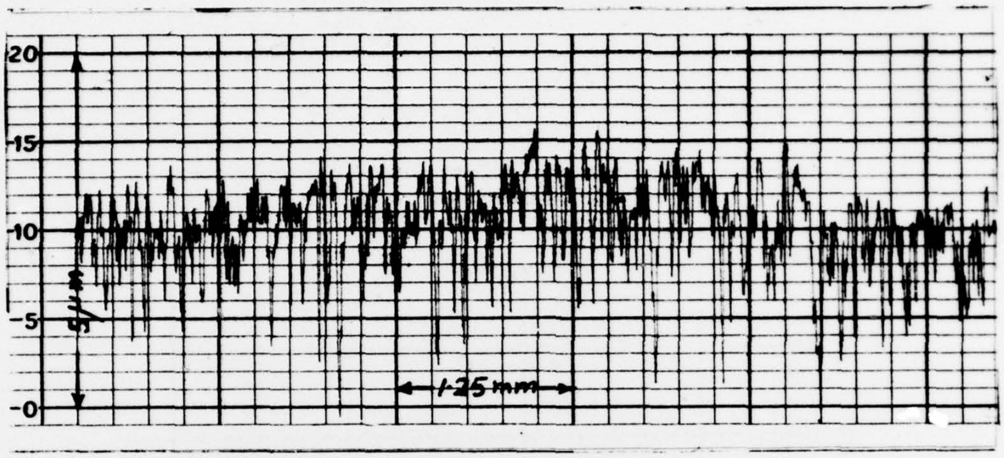
5517 1000X



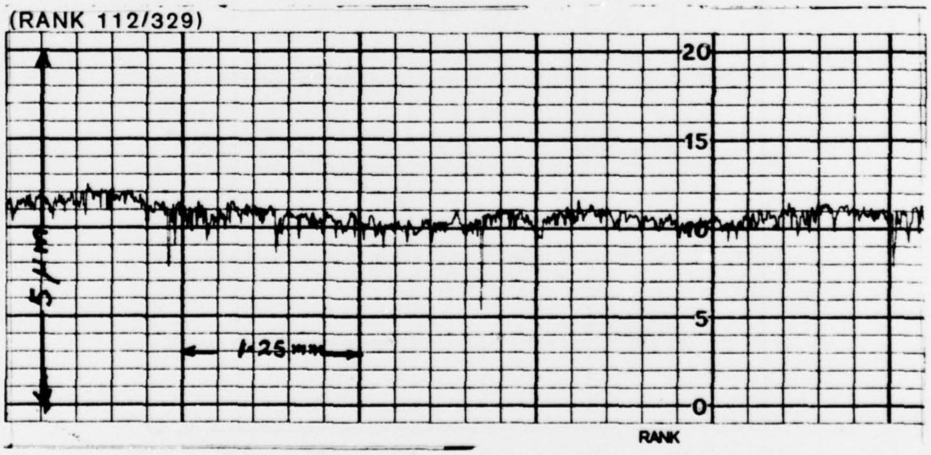
5518 5000X

Figure 4. Surface Topography of Diamond Rough Lapped Balls

Abundant Slurry
44 N (10 lbs.)/Ball



a. Using 44 µm Grit SiC



b. Using 15 µm Grit Diamond

Figure 5. Talysurf Traces of Grade NC132 Silicon Nitride Ball Rough Lapped at a Unit Ball Load of 44 Newtons (10 lbs.)

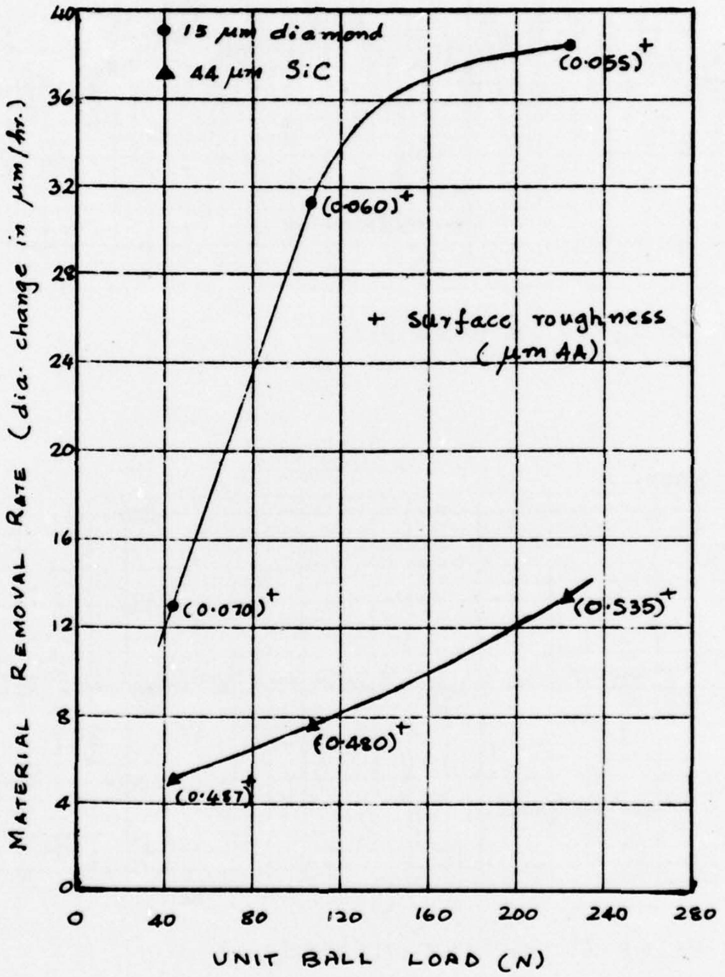
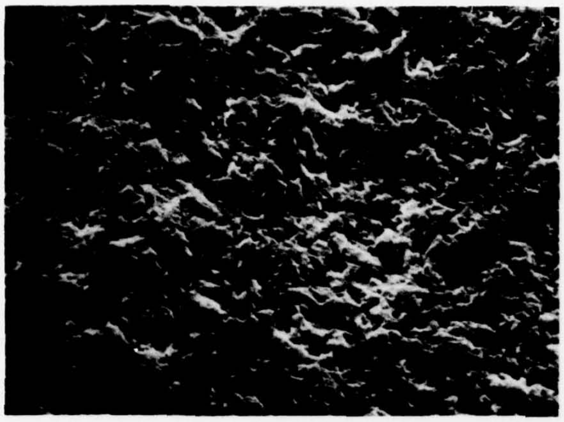
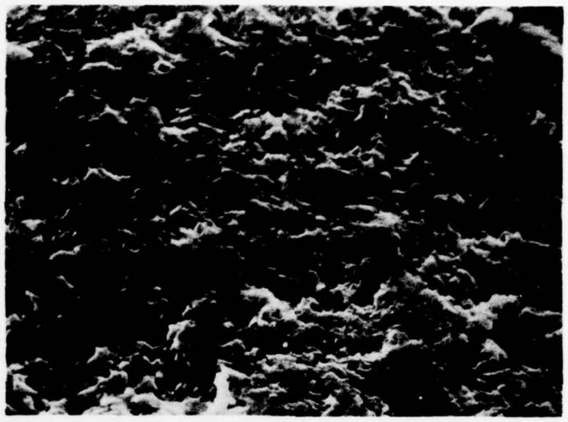


