MRC Bearings

SKF
AEROSPACE BEARINGS

LIFE OF CONCENTRATED CONTACTS IN THE MIXED EHD AND BOUNDARY FILM REGIMES

John I. McCool

MRC Bearings - SKF Aerospace
402 Chandler Street
Jamestown, New York 14701

August, 1989

Final Report

Approved for Public Release: Distribution Unlimited

NAPC Contract Number NAPC-PC-204C

PREPARED FOR

Naval Air Propulsion Center
Post Office Box 7176
Trenton, New Jersey 08628

NAPC-PE-204C

LIFE OF CONCENTRATED CONTACTS IN THE MIXED EHD AND BOUNDARY FILM REGIMES

JOHN I. MCCOOL

MRC BEARINGS - SKF AEROSPACE
402 CHANDLER STREET
JAMESTOWN, NY 14701

AUGUST, 1989

FINAL REPORT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

PREPARED FOR:

NAVAL AIR PROPULSION CENTER
P O. BOX 7176
TRENTON, NJ 08628

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NAPC-PE-204C

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
LIFE OF CONCENTRATED CONTACTS IN THE MIXED EHD AND BOUNDARY FILM REGIMES

5. TYPE OF REPORT & PERIOD COVERED
JANUARY 1986-JULY 1987
FINAL REPORT

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
JOHN I. MC COOL

8. CONTRACT OR GRANT NUMBER(s)
N00140-83-C-7149

9. PERFORMING ORGANIZATION NAME AND ADDRESS
MRC BEARINGS - SKF AEROSPACE
402 CHANDLER STREET
JAMESTOWN, NEW YORK 14701

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
NAVAL AIR PROPULSION CENTER
POST OFFICE BOX 7176
TRENTON, NEW JERSEY 08628

12. REPORT DATE
August, 1989

13. NUMBER OF PAGES

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)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
- Rolling Contact Fatigue
- Microspalling
- Transmission Bearings
- Mixed EHD Film Regimes
- Surface Roughness
- Bearing Lubricants

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

This analytical and experimental program investigates the influence of surface finish, material and lubricant on rolling contact bearings operating in the low or marginal lubricant film regime. The investigation includes failure analysis of field failures encountered with Helicopter mast support and planetary gear transmission bearings, computer analysis of the above two bearing applications using SKF computer programs SHABERTH and PLANETSYS

and testing of specimens made of M50 and 9310 steel using a geared roller tester at NAPC.

FOREWORD

This final technical report presents the work performed by SKF Aerospace Bearings Division under U.S. Navy Contract N00140-83-C-7149. This report covers work accomplished from January 1986 through July 1987.

The principal investigator was Mr. John I. McCool. The experiments were conducted at the Naval Air Propulsion Center, Trenton, New Jersey, under the direction of Mr. Daniel Popgoshev and Mr. Dy D. Le.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
Continued

LIST OF ILLUSTRATIONS
Continued

LIST OF TABLES

1.0 INTRODUCTION & SUMMARY

United States Navy interest became focussed on the problems of bearings operating in the low or marginal lubricant film regime because of early field failures encountered in two applications: 1) a single row, split inner ring ball bearing used to support the mast of the ATH1 helicopter, and 2) a double-row, cylindrical roller bearing used in the main planetary gear transmission of the H3 helicopter.

The investigation described herein was devised to explore the low lubricant film regime within the range of variables represented by these field failures, in order to determine the influence of finish, material and lubricant on successful operation.

The investigation began with a failure analysis of field failures of both types. Both exhibited the form of widespread microscale pitting known as surface distress. The reports documenting the failure analyses for the mast and planetary gear transmission bearings are included as Appendices A and B, respectively.

Computer analyses were then performed for these two bearing applications using SKF computer programs SHABERTH and PLANETSYS, to determine the load distributions, film thicknesses, sliding velocities, contact stresses, contact dimensions and estimated lives under the various conditions of operation. These results are discussed in Section 2.0.

To assess the conditions at the microcontacts of these marginally lubricated bearings, surface roughness traces were made and digitally processed to yield the surface geometry characterization needed for analyzing the microcontact stresses and deflections. The data acquisition and processing system employed for this purpose is described in Appendix C. An evaluation of the accuracy of the system was performed using precision sinusoidal specimens developed by the National Bureau of Standards. Appendix D contains the results of that evaluation and affirms the adequacy of the system's accuracy.

Section 3.0 contains the results of the digital processing of surface roughness profiles and summarizes the microcontact conditions predicted for the field failures by SKF computer program ASPERSIM as well as by the Greenwood-Williamson model as implemented using the computer program RUFFIAN. The RUFFIAN output is given in Appendix E.

A test plan was devised for the geared roller tester at NAPC (Naval Air Propulsion Center) to attempt to reproduce micropitting under conditions comparable to the field failures, but with two levels of surface finish (polished and tumbled), material (M50 and 9310 steel) and lubricant (MIL-L- 23699 and Shell 555).

These tests are discussed in Section 4.0. After an initial period of testing, a pair of failed specimens was examined using scanning electron microscopy. The results of that examination, included as Appendix F, revealed extensive denting due to contamination. Modifications to the test system and procedures were then effected prior to resumption of tests. Further modifications were found to be needed for timely completion of the tests, namely, 1) a reduction in the number of tests from 16 to 8, 2) an increase in the sliding velocity for 7 of the 8 specimens, and 3) an increase in load for 4 of the 8 specimens.

An equivalent life was computed for the load-accelerated tests using a load/life exponent of 3.3. The life results are analyzed in Section 6.0 using a graphical method for interpreting the results of 2^3 factorial experiments applicable when there is no independent measure of error (no replication). Although the results cannot be thought conclusive, the data suggest a possible material/lubricant interaction effect in which the life of M50 is lowered by the use of MIL-L-23699, but not by Shell 555.

Section 7.0 includes values of the surface roughnesses of the test specimens measured before and after testing and the microcontact parameter values predicted using these roughness values. It is clear that operation reduces slopes and gives lowered predicted mean real contact pressure and numbers of plastic contacts. The complete output of the microcontact program is included as Appendix G. An analysis of the microcontact values indicated that they are lower for M50 lubricated with MIL-L-23699 than for the other material/lubricant combinations.

Thus, both the life tests and the microgeometry results have independently pinpointed the M50/23699 tests as unusual. There could be a common explanation, e.g., an inadvertent overload in these tests could have both lowered the life and further flattened the surface slopes to give lowered microcontact variable values.

Section 8.0 is a brief narrative account of what has been found and some general and specific recommendations for further work.

2.0 FIELD FAILURES

2.1 Mast Ball Bearing

The Bell AH-1T helicopter mast is supported by a duplexed pair of split inner ring angular contact ball bearings. The bearings have a 110 mm bore, a 170 mm O.D., a nominal 30° contact angle and a complement of 20, 19 mm diameter balls. The specified raceway roughness is 8 AA or 12.5 RMS. The bearing rotates at a constant speed of 301 RPM. The bearing is lubricated with an oil that meets specification MIL-L-23699. The normal oil operating temperature is 160°F. The loading conditions and the percentage of time the bearing operates at each condition, are given below:

Load Condition	Radial Force (lbs)	Axial Force (lbs)	Run Time (%)
1	2362	12,750	44
2	3082	14,312	26
3	3748	14,950	11
4	4428	17,212	11
5	5026	20,750	5
6	5706	19,545	2
7	500	-1,500	1

A bearing analysis was performed at each of the above load conditions using SKF computer program SHABERTH [1]. Assuming that the bearings shared the applied load equally, SHABERTH was modified for these analyses to give 1) the load on each of the 21 slices along the contact ellipse perpendicular to the major axis, 2) the contact ellipse dimensions and 3) the sliding velocity on each slice perpendicular and parallel to the major axis. Some relevant program output is given in Table 2.1. Column 4 of Table 2.1 gives the maximum Hertzian stress at the most heavily loaded ball. Columns 5 and 6 give the contact ellipse dimensions. V_{max}, the maximum sliding velocity, is given in Column 7. The rolling velocity is on the order of 40 inch/second so the largest slide-to-roll ratio is 2.6/40, or roughly 6.5%. P_{max}, the load on the most heavily loaded ball, is given in Column 7.

The calculated life in hours is listed in Column 9. The life calculations employed a material factor of unity, but did have a calculated reduction factor on the order of 0.2 due to the low specific lubricant film thickness. The lubricant film thickness calculated using the properties of MIL-L-23699 oil at 160°F is given in Column 10. Based on the nominal (specified) roughness of the races, the film parameter h/σ ranges from $1.89/12.5 = 0.151$ to $2.20/12.5 = 0.176$; clearly in the low or marginal lubricant film regime of operation.

Appendix A is a metallurgical report on a failed bearing documenting the glazing and microspalling that typifies failure in the low film regime.

TABLE 2.1

SHABERTH Output
Mast Bearing At Various Load Conditions

Fr (lbs)	Fa (lbs)	% Relative Duration	σmax KSI	a (in)	b (in)	V_{max} (in/sec)	P_{max} (lb)	Life (Hrs)	h (μin)
6375	1181	44	300	0.0765	0.0149	2.05	714	1053	2.00
7156	1541	26	318	0.0813	0.0159	2.18	855	682	1.96
7475	1874	11	332	0.0848	0.0166	2.27	968.5	526	1.94
8606	2214	11	348	0.0888	0.0173	2.42	1111.2	347	1.92
10375	2513	5	363	0.0926	0.0181	2.59	1263	219	1.90
9772	2853	2	370	0.0945	0.0184	2.60	1339	214	1.89
750	250	1	188	0.0480	0.0094	1.06	176	1.45E5	2.20

2.2 Planetary Gear Transmission Bearing

The double-row, geared outer ring cylindrical roller bearing used in the five planet positions in the Sikorsky H53 helicopter transmission has experienced early field failures. The bearing utilizes 42 (forty-two) rollers per row. The rollers are 7/16 inch diameter and have a total length of 1.16 inch. The flat central section of the roller has a length of 0.6600 inch. The crowned lateral portions of the roller are finished with a crown radius of 119 inch. The bearing pitch diameter is 7.2 inch.

Geometrical data on the planetary gear system are as follows:

Input:		Sun Gear
Output:		Carrier
No. of Planet Gears:		5
Planet Gear Data:	Root Diameter:	8.5714 inch
	Pitch Diameter:	8.875 inch
	Number of Teeth:	71
Sun Gear Data:	Pitch Diameter:	6.75 inch
	Number of Teeth:	54
Ring Gear Data:	Pitch Diameter:	24.5 inch
	Number of Teeth:	196

The pressure angle is 22.5° for all gears. The lubricant (MIL-L-23699) operating temperature was given as 180°F. The nominal operating radial clearance is 0.0015 inch. The horsepower input to the rotor, the rotor speed, and the percentage of time at each operating condition were given for four conditions as follows:

Percentage Of Time	Rotor Speed (RPM)	Horsepower
1.9	185	2090
4.8	203	1710
92.3	203	1500
1.0	203	1140

The horsepower values given above represent a 5% reduction from the engine horsepower to account for the power to the tail rotor. The oil temperature during operation is 180°F.

SKF computer program PLANETSYS was modified to yield for each roller, the normal load and sliding speed at both rings for each of the twenty-one (21) slices into which a roller is divided.

PLANETSYS accommodates a maximum of 40 (forty) rollers, a restriction that can not be relaxed without appreciable effort. Accordingly, PLANETSYS was run at each of the conditions given above for 36 (thirty-six), 38 (thirty-eight) and 40 (forty) rollers. The results were projected to 42 (forty-two) rollers. The program was run at epicyclic conditions. Because the roller analysis employed by PLANETSYS treats the roller slices as independent, all slices deform by the same amount over the flat portion of the roller and thus, no "Heathcote" type sliding is calculable except at the crowned roller ends. To gage the sliding effect more accurately, a roller contact was examined via SKF program HARMONY which performs an analysis of roller deflection which accounts for the interdependence of slices.

Table 2.2 summarizes the PLANETSYS results. Using a nominal value of 8 μ inch rms for the surface roughness of the raceways and 4 μ inch rms minimum for the rollers, the composite surface roughness is approximately 9 μ inch rms. The lubricant film parameter values thus range from 0.49/9 = 0.054 to 0.58/9 = 0.064. These values are well into the low film regime.

Table 2.3 summarizes the results of the calculation using HARMONY. Column 4, gives the maximum deflection δ at each of the load conditions. Using the roller rotational speed, a conservative (i.e., an overestimate) of the sliding velocity was computed as

$$V_{max} = \omega\delta$$

where ω is the angular velocity of the roller about its own axis. These values are given in Column 5 of Table 2.2.

TABLE 2.2

SUMMARY OF PLANETSYS RESULTS

INPUT HP		NO. OF ROLLERS 36	38	40	(EXTRAPOLATED) 42
	Max. Load (Lbs)	2107	2006	1911	1820
1140	Film Thickness (μin)	0.569	0.572	0.578	0.584
	Life (Hrs)	61	70	79	88
	Max. Load (Lbs)	2765	2639	2522	2402
1500	Film Thickness (μin)	0.552	0.555	0.561	0.567
	Life (Hrs)	23	26	29	32
	Max. Load (LBs)	3158	3001	2870	2733
1710	Film Thickness (μin)	0.544	0.547	0.553	0.559
	Life (Hrs)	14	16	18	20
	Max. Load (Lbs)	4274	4055	3854	3670
2090	Film Thickness (μin)	0.474	0.477	0.481	0.485
	Life (Hrs)	5.6	6.3	7.1	7.8

TABLE 2.3

"Harmony" Output and Estimated Maximum Sliding Velocity

%	HP	LOAD (LBS)	σ_{MAX} (ksi)	δ (in)	V_{MAX} (in/sec)	S/R (%)
1.0	1140	1820	272	6.24E-4	0.059	0.30
92.3	1500	2402	306	7.82E-4	0.0814	0.36
4.8	1710	2733	324	8.70E-4	0.091	0.40
1.9	2090	3670	367	1.10E-3	0.115	0.5

The slide-to-roll ratio in percent is computed as

$$S/R = 100 \times V_{max}/V_r$$

where $V_r = r \times \omega$ is the rolling velocity.

