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INVESTIGATION OF THE USE OF CERAMIC MATERIAL IN AIRCRAFT ENGINE BEARINGS

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ERRATA

p.31 ADDENDUM

Data in Table 9 tabulates maximum tensile stresses at failure load resulting from the Hertzian contact. The average compressive stresses at failure (tensile failure), failure load ÷ contact area, are: NC-132 - 10.3 GN/m^2; Si_3N_4/ZrO_2 - 10.9 GN/m^2; and Si_3N_4/Y_2O_3 - 13.4 GN/m^2.

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A program to initiate life factor correlation between hot-pressed silicon nitride rolling elements and M-50 steel hybrid rolling elements has been completed. All materials for component fabrication have been procured and qualified. Retainers and test tooling are complete. Complications in rolling contact fatigue qualification of roller stock, traced to specimen preparation techniques did not allow completion of bearing fabrication. A considerable efford was dedicated to study of the RCF qualification for ceramic

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20. ABSTRACT (continued)

materials resulting in development of machining techniques to produce bearing quality silicon nitride surfaces without "superfinishing". Static Hertzian indentation of silicon nitride surfaces, fracture energy measurements, and radioactive gas penetrant tracers were found to be potentially valuable evaluation techniques for ceramics in the rolling contact environment.

SUMMARY

To date, the evaluation of hybrid rolling contact bearings has been carried out under "accelerated" test conditions or on a marginally significant statistical sample. The objective of this program was to initiate testing on a significant population to determine life-factors in a loading environment more closely simulating an actual application. Subtasks under this objective were to:

1. Design and build 60 mm bore, 20 roller complement hybrid Si_3N_4/M-50 and all steel M-50 bearings.
2. Initiate "slightly accelerated" testing.
3. Experiment with static Hertzian indentation as a qualification tool.
4. Evaluate Si_3N_4-Y_2O_3 hot pressed ceramics.

Because of complications encountered in the rolling contact fatigue qualification of the silicon nitride roller stock, considerable effort was expended to study the techniques used from the standpoints of specimen preparation, evaluation, and testing. This delay resulted in not completing bearing fabrication; nor initiating testing. A follow-on program is currently underway to complete these objectives.

A design study aimed at reducing the higher relative contact stresses in the hybrid bearing was carried out. The resulting analysis required geometries impractical to manufacture and were not pursued further. At the close of this contract all materials for bearing fabrication have been procured, qualified, and accepted. The retainers for the 20 roller complement bearings are complete. All tooling for testing the hybrid and all-steel bearings is on hand.

A major effort was made to clarify the variables associated with the RCF qualification of hot-pressed silicon nitride materials. The material properties, specimen fabrication techniques, and test methods all contribute equally to the data generated in the RCF test. In this program, the recurring anomalous data obtained was directly related to the techniques used to prepare specimens. The honing and lapping techniques previously used for final finishing of RCF rods imparted a degree of variability to the surface properties of the material. Once this had been determined, alternate finishing techniques were sought that would yield uniform surface properties. Systematic studies to prepare bearing quality finishes by grinding resulted in uniformly fine, damage-free surfaces that yielded acceptable RCF behavior

allowing material qualification. It is felt that the machining sequence developed can yield an optimized surface compared to earlier work and is applicable to bearing production as well as test specimen preparation.

Experimental study of static Hertzian indentation of silicon nitride surfaces has demonstrated the technique is sensitive to both machining variables and material properties; it is of use for ranking materials with regard to fracture energy, surface flaw distributions, and stress corrosion rates. Evaluation of both Si_3N_4/ZrO_2 and Si_3N_4/Y_2O_3 hot pressed ceramics have shown them both superior to NC-132 (Si_3N_4/MgO) in terms of resistance to static Hertzian stresses. The rolling contact fatigue behavior remains to be determined. Fracture energy measurements did not differentiate between NC-132 Si_3N_4 and Si_3N_4/Y_2O_3 materials. Efforts to characterize machining damaged surfaces in the RCF studies included evaluation by radioactive gas penetrants.

The KET* technique resolved surface structures not otherwise detectable, but, as yet, no clear correlation between these structures and RCF performance exists.

The evaluation of RCF specimen surfaces delayed bearing fabrication but also resulted in closer control of this qualification technique and the optimization of machining methods for finishing Si_3N_4 ceramics in bearing applications. Test tooling and some component fabrication are complete. No new impediments to the development of ceramic rolling contact bearings were discovered.

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*QUAL-X, Inc. Hilliard, Ohio

FOREWORD

This final report describes efforts at the Norton Company under contract to Naval Air Systems Command for the period 14 June 1976 through 19 December 1978 on Contract N00019-76-C-0251. The objective of this program was to investigate the behavior of ceramic materials in rolling contact environments.

This program was administered by both Mr. C. Bersch and Mr. P. Weinberg, NAVAIR, Washington, DC. The program was initiated by Dr. H. R. Baumgartner, Norton Company, who was principal investigator through 20 December 1976. For the remaining portion of the program, Mr. J. W. Lucek served as principal investigator; technical management was provided by Dr. M. L. Torti. Bearing design, material qualification, and component manufacture efforts were carried out by the Bearing Research Group of Federal-Mogul Corporation, Ann Arbor, Michigan 48104; Mr. P. Cowley was principal investigator at that facility.

The authors wish to thank the research support groups at both the Norton Company and Federal-Mogul Corporation. They wish to acknowledge the consultation time provided by Dr. Baumgartner throughout the program. The authors also wish to thank the NAVAIR administrators for their cooperation.

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1. INTRODUCTION

Hot-pressed silicon nitride has been shown to be a viable material for use in rolling contact bearings. Programs under the sponsorship of the Naval Air Systems Command have shown that properly machined silicon nitride surfaces are superior to AISI CEVM M-50 steel in terms of rolling contact fatigue life.[1] Hybrid, as well as all silicon nitride test bearings have been manufactured and successfully tested under accelerated life conditions.[2,3] High speed rig tests (2.5 million DN) of hybrid silicon nitride ball bearings have demonstrated that such bearings generate less heat than an equivalent steel bearing.[4] Hybrid roller bearings performed acceptably in a similar environment.[5] A contract to the Army Materials and Mechanics Research Center to develop final finishing techniques for silicon nitride components[6] has shown that diamond honing as well as silicon carbide and diamond grinding can produce long contact fatigue life surfaces. A recent all silicon nitride bearing test carried out under a joint Navy/Army contract has demonstrated the feasibility of operating ceramic roller bearings both with minimal lubrication and without lubrication for sustained periods of time in a J402 gas turbine engine.[7]

Silicon nitride rolling contact bearings are of interest in hostile chemical and thermal environments for several reasons:

1. The low density of silicon nitride rolling elements, approximately one-third that of tool steel, allows for higher residual bearing capacity through the reduction of centrifugal body forces. This lower density also reduces element skidding during rotational velocity transients.

2. The low coefficient of thermal expansion of this ceramic material, under conditions of a radial thermal differential through a bearing, reduces skidding tendencies due to loss of internal clearance.

3. Silicon nitride's low coefficient of friction and high temperature hardness potentially allow operation without external lubrication. The response of hot pressed NC-132 silicon nitride to stress fields is essentially elastic to beyond 1000°C. This may allow relaxation of current cooling and lubrication requirements in some applications.

4. The silicon nitride ceramic is essentially inert in the bearing environment. Oxidation does not begin until 700°C and reaction with fused salts is negligible until 700°C also. In light of the above considerations, it is unlikely that any long term reactions with lubricants should occur.

Previous work has shown that the formation of Hertzian cracks which lead to bearing component failure is highly dependent on the component composition, finish, and may be influenced by its environment through stress corrosion mechanisms. Yttria containing silicon nitride (Y_2O_3/Si_3N_4) hot pressed materials have shown mechanical properties superior to those of current MgO/Si_3N_4 hot pressed material. Initial evaluation of this material indicates that it possesses a higher modulus of rupture, lower strength variations, and a higher fracture energy than regular hot-pressed silicon nitride, NC-132.[8]

Earlier work with silicon nitride rolling contact element testing has indicated there may be a "transition stress level" below which silicon nitride bearing life may be considerably greater than calculated by conventional load/life formula. At Hertz stress levels of 600,000 psi, rolling contact fatigue testing (RCF) of silicon nitride has demonstrated fatigue lives ten times greater than those of M-50 tool steel.[2] See Table 1. The actual advantage is not known as an insufficient number of element failures occurred; most tests were suspensions and, therefore, the data is of limited use for life calculations. This "transition stress level" is felt to be well above bearing design limits, but is below the stresses encountered in conventional "accelerated-life" testing. Testing of bearings under load conditions more representative of an actual application may demonstrate the existence of such a transition level.

II. BEARING DESIGN

The bearing design intended for testing in this program was a slightly modified Bower Aircraft design utilized in previous silicon nitride bearing development work.[2,8] It is comprised of a 60 mm bore inner race assembly with a separable outer race, 20 roller complement, and a one piece silver-plated machined steel retainer.

Two design modifications were considered for this program:

A. Increasing the silicon nitride roller crown radius to reduce the stresses in the contact zone. Silicon nitride's high Young's modulus results in higher stresses than in an all-steel bearing under the same conditions. This modification was not recommended because the larger radius would be impractical to manufacture and might compromise the crown's capacity to accomodate misalignment.

B. Crowning of the outer raceway to bias the contact stress to the outer race; more closely simulating a high speed application. This change was also not pursued because of uncertain mating crown alignment effects.

TABLE 1

Summary of RCF Tests on Silicon Nitride and M-50 CVM Steel as a Function of Loading

Hertz Stress (psi)	Silicon Nitride	M-50
600,000	16 suspensions in range of 30.92 - 93.65 million cycles	L_{10} = 2.38 million cycles L_{50} = 3.70 million cycles
700,000	6 failures in range of 3.85 - 141.54 million cycles 10 suspensions in range of 32.57 - 113.44 million cycles	L_{10} = 1.60 million cycles L_{50} = 2.58 million cycles
750,000	4 failures in range of 19.72 - 100.61 million cycles 2 suspensions at 97.64 and 125.74 million cycles	No tests conducted
800,000	11 failures in range of 1.35 - 47.36 million cycles	Testing caused excessive deformation of the steel bars.