Figure 6. Material Removal Rate as a Function of Unit Ball Load Using a Single Slurry Charge

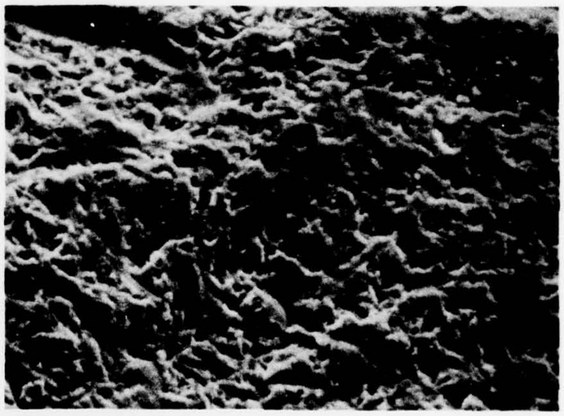
44 N (10 lbs)/ball


5728 1000x

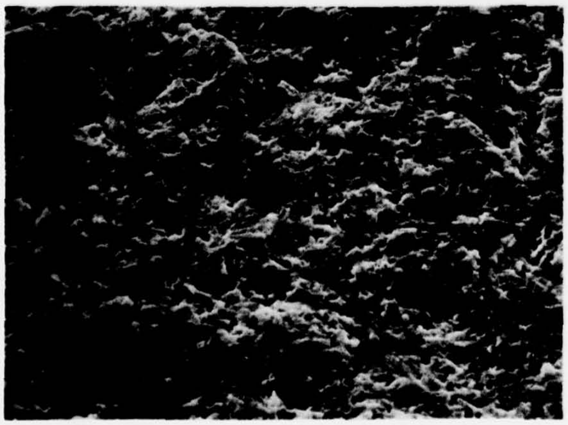

5729 2500x

111 N (25 lbs)/ball


5722 1000x


5723 2500x

222 N (50 lbs)/ball


5725 1000x

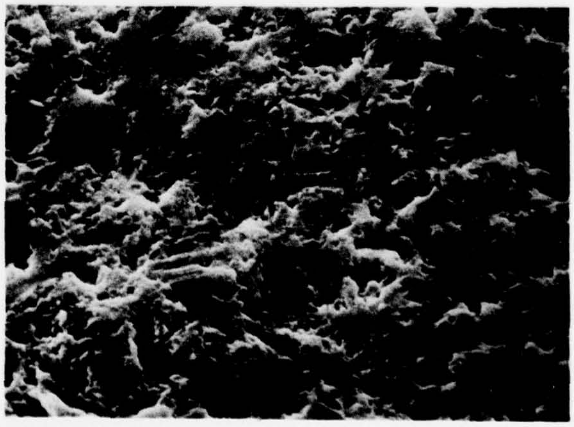
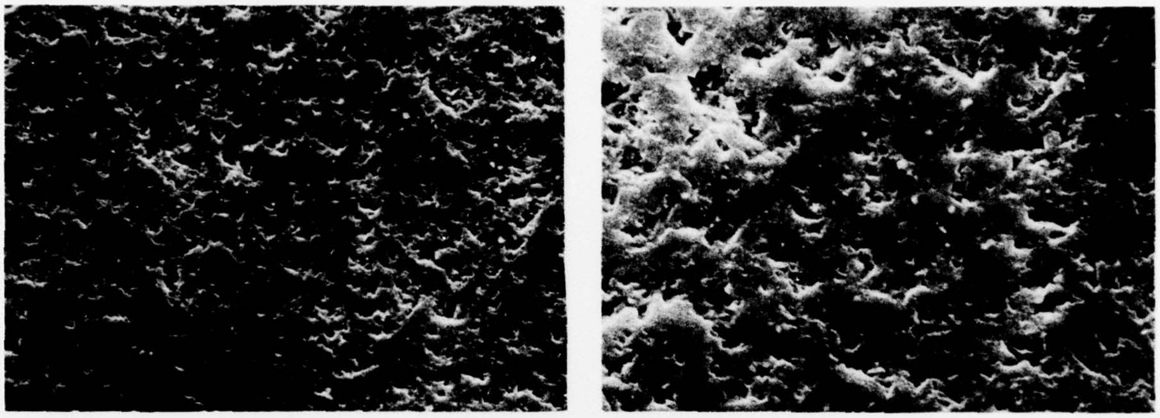
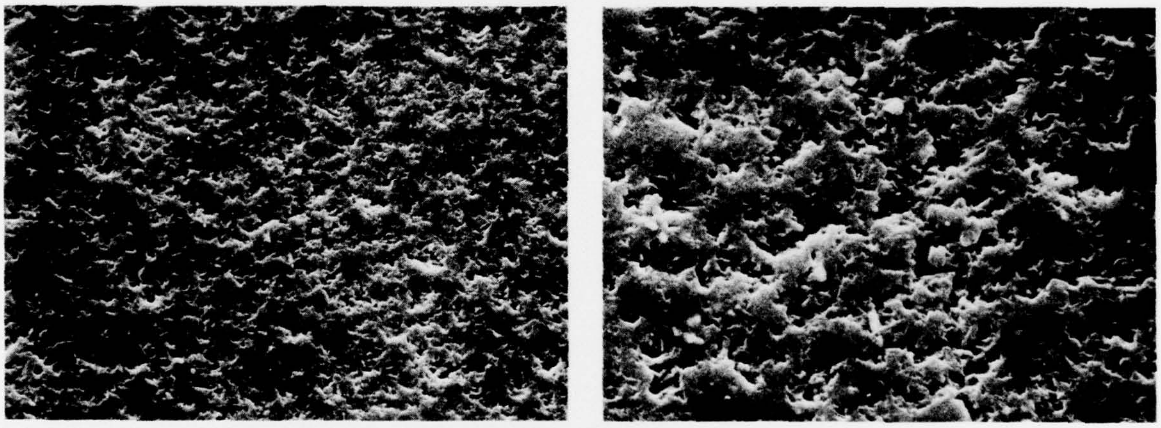