The largest slide-to-roll ratio among the load conditions is only 0.5%.

3.0 MICROCONTACT CONDITIONS OF FIELD FAILURES

In order to assess the microcontact conditions experienced by the failed bearings, surface roughness traces were digitized and analyzed using the system described in Appendix C. The purpose was to estimate the mean square height (m_0), slope (m_2) and curvature (m_4) needed for performing a microcontact analysis. A validation of the system accuracy determined by tracing and analyzing precision sinusoidal specimens loaned by the National Bureau of Standards, is given in Appendix D.

Roughness profile traces were made on unrun portions of the angular-contact mast bearing inner raceway and on the unrun portions of the rolling paths of the two cylindrical roller bearing inn^er raceways, S/N 3922 and S/N 6065. It will be recalled (Appendix B) that the ring S/N 6065 was hard-turned.

A single cross-groove profile was traced on the angular-contact ring while eight (8) traces spaced at 22.5° apart were made on the cylindrical roller bearing raceways. Single axial traces were made on two rollers from each cylindrical roller bearing.

The tracing speed used in acquiring the roughness data was 0.00233 inch/second. A total of 8,000 (eight thousand) sampled values were digitized on each profile. The sampling frequency used was 60/second.

The spatial sampling frequency was thus

$$\frac{60 \text{ samples/second}}{0.00233 \text{ inch/second}} = 25{,}750 \text{ samples/inch}$$

The sample spacing Δx is, therefore

$$\Delta x = 1/25{,}750 = 38.8 \ \mu \text{ inch}$$

The computer program PRODOE (cf. Appendix C) was used to compute the spectral moments m_0, m_2, and m_4 before and after a digital filtering operation. The filter bandpass used was 33 (thirty-three) cycles/inch to 5,000 (five thousand) cycles/inch. The resultant values are given in Table 3.1.

The asperity contact analysis program ASPERSIM [2], requires as input in the general anisotropic case, nine (9) numbers, known as bispectral moments, to characterize each contacting surface to the extent required by an analysis in which asperities are treated as microhertzian contacts. These numbers are designated m_{00}, m_{02}, m_{20}, m_{11}, m_{40}, m_{31}, m_{22}, m_{13} and m_{04}. These numbers must be deduced from the values of m_0, m_2, and m_4 measured on eight (8) traces, angularly spaced 22.5° apart, on the inner rings of cylindrical roller bearings S/N 3922 and S/N 6065. These values have been used to deduce m_{20}, m_{11}, and m_{02} using the fact that m_2 at an angle θ is expressible as:

TABLE 3.1

Summary of Roughness Data

DIRECTION	SPECIMEN	$m_0(\mu in^2)$	m_2	$m_4(\mu in)^{-2}$
AXIAL TRACE	ROLLER S/N 3922	218	4.79E-3	1.79E-6
	ROLLER S/N 3922	269	8.22E-3	2.65E-6
	ROLLER S/N 6065	337	1.53E-2	5.47E-6
	ROLLER S/N 6065	301	1.43E-2	4.99E-6
CROSS GROOVE	ANGULAR CONTACT INNER	51.9	1.37E-3	5.46E-7
CROSS GROOVE	0° INNER S/N 3922	46.8	2.62E-3	9.49E-7
	22° "	64.2	2.51E-3	9.01E-7
	45° "	56.9	2.15E-3	6.80E-7
	67° "	54.0	1.21E-3	3.20E-7
	90° "	32.8	3.27E-4	1.29E-7
	112° "	71.7	1.31E-3	3.54E-7
	135° "	86.7	2.97E-3	9.31E-7
	157° "	92.2	3.96E-3	1.31E-6
CROSS GROOVE	0° INNER S/N 6065	534	1.99E-2	4.82E-6
	22° "	165	4.31E-3	9.74E-7
	45° "	53.2	1.19E-2	2.74E-6
	67° "	51.9	5.08E-3	1.14E-6
	90° "	19.9	7.56E-4	3.58E-7
	112° "	600	6.16E-3	1.31E-6
	135° "	463	1.10E-2	2.63E-6
	157° "	471	1.62E-2	3.92E-6

$$m_2(\theta) = m_{20}\cos^2\theta + m_{11} \times 2\cos\theta\sin\theta + m_{02}\sin^2\theta \quad (3.1)$$

Regarding $m_2(\theta)$ as response and the various functions of θ as regression variables, the values m_{20}, m_{11} and m_{02} may be deduced as the estimated regression coefficients in a zero intercept, multiple regression equation of the form:

$$y = ax_1 + bx_2 + cx_3 \quad (3.2)$$

The values of m_{20}, m_{11} and m_{02} and their standard errors are shown in Table 3.2. Also shown in Table 3.2 are the values and standard errors of the quantities m_{40}, m_{04}, m_{31}, m_{22} and m_{13}. These were likewise deduced from a multiple regression run using the relation between m_4 measured at the angle θ and these five (5) values. This relation is:

$$m_4(\theta) = m_{40}\cos^4\theta + m_{31}\,[4\cos^3\theta\sin\theta] + m_{22}\,[6\cos^2\theta\sin^2\theta] +$$

$$m_{13}\,[4\cos\theta\sin^3\theta] + m_{04}\sin^4\theta \quad (3.3)$$

which is of the form

$$y = ax_1 + bx_2 + cx_3 + dx_4 + ex_5 \quad (3.4)$$

where the x_i denote the various functions of θ and the constants a-e the respective spectral moments.

TABLE 3.2

Bispectral Moments and Estimated Standard Errors
NAPC Specimens

		S/N 3922		S/N 6065		ANGULAR CONTACT
m_{00}	$(\mu in)^2 \times 10^3$	63.2	(19.9)	334.0	(235.0)	51.9
m_{20}	$(\mu in)^2 \times 10^3$	3.40	(0.370)	15.8	(2.91)	1.37
m_{11}	$(\mu in)^2 \times 10^3$	-0.479	(0.302)	-2.07	(2.38)	0.0
m_{02}	$(\mu in)^2 \times 10^3$	0.861	(0.370)	2.99	(2.91)	1.37
m_{40}	$(\mu in)^{-2} \times 10^7$	10.4	(0.701)	37.4	(9.67)	5.46
m_{31}	$(\mu in)^{-2} \times 10^7$	-1.64	(0.495)	-9.56	(6.84)	0.0
m_{22}	$(\mu in)^{2} \times 10^7$	3.66	(0.455)	7.94	(6.28)	1.82
m_{13}	$(\mu in)^{-2} \times 10^7$	0.232	(0.495)	4.32	(6.84)	0.0
m_{04}	$(\mu in)^{-2} \times 10^7$	0.868	(0.701)	6.41	(9.67)	5.46

For the angular-contact ball bearing, only a cross groove tracing was made. If the surface is regarded as isotropic, the nine (9) parameters are related to the three (3) cross-groove parameters m_0, m_2 and m_4 as:

$$m_{00} = m_0$$

$$m_{11} = 0$$

$$m_{02} = m_2$$

$$m_{20} = m_2$$

$$m_{22} = m_{4/3}$$

$$m_{13} = 0$$

$$m_{31} = 0$$

$$m_{40} = m_4$$

$$m_{04} = m_4$$

The values in Table 3.2 were computed in this way for the angular-contact ball bearing.

The results of an ASPERSIM analysis of the contact at an arbitrary separation $h/\sigma = 1.5$ of this "isotropized" surface and a smooth plane are given in line 1 of Table 3.3. Also shown are the corresponding contact parameters computed by application of the Greenwood-Williamson (GW) model. These values are quite close in each case to the corresponding values computed via ASPERSIM and supply in addition the density, N_p, of the "plastic" contacts for which the subsurface shear stress exceeds one-half the yield strength in simple tension.

TABLE 3.3

Contact Parameters Via Aspersim & GW Model
At h/σ = 1.5 Isotropic With Cross Groove Parameters

BEARING	CONTACT MODEL	N (in^{-2})	P/A_o (lb/in^2)	A_c/A_o	P/Ac (lb/in^2)	N_p (in^{-2})	N_p/N
ANGULAR	ASPERSIM	2.10E6	13250	0.0252	526000	-	-
CONTACT	GW	2.09E6	115100	.0221	566000	1.36E6	0.651
MAST BEARING							
PLANETARY	ASPERSIM	2.59E6	17050	0.0244	699000	-	-
TRANSMISSION							
CYLINDRICAL	GW	2.64E6	16582	0.0230	720000	2.07E6	0.784
BEARING							
S/N 3922							
PLANETARY	ASPERSIM	1.91E6	41480	0.0241	1.72E6	-	-
TRANSMISSION	GW	1.94E6	40817	0.0228	1.79E6	1.87E6	0.962
CYLINDRICAL							
BEARING							
S/N 6065							

ASPERSIM analyses using the nine (9) values in Table 3.2 for the two (2) cylindrical roller bearings did not give reasonable results, probably because the values are not statistically significant (i.e. they are small compared to their standard deviations) and may not be internally consistent.

Accordingly, the cylindrical roller bearings were analyzed using the cross groove roughness as the values for an isotropic surface. For the bearing S/N 3922, this was done by setting $m_2 = m_{20}$ and $m_4 = m_{40}$. For the hard-turned ring S/N 6065 the actual results of the trace perpendicular to the surface grooves or furrows were felt to be more reliable, since as seen in Table 3.2, the traces made in the directions close to parallel with the grooves had very low m_2 and m_4 values, possibly due to the stylus riding in the furrows. Spurious results in any direction will bias the regression estimates. Table 3.4 is a summary of the values finally used.

The values of m_0 obtained by digital processing for the angular-contact ball bearing and cylindrical roller bearing inner rings were quite consistent with independent measurements of R_q made with the Talysurf V in its usual operating mode. The values for the four (4) rollers, however, ranged from 218-337 (μ inch^2) implying a range in R_q of 15-18 μ inch which seemed abnormally high. Several Talysurf V determinations, however, showed that the R_q value could be as high as 26 μ inch if one traverses the wear scars that formed bands at the center of the roller. Since these values are not representative of the finish of a virgin roller, the microcontact analysis discussed above was conducted assuming the ring surfaces to be contacting a smooth plane.

TABLE 3.4

Cross Groove Values Used In Isotropic Contact Analysis

BEARING	$m_0 (in)^2$	m_2(non-dim)	$m_4 (in^2)^{-1}$
ANGULAR CONTACT MAST BEARING	51.9E-12	1.37E-3	5.46E5
PLANETARY TRANSMISSION CYLINDRICAL BEARING S/N 3922	63.2E-12	3.4E-3	1.04E6
PLANETARY TRANSMISSION CYLINDRICAL BEARING S/N 6065	534E-12	19.9E-3	4.82E6

The ASPERSIM and GW model predictions for the cylindrical roller bearings at $h/\sigma = 1.5$ are shown in Table 3.3. S/N 6065 appears to have the most severe loading condition as judged by the ratio of plastic to total contacts (N_p/N) and by the average real stress P/A_c defined as the average load per unit of average contact area. By these same criteria, the angular-contact ball bearing is least severe.

As noted, the values in Table 3.3 are computed at a standardized separation $h/\sigma = 1.5$ and show the essential agreement of ASPERSIM and the simpler GW model. The GW model was next applied using the smallest h value computed using the programs SHABERTH and PLANETSYS.

The program used to implement the GW model is called RUFFIAN (Rough Interface Analysis). It is written in Fortran 77 and runs on a PC. The complete RUFFIAN output for the field failures is given in Appendix E. Table 3.5 is a comparative summary of the results. This comparison further accentuates the differences noted previously, i.e. that the angular-contact ball bearing microcontacts are not as heavily loaded as the planetary gear transmission bearings and that the hard-turned cylindrical roller bearing has more severe microcontact conditions than the conventionally finished bearing.

TABLE 3.5

Contact Parameters At the Computed Film Parameter Values

BEARING	h/σ	N (in^{-2})	P/A_o (lb/in^2)	A_c/A_o	P/A_c (lb/in^2)	N_p (in^{-2})	N_p/N
ANGULAR CONTACT MAST BEARING	0.262	7.93E6	114,150	0.138	8.18E5	6.54E6	0.824
PLANETARY TRANS-MISSION BEARING S/N 3922	0.061	8.21E6	235,300	0.148	1 59E6	7.59E6	0.925
PLANETARY TRANS-MISSION BEARING S/N 6065	0.021	6.43E6	604,200	0.156	3.87E6	6.36E6	0.989

4.0 MICROPITTING TESTS

A set of tests were devised to explore the effect of finish, lubricant and material on the incidence of micropitting, under conditions approximating those encountered in the marginally lubricated bearings discussed in Section 2.0. The test apparatus was a geared roller tester shown schematically in Figure 4.1. The test specimens are 1.5 inch diameter disks having a crown radius of 14 inch.