III. MATERIAL QUALIFICATIONS

A. Silicon Nitride

Four billets of NC-132 silicon nitride have been produced for use as roller stock in this program. Standard material qualifications have indicated that all of the billets provided meet the published specifications for this material. A summary of these qualifications appears in Table 2. Four billets provided for roller stock material all exceeded the strength density and chemical specifications of NC-132 silicon nitride. Additional testing to determine fracture energy, also shows that the material exhibits behavior typical of material used in past bearing programs. Based on the poor rolling contact fatigue performance (below) of billet 300502 it has been rejected as roller stock material. This may be due to the low concentration of the magnesium oxide/silicate intergranular phase. The last billet, 428841, was not provided as roller stock material; but was supplied to Federal-Mogul for material to be used in grinding studies. The roller stock material has been qualified in rolling contact fatigue at program completion.

B. Metallic Components

The first lot of 4340 steel for bearing retainers was judged acceptable by the fourth month of the program and retainer fabrication was initiated. The first lot of M-50 race material was judged unacceptable by reason of Class 8 carbide segregation and was rejected by Federal-Mogul for this program and a reorder placed. The second lot of race material was accepted and reserved for fabrication after roller stock qualification. M-50 roller stock was accepted by the eighth month of the program.

IV. RCF TESTING OF NC-132 SILICON NITRIDE

The billets of NC-132 silicon nitride supplied as roller stock for this program initially exhibited highly variable rolling contact fatigue performance. Previously qualified specimens of silicon nitride also exhibited a larger proportion of early fatigue failures than they had when originally qualified. Because of the inability to qualify otherwise acceptable ceramic roller stock, or requalify previously accepted specimens, an effort was mounted to clarify the RCF variables pertinent to ceramic materials.

The study revealed the primary reason for fatigue life scatter was the technique used for machining specimens. Lapping and honing did not provide silicon nitride surfaces with uniform properties. Some scatter was attributed to the test equipment. Both of these complications were resolved in this program. A method to fabricate RCF specimens by diamond grinding was developed that resulted in extremely uniform finishes and acceptable geometries. Testing of of these specimens on repaired test rigs resulted in acceptance of the silicon nitride billet stock.

TABLE 2

STANDARD Si_3N_4 MATERIAL QUALIFICATIONS

SPECIFICATION	Billet	DR300502	ER300503	FR300504	F323010	F-428841*
	Powder Lot	HN11	HN10B	HN10B	HN12	HN8
3.21 min	Density g/cc	3.23	3.25	3.26	3.24	3.21
	Strength					
>110,000 psi	a. Mean MOR	115,500	133,300	132,200	116,700	102,200
	b. Std. Dev.	9,600	11,500	16,300	13,500	6,000
> 80,000 psi	c. $\overline{X} - 2\sigma$	96,300	110,300	99,500	89,700	90,200
≥ 8	d. n	10	8	8	9	
	Chemical (w/o)					
<1.0	Mg	0.43	0.75	0.75	0.60	3.0
<0.05	Ca	0.01	0.01	0.01	0.01	
<0.75	Fe	0.16	0.21	0.21	0.17	
<0.5	Al	0.18	0.18	0.18	0.27	
<3.0	W	2.1	1.9	1.9	2.2	
	Fracture Energy†					
25.5 - 35.9	γ (J/m^2)	25.4	32.5	39.6		
13 - 19	δ	6.2	8.1	15.6		
	n	6	3	5		

†Courtesy S. Frieman NRL (Typical values/not a specification)
*Experimental compositon - grinding studies only

A. Introduction

The rolling contact fatigue test is a rapid means of evalting bearing materials. The test equipment applies a high magnitude (700-800 KSI), cyclic contact stress to the test sample, a cylindrical rod, approximately 1 cm OD x 7.5 cm long. This rod is rotated around its cylindrical axis at 10,000 rpm between two crowned steel discs which apply a contact stress to a 0.1 cm wide circumferential band on the specimen. The test band undergoes 1.2 million stress cycles per hour and at the stress levels used, several times the design stress for bearings, M-50 steels fail reproducibly in 4-5 hours. Use of this test to qualify ceramic materials for rolling contact bearings poses unique complications in that ceramics do not possess microplasticity at ambient test temperatures. Ceramics fail when the local stress exceeds the inherent strength of the material. Several aspects of RCF material evaluation can result in magnification of the nominally applied stress.

1. Material Flaws - inhomogeneities at or near the highly stressed contact surface can act as stress concentrators; i.e., pores, or large inclusions.

2. Machining Flaws - on the surface, scratches or small pullouts have sharp boundaries and greatly multiply nominal stresses. A uniformly fine finish, with no large "occasional" flaws, is a necessity.

3. Subsurface Damage - even though the contact stress field's magnitude decreases rapidly with penetration; it can intersect subsurface grinding damage left by improper machining. Resulting failure is not typical of the material, but of the finishing technique.

4. Test Rig Alignment - causes additional strain in the sample. Ceramic's high Young's modulus makes these strains induce higher magnitude stresses.

5. Loading Disc Condition - the roughness of the loading disc crown can play a major role in the RCF performance of both ceramic and metallic specimens. Line asperities from crown grinding act as point indenters on the test surface, generating very high magnitude, localized stresses. Metallic materials yield microstructurally to reduce these stresses; ceramics, generally, do not. This variable is closely controlled as a result.

Thus the RCF test results reflect several, interdependant variables in addition to basic material integrity. In all cases, metallic materials will be more forgiving of anomalies than ceramics; reproducible test results on ceramics are a direct funtion of the uniformity that can be maintained in each variable.

The following sections discuss the RCF performance of the supplied roller stock in light of the above considerations.

B. Diamond Honed Specimens

The first set of RCF specimens provided for qualification of NC-132 billets, 300502, 300503, and 300504 exhibited only one of eight lives in excess of three times the steel Q-bar life; the qualification standard. These specimens, of marginal geometry, and exhibiting varying degrees of longitudinal and spiral scratches had originally been judged suitable for material qualification but after early results a second lot was prepared. This second lot of RCF rods, also prepared by 320 grit diamond cylindrical grinding followed by a 400 grit diamond hone, exhibited considerably better geometry but surface finishes were poor; in the range of 2-1/2 to 6 micro inches AA. This average roughness, in excess of that considered acceptable, was further complicated by dense distributions of fine scratches. These fine scratches are felt to contribute heavily to poor rolling contact fatigue performance because they act as preferential initiation sites for Hertzian cone cracks due to their extremely high stress concentration factor. The surfaces of this second lot of specimens were further prepared by hand finishing (diamond stropping) to remove visual evidence of scratches. RCF test results were still unacceptable, probably due to the additional finishing operation's not removing subsurface damage. Table 3 summarizes these results.

C. Lapped Rods

The third set of RCF specimens for billets 300502 through 300504 was prepared by a lapping technique. This series of test specimens exhibited better RCF performance than thos previous to it, but still possessed an unacceptably high percentage of very low fatigue lives at the 800,000 psi stress level. In addition, the character of both the failure spall and the wear track resulting from the RCF evaluation differed from that observed in previous programs. Figure 1 shows a failure spall on Rod 13, billet 300502, in which not only a spall but an area where surface material has been removed is apparent. Figures 2A and B, illuminated by polarized light to highlight cracks by internal reflection, show cracks both within and at the edges of the wear track. The cracks within the wear track may be indicative of either skidding or a weakened surface layer of material. A detailed review of both the RCF testing techniques as well as the specimen preparation operations was initiated.

D. Technique Investigations

Ceramic materials are brittle and highly susceptible to point loading. An increase in the surface roughness of the steel loading discs used in the RCF test could adversely affect the contact fatigue life of the silicon nitride ceramic. Review of the techniques used in finishing the loading discs showed that the

TABLE 3

RCF Data Summary - 800,000 psi Stress

Rod	Billet	Axial Surface Roughness (μ"AA)	RCF Lives (x 10^6 cycles)	Comments
1	300502	1.9	0.8	Marginal geometry, originally accepted for material qualification. Cylindrical grind/400 grit diamond hone (probably contaminated) longitudinal scratches, spiral hone marks, 502 shows chatter.
2	300502	2.4	17.7S, 0.2, 1.6	
3	300503	3.0	4.5	
4	300503	2.6		
5	300504	3.2		
6	300504	3.8	7.8S	
7	300502	5.7	4.1S, 5.4, 0.4	Geometry acceptable, honed, stropped with diamond to remove scratches, probably didn't remove subsurface damage.
8	300502	5.2		
9	300503	2.2		
10	300503	3.6		
11	300504	2.8		
12	300504	4.9	16.2	
A	Si_3N_4-Y_2O_3	2.5		
B	Si_3N_4-Y_2O_3	3.9		
13	300502	~1.0	0.2, 0.8	Cylindrical ground 220 diamond 0.001"/pass infeed, cast iron ring lapped, light random scratches, #13 not completely clean, geometry acceptable. Definite subsurface damage.
14	300502	~1.0	0.2	
15	300503	~1.0	4.3, 9.4, S*, S*	
16	300503	~1.0	0.1	
17	300504	~1.0	12.0S, 6.2, 2.6, 15.3S 0.2, 8.0S	
18	300504	~1.0	12.0, 13.5, 6.6 0.02, 8.6, 9.8	
19		<1.0	0.7, 29S, 2, S*, S*, 252.5S†	
20		<1.0	2.3, 0.4, 35.5S 111.2S	320 dia. cylindrical grind. 0.0002"/pass infeed. Cast iron ring lap. Geometry/surface finish acceptable