5726 2500x

Figure 7. Surface Topography of SiC Rough Lapped Balls with Increasing Unit Ball Load Using Single Slurry Charge

44 N (10 lbs) / ball


5737 1000x 5738 2500x

111 N (25 lbs) / ball


5734 1000x 5735 2500x

222 N (50 lbs) / ball

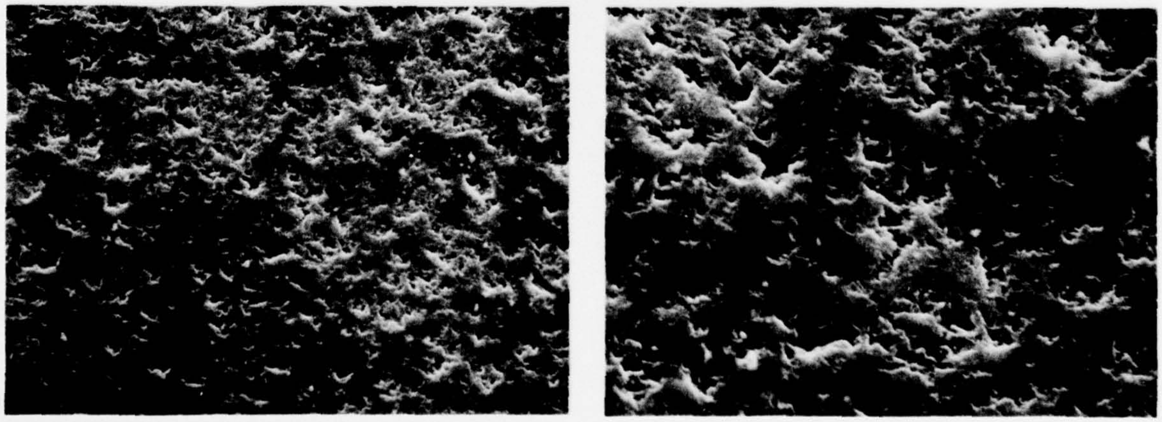
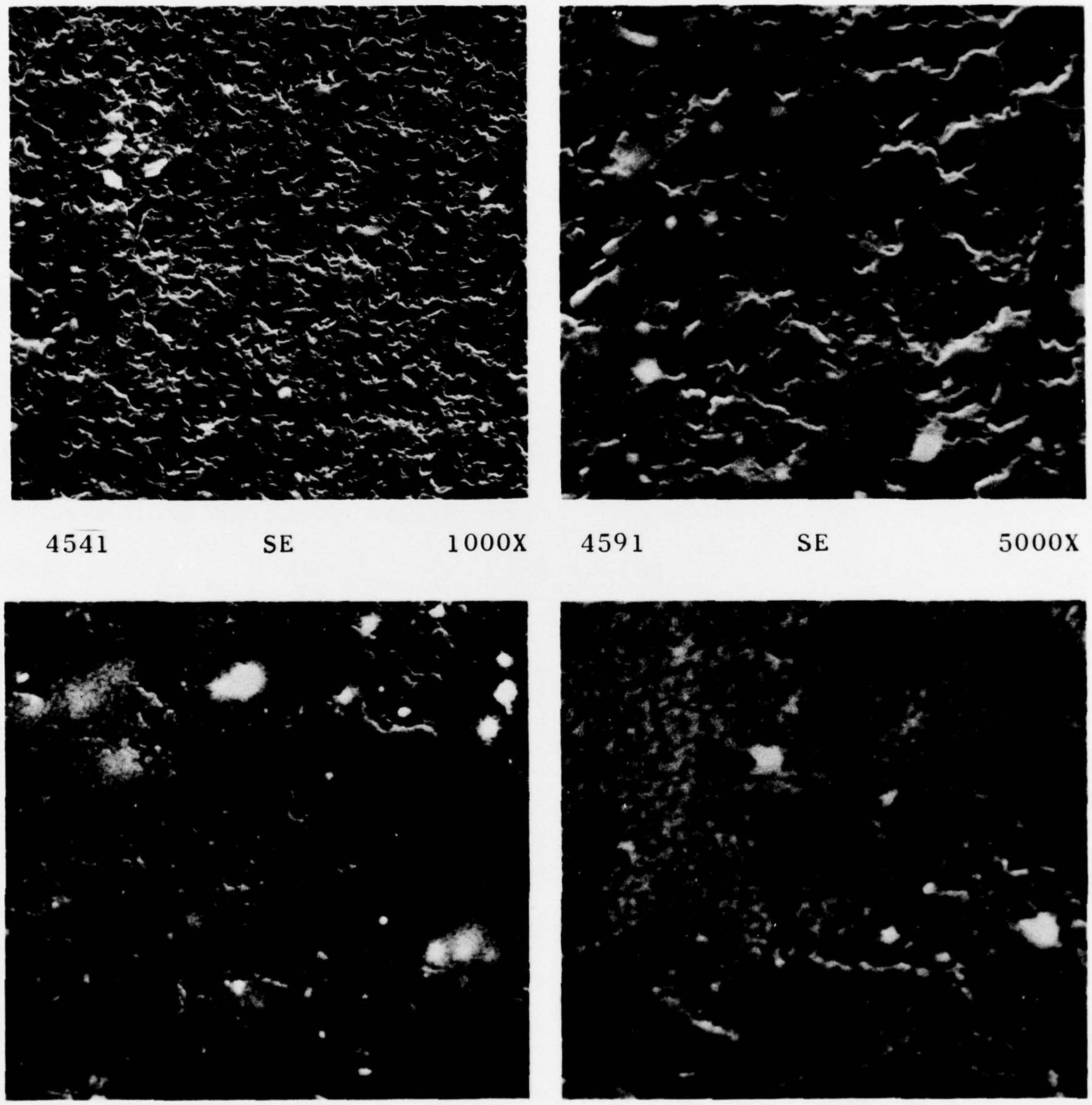