They were run together under an applied load of 1250 pounds. Initially, the speeds were set so as to produce pure rolling, i.e. equal peripheral speeds for both disks. Subsequently, the speeds were modified to yield a slide-to-roll ratio of 3% by setting the rotational speeds so that the peripheral velocities of the two disks were 58.824 inch/second and 54.975 inch/second. The test variables selected were:

Material:	M50 and 9310
Finish:	Polished and Tumbled
Lubricant:	MIL-L-23699 and Shell 555 supplied at 180°F

The test matrix is shown as Table 4.1.

Two replications at each treatment combination were originally planned for a total of sixteen (16) tests. Table 4.2 shows the randomized sequence for conducting the sixteen tests and the serial numbers assigned to the specimens.

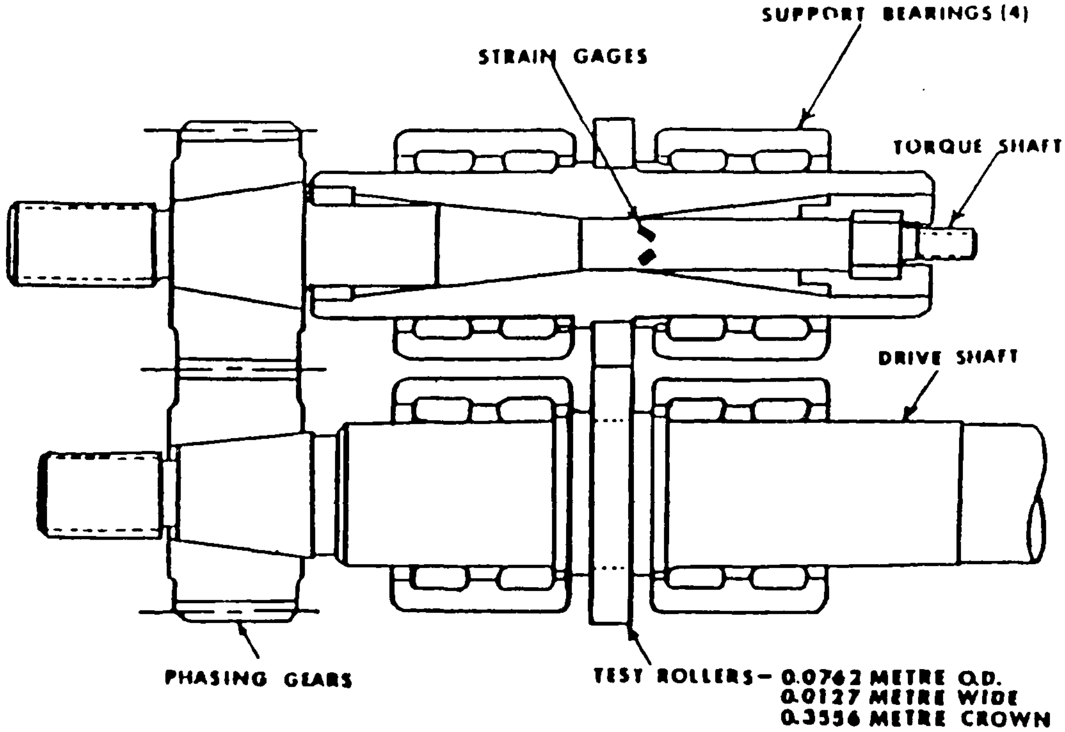


Figure 4.1
Geared Roller Test Machine Schematic

TABLE 4.1

Test Matrix For Micropitting Tests

INVESTIGATION OF FINISH, LUBE AND MATERIAL EFFECTS DURING LOW-FILM OPERATION

		F1 (POLISHED)	F2 (TUMBLED)	
M1 (9310)	O1 -23699			
	O2 (555)			
M2 (M50)	O1 -23699			
	O2 (555)			

TABLE 4.2

Geared Roller Test Machine Low-Film Life Study Test Plan

RUN NO.	MATERIAL	TEST OIL	FINISH	UPPER DISK	LOWER DISK	HOURS
1	9310	23699	Polished	S-145	S-146	702.0
2	M50	23699	Tumbled	V-15	V-16	402.0
3	M50	23699	Polished	V-5	V-6	404.0
4	9310	23699	Tumbled	S-151	S-152	0.0
5	M50	555	Polished	V-7	V-8	557.5
6	9310	555	Tumbled	S-143	S-144	642.0
7	9310	555	Polished	S-163	S-164	630.0
8	M50	555	Tumbled	V-13	V-14	0.0
9	9310	23699	Polished	S-167	S-168	0.0
10	M50	23699	Polished	V-9	V-10	0.0
11	M50	23699	Tumbled	V-17	V-18	0.0
12	9310	23699	Tumbled	S-159	S-160	632.0
13	M50	555	Tumbled	V-11	V-12	600.0
14	9310	555	Polished	S-169	S-170	0.0
15	9310	555	Tumbled	S-173	S-174	0.0
16	M50	555	Polished	V-19	V-20	0.0

An initial test, performed using the pair S181 and S182, was subjected to metallurgical examination after failure had occurred. The report of this examination is given in Appendix F. As noted, therein, the specimens exhibited extensive denting, but not micropitting.

Following this, elaborate precautions were introduced in the test and specimen examination procedures to minimize contamination, and testing was resumed using the specimens listed in Table 4.2. Under these circumstances the test Number 5 in Table 4.2 was undertaken. The test was terminated after 667.5 hours of testing with what was thought to be micropitting.

Subsequent testing was conducted at 3% sliding to attempt to accelerate failure while remaining consistent with the magnitudes of sliding that occurs in the field failures.

Despite the introduction of sliding, test durations were found to be quite long. In the interest of speeding the completion of the tests two further steps were then taken:

1) It was decided to do just a single replicate (8 tests) rather than doubly replicating the experiment and,

2) The load was increased to 2151 pounds on four (4) sets of specimens. Using a roller bearing load-life exponent of 3.3, this load increase results in a sixfold decrease in life. The table below lists the specimen numbers, the accumulated life prior to the load increase, L_1, the life to failure at the increased load, L_2, and the equivalent life at the lower load computed as $L = L_1 + 6L_2$ (4.1)

Specimen No.	Life at 1250 lbs L_1 (hours)	Life at 2151 lbs L_2 (hours)	Equivalent Life $L_1 + 6L_2$ (hours)
S145/S146	30	112	702
S163/S164	270	60	630
S143/S144	462	30	642
V15/V16	213	31.5	402

These equivalent lives and the lives of the specimens that failed at the 1250 pound load are listed in the last column of Table 4.2.

The accelerated tests are balanced with respect to the "finish" factor in that two (2) of the tests are with tumbled specimens and two (2) are with polished specimens. Similarly, the tests are balanced with respect to oils; two (2) being MIL-L-23699 and two (2) Shell 555. They are not balanced with respect to material, however, in that three (3) of the accelerated tests involved SAE 9310 steel. A consequence is that any deficiency in the acceleration technique, i.e., a difference from the assumed 3.3 power is the load/life relation will manifest itself as a difference in the materials.

Taking the data at face value however, the effects of the three (3) factors and their interactions were computed. This analysis is given in Section 6.0.

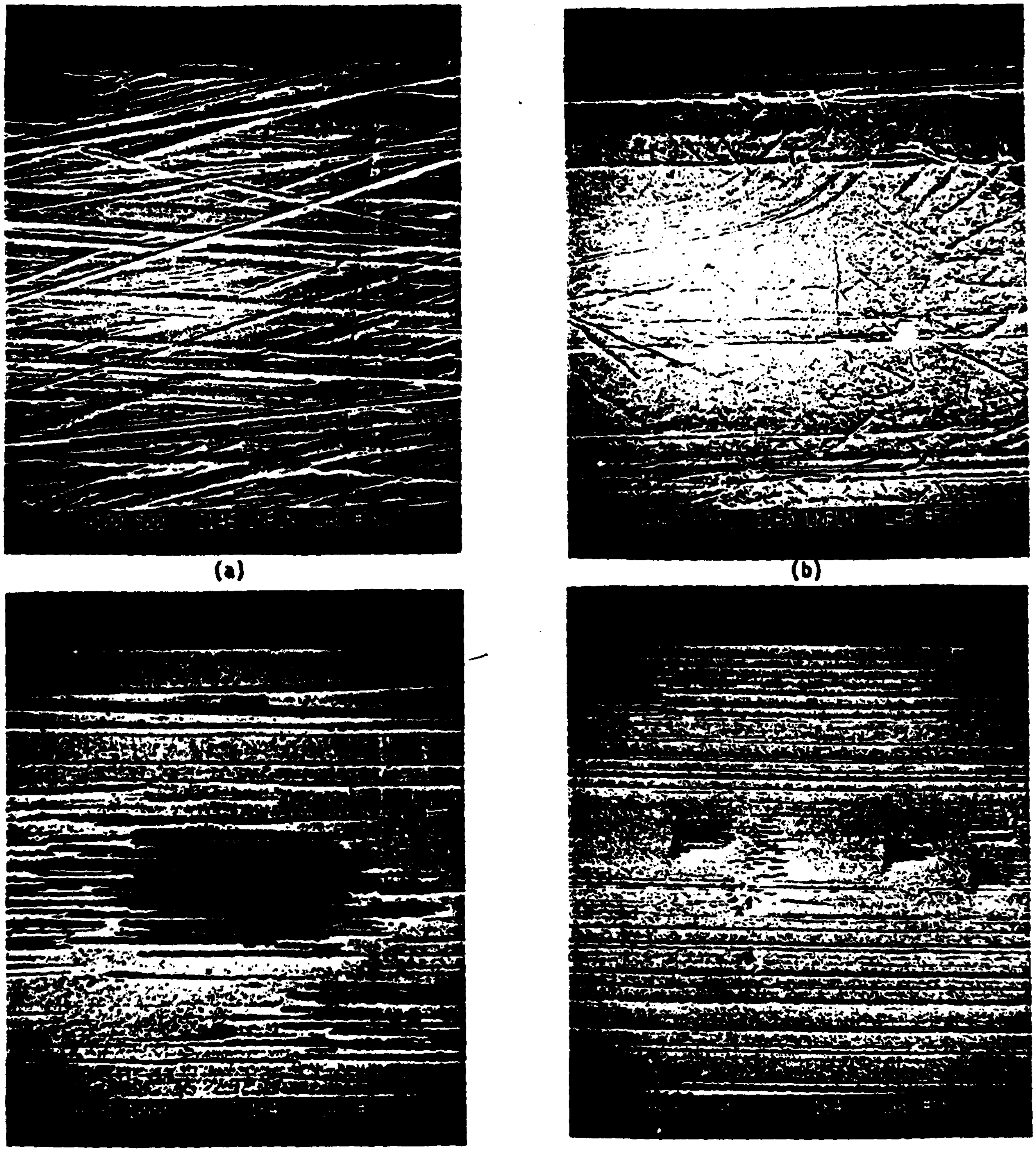
5.0 EXAMINATION OF FAILED SPECIMENS

SEM photographs were taken at various magnifications of the surfaces of the micropitting specimens after running. The results, discussed further below, indicate the presence of spalls emanating from dents and corrosion pits, but not the wholesale micropitting, i.e., pitting on the asperity scale that typified the field failures.

Photographs (a) and (b) of Figure 5.1 show the unrun polished and tumbled surfaces respectively on the 9310 steel specimens 5146 and 5160. The working of the tumbled surface is quite evident. Photograph (c) is Specimen Number S164, a polished 9310 steel specimen that had been run with lubricant Shell 555. The central feature is believed to be a shallow dent. The finishing marks are visible at the bottom and the surrounding material, elevated by the depression, is glazed. Photograph (d) taken at 250X shows comparable denting damage and attendant glazing over a wider area.