*Suspension - >115 million at NAPC, Trenton

†700,000 psi

S = Suspension † 600 KSI

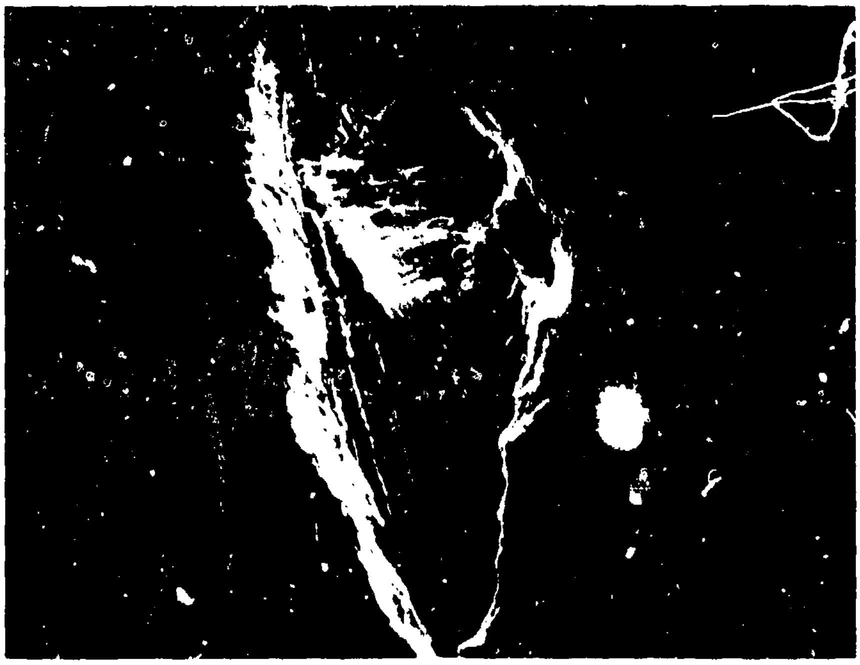
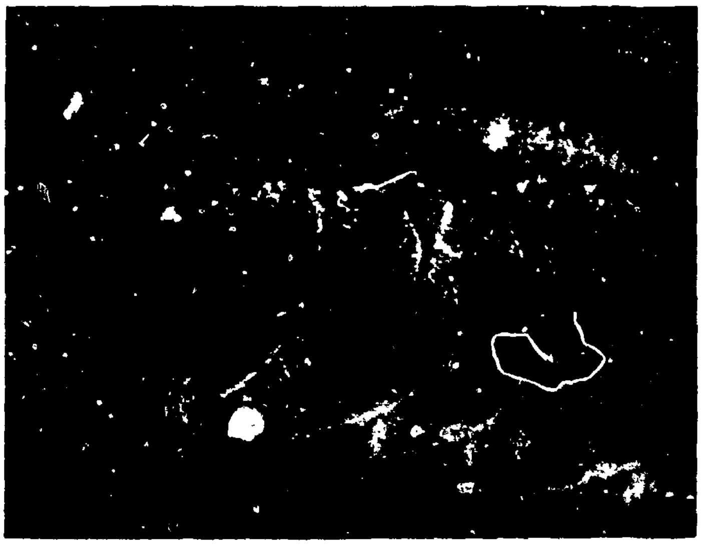
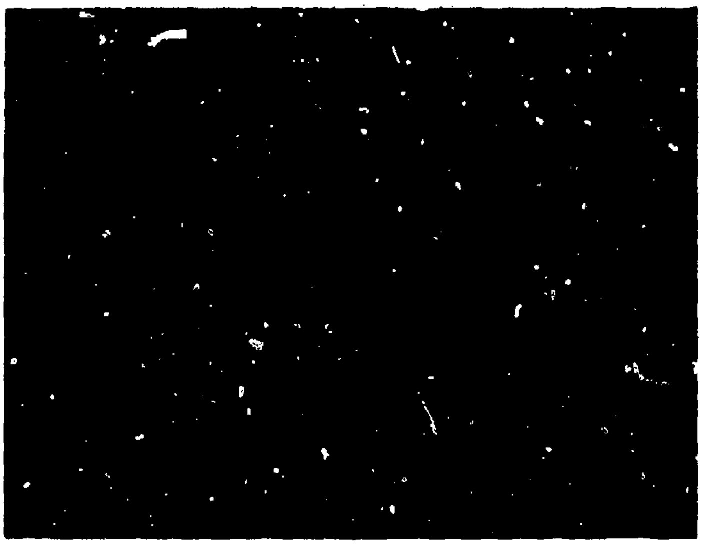


FIGURE 1 - Rod 13 failure spall, 50X SEM



2A

Rod 13 150X,
crossed nichols



2B

Rod 14 150X,
crossed nichols

FIGURES 2A & B - Wear tracks Rods 13 and 14 technique itself had not changed; but that it is a hand operation and subject to operator variance. The roughness of the loading discs used may have increased marginally during this program but, in the final review, it was felt that this was not a major factor in the change in RCF performance. Early in the testing of the third series of RCF specimens, the controlled lot of steel "Q-bars" began to show a large variability in their contact fatigue lives. This behavior was traced to a worn set of contacts in a balancing circuit for the load cell on the RCF tester. These worn contacts made exact determination of the load applied to a specimen during testing uncertain. It is not known whether this condition existed, to a lesser degree, during the testing of the first two lots of RCF rods. After repair of the bridge circuit testing resumed.

Review of the machining parameters for the third lot of RCF specimens revealed that improper final finishing operations were used. Specimens were cylindrically ground with a 320 grit diamond wheel to 0.005" oversize radius. An infeed of approximately 0.0002" per pass was used in this machining operation; samples were then delivered for lapping. Prior to this operation, however, a 220 grit diamond wheel at 0.001" per pass was used to reduce the radius to 0.001" oversize. The specimens were then cast iron ring lapped with 6 and 3 micron diamond paste to provide a matte finish; this was followed by a SnO_2 slurry polish to remove any very fine scratches. The resulting geometry and surface finish were excellent; however, there was undoubtedly considerable subsurface damage in these specimens. Investigation of these rods with the KET surface characterization technique at QUAL-X Industries, Inc. did not greatly clarify the surface characteristics of these specimens; but did point out that the technique has potential use in ceramic surface characterization. See Appendix A.

A replacement billet, 323010, was pressed after billet number 300502 was judged unsuitable. All RCF test results for 300502 had been extremely poor and it was felt that a second lot of material might shed further light on the RCF testing situation by sampling silicon nitride materials from completely different lots than those originally provided. RCF specimens from this billet were ground with a 320 grit diamond wheel at 0.0002" per pass radial infeed to 0.001" oversize diameter. These specimens were then cast-iron ring lapped. Both geometry and surface finish were excellent. Testing of this billet, still yielded fatigue lives ranging from less than a million stress cycles to over a hundred million stress cycles. Additional testing on billet 300503 at 700,000 psi Hertz stress rather than the customary 800,000 psi Hertz stress yielded two suspensions at 43 and 58 million stress cycles. Testing of billet 300503 and 323010 at the Naval Air Propulsion Center in Trenton, New Jersey, yielded four suspensions all greater than 115 million stress cycles. These results cannot be compared to the Federal-Mogul results as the test conditions differ greatly between the two facilities. It is also disturbing that no differentiation between Rod 15 (300503) and Rod 19 (323010) was possible at NAPC even though Rod 15 was felt to have suffered serious subsurface machining damage.

Final finishing of this third lot of RCF specimens by ring lapping was chosen as the most expedient method of obtaining an acceptable surface finish and geometry. Final finishing of RCF specimens by honing did not provide acceptable specimens. To some degree, the variability noted in the testing of the lapped specimens can be justified on a historic basis. A previous program, dedicated to investigating finishing techniques for silicon nitride, noted that honing as a final finishing operation provided specimens which gave reproducibly long contact fatigue lives.[5] RCF specimens final finished by lapping techniques, from the same material and the same program, exhibited considerably lower lives and much more scatter. See Table 4. For example, a specimen of acceptable silicon nitride material finished by lapping plus a SnO slurry polish gave rolling contact fatigue lives ranging from 0.5 to 88 million stress cycles at the Federal-Mogul test facility. Rod 20, from this program and finished by the same technique, yielded lives ranging from 0.4 million to 111 million stress cycles; also at the Federal-Mogul facility. Accordingly, some of the variability noted in this program may be traced to the finishing technique used.

TABLE 4

RCF Life Versus Finish for NC-132[6]

Finish	RCF Life (cycles x 10^6)
320 Diamond Cylindrical Grind	165, 24, 5
320 Diamond Cylindrical Grind plus 400 grit hone	77, 71, 34, 62, 12, 10, 11, 11, 11, 12, 11, 10, 10, 11
320 Diamond Cylindrical Grind plus 600 grit hone	121, 52, 51, 11, 11, 11, 9, 11, 10, 12, 11
320 Diamond Cylindrical Grind plus 6μ diamond lap	5, 3, 11, 2, 8
320 Diamond Cylindrical Grind plus 6μ diamond lap plus SnO_2 slurry polish	30, 88, 0.6, 3, 12, 11, 11
220 Diamond Cylindrical Grind plus 600 grit hone	50, 40, 3

An additional component of variability may be attributed to the RCF testing equipment itself. Coincident with the testing of the lapped silicon nitride rods from this program, several tests were run on RCF specimens from other bearing programs that had been used to qualify silicon nitride stock based on uniformly acceptable fatigue performance. These specimens now yielded variable fatigue lives ranging between 0.7 and 55 million stress cycles; similar to the results currently being obtained on roller stock supplied.

E. Conclusions

A review of these results indicated that RCF rods from Lots A and B, both honed, gave highly variable and unacceptable contact fatigue performance primarily because of surface scratches caused by a contaminated diamond hone. The variability exhibited by Lot C is attributed to several sources; machining damage is a certainty, load cell variability noted previously, and that lapped specimens have historically exhibited wider scatter than properly honed specimens. Given that some scatter was expected from the lapped rods and that the RCF testers were yielding more variable results than usual it was decided that either or both factors were affecting the RCF lives.

Within programs constraints, an effort was mounted at Federal-Mogul to eliminate the effect of machining variables in RCF performance by systematic grinding studies. These efforts are discussed in Section V of this report. The result of this study was that excellent surface properties were obtained without resorting to either lapping or honing as final finishing steps. RCF testing data on these rods are presented in Table 5.