5731 1000x 5732 2500x

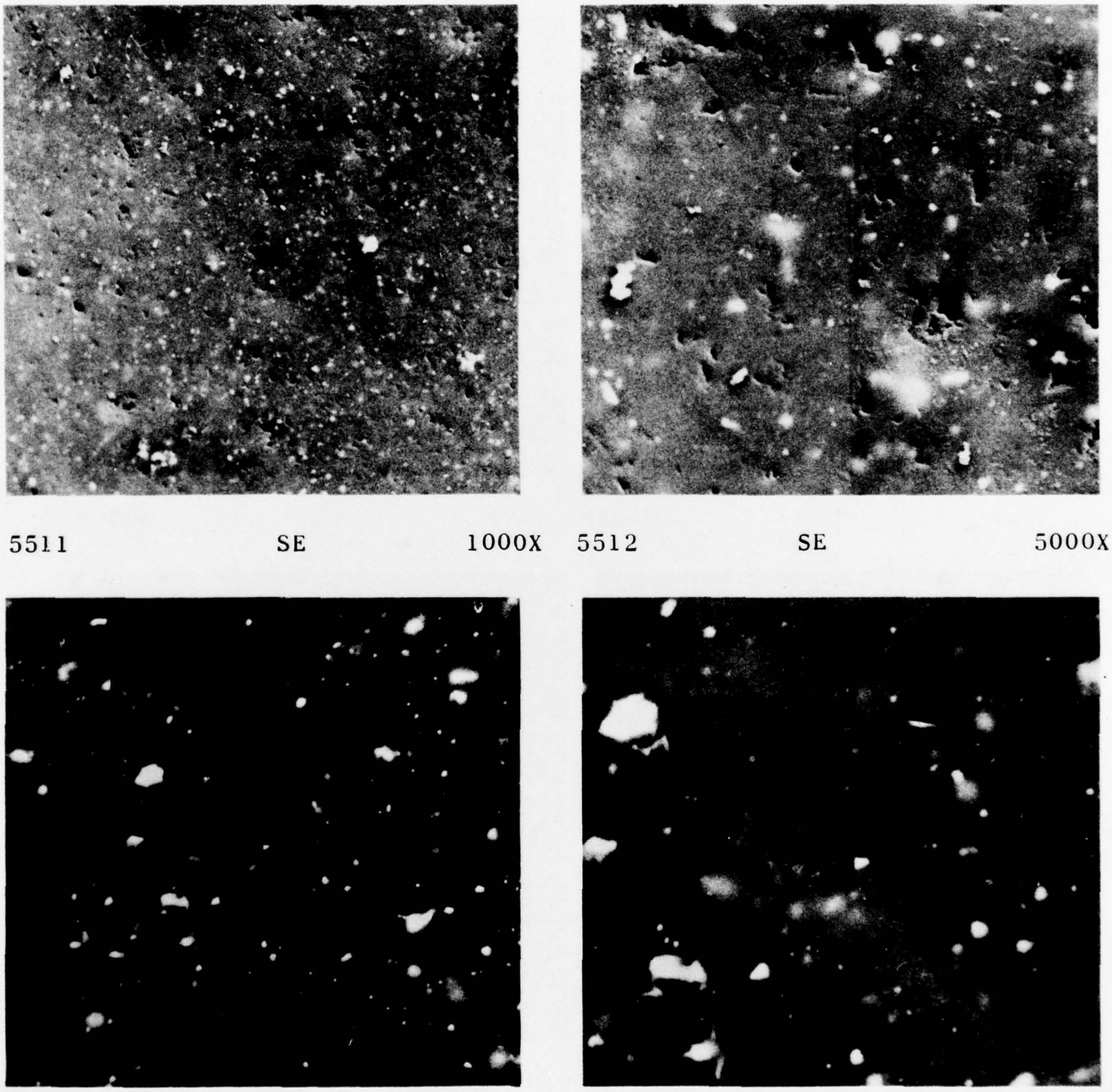
Figure 8. Surface Topography of Diamond Rough Lapped Balls with Increasing Unit Ball Load Using Single Slurry Charge