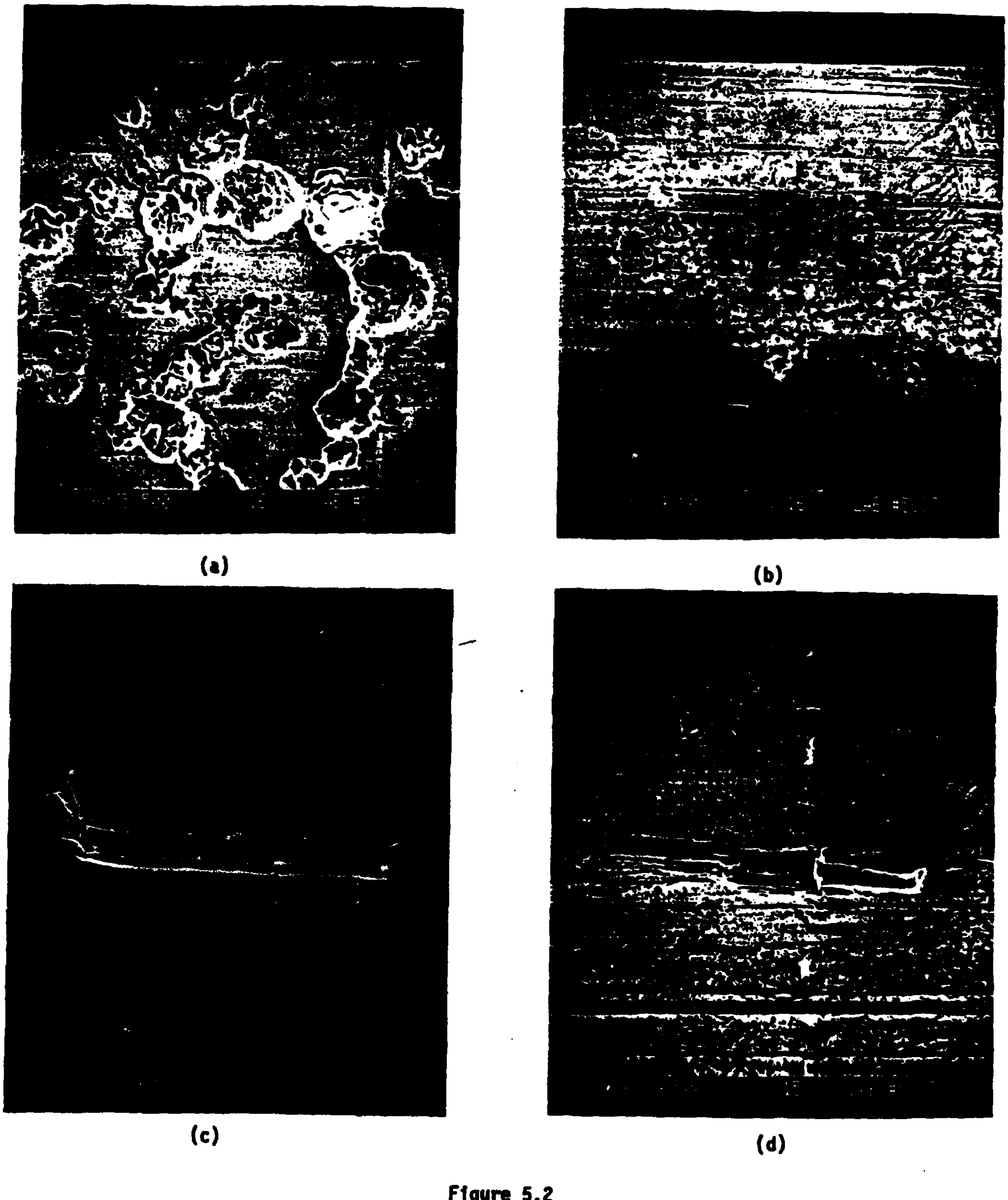
Photographs (a) and (b) of Figure 5.2 show specimen V16 at 50X and 500X magnification. This specimen is tumbled M50 lubricated with MIL-L-23699. The features are believed to be corrosion damage.

Photographs (c) and (d) are specimens V11 and V15. Both are tumbled M50. V11 was tested with Shell 555 and V15 with MiL-L-23699. Both show damage suggestive of the incursion of hard particle.



(a) (b) (c) (d)

Figure 5.1
9310 Specimen



(a) (b) (c) (d)

Figure 5.2
M50 Specimen

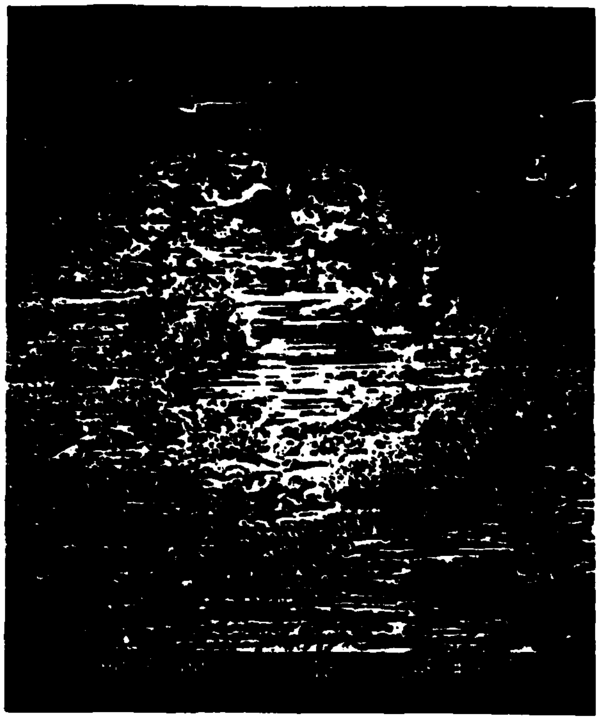
Photograph (a) of Figure 5.3 shows specimen S145 (9310 steel, polished, Shell 555). The surface damage indicated is thought to be due to dislodged inclusions. Photograph (b) taken at 250X of specimen V6 (M50 Steel, polished, MiL-L-23699) shows distinct surface damage with a widespread surrounding glazed area. The shape is not typical of a surface fatigue spall. Photograph (c) (9310 Steel, polished, Shell 555) and (d) M50 steel, tumbled Shell 555 show further examples of surface damage. The source is believed to be corrosion.

Other than the visual difference between polished and tumbled specimens, the SEM photos were too varied to suggest systematic behavioral differences due to the differences in material and lubricants.

(a) 9310 steel

(b) M50 steel

(c) 9310 steel



(d) M50 steel

Figure 5.3

6.0 ANALYSIS OF MICROPITTING LIFE DATA

The micropitting life data were analyzed as a 2^3 experiment, i.e. an experiment with three (3) factors, material (M), finish (F), and oil (O), each having two (2) levels. The low level indicated with a minus (-) sign and the high level, indicated with a plus (+) sign were arbitrarily assigned as follows:

Factor	-	+
M	9310 Steel	M50 Steel
F	Polished	Tumbled
O	MiL-L-23699	Shell 555

The "effect" of the lubricant factor "O" is computed as the average life of the four observations at the upper level of O minus the average life of the four observations at the lower level of O. From the data in Table 4.2, this computation yields:

$$O = 1/4[- 702 - 404 - 632 - 402 + 630 + 667.5 + 642 + 600] = 99.9$$

In terms of these same observations the material effect is

$$M = 1/4[- 702 - 404 - 632 + 402 - 630 + 667.5 - 642 + 600] = -133$$

The interaction effect "MO" measures whether a change in O from MiL-L-23699 to Shell 555, produces a different effect when the material is 9310 steel than when the material is M50 steel. The interaction effect is computed as a linear combination of the observed lives in which the coefficient of each life value is the product of the coefficients of that same life value in the M and O effects, i.e.

$$MO = 1/4[+ 702 - 404 + 632 - 402 - 630 + 667.5 - 642 + 600] = 130.9$$

The main effects of the three (3) factors and their two (2) and three (3) way interactions computed in this manner are listed below.

Effect Name	Effect Value
M	-133
F	- 31.9
MF	- 2.88
O	+ 99.9
MO	+130.9
FO	4.12
MFO	- 36.9

Since the experiment was not replicated, there is no independent measure of variability to gauge which, if any, of these effects is real.

The approach taken in these situations (cf. [3]) is to note that, under the assumption that the factors are totally without real effect, the computed effects will be normally distributed random variables with an expected value of zero and will have a common variance. This is so, to a good approximation, even if the individual lives are not normally distributed.

If the computed effects are plotted on probability paper (paper on which normally distributed data plots as a straight line), then significant effects, provided there are just a few, will fall away from this straight line.

Figure 6.1 shows the effects calculated above, plotted on a probability grid, along with two fitted straight lines labelled A and B.

Line A is a reasonable fit to all the data. With respect to line A there are no outliers and hence no significant effects. On the other hand if line B is fitted, the material effect M, the oil effect 0 and the material x oil interaction effect, MO, appear significant.

Line B is fitted to the main effect of finish and all of the interactions involving finish. Line B is consistent with an innocuous finish effect. With the independent measurement of error that could be computed from replicated tests, the uncertainty could be resolved.

As it stands, the data indicate the possible existence of material and oil effects. The effect of a change of oil from MiL-L-23699 to Shell 555 is computed separately below for the two (2) steels.

	9310	M50
Oil Effect:	-31	+230.5

This computation indicates that Shell 555 improves life over MiL-L-23699 for M50 but not for 9310.

The finding is, of course, tentative as discussed above, but warrants further investigation. For completeness, the material effect computed for each oil is also listed below.

	23699	555
Material Effect:	-264	-2.25

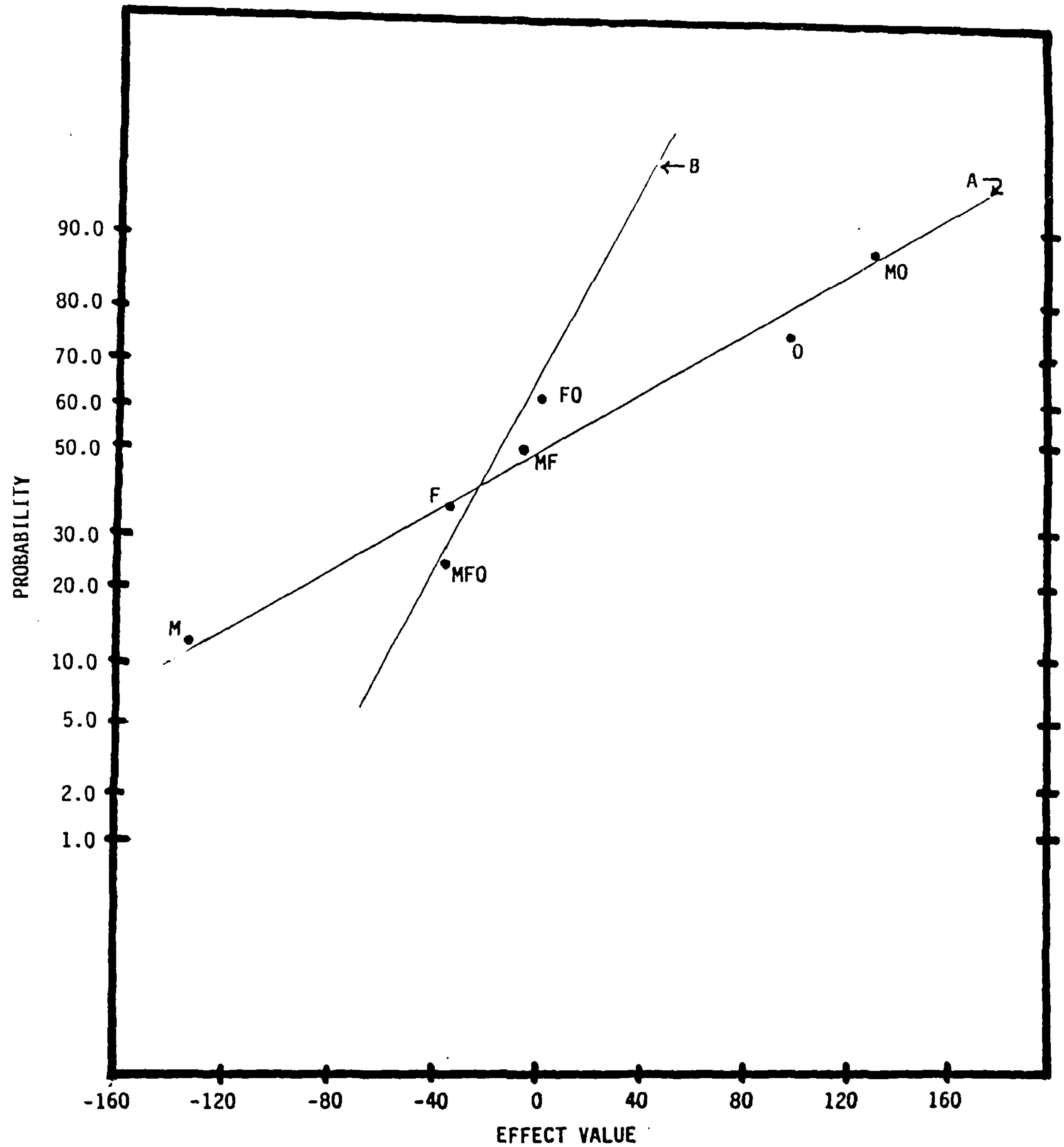


FIGURE 6.1

Data Analysis of Micropitting Test Results

This shows that changing material has negligible effect with Shell 555 but shows a superiority for 9310 steel when MiL-L-23699 is used. As noted in Section 4.0, when the tests were accelerated by increasing the load, three (3) of the 9310 steel tests and only one (1) of the M50 steel tests were affected. Any error in computing the acceleration effect would affect the computed material effects.

7.0 SURFACE FINISH AND MICROCONTACT ANALYSIS OF MICROPITTING SPECIMENS

Surface roughness measurements were made on several specimens of each finish type (tumbled/polished) and material (9310/M50) prior to testing.

The measurements consisted of the RMS profile height R_q and slope Δ_q measured axially and circumferentially at six (6) equispaced angular locations on the surface of each specimen. An as-received (i.e. prior to the polishing or tumbling operations) M50 steel ring was also measured.

The averages of the six (6) readings are listed in Table 7.1.

Comparable axial readings were made after running on all of the specimens that had been tested. Unfortunately, many of the rings measured prior to testing were not actually tested, i.e. they were part of the experiment half that was not run.

The results of the post test roughness measurements are listed in Table 7.2. Comparing the values of axial roughness before and after testing for specimens V11/V12 and V5/V6 indicates that R_q changes little if at all, but that Δ_q invariably decreases with running. With this fact in mind, it is evident that there is considerable specimen-to-specimen variability in the R_q values. Specimens V5/V6, S143/S144, S163/S164 and V8 all have R_q values in the 5-7 μ inch range. The other specimens vary over the 10-16 μ inch range.