TABLE 5

RCF Lives of Diamond Ground NC-132
at 800,000 psi Contact Stress

Billet/Rod	Surface Finish µ" AA	Roundness µ" AA	RCF Lives* x 10^6 cycles
300503/1T	1.5	15	6.3, 6.4, 6.6
300503/1H	1.5	20-30	15.9, 16.3, 6.2
300504/2T	1.5	25	6.4, 6.8, 7.8
300504/2H	1.5	15	6.8, 6.8, 6.7
323010/3T	1.5	20	6.7, 8.7, 7.2
323010/3H	1.5	30-50	7.3, 7.3, 6.7

*All tests were suspended after exceeding Q-bar lives ranging from 4.5-6.7 x 10^6 cycles @ 700 KSI with an average life of 5.6 x 10^6 cycles

RCF testing of specimens fabricated by the developed grinding techniques was carried out only to detect the early failures that had been experienced previously. It was decided that if no failures occurred before the M-50 qualification bar life limit (5-6 x 10^6 stress cycles) was reached, the material would qualify as roller stock. This premise is based on the fact that occasional long lives were noted in the damaged bars. If the low lives were eliminated by a machining technique; sufficient data existed on the longer lives normally expected.

Table 5 shows that all testing carried out on the ground specimens was suspended at a level higher than the M-50 Q-bar life. There were no early failures. This data, combined with the occasional long lives exhibited by machining damaged specimens, qualified billets 323010, 300503, and 300504 as roller stock. The data also strongly highlighted that uniformity of finish is a prime consideration in these specimens. Lapped rods from billet 323010 were, by averaging profilometry, smoother than the Federal-Mogul ground specimens, but at 800 KSI contact stress levels yielded 4 of 6 lives lower than the M-50 Q-bar. The role of sub-surface damage in RCF life variability is also clear from comparison of lapped and ground data.

V. RCF SPECIMEN PRODUCTION DEVELOPMENT

The variability noted in RCF testing of current NC-132 billet stock material necessitated the development of a machining technique providing suitable specimens. Efforts carried out by Federal-Mogul were aimed at eliminating the final honing or lapping operation and reproducibly producing specimens by diamond grinding only. A three phase effort was conducted as outlined below:

- Establish conditions and parameters required to produce the desired uniform finish and geometry.
- Produce six RCF specimens from previously qualified silicon nitride stock and conduct RCF tests to demonstrate the finishing technique's suitability.
- Produce six RCF specimens from current billets (2 from each) and conduct sufficient tests to qualify material.

The finished RCF specimen is a right cylinder, approximately 3 inches long and 0.3750 inches (+0 -0.0002) in diameter. The roundness is controlled to less than 50 microinch and the surface finish is normally 4 microinch AA or better. The material blank form is typically 6 inches long with a 0.4 inch square cross section and is sliced from the material to be qualified.

The grinding parameters established in the first phase that were employed in specimen preparation for subsequent work are summarized in Table 6. Characteristics of specimens prepared in the first and second phases is presented in Table 7. Prior to cylindrical grinding, the first phase bars were surface ground to an octagonal cross section to reduce cylindrical grinding time. This step was eliminated in phases two and three; specimens were rough ground directly from square stock. Steel female centers were cemented on the bar ends as shown in Figure 3A.

Figure 3B depicts the surface obtained by final grinding with a 600 grit diamond wheel on a cylindrical grinder equipped with a five micron particle filter in the grinding coolant line. This surface exhibits no large random flaws (common without the filter) and very little smearing. The surface finish is 1-2 microinch AA. The mottled structure evident in Figure 3B is due to a high magnesium silicate concentration in the test material; that the structure is clearly evident attests to the minimal surface damage imparted in this final grinding procedure. While the surface finish of these first phase rods is quite acceptable, the geometry was not satisfactory. These rods were 30-60 microinch out of round and the 6 inch rods exhibit a 0.0005 inch barrel shape due to deflection under the high finish grinding pressures.

The geometries of the second and third phase rods were improved by slicing the 6 inch rods into 3 inch lengths between rough and intermediate grinds. The roundness was improved by improving the steel female centers used to hold the rod.

The 150 and 320 grit diamond wheels were trued with a Norton brake controlled truing device used with a 60 grit silicon carbide wheel. They were dressed with fixtured Norton SiC dressing sticks. The 600 grit wheel was trued with the fixtured dressing sticks and cleaned with chlorethane prior to grinding.

The 320 grit diamond wheel produced a 3-4 microinch surface finish when the wheel was optimally conditioned. Freshly dressed, the resulting finish was likely to be much rougher, perhaps 8-14 microinch. The finish with a 320 grit wheel is, thus, difficult to control due to the critical nature of the wheel conditioning. The 600 grit wheel, consistently produced a 1-2 microinch finish when the grinding stock was 0.0002"/side or less. Finish and geometry generally deteriorated with greater stock removal.

The procedures outlined in Table 6 allow the production of sound silicon nitride surfaces; possessing a uniform and reproducible machining flaw size distribution. Prior to the study, this information did not exist. Careful mounting of minimum length specimens during final grinding operations will reduce deflection and insure roundness is obtained.

TABLE 6

RCF Rod Diamond Grinding Parameters

	Rough	Intermediate	Semi-Finish	Finish
Wheel Grit*	150	320	320	600
Wheel Speed (SFPM)	6400	6400	6400	6400
Work Speed (RPM)	500	500	500	500
Table Speed (IPM)	30	30	30	15
In-Feed (In./Pass)	0.0005**	0.00025	0.0001	0.0001
After Grind:				
Rod Size (dia.)	0.396	0.385	0.3754	0.3750
Stock (In/side)	0.01	0.005	0.0002	-0-

*Diamond Wheel Specifications
150 = SD150R100B69
320 = SD320R100B69
600 = D600N75B35

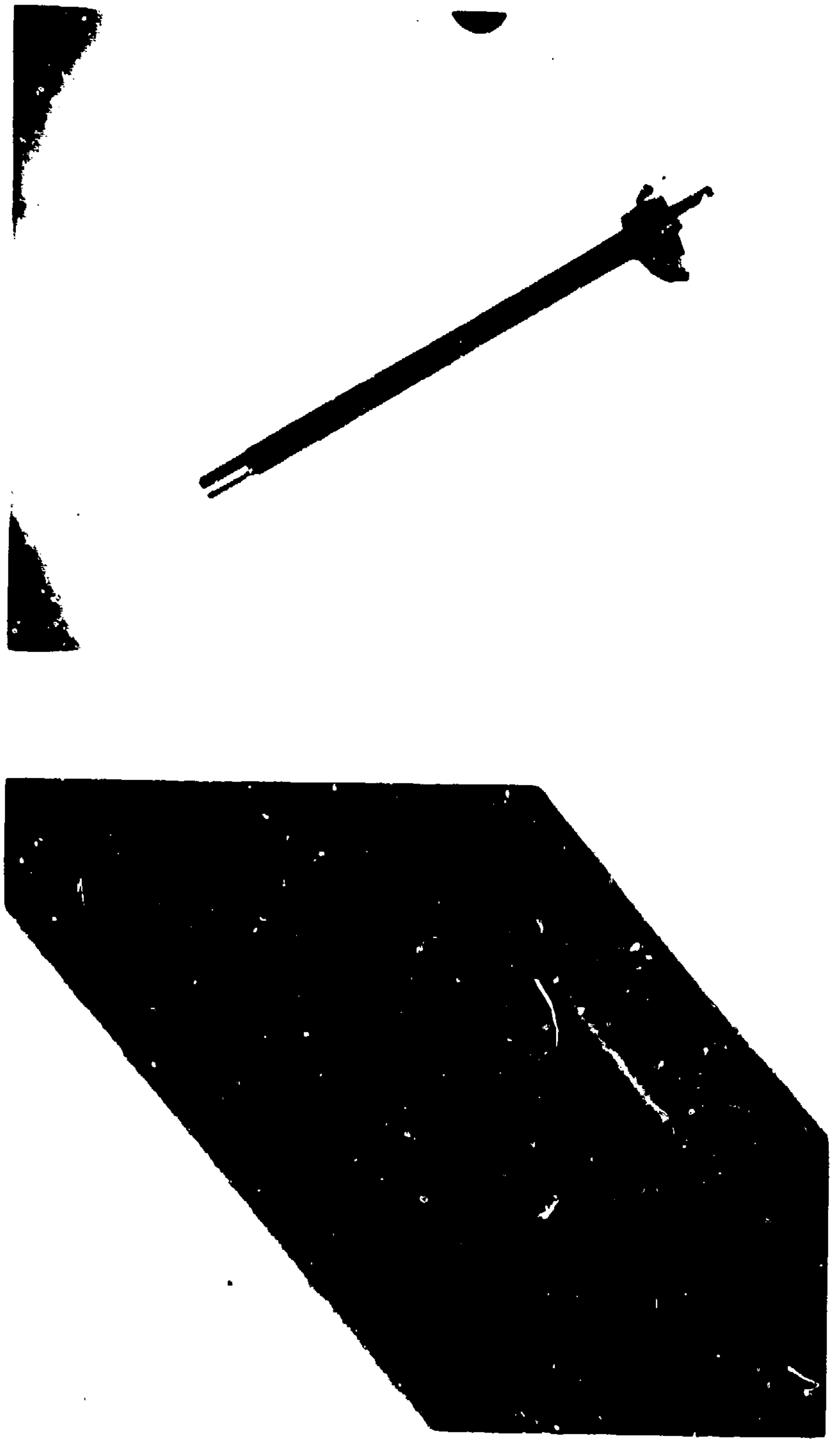
**0.00025 after rod is round

TABLE 7

Grinding Development RCF Specimens

Rod	Billet	Surface Finish μ" AA	Roundness μ" AA	RCF Lives x 10^6 cycles
1-6	Scrap	1.5-2.0	30-60	ND
1A	428841	1.5-2.0	25	17.4S, 2.9, 17.5S*
1B	428841	1.5-2.0	30	12.6S, 12.9S
2A	428841	1.0-1.5	20	19.7S, 16.6S
2B	428841	2.0-2.5	45	16.8S
3A	428841	1.5-2.0	20	14.0S, 12.6

S = Suspension
*Previous lives



FIGURES 3A & B - RCF rod, Federal-Mogul

VI. COMPONENT MANUFACTURE

Other than the material qualification difficulties discussed in the previous section, metallic bearing component fabrication proceeded smoothly. At the close of the current contract, the following work had been completed:

1. Retainers for both the metallic and hybrid bearings are complete.
2. Endurance test tooling is complete.
3. M-50 steel roller material has been accepted. Final machining of steel rollers will be done at the same time as the NC-132 rollers in order to obtain maximum continuity.
4. M-50 steel race materials for both hybrid and metallic bearings has been accepted and is ready for machining.
5. Silicon nitride roller material has now been qualified and accepted for fabrication.