4541 SE 1000X 4591 SE 5000X

4539 BSE 5000X 4540 BSE 10,000X

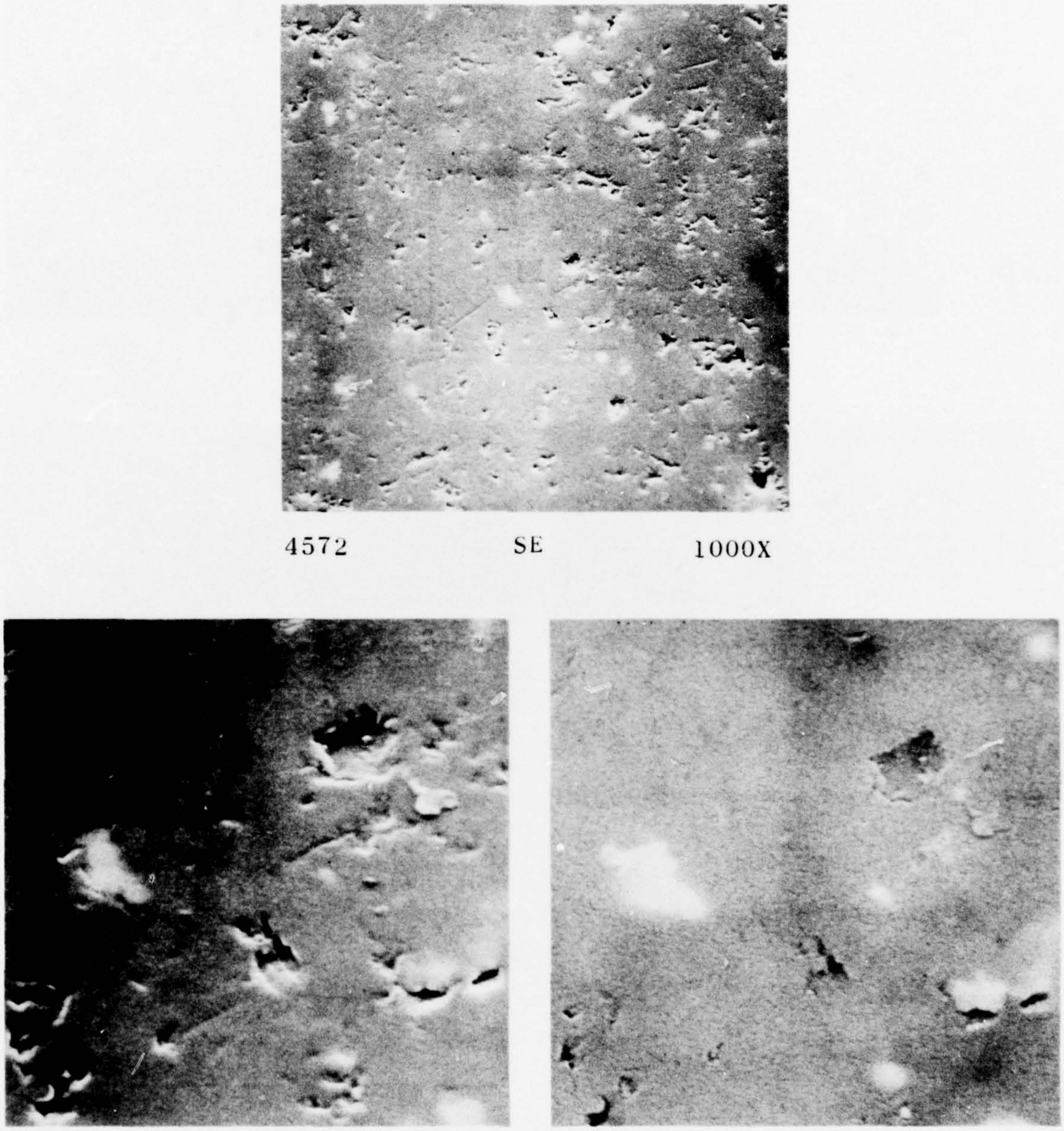
Figure 9. Surface Topography and Structure of an As-Received 17.5mm Silicon Nitride Ball



5511 SE 1000X 5512 SE 5000X

5513 BSE 5000X 5514 BSE 10,000X

Figure 10. Surface Topography and Structure of an Al_2O_3 Polished 17.5mm Silicon Nitride Ball



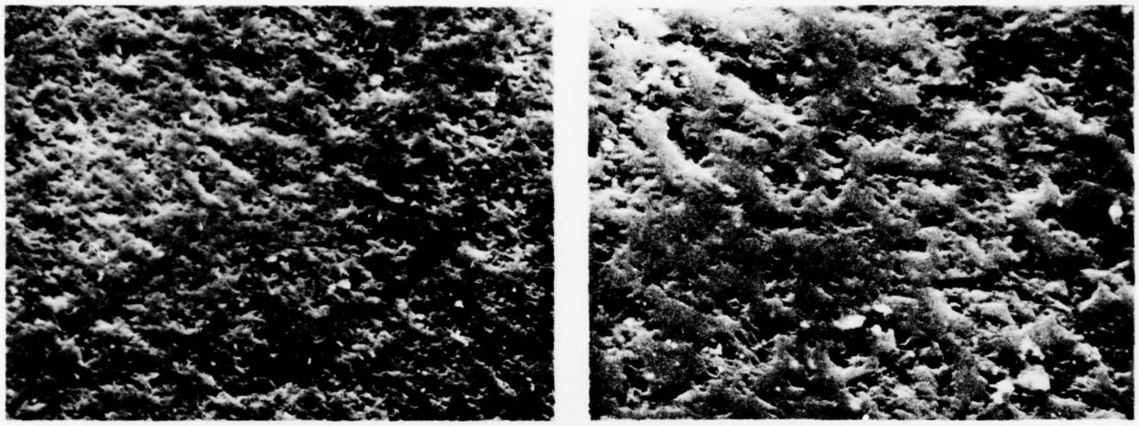
4572 SE 1000X

4575 SE 5000X

4574 BSE 5000X

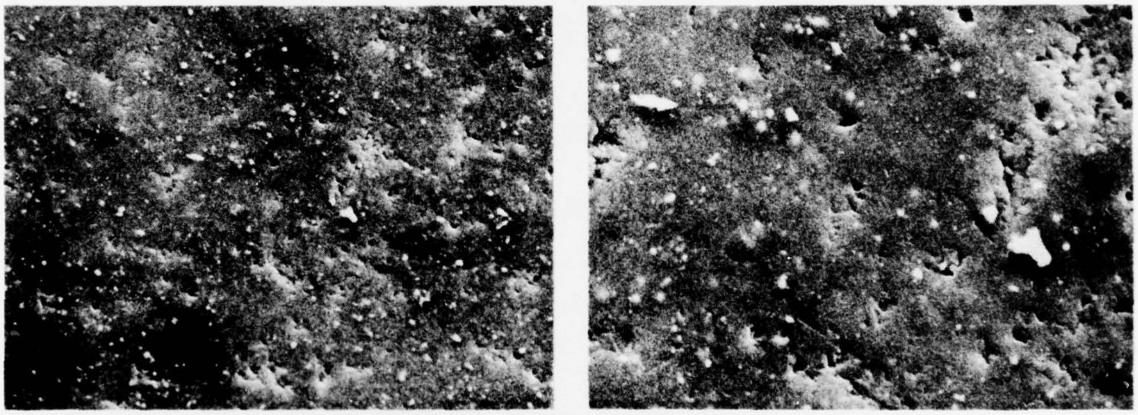
Figure 11. Surface Topography and Structure of a 7mm Silicon Nitride German Ball

Partially Polished (A2)