TABLE 7.1

Averages of Six Axial and Circumferential Readings of R_q and Δ_q for Micropitting Specimens Prior to Test

SPECIMEN NUMBER	MATERIAL	FINISH	AXIAL R_q(μin)	AXIAL Δ_q(deg)	CIRCUMFERENTIAL R_q(μin)	CIRCUMFERENTIAL Δ_q(deg)
S-151	9310	Tumbled	10.8	1.25	4.42	1.58
S-152	9310	Tumbled	12.0	1.47	3.60	1.55
S-173	9310	Tumbled	12.3	1.67	3.68	1.52
S-174	9310	Tumbled	12.8	1.8	3.97	1.52
V-11	M50	Tumbled	8.67	1.12	2.05	0.430
V-12	M50	Tumbled	10.25	1.60	2.65	0.500
S-169	9310	Polished	14.4	2.17	3.73	0.97
S-170	9310	Polished	13.7	2.23	3.07	0.70
V5	M50	Polished	5.68	1.05	3.43	1.52
V6	M50	Polished	6.10	1.07	3.35	1.53
V7	M50	As-Received	12.0	1.48	4.63	1.53

TABLE 7.2

Averages of Three Axial Readings of Rq and Δq for Micropitting Specimens After Test

SPECIMEN NUMBER	MATERIAL	OIL	FINISH	AXIAL R_q(μin)	AXIAL Δ_q
S159	9310	23699	Tumbled	10.8	1.09
S160	9310	23699	Tumbled	10.8	1.19
S143	9310	555	Tumbled	11.2	0.73
S144	9310	555	Tumbled	16.0	1.11
V11	M50	555	Tumbled	10.5	0.63
V12	M50	555	Tumbled	12.0	0.65
V15	M50	23699	Tumbled	13.8	0.80
V16	M50	23699	Tumbled	12.2	0.72
V5	M50	23699	Polished	5.96	0.70
V6	M50	23699	Polished	5.79	0.51
V7	M50	555	Polished	12.9	1.44
V8	M50	555	Polished	5.4	0.60
S145	9310	23699	Polished	5.60	0.88
S146	9310	23699	Polished	7.47	1.04
S163	9310	555	Polished	5.24	0.62
S164	9310	555	Polished	4.31	0.58

The polished specimens appear to exhibit more variability in R_q than the tumbled specimens, but it is not clear whether this variability existed in specimens prior to polishing. Because the polished specimens are not uniformly distinctly different than the tumbled specimens, the effect of the variable "finish" in the experiments is confounded, i.e. the differences in surface finish level could and presumably must, have an effect on life in the low lubricant film regime, but if the factor called "finish" has comparable roughness values in the two groups that compare the "high" and "low" levels of the factors, no difference will be seen. (It will be recalled that the effect of the factor "finish" on the observed life, computed in Section 6.0, was found to be insignificant).

The roughness data for each disk pair in Table 7.1 were used as input to computer program RUFFIAN. The cross-groove roughness was taken as was done for the cylindrical roller bearings in Section 3.0. The program was run in the mode wherein the plateau lubricant film thickness is computed from the geometry, lubricant properties, and speed and the microcontact parameters are then computed at a separation equal to the computed plateau lubricant film thickness.

The values of m_0, m_2 and m_4 are computed from R_q and Δ_q using the methdology given in [4]. The two lubricants do not differ with respect to the properties (viscosity and pressure viscosity index) which affect computed film thickness. The complete RUFFIAN output is included in Appendix 7. Table 7.3 lists the computed values of the mean real contact pressure (P/A_c), the plastic contact density N_p, the fraction of the contacts that are plastic, N_p/N and the lubricant film parameter h/σ.

TABLE 7.3

Ruffian Output for Unrun Specimens

SPECIMEN NUMBER	MATERIAL	FINISH	P /Ac (ksi)	N_p (in^{-2})	N_p/N	h/σ
S151/152	9310	Tumbled	1175	1.32E7	0.929	0.139
S173/174	9310	Tumbled	1450	1.53E7	0.953	0.125
V11/V12	M50	Tumbled	1110	1.49E7	0.921	0.165
S169/170	9310	Polished	1967	1.86E7	0.973	0.055
V5/V6	M50	Polished	771	1.43E7	0.836	0.265

Compared to the corresponding values in Table 3.5, it is seen that the values of h/σ, N_p/N and P/A_c are comparable for the unrun micropitting specimens and the unrun portions of the field failures. N_p is a higher magnitude for the micropitting specimens.

The last column of Table 7.4 gives the observed life in hours transcribed from Table 4.2. The first question that arises, is: Is there any evident relationship between the observed life and the initial microcontact variables? Since the initial values were only available for two (2) of the tested specimen pairs, this question is moot. To see if the final values relate to the observed life, the plots of Figs. 7.1-7.3 were produced. These show life plotted against mean real stress P/A_c, plastic contact density N_p and film parameter h/σ. No relationship is evident.

Another question is, has the final microgeometry and hence the microcontact variables been influenced by the test variables: materials, finish or lubricants?

To assess this possibility, we compute the factor effects as was done in Section 6.0, but using P/A_c, N_p, and N_p/N in lieu of life as the experimental response. The results are:

TABLE 7.4

Ruffian Output for Tested Specimens

SPECIMEN NOS.	MATERIAL	FINISH	LUBRICANT	P/A_c (KSI)	N_p (in^{-2})	N_p/N	h/σ	LIFE (HRS)
S159/160	9310	Tumbled	23699	1004	1.52E7	0.905	0.145	632
V11/12	M50	Tumbled	555	620	4.06E6	0.753	0.055	600
V15/16	M50	Tumbled	23699	742	4.87E6	0.827	0.121	402
V5/6	M50	Polished	23699	528	7.42E6	0.657	0.657	404
V7/8	M50	Polished	555	808	1.18E7	0.894	0.158	668
143/144	9310	Tumbled	555	912	6.81E6	0.884	0.113	642
146/145	9310	Polished	23699	757	1.27E7	0.830	0.237	702
163/164	9310	Polished	555	486	7.50E6	0.596	0.326	630