VII. EXPERIMENTAL MATERIALS TESTING

A. Fracture Energy

Fracture energies for the three original NC-132 billets and the Si_3N_4-Y_2O_3 (NCX-34) were determined by the double cantilever beam technique at the Naval Research Laboratories. This testing technique is believed to accurately characterize hot-pressed silicon nitrides in the rolling contact environment;[4] but it yields data with a high standard deviation. The results indicate that there is some experimental difference between 300502 and 300504 but this is due to a single, unexplained, very high value for 300504. Disregarding that one data point, there is no statistical difference between the billets. See Table 8.

Testing of the Si_3N_4-Y_2O_3 (NCX-34) hot pressed material indicates its fracture energy falls in the same range as the NC-132 silicon nitride and may be slightly (5 percent) higher. This is slightly at variance with expected results based on the MOR data on these two materials, which indicates that NCX-34 should possess a measureably higher fracture energy.[8]

B. Hertzian Contact Characterization

The rolling contact bearing environment is characterized by essentially static loading to very high magnitudes. See Appendix B. Static indentation of various silicon nitride

TABLE 8

Fracture Energy Measurements

Material	Individual Values J/m^2	Sample Mean J/m^2	Standard Deviation
NC-132 (300502)	27.8, 33.3, 23.1 18.0, 19.6, 30.7	25.4	6.2
NC-132 (300503)	32.1, 40.8, 24.6	32.5	8.1
NC-132 (300504)	30.7, 29.9, 35.6 34.5, 67.2	39.6	15.6
NCX-34 (Si_3N_4-8% Y_2O_3)	18-62	34	14

materials, using MgO, Y_2O_3, and ZrO_2 as densification aids, with various surface finishes and in two environments using tungsten carbide indenters was studied as a possible materials characterization tool. The Hertzian stress fields resulting when semi-infinite plates are indented with spherical tools have been described in the literature.[9,10] The use of acoustic emission equipment to detect the formation of the "cone" crack has also been described for glass specimens.[11]

Hertzian indentation testing of silicon nitride surfaces with tungsten carbide balls at constant indentation rates* was carried out to determine the technique's sensitivity to several material variables. Failure was detected by acoustic emission equipment** and verified by metallographic investigation.

Plates of silicon nitride materials nominally 1" x 3" x 1/8" were indented with 0.1875" diameter WC spheres*** at a crosshead speed of 0.02"/minute. A piezo-electric transducer was attached to the specimen whose signal after amplification was integrated electronically for display. Recording of both load and summed acoustic emission was done on a dual strip chart recorder. Figures 4 and 5 show the equipment layout. Figures 6A and B show typical load/emission plots. The large emission of sound was demonstrated to correspond to the formation of the cone crack, the physical nature of which is depicted in Figure 7.

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*Instron Mechanical Tester, Canton, MA
**Duneagan Acoustic Count Totalizer NS-1A
***Kennemetal Inc. Latrobe, PA

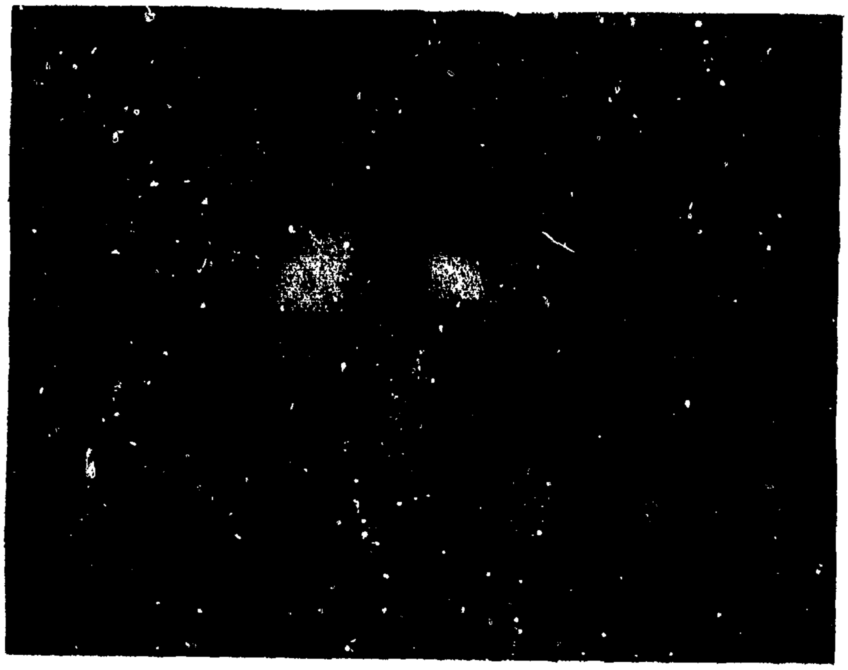


FIGURE 4 - Hertzian indenter

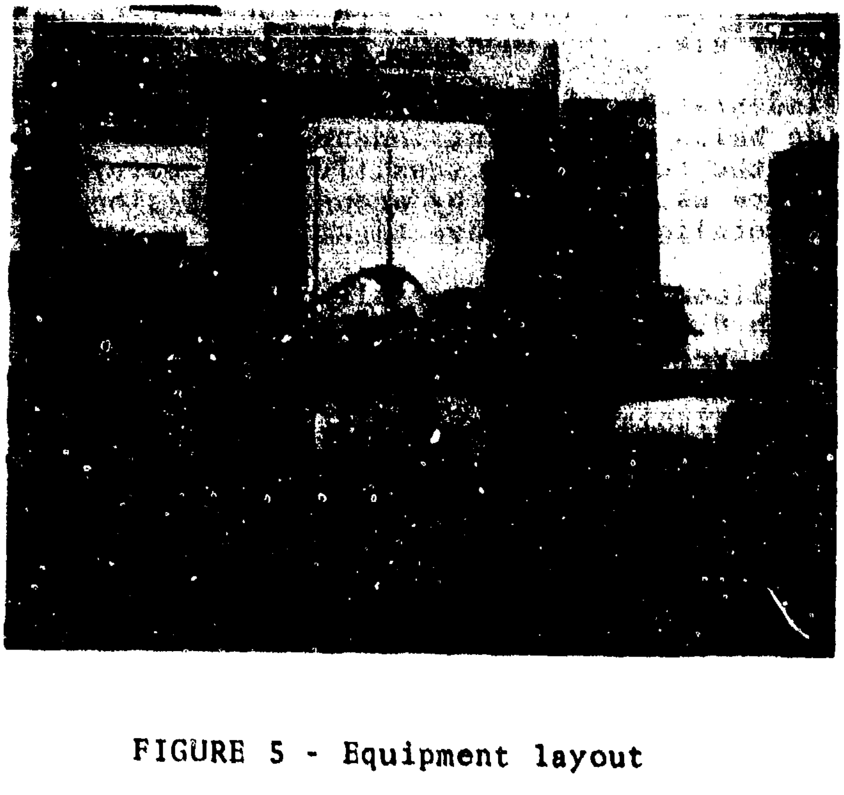


FIGURE 5 - Equipment layout

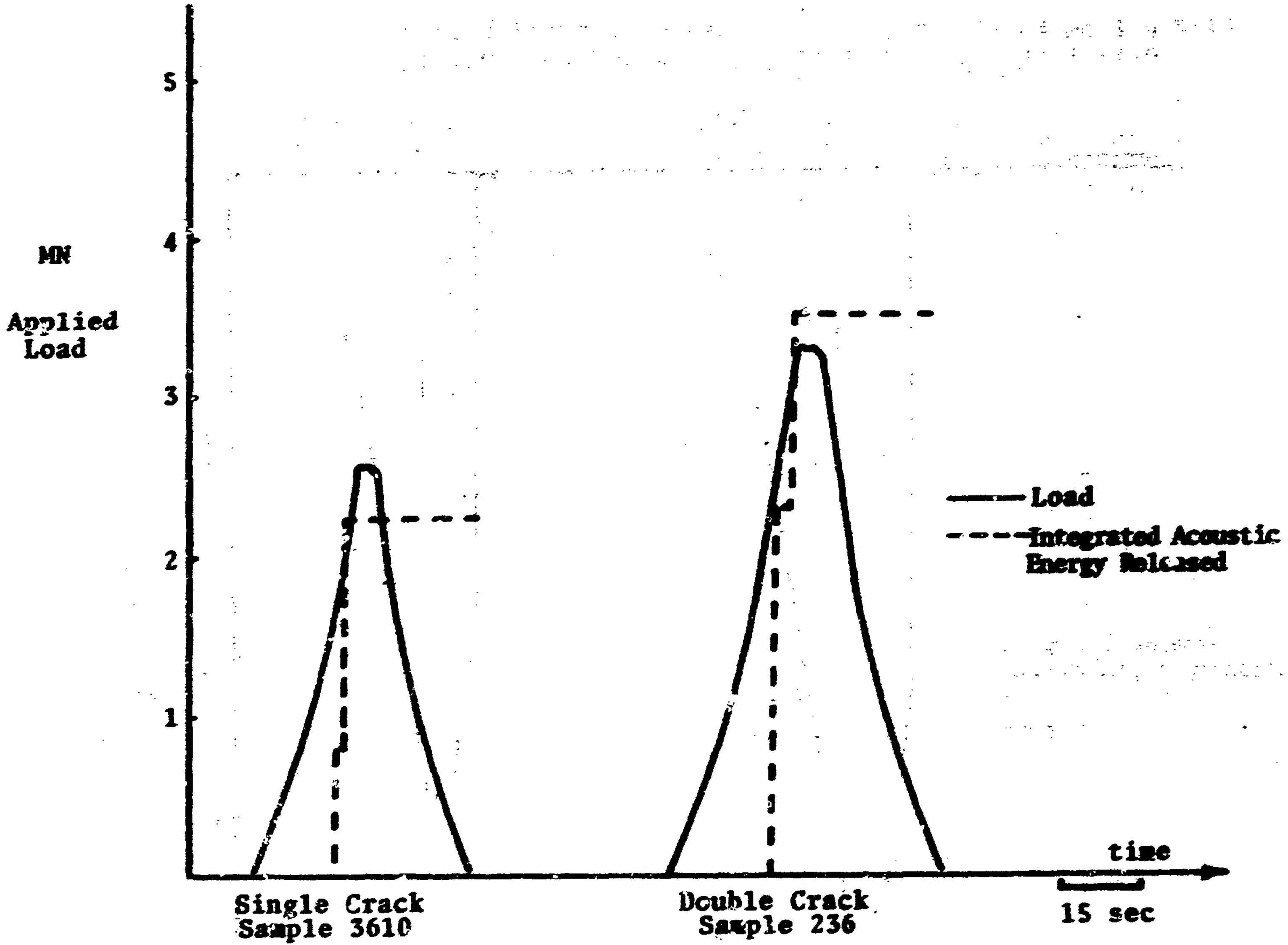


FIGURE 6A - NC-132 Silicon Nitride - Hertzian Contact Behavior - 4.75 mm radius WC indenter