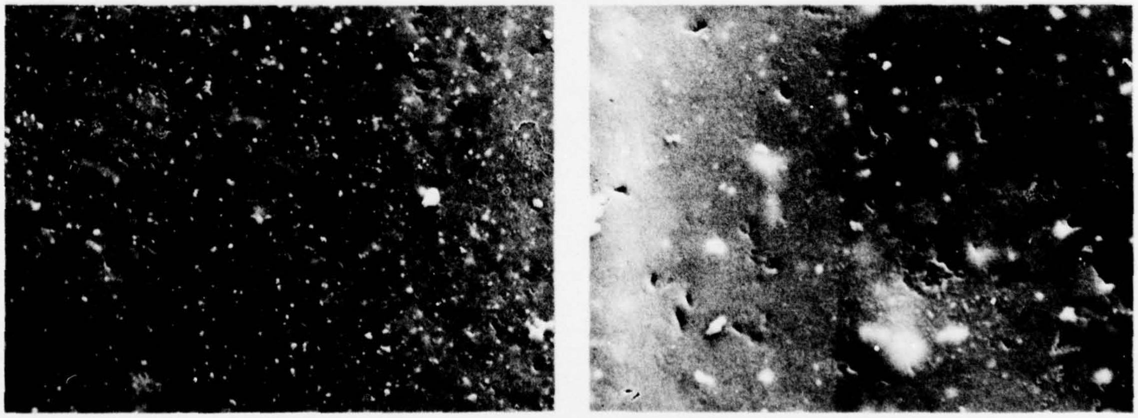
5754 1000x 5755 2500x

Partially Polished (A3)



5757 1000x 5758 2500x

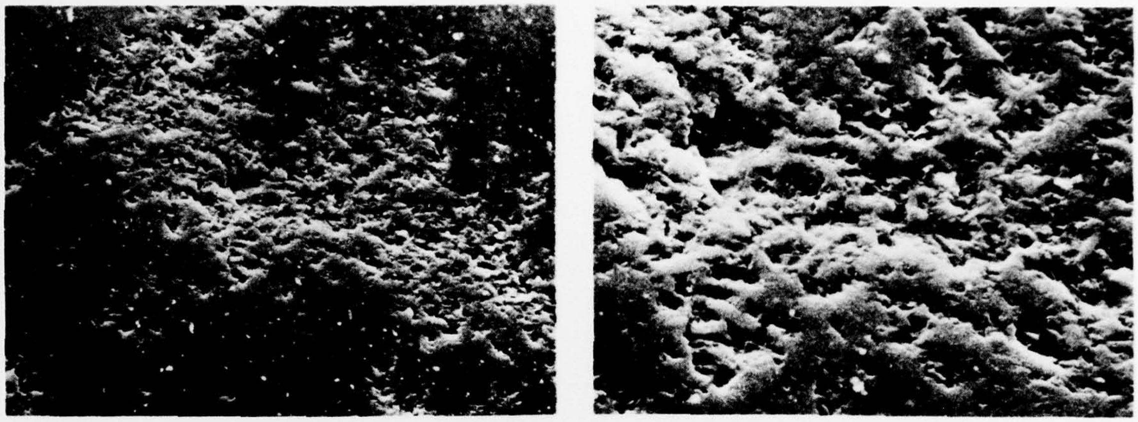
Finish Polished (A4)



5511 1000x 5512 5000x

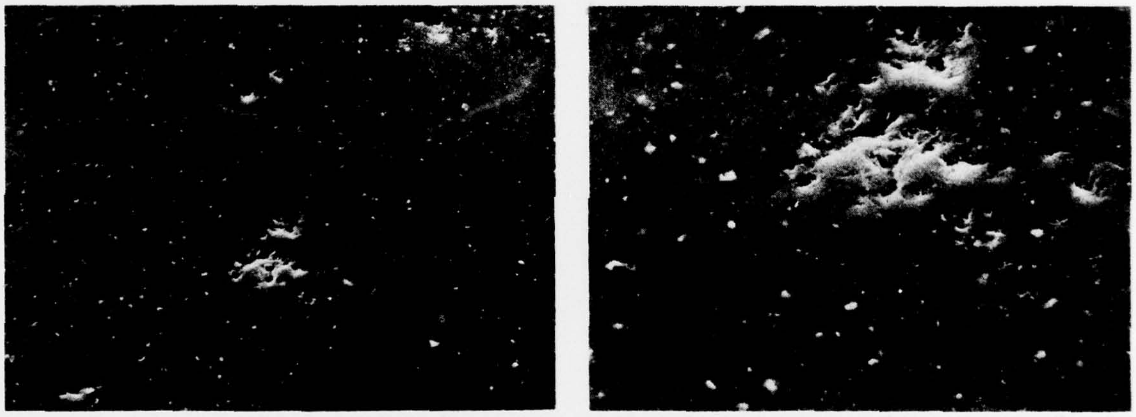
Figure 12. Surface Topography of Polished Diamond Rough Lapped Balls (A2-A4) Using Abundant Slurry

Partially Polished (B2)



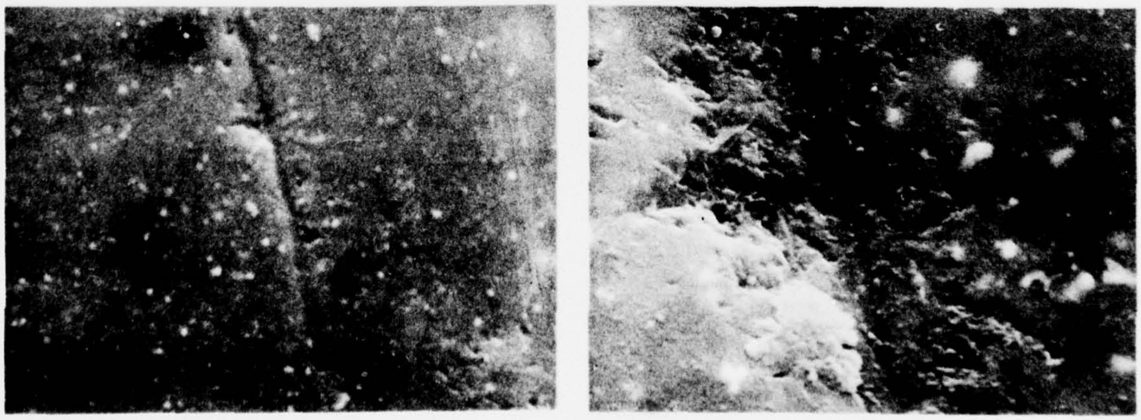
5751 1000x 5752 2500x

Partially Polished (B3)



5760 1000x 5761 2500x

Finish Polished (B4)



5701 1000x 5702 5000x

Figure 13. Surface Topography of Polished SiC Rough Lapped Balls (B2 - B4) Using Abundant Slurry.