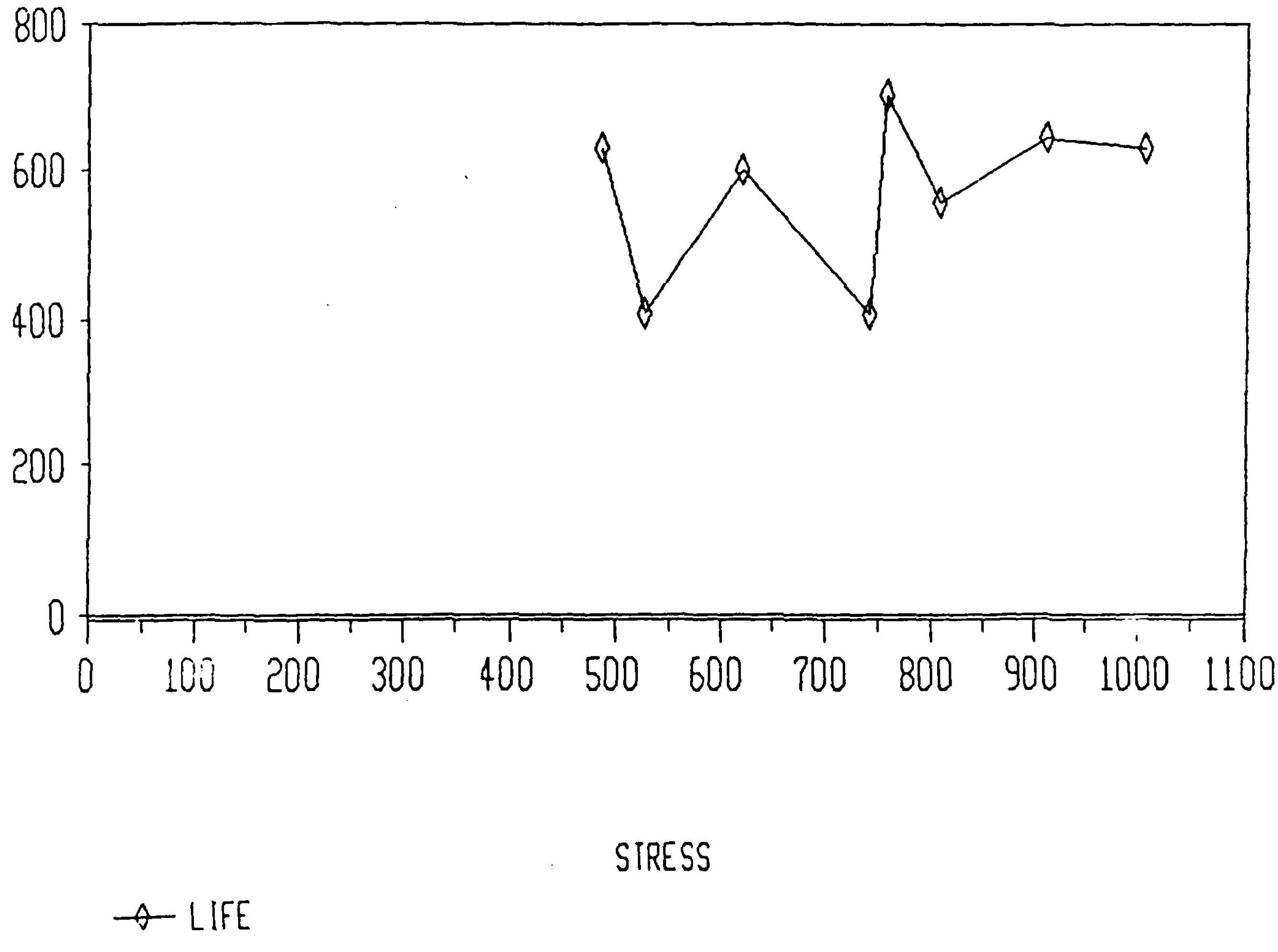


FIGURE 7.1

Geared Roller Life Vs. Mean Real Stress

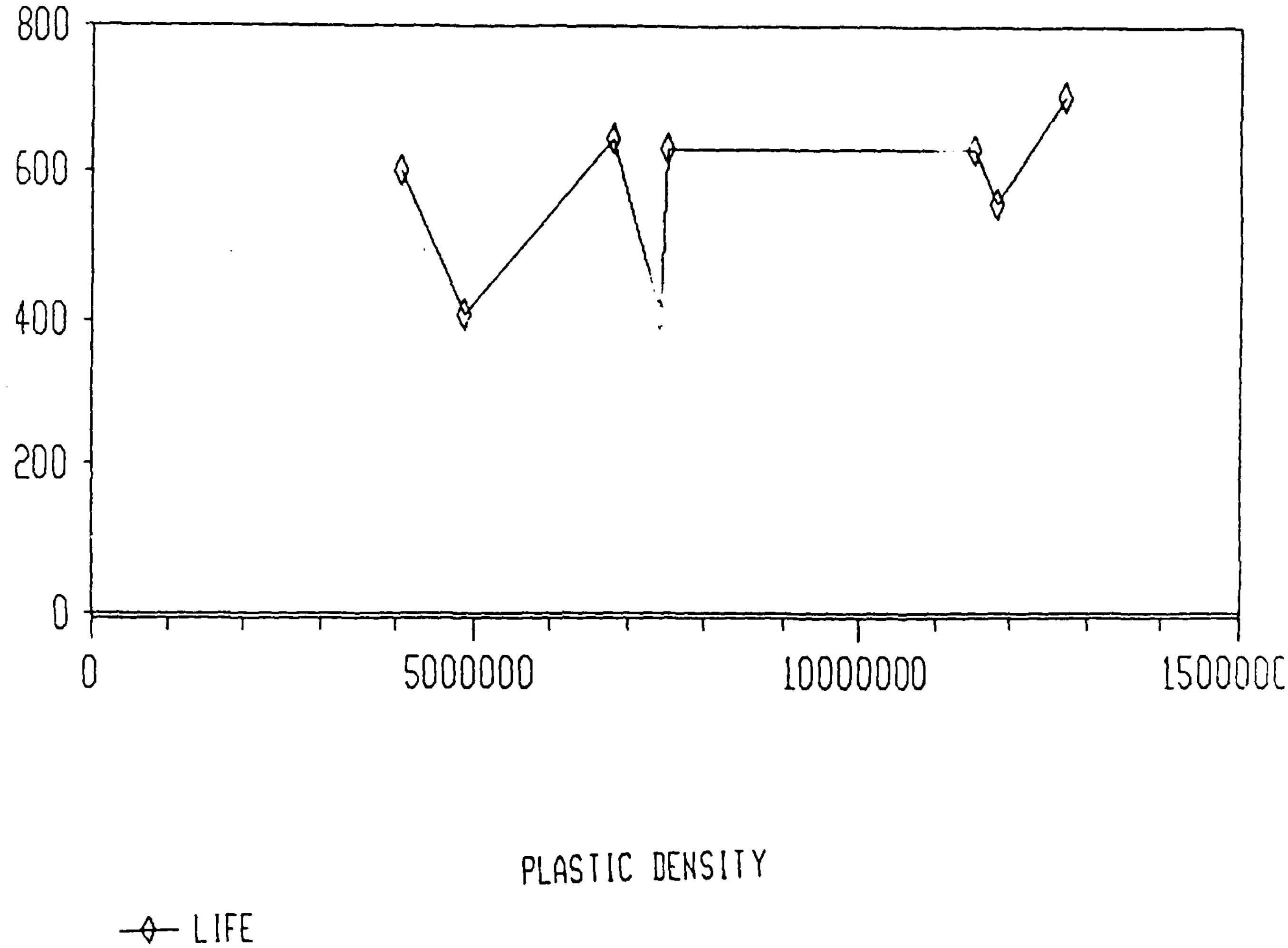


FIGURE 7.2

Geared Roller Life Vs. Plastic Density

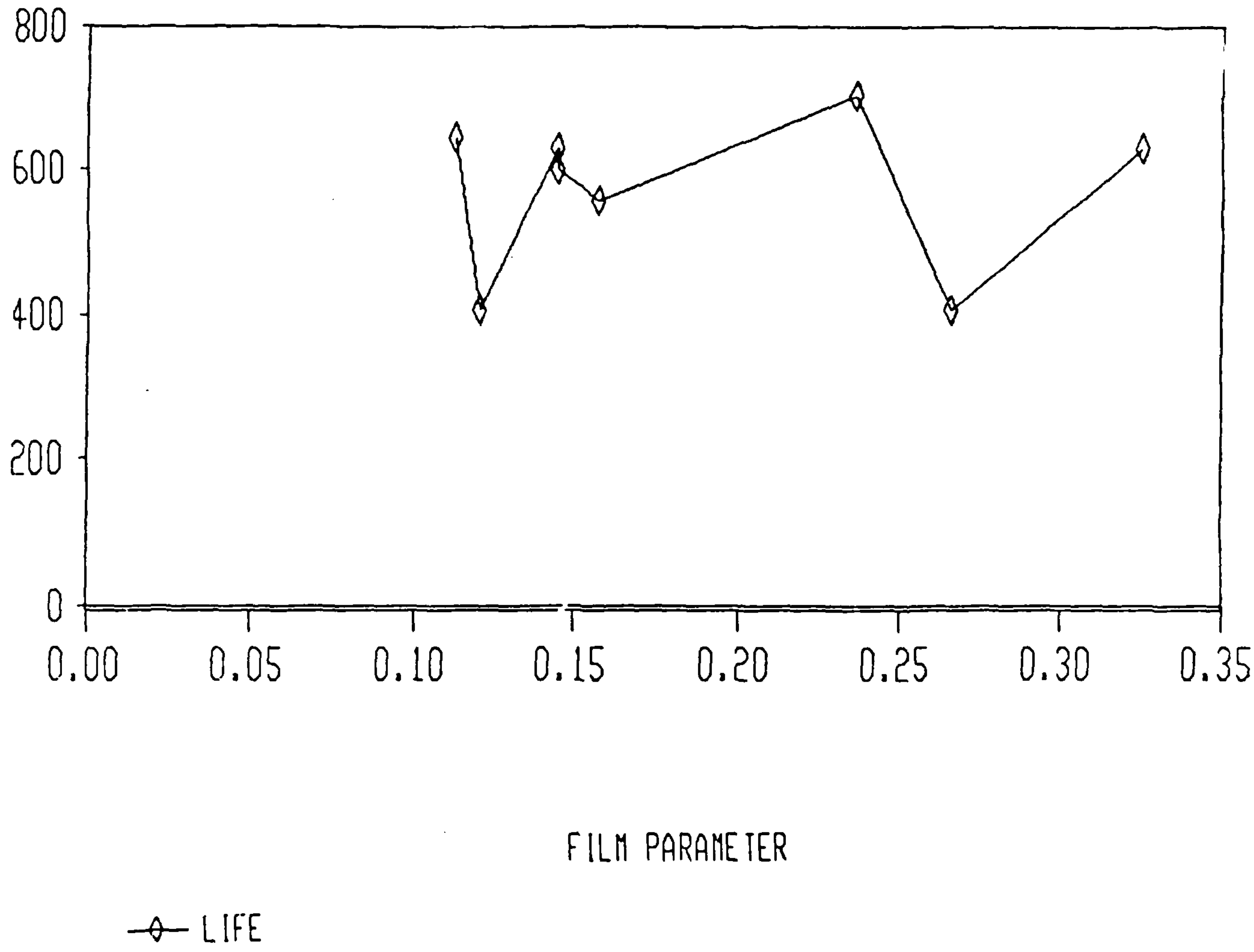


FIGURE 7.3
Geared Roller Life Vs. Film Parameter

Effect	P/A_c	N_p/N	N_p
M	-115.25	-0.021	-2.59
F	+174.75	-0.098	-3.05
MF	-161.75	-0.083	-2.1
O	- 51.25	-0.022	-1.58
MO	+130.25	-0.1045	+3.37
FO	55.75	-0.025	-1.17
MFO	-146.25	-0.131	-1.43

For all three analyses, the MO interaction effect appears large. For P/A_c the finish effect also appears large. With the microcontact variables as the response, the MO interaction cannot be due to an error in the acceleration factor as was the case for life. However, the accelerated tests could have had different final microgeometry by reason of the heavier load.

To better understanu uie MO interaction, the computed material effect is given below separately for each oil as was done for the life response analysis in Section 6.0.

Response Variable	23699	555
P/A_c	-245	+15
N_p/N	-0.126	+ .0835
N_p	-5.96	+ 0.775

Material Effect for each Oil & Three Response Variables

As with the life data, the material effect is negligible with Shell 555 but is significant with MiL-L-23699. Since 9310 steel was arbitrarily taken as the lower and M50 steel as the higher levels of the material factor, the interpretation is that with MiL-L-23699, going from 9310 to M50 steel lowers the values of P/A_c, Np/N and Np. The life analysis suggests that this also lowers the life. Although one would normally think that lower P/A_c, N_p/N and N_p values would increase the life, it must be recalled that these are computed from post test microgeometry. Thus, both lowered life and lowered microcontact values could be explained by an inadvertent overload in the M50 steel tests run with MiL-L-23699 or some unusual corrosion condition which caused early pitting and altered microgeometry.

8.0 DISCUSSION AND RECOMMENDATIONS

This investigation has made it clear that producing wholesale micropitting even at low lubricant film conditions is not easily achieved, particularly with the modest amounts of sliding present in ball and roller bearings. Although the test specimens did eventually develop pits after long periods of running and then only with increased loading, it is believed that these pits are more related to contamination damage and corrosion then to the form of surface distress found in the field failures.

It is clear that the process of running alters the surface slope, but not to any great degree its RMS values. The final microgeometry has characteristically lower predicted asperity pressures and plastic microcontacts as determined by using its final microgeometry as input to a microcontact model. Sufficiently gentle run-in processes could therefore be of benefit in developing surfaces resistant to micropitting.

The surface finish differences produced by polishing and tumbling were insufficiently distinct to produce a clear effect of this factor. It is recommended that, in future tests, steps be taken to assure distinct differences between differently finished groups and high uniformity within the groups.

Suspension of half the tests due to the long running times had two (2) unfortunate consequences: 1) there was no independent error measurement against which to judge the effects of the test variables and their interactions and 2) there were too few tests for which pretest surface data were available. It is recommended that the remaining experiment replicate be run as time permits.

The data suggested an intriguing interaction effect between steel and oil that could be resolved by running the remaining specimens. The data suggested that the life was lower for the M50 specimens lubricated with Mil-L-23699 lubricant, but that the material did not matter for the specimens lubricated with Shell 555. Independently, the microcontact data suggested that the variables P/A_c (mean real contact pressure) N_p, (number of plastic contacts) and N_p/N (plastic contact fraction) were lower for the M50 tests lubricated with Mil-L-23699. An accidental overload affecting just the M50 steel/ MiL-L-23699 lubricant tests could explain both these findings as could a source of contamination or corrosion damage that affected just these tests. It is, in any case, an important indication that is worth further effort to confirm or disprove.

REFERENCES

1. W.J. Crecelius, SHABERTH User's Manual for SKF Computer Program "SHABERTH", Steady State and Transient Thermal Analysis of a Shaft Bearing System Including Ball, Cylindrical and Tapered Roller Bearings, February 20, 1978, SKF Report No. AL77P015.

2. McCool, J.I. and Gassel, S.S., "The Contact of Two Surfaces Having Anisotropic Roughness Geometry," ASLE Special Publication SP-7, pp. 29-38, 1981.

3. Box, G., Hunter, W., and Hunter, J., Statistics for Experimenters, J. Wiley & Sons, New York, 1978.

4. McCool, J.I., "Relating Profile Instrument Measurements to the Functional Performance of Rough Surfaces," ASME Transactions, Journal of Tribology, Vol. 9, No. 2, pp. 264-270, April 1987.

APPENDIX A

SKF LETTER REPORT TO AT83M003L

"FAILED M-50 ALLOY HELICOPTER ROTOR BEARING"

LETTER REPORT

TO: J. McCool

REPORT NO: AT83M003L
PROJECT CODE: L0914
DATE: January 5, 1983
FROM: A. S. DiGiorgio
COPIES TO: J. Phinney
F. Morrison
G. Baile
Laboratory
Library

TITLE: Failed M-50 Alloy Helicopter Rotor Bearing

REFERENCE: Lab No. 1497

A helicopter rotor bearing, manufactured by a competitor, was examined to identify the cause for premature failure. The bearing is a single row, split inner ring ball bearing type, identified M6062, S/N 180-1 which functioned under loads varying from 250 Ksi to 440 Ksi at approximately 300 RPM.

Visual observations showed two ball tracks on the outer ring and one on each split inner ring. One inner displayed a track midway in the raceway that was estimated to be 50% of the raceway surface area. This is indicative of a relatively heavy load in thrust. The second ball track is located on the mating inner ring near the bottom. This ball track area is approximately 10% of the raceway surface, indicating that the load is lighter and primarily radial. Observations related above suggest a change in operating conditions. Both ball tracks were evident over 360° on both the outer ring and inner ring complement. Apparently, the bearing was preloaded.

Binocular microscope examination showed that the ball tracks were highly burnished. The split inner ring displaying the heavier load contained a circumferential microspall band in the center of the load zone. Randomly scattered macroscopic spalls were also observed. The other inner ring section exhibited no spalls. Initial microspall patterns were evident within the wider ball track in the outer ring. Here again, both ball tracks were glazed. Fragment dents were observed on all raceways. Refer to Figures 1 and 2.

The split inner ring sustaining the lower load displayed adhesive wear 360° around the bottom half of the side face. Seized particles were evident, probably resulting by sliding contact against another metallic component during operation (see Figure 3).

Scanning electron microscope (SEM) examination of both inner rings clearly showed generalized surface distress caused by the interaction of the rolling elements on the rings surfaces. Spalls were also apparent. Regions across the raceway were photographed to show the changing surface conditions ranging from unaltered grinding furrows to the cold worked surface. Also, silver particles were randomly embedded in the ball track. See Figures 4 through 11.

An inner ring specimen was prepared for microstructural and material cleanliness evaluation. Martensite needle size was fine with no soft constituents and carbide distribution was normal, rated N-1 and 3A, respectively. The material was typical of M50 alloy CVM quality containing scattered sulfide and alumina inclusions rated $<1/2$. Ring hardnesses were Rc 60.5-61 which is consistent with SKF practices. No metallurgical abnormalities were observed and consequently, bearing failure was not considered to be materials related.

The raceway surface conditions described earlier are characteristic of bearings functioning in an inadequate lubricating environment. If a serviceable elastohydrodynamic film had been formed during operation, raceway surfaces would not have cold worked and spalled. Observations regarding two ball paths suggest that there is a change in operating conditions. The narrower load zone would no doubt have been generated by lighter loads. Yet, it too was glazed. Surface characteristics indicate that with current operating conditions, assuming an ample volume of lubricant was available, the lubricant is not capable of forming a suitable load carrying film. The adhesive wear condition may have been a secondary effect, but it should be noted that it will produce debris that could affect bearing life.