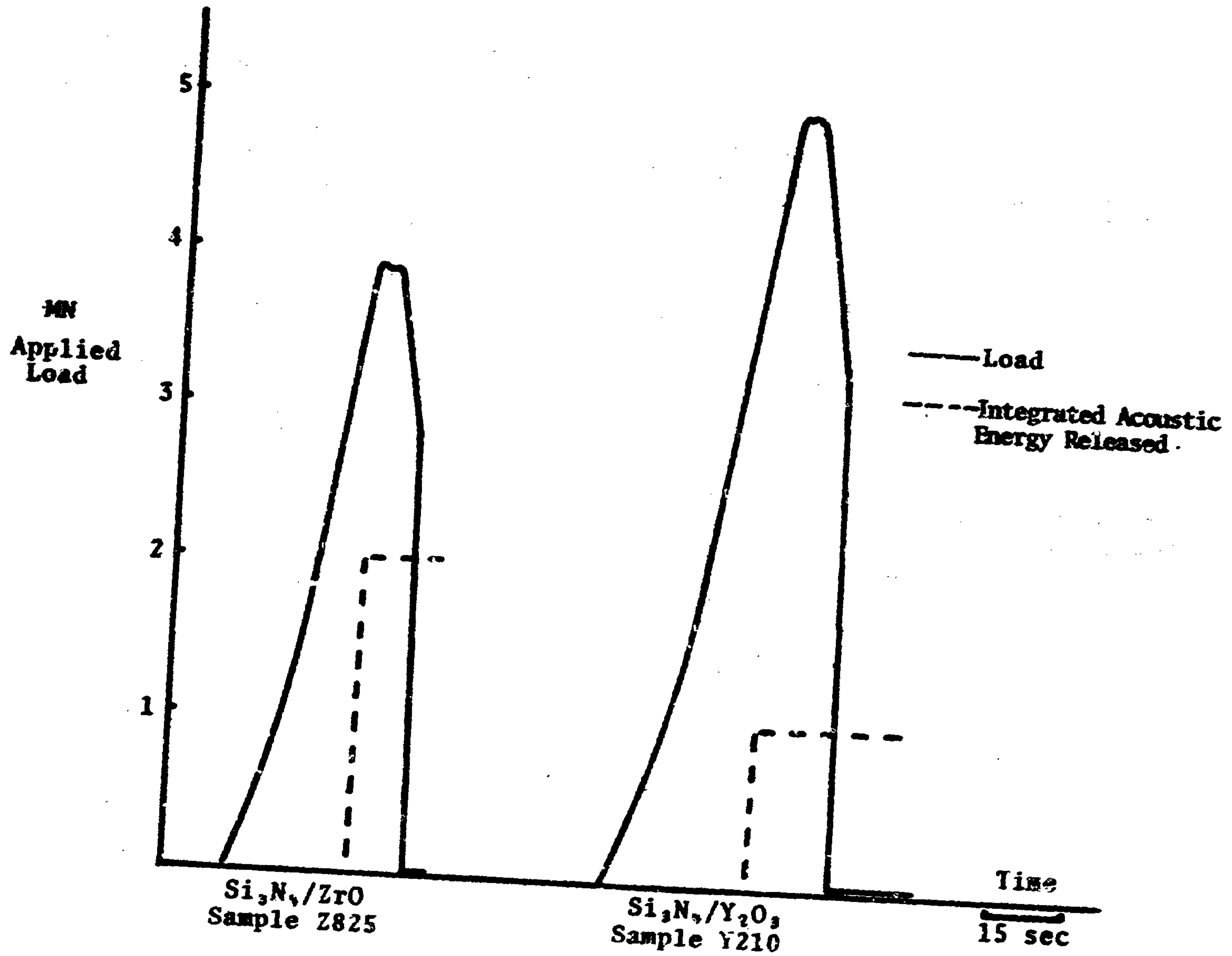


FIGURE 6B - Alternate composition hot-pressed silicon nitride - Hertzian Contact Behavior - 4.75 mm radius WC indenter

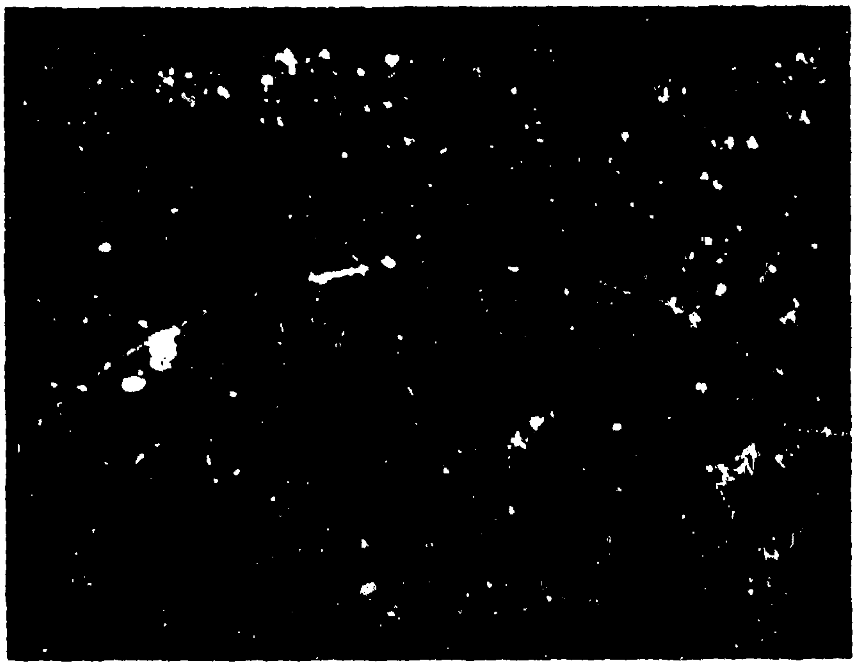
FIGURE 7 - Hertzian cone crack 50X SEM

The cone cracks are difficult to detect in an opaque material. Dye penetration characterization of the cone cracks is possible, but of low sensitivity. Under crossed nichols in reflected light, internal reflection of light in the crack allows the cracks to be detected and accurately measured. Figures 8A and B show both the contact zone where the carbide ball disturbed the machined surface (shear stress) and an arc of a cone crack under crossed nichols.

The results of the testing on standardized surfaces are presented in Table 9. The testing shows that the technique is sensitive to changes in material (fracture energy, most likely); but does not accurately reflect measured differences in MOR or small measured changes in fracture energy in a single material. Testing in a 100 percent humidity environment was carried out. NC-132 samples were loaded to 75-85 percent of their mean measured failure load, and held for up to fifteen minutes in the saturated environment. Loading then proceeded to failure; no statistical difference in P_C, the critical load, was detected. Thus, the test has not demonstrated that stress corrosion mechanisms operate in NC-132. Testing of abraded surfaces did not greatly reduce the load required for fracture; however, heavy oxidation coatings did impair performance. The heavily oxidized surfaces do not have the integrity of NC-132, most likely due to high contact stresses being

A

Contact area
90X



B

Crack front
240X

FIGURE 8 - Hertzian contact areas of NC-132

TABLE 9

Hertzian Indentation Testing
Hot-Pressed Silicon Nitride
0.1875" WC Indenter

Material	Modulus of Rupture MN/m²	Fracture Energy J/m²	Maximum Contact Stress MN/m²	Standard Deviation and Sample Size
NC-132 (300502)	751	35	2610	103/36
NC-132 (300503)	917	33	2550	69/33
NC-132 (300504)	910	40	2570	62/54
$_3N_4$+5% ZrO_2	896	87	2700	200/11
N_4+8% Y_2O_3	965	34	2820	160/11

set up in the SiO_2 layer rather than in a "crack-blunted" silicon nitride surface.

The Hertz indentation test is of sufficient sensitivity to detect large changes in material behavior. It is interesting to note that static loading failures occurred in the region of 400 KSI Hertz stress. RCF tests are run at 800 KSI; indicating the large effect of the lubricant film on stress reduction. Currently the test cannot be recommended as a qualification tool for bearing materials.

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NORTON COMPANY

APPENDIX A

Evaluation of KET*
Surface Characterization Technique
for Si_3N_4 Surfaces

prepared for
Naval Air Systems Command

April 1978

J. W. Lucek
Research Engineer
Industrial Ceramics Division

*Registered Trademark - Qual-X, Inc.

NORTON COMPANY

Evaluation of KET
Surface Characterization Techinque
For Si_3N_4 Surfaces

SUMMARY

KET surface characterization of NC-132* silicon nitride specimens with bearing quality surface finishes was carried out. Characterization by several other techniques; fluorescent dye penetrant, SEM, Dispersive Wavelength X-ray analysis (EDAX), and optical microscopy failed to substantiate the surface structure revealed in the KET signatures. Correlation of the KET signatures to RCF data for the surfaces proved difficult.