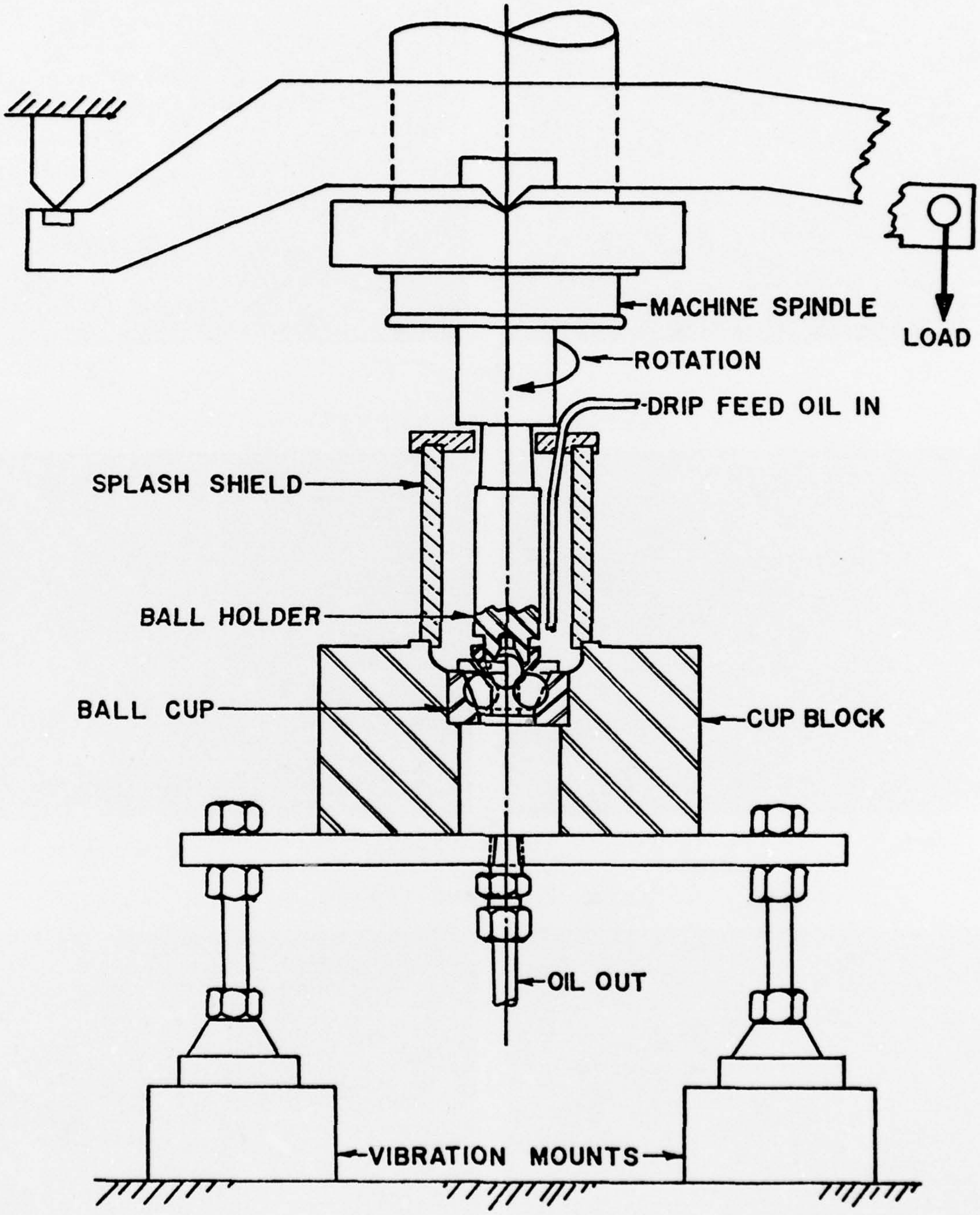


Figure 14. Schematic Drawing of Rolling Four-Ball Tester

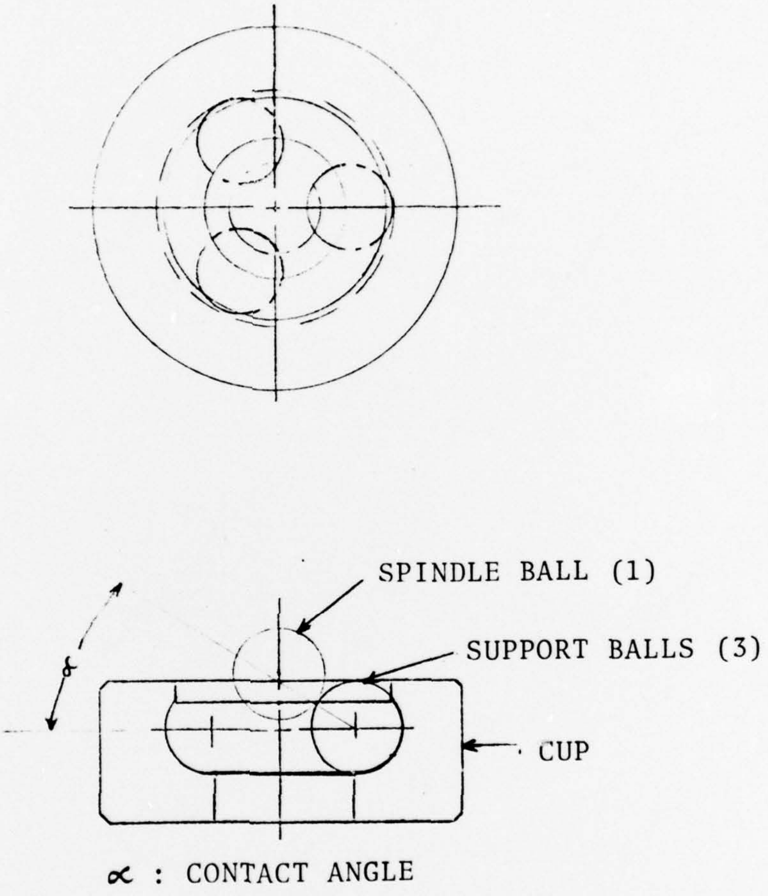


Figure 15. Schematic Drawing Showing the Relative Positions of Test and Support Balls