A. S. DiGiorgio

ASD/jt
Attachments

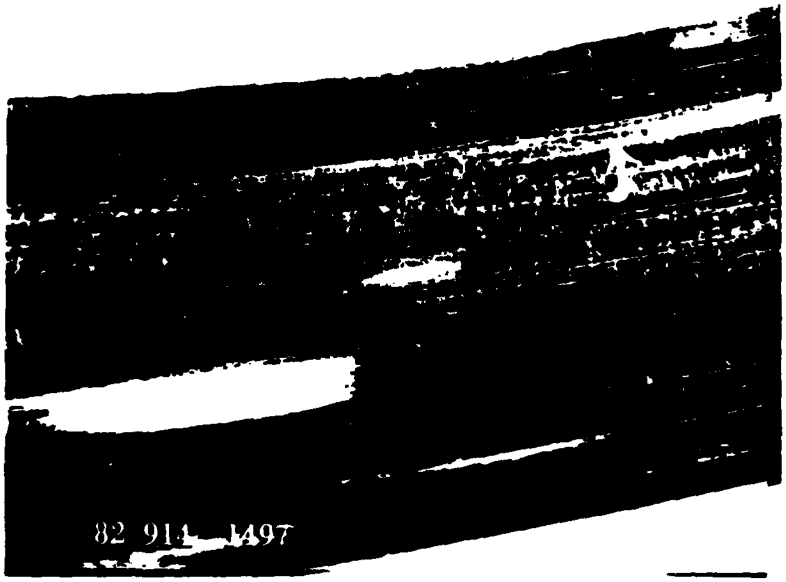


Figure A-1 Outer ring raceway displaying microspall pattern developing in the heavier load zone (arrow). The narrower burnished band below is the lighter ball path. Mag.: 4X

Figure A-2 Inner ring half that sustained the heavier load showing the circumferential microspall band (arrow) and macroscopic spalls. Mag.: 5X

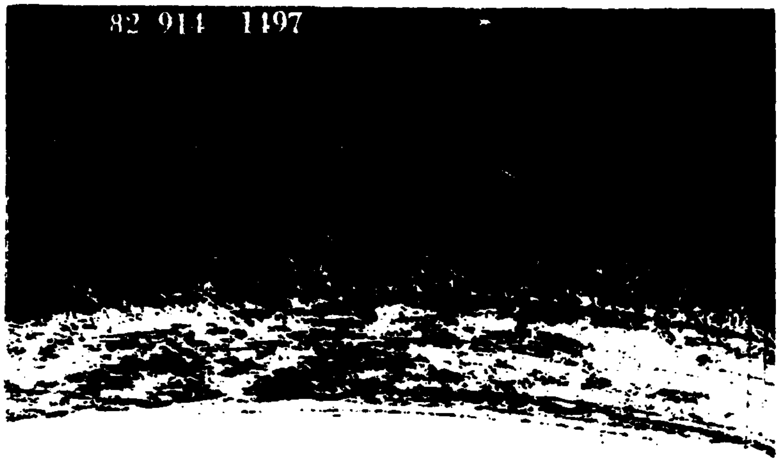


Figure A-3 Inner ring side face displaying seized metallic particles due to adhesion. Mag.: 5X

Figure A-4 Raceway of inner ring section sustaining heavier load. Surface finish near the land showing unaffected grinding furrows. Mag.: 1000X

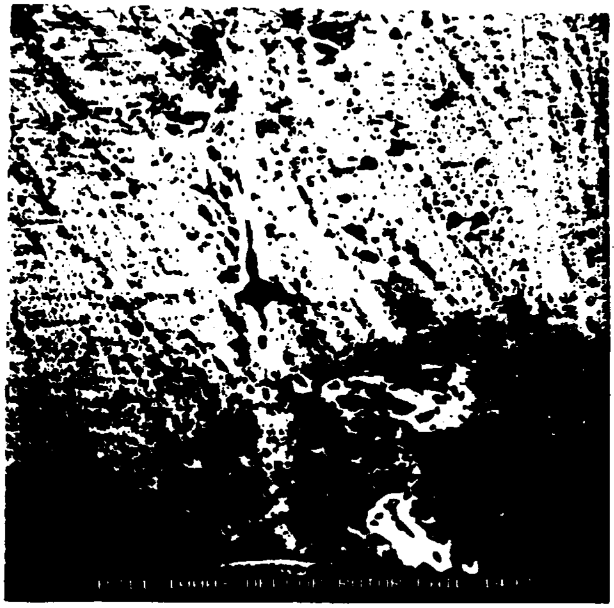


Figure A-5 Same as Figure 4. Surface finish in the load zone just below area in figure showing that grinding furrows have been obliterated. Microcracks are evident eminating from microspalls. The black features are oil residue. Mag.: 1000X

Figure A-6 Same as Figure 4. Spalls and microcracks are more prominent near the center of the load zone. Mag.: 1000X

Figure A-7 Same as Figure 4. Surface finish near the opposite edge of the load zone showing remnants of grinding furrows. White particles on surface identified as silver (shown in the Figure 8). Magn.: 1000X

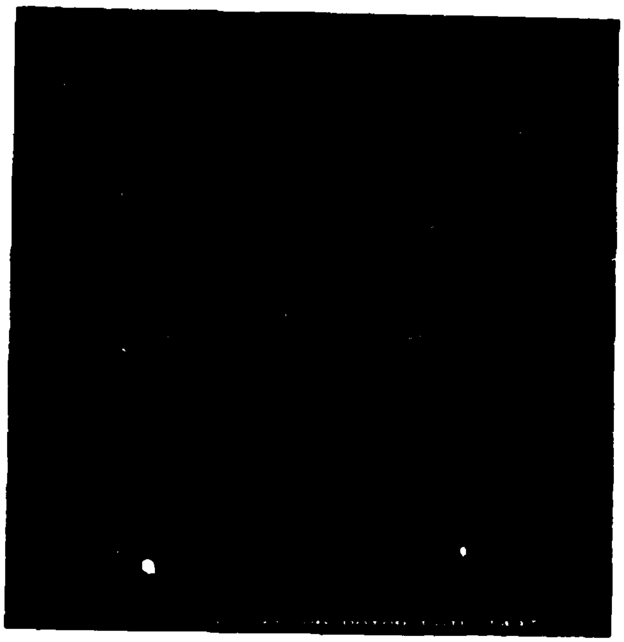


Figure A-8 SEM microprobe displays x-ray map showing silver concentrations. Mag.: 1000X

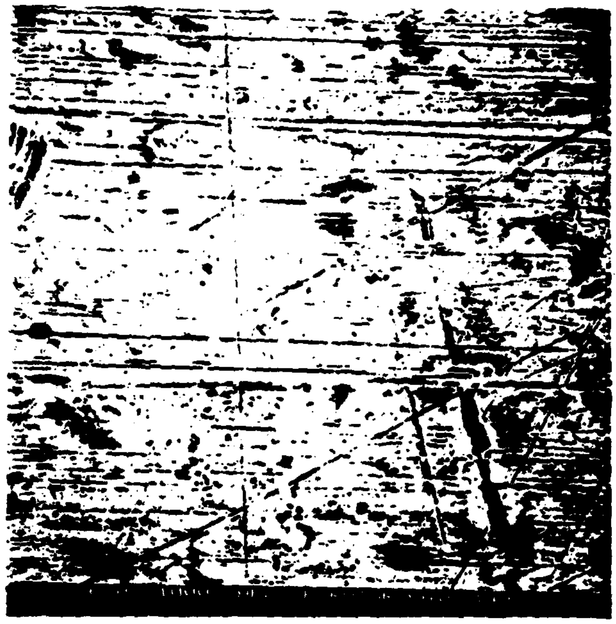


Figure A-9 Area just bordering the edge of the ball track toward the center of the ring. More grinding furrows are in evidence. Mag.: 1000X

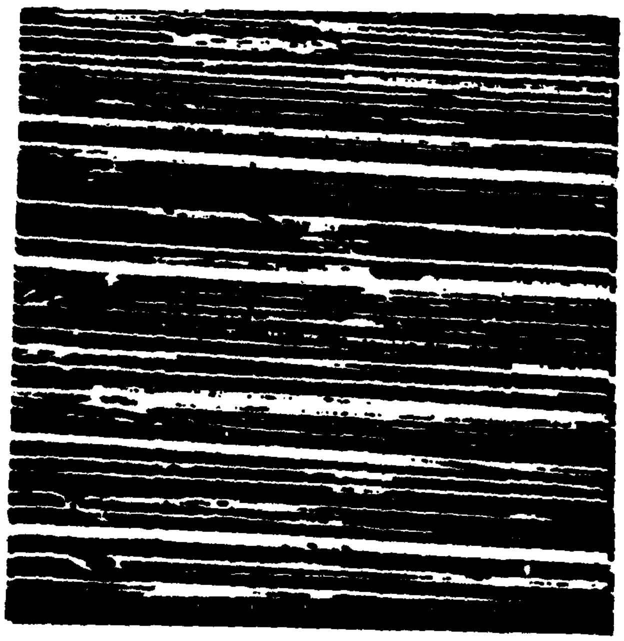


Figure A-10 Raceway of the inner ring sustaining the light load. Surface finish near the land contains unaffected grinding furrows. Mag.: 1000X

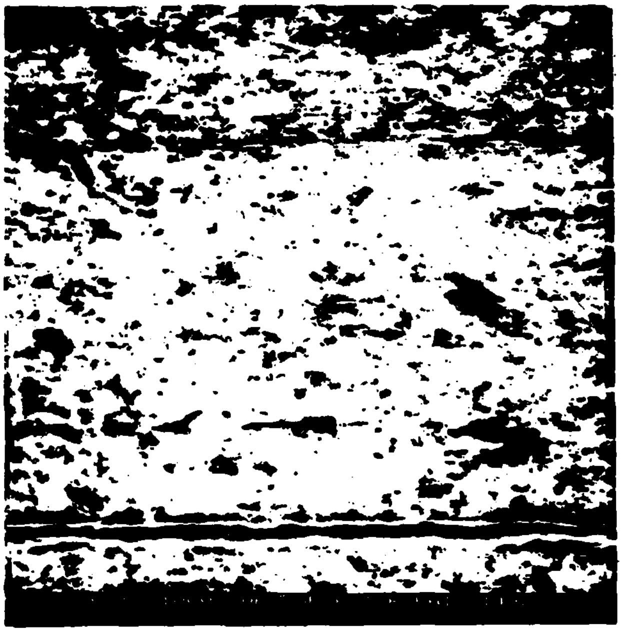


Figure A-11 *Same as Figure 10.* Surface finish within the load zone showing that most of the grinding furrows have been obliterated. Mag.: 1000X

APPENDIX B

"METALLURGICAL EXAMINATION OF FAILED

PLANETARY BEARINGS"

LETTER REPORT

TO: Jack McCool

REPORT NO: AT84M002L
PROJECT CODE: LC744
DATE: 1/10/84
FROM: G. H. Baile
COPIES TO: A. S. DiGiorgio
F. R. Morrison
J. M. Phinney
Laboratory

TITLE: Failed Helicopter Transmission Bearings

REFERENCE: Lab. No. 2401

Two inner rings from the same size helicopter planetary transmission bearings were examined to determine cause of failure. These bearings are double row cylindrical roller bearings identified as Rollway SG2405-4 S/N 6065 and McGill SB2405-4-R S/N 3922. Both had been in service for an unspecified length of time and had subsequently been determined to be unfit for reworking and are thus classed as scrap.

Visual and binocular observations of inner ring S/N 3922 revealed one damaged area about 10 x 15 mm on the roller path adjacent to the larger extended flange. Visually, this area which is glazed and pulled, appears as though the surface were locally frosted. However, higher magnification reveals extensive incipient spalling which obliterates most finishing lines. There is also evidence of very small incipient spalls scattered throughout the loaded portion of the roller path. The other roller path adjacent to the short flange side is similar, but the concentrated patch of incipient spalling is slightly smaller (10 x 12 mm). Also, the scattered spalls throughout the remainder of the load zone are not as numerous. Figure 1 illustrates the condition of this ring.

Similar observations on inner ring S/N 6065 revealed a significantly higher degree of surface degradation. Both roller paths exhibit a 360° contact zone. In addition, each has a zone extending about 200° in which the area is frosted with extensive incipient spalling. There is, however, a narrow (about 1-2 mm) band in the center of each roller path which exhibits very little evidence of roller contact. A typical example of these roller paths are shown in Figure 2. It was also observed that the roller paths on this ring appears to have been formed and finished by "hard turning" with a single point tool rather than the conventional hard grinding and honing and/or polishing historically found in this type of bearing ring.

Scanning Electron Microscope (SEM) examination of the roller paths of both inner rings was conducted. The surface of S/N 3922 shows wide spread and generalized surface distress typical of rather heavy interaction of the surface asperities on the rings and rolling elements As shown in Figures 3 and 4 many of the fine finishing lines have been obliterated by a cold working of the surface leaving only the heavier finishing lines still visible. This condition is evident both at a distance from the highly distressed area as typified by Figure 3 as well as in the load zone typified by Figure 4. It can also be seen within the distressed area the surface is virtually covered with small superficial spalls. This is typical of a surface which has been operating under very marginal lubrication conditions.

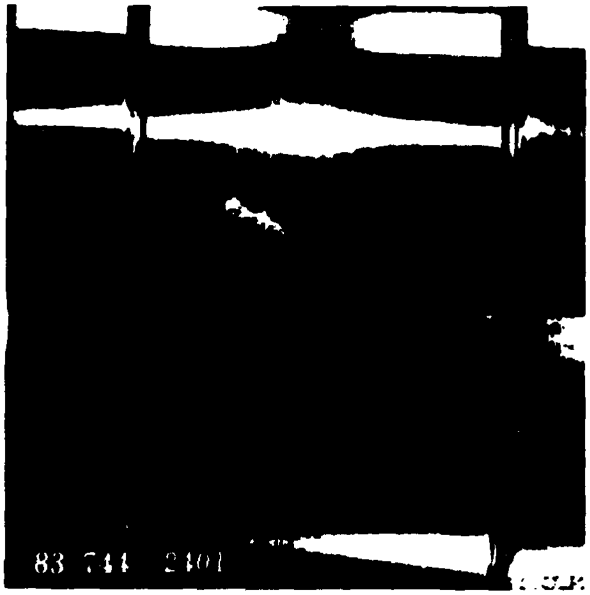
SEM evaluation of ring S/N 6065 reveals a similar pattern of surface distress outside the load zone and heavy plastic deformation and shallow spalling within the load zone. Figures 5 and 6 show such typical areas.

As noted previously, the rolling path surface of this ring apparently was finished by hard turning. Figure 7 illustrates the surface characteristics at 50 magnification. From this it is seen that the surface is characterized by long parallel grooves. In fact, a single individual groove can be traced 360° around the ring in a tight spiral indicating the finish was generated by a single point tool. It should also be noted from Figure 6 that most of the shallow spalls are concentrated upon the ridges of these spiral grooves. In as much as the comparative use cycles and lives of the two bearings are not available, no judgement can be made as to the effects of two types of surface finish on the useful life of the bearing.