INTRODUCTION

The KET surface characterization technique utilizes a surface adsorbed radioactive tracer as a "penetrant" to detect microscopically fine surface flaws. Krypton gas enriched with ${}_{36}Kr^{85}$ is adsorbed on surfaces and then allowed to diffuse off while exposing photographic emulsion. Cracks and pores in the surface retain more krypton; due to higher surface area and more tortuous diffusion paths; than a flat, smooth surface and darken the emulsion to a greater degree.

Several RCF test specimens of silicon nitride with various surface preparation techniques and documented contact fatigue behavior were surface characterized by KET. Efforts were made to relate the KET signature to either finish technique or RCF life. Pores or machining flaws in HP Si_3N_4 are not easily detectable by traditional penetration techniques.

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*Norton Company

KET CHARACTERIZATION

Four runs were made on each sample to verify that the signatures obtained were due to the sample surface structure and not process variables. The typical pore size of NC-132 silicon nitride is less than 5μ and the machining flaws expected were even finer.

Process variables with high speed emulsion could conceivably play an important part in the results obtained. KET signatures similar to each other were obtained each time. It is felt that the signatures obtained are characteristic of the surface studied and not due to a controlled process variable.

Three characteristic surface signatures were obtained from the RCF rods. The first signature is fairly uniform in density. This type of signature would be expected from a uniform distribution of fine pores. This particular rod was ground with 150 and 320 grit diamond wheels sequentially and finished with 1000 grit SiC. This rod had highly variable (poor) RCF characteristics.

The second signature is one that shows varying degress of response to KET. This density variation should represent a considerable difference in porosity of the sample. This rod was 150 and 320 grit ground and then 400 grit diamond honed. Its RCF performance was excellent. Another rod with a similar signature, 100 grit and 320 grit diamond ground with no final step, also gave excellent life in RCF testing. Traditional liquid dye penetrant, optical, and SEM characterization do not reveal any of this structure. See Figure 1.

The third signature shows an "island" structure where the indications are between 500 and 2000μ in diameter. This particular signature was found on three rods. Sample 73-25 was 220 grit ground and then lapped with 6 and 3μ diamond paste. Rods 15 and 17 were 220 grit diamond ground, lapped with successively finer diamond to 3μ diamond, and polished with CeO_2. All three are felt to have suffered varying degrees of subsurface damage in their processing. RCF performance on all three was fair to poor. See Figures 2 and 3.

This is the most interesting structure, particularly in the light that all these rods are felt to have some sub-surface damage. One of these samples was given a thorough optical, SEM, and EDAX characterization in efforts to relate the "island" structure to discernable surface details. A reconstruction of the island structure signature at 100X appears in Figure 4. Indications of such a structure were looked for in various SEM modes. See Figures 5-8. No concentration gradients of the elements detected by dispersive x-ray clearly fall in a similar pattern. Figure 8, SEM in backscatter mode 1000X, clearly shows the pores in the surface; but scanning the surface shows that they are uniformly dispersed. The source of the potassium in the EDAX characterization is unknown. The potassium concentration in NC-132 silicon nitride is considerably below the threshold of sensitivity for dispersive x-ray analysis. Conference with both Qual-X and Kodak have not revealed any likely source. Optical microscopy of the same area with crossed nichols did not detect fine surface cracks due to internal reflection; nor any other indications of flaws. Fluorescent dye penetration revealed none of the island structure.

The KET penetration technique routinely detected the spalls and Hertzian cracks due to RCF testing. It is interesting to note that in most cases the test bands are lighter than the surrounding material in the signature, perhaps indicating the surface structure is filled with wear debris from the testing.

CONCLUSIONS

The KET signature for a very uniformly finished, high contact fatigue life sample indicates considerable variations in surface porosity. Such a surface would not be expected to give good performance. The KET indication of uniform porosity, a desireable characteristic, occurred on a rod with highly variable RCF performance. Rods felt to have been damaged in their near surface layers with poor RCF performance gave an island structure in the KET signature. This indication is significant; but based on the previous two signature types this result must not be accepted as completely reliable. If the third signature is an indication of subsurface damage in HP Si_3N_4, KET is the only NDE technique to reveal it to date. That single characteristic makes this technique of interest for ceramic bearing surface characterization.

RECOMMENDATIONS

Because of the technological promise of the KET characterization technique further work on subsurface damaged materials is in order.

1. Simpler specimen geometries - test bars.
2. Various finishing techniques.
3. Relate to simple strength characteristics - flexure.
4. Constant base material.
5. Documented control of KET technique
    A. film lot
    B. emulsion contact with surface
    C. sample cleaning procedures
    D. uniform processing techniques

Once such an investigation has been made, the known strength and finishing relationships will be definitively related to characteristic KET usefulness of the technique can be determined.

FIGURE 1 - KBT Signature Rod 19A Mottled - 1X

FIGURE 2 - Rod 15 KBT Signature 1X

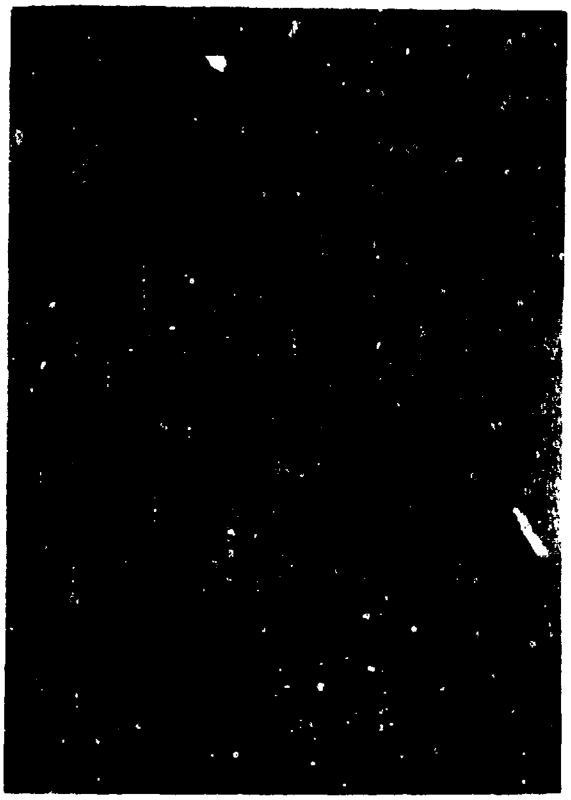


FIGURE 3 - Rod 72-25 KET Signature 2.5X

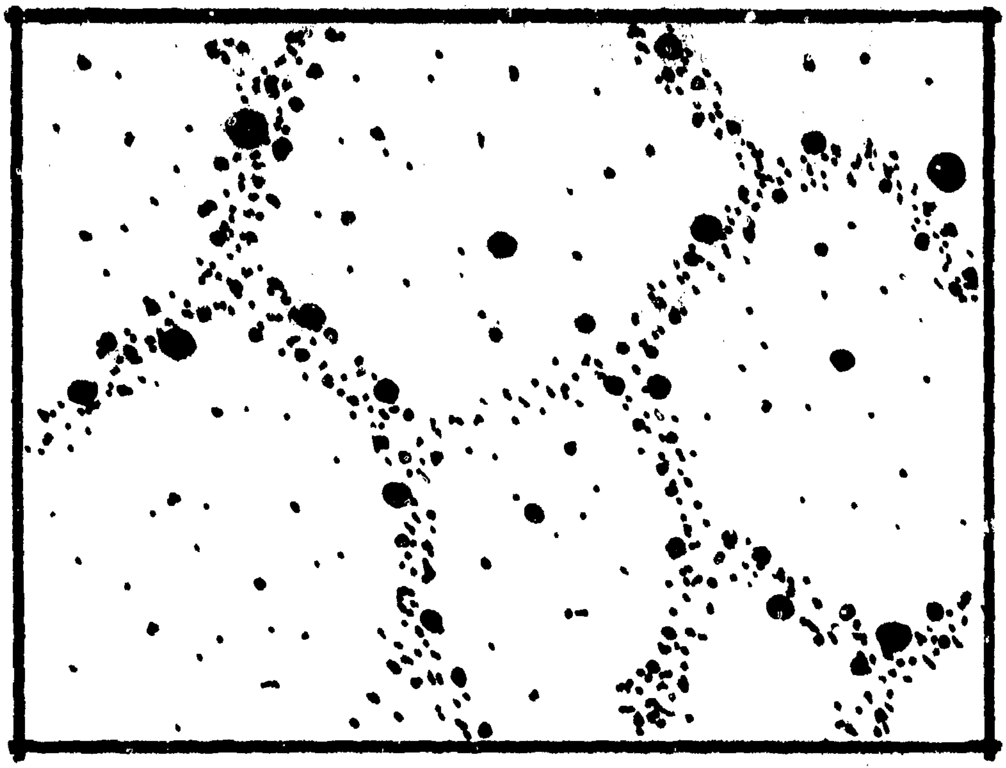
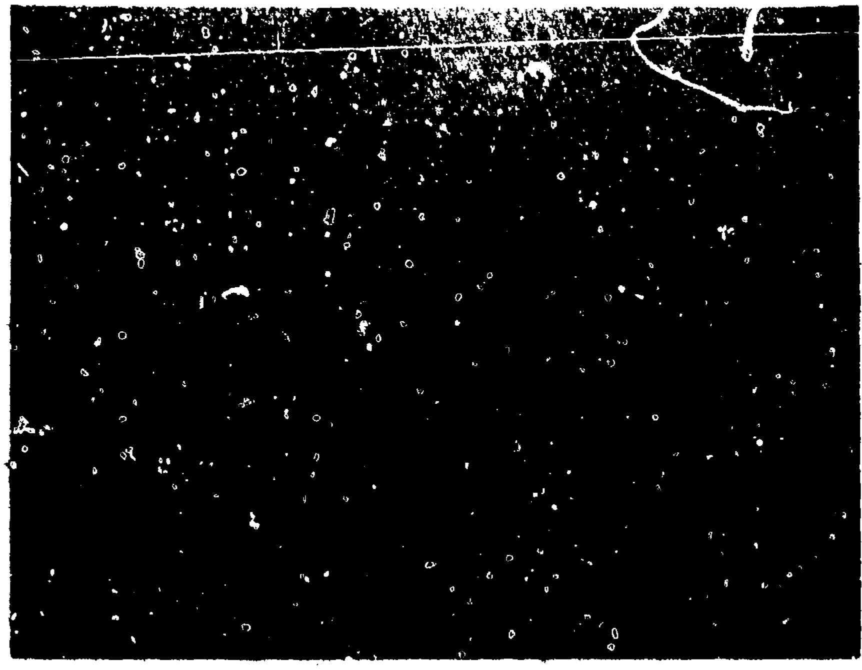
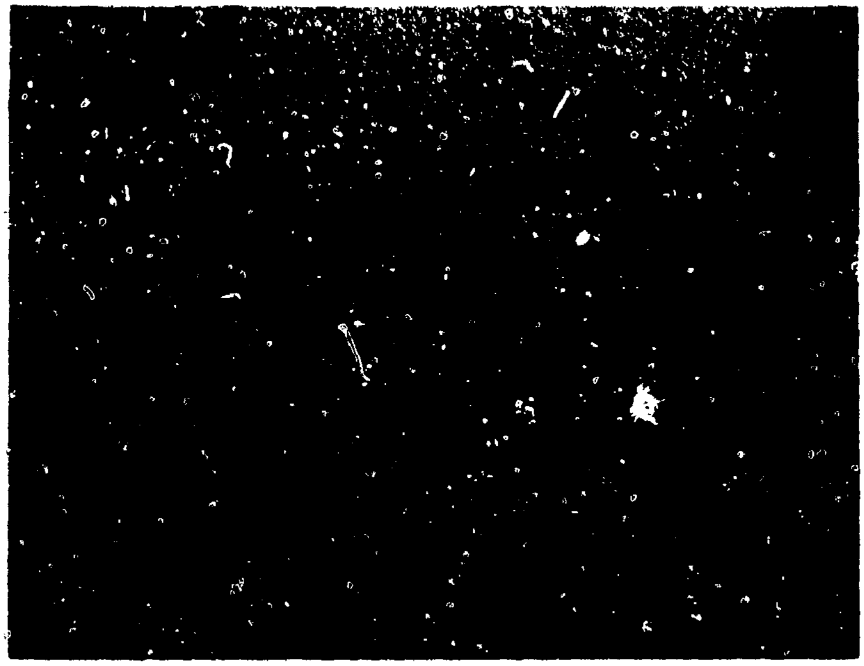