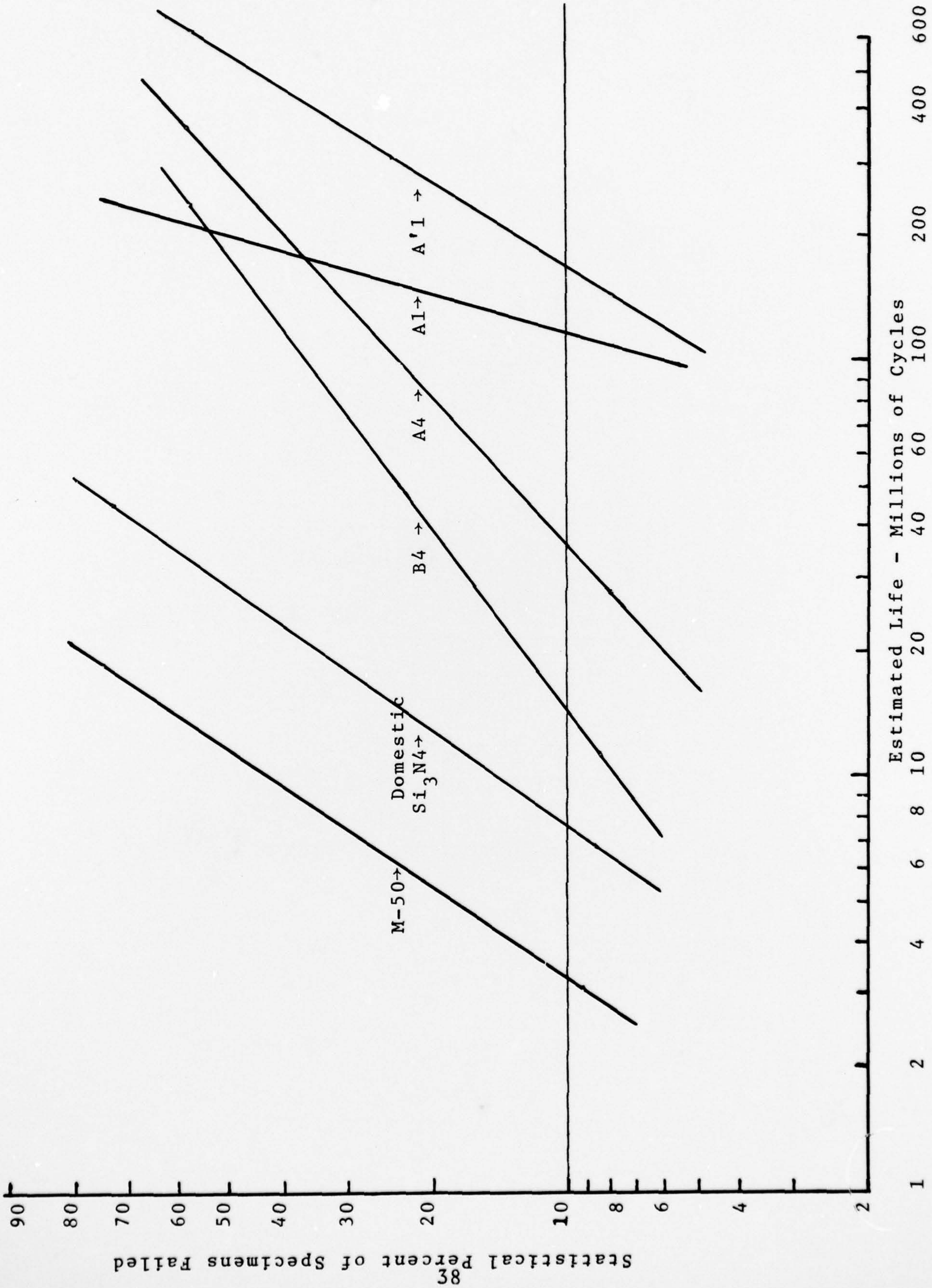


Figure 16 - Graph of Maximum Likelihood Analysis of Test Groups

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. ~~REPORT NUMBER~~ 14 AL76T026 ✓
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (*and Subtitle*) 6 Effect of Lapping Parameters on Generation of Damage on Silicon Nitride Ball Surfaces
5. ~~TYPE OF REPORT & PERIOD COVERED~~ Final Report. Nov. 1975-Nov. 1976.
6. PERFORMING ORG. REPORT NUMBER AL76T026
7. AUTHOR(s) 10 Harish H. M. Dalal; J.W. Rosenlieb ~~and~~ L. B. Sibley
8. CONTRACT OR GRANT NUMBER(s) 15 N00019-76-C-0147 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS
SKF Industries, Inc., Technology Center
1100 First Avenue
King of Prussia, Pa. 19406
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Systems Command
Code AIR 310C (JPI)
Washington, D.C. 20360
12. REPORT DATE 11 December, 1976
13. NUMBER OF PAGES 38 12 46p.
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)
15. SECURITY CLASS. (*of this report*) UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (*of this Report*)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

400 241

18. SUPPLEMENTARY NOTES
19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Micrometers

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This is the final report on the effect of lapping parameters on generation of damage on silicon nitride ball surfaces. Two rough lapping experiments were conducted using 44μm SiC and 15μm diamond abrasives in free and controlled quantities and with various unit ball loads. The results indicate that, under the test conditions chosen, diamond generates a more uniform finer surface finish compared to the SiC and provides a larger increase in material removal rate with increase in unit ball load.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*) micrometers

It was also found that, by using the Al_2O_3 polishing procedures developed, silicon nitride balls can be polished to meet surface roughness specification of 0.01µm AA for aircraft quality balls. The more uniform and finer surface generated by diamond rough lapping is polished to the required quality more readily than the rougher surface generated by SiC.

Rolling-contact four-ball fatigue test results clearly demonstrate the improvement in fatigue life of silicon nitride balls due to the use of proper finishing procedures.

The lapped and polished balls are shown by scanning electron miscroscopy to be free of the cracking observed on silicon nitride balls having much lower fatigue life.