FIGURE 4 - KET Grainy Signature Reconstructed 100X

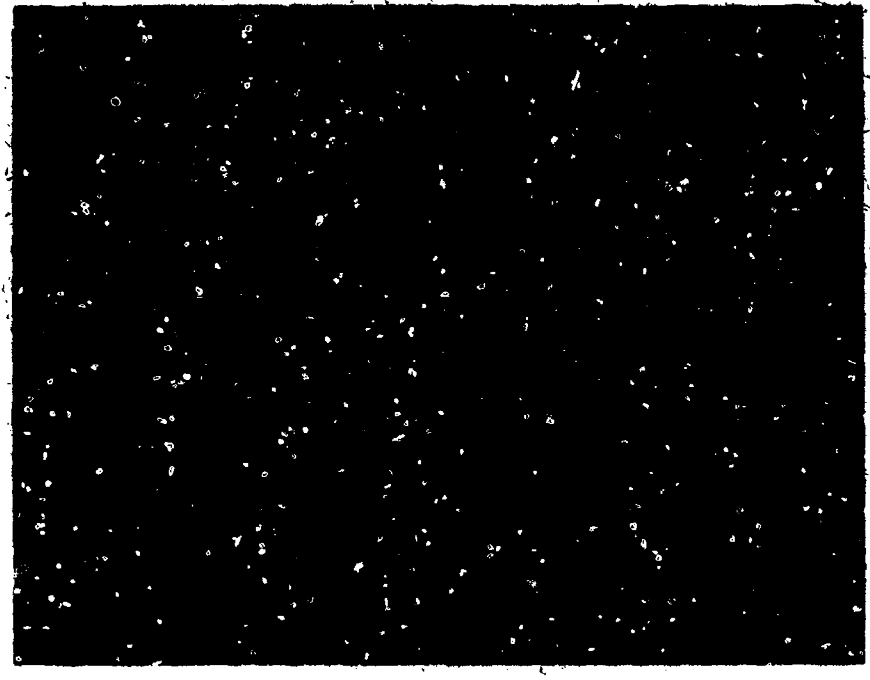


SEM - Secondary Emission - 100X

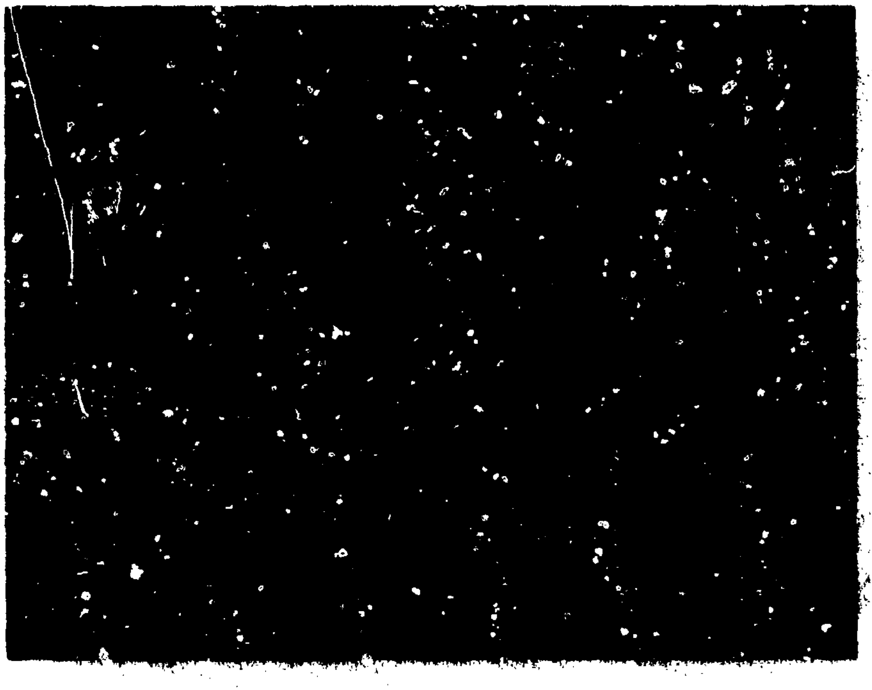


SEM - Backscattered - 0 spot - 100X

FIGURE 5



EDAX Fe concentration map 100X



EDAX W concentration map 100X

FIGURE 6

EDAX Element Plot

EDAX K Concentration Map 100X

FIGURE 7

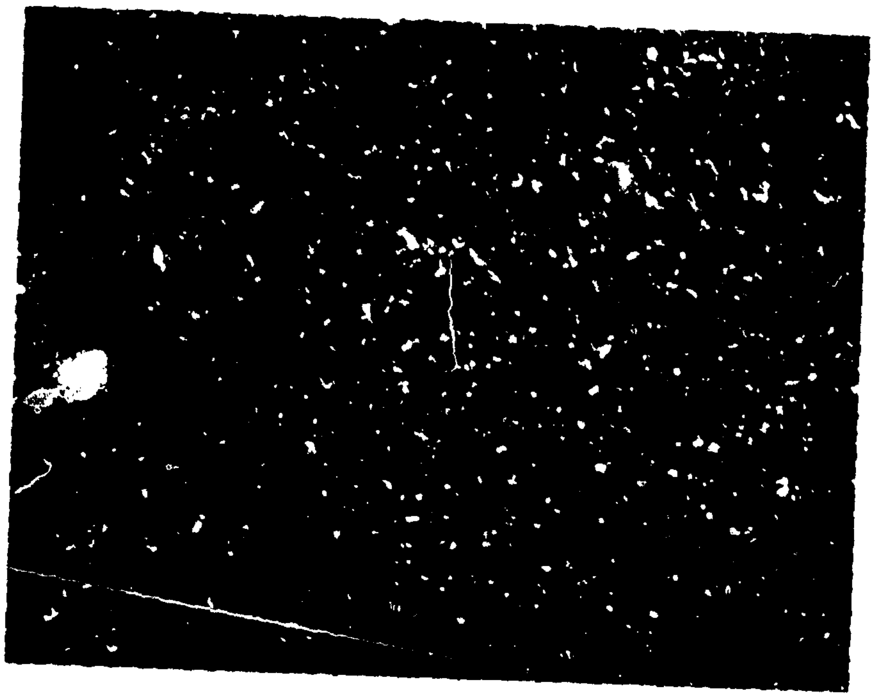


FIGURE 8 · SEM Backscattered Mode
0 spot 1000X

APPENDIX B

Semi-Static Loading on RC Environment

Response of ceramic materials to stress fields must be treated dynamically if the stress fronts advance at significant portion of the velocity of sound on the material. Thus, the rate of speed with which the Hertzian contact zone advances must be considerably less than 10^3-10^4 m/s. In the RCF test, the test specimen rotates at 1050 radians/second. The calculations below justify the consideration of this test as essentially static, and thus, similar to indentation Hertzian testing as far as loading rate is considered.

The contact zone in the 800 KSI RCF test is an ellipse due to the fact that the steel rollers are crowned. The major axis of the contact area, parallel to the RCF rod axis, is the direction in which the major stresses are applied and approximately 0.015 inches long. Assuming the contact area to be planar, a reasonable assumption, the minor axis is 0.13" long.

At a rotational velocity of 1050 radians/second the sample's major axis will increase from 0 → 0.015" in 0.005 sec. Thus the contact major axis increases at an average rate of 3"/second or 0.07 m/sec; considerably lower than the acoustic velocity.

The initial increase in "diameter" of the contact area occurs at a rate approaching infinity in the unlubricated state. The actual rate is much lower and the sizes are only approximations because of the lubrication film present during testing.

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