G. H. Baile

GHB/jt
Attachments

F 4186A



2X

Figure B-1

Light Micrograph of Typical Distressed Area of Double Row Cylindrical Inner Ring S/N 3922

0.7X

Figure B-2a

View of Distressed Area on Double Row Cylindrical Inner Ring S/N 6065. Arrow Indicates Start of Distressed Area.

2X

Figure B-2b

Higher Magnification View of Start of Distressed Area on Double Row Cylindrical Inner Ring S/N 6065.

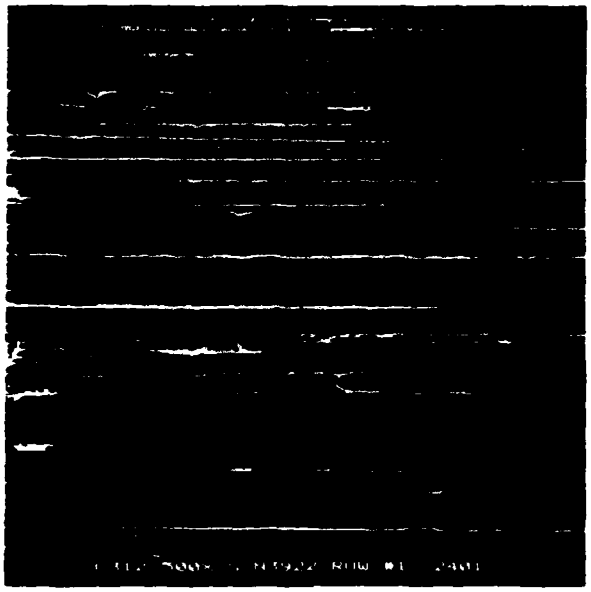


Figure B-3

SEM Photograph of Inner Ring Rolling Path
S/N 3922 Away From Distressed Area Showing
Occasional Lack of Surface Asperities.

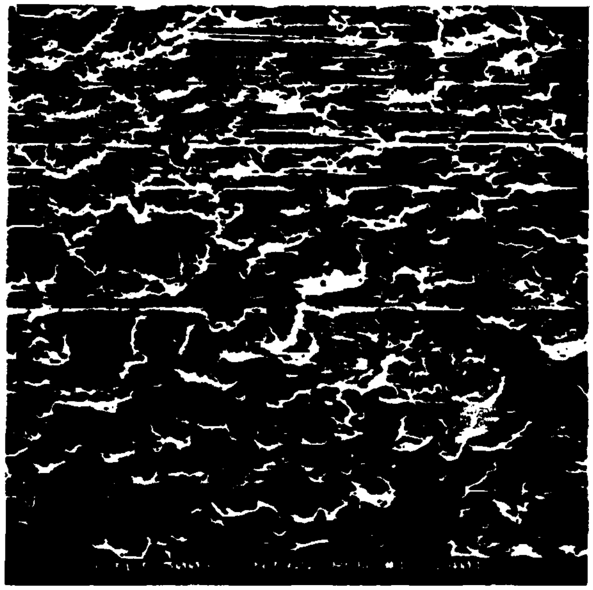


Figure B-4

SEM Photograph of Inner Ring Rolling Path (S/N 3922) In Distressed Area Showing Widespread Shallow Spalling and the Generally Worn Condition of the Surface.

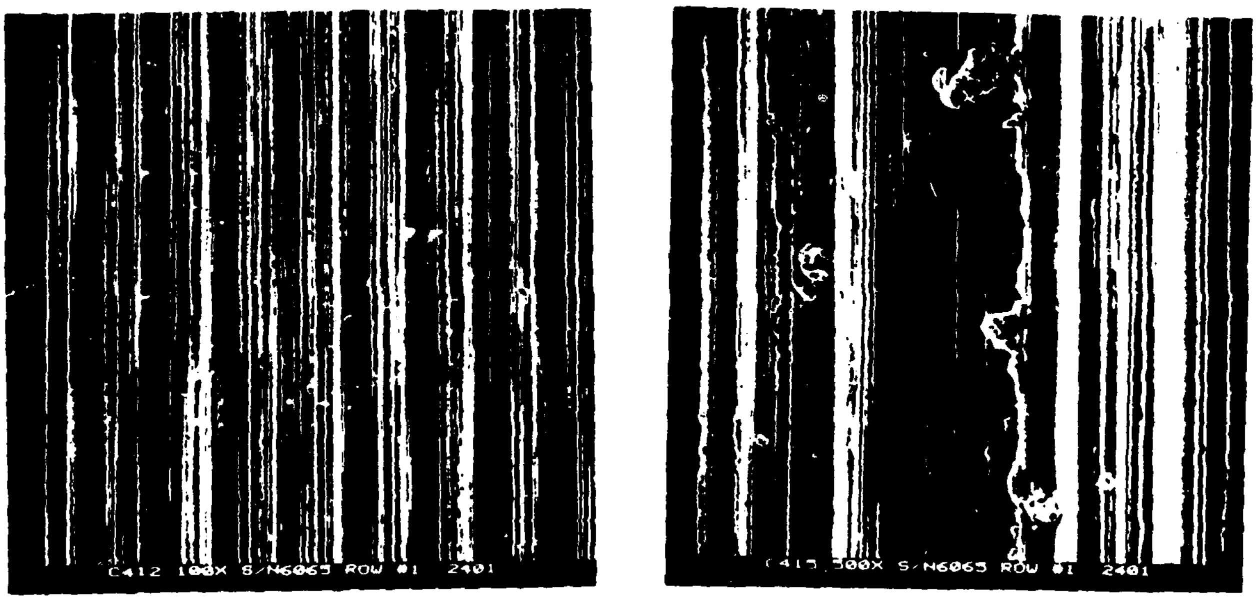


Figure B-5

SEM Photograph at Two Magnifications of Inner Ring Rolling Path (S/N [illegible]5) Away From Distressed Area Showing Occasional Small Spall and Slightly Deformed Surface Material.

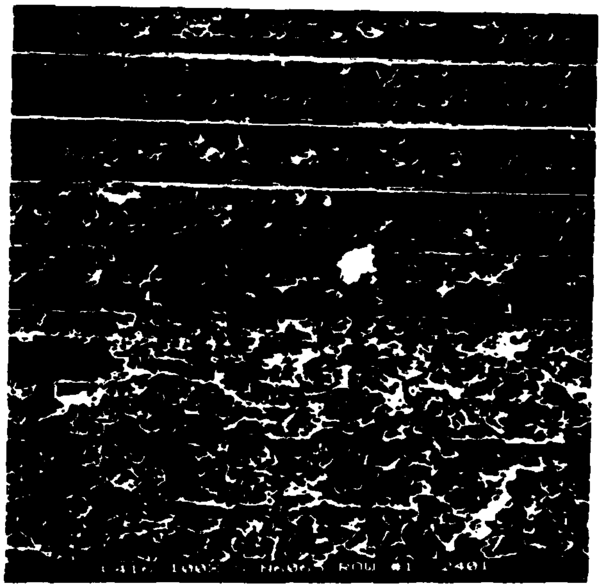
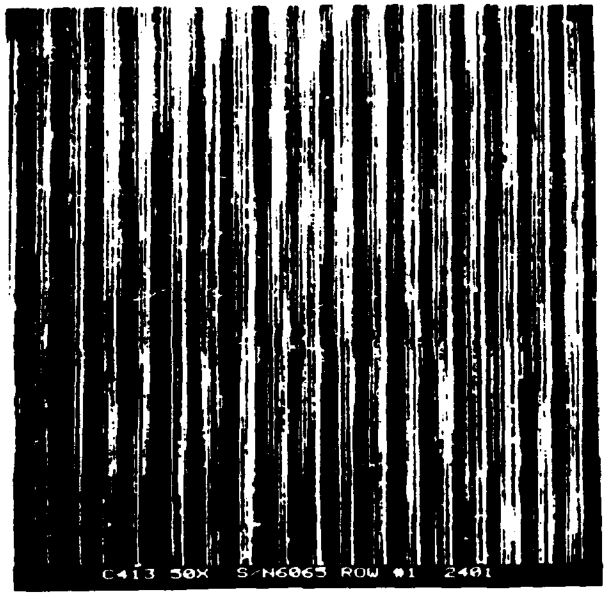


Figure B-6

SEM Photograph of Inner Ring Rolling Path (S/N 6065) In Distressed Area Showing Extensive Shallow Spalls and Plastic Working of the Surface.



Figur_ 5-7

SEM Photograph of Inner Ring Rolling Path (S/N 6065)
Showing Spiral Grooves Formed by Hard Turning

APPENDIX C

"DESCRIPTION OF THE LSI/11 ROUGHNESS

DATA PROCESSING SYSTEM"

SURFACE DATA PROCESSING

Data Acquisition System

Figure 1 is a schematic representation of the data acquisition system to be used in this investigation. At the heart of the system is the Talysurf 4 surface profile measurement device. In operation, the Talysurf 4 causes a contacting stylus to move across the surface of interest and a voltage proportional to the stylus' excursions is produced. In the conventional mode of operation this voltage is filtered and used in a computation of the CLA average value of the roughness. In the present application the unfiltered voltage is fed into an amplifier and then into the A/D converter that operates in conjunction with a Digital Equipment Corporation PDP 11/03. In order to minimize electrical noise problems, the lowest possible stylus traverse velocity of 0.000466 in/sec is used to assure that the roughness signals correspond to frequencies well below 60 Hz.

Data Acquisition Software and Calibration

The data is acquired and stored on a floppy disc under the control of a computer program entitled "GETAD".

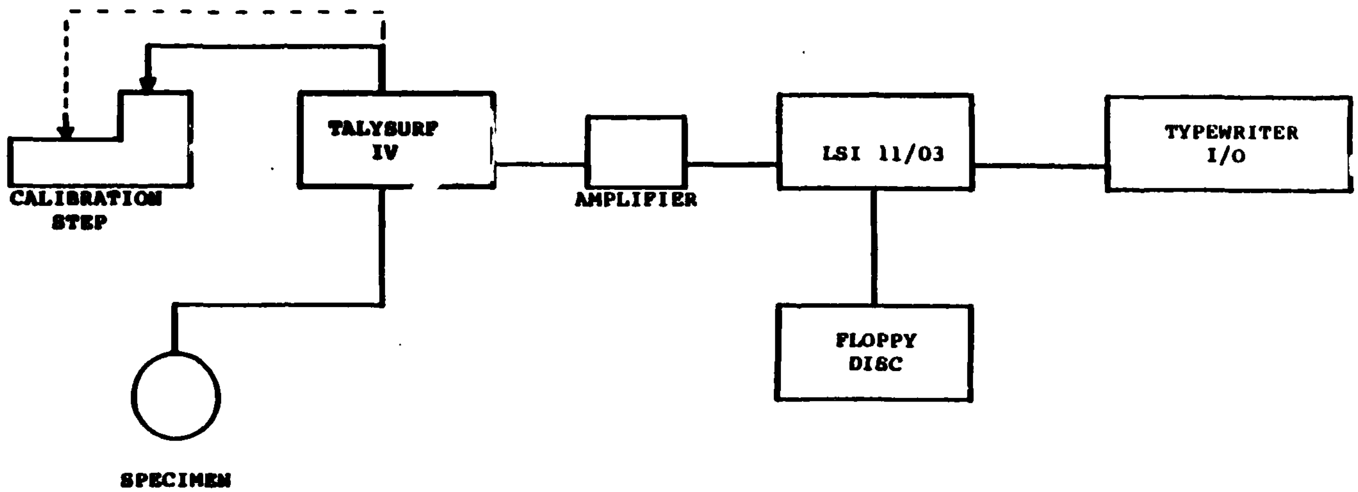


Figure C-1 ROUGHNESS DATA ACQUISITION SYSTEM

A system typewriter controls the input/output operations (I/O). Prior to the acquisition of data a calibration constant is computed that relates, for the magnification setting at which the Talysurf is being used, the number of digitized integer values of the signal to the surface displacement. In performing the calibration constant determination, the user is directed under the control of the program GETAD to place the stylus in contact with the lower level of a calibration step. This step consists of two Johansson blocks. The stylus remains in steady contact with the lower of the pair of blocks until 200 digitized values are read. The user is then directed to place the stylus in contact with the higher level of the pair of blocks and an additional 200 digitized values are read. The program then averages the digitized values corresponding to the lower and higher levels of the step and asks the user to supply the actual height difference of the pair of blocks that comprise the step. The step height is then divided by the difference between the average digitized height values to yield the number of linear units (microinches) corresponding to a unit charge in the digitized value of the surface. This ratio is termed the calibration factor.

The calibration factor and a user specified 6 digit file name are stored in a "header" block preceding the digitized profile data. The user of the system specifies the total number of points to be digitized and the frequency with which the points are to be taken. These two values together determine the total length of trace.

Processing Software

The digitized profile data is re-read from the disc and processed by means of another program called "PRODOE". PRODOE reads the header information including the calibration factor and calculates the grand average of the digitized values. It then computes the distance, in digitized units, of each data point from the grand mean and scales it, by means of the calibration factor, into length equivalent units. The mean square surface height (m_0), the mean square slope (m_2) and the mean squared value of the second derivative of the surface (m_4) are computed. m_4 is, to a good approximation, the mean square curvature of the surface.

PRODOE performs an editing function to remove outliers in the data record. For this purpose it uses either a user specified criterion or a computed criterion, being a multiple of the RMS value of the unfiltered surface to determine whether the difference between successive pairs of values could be real. If the criterion is exceeded, the second value is equated to the first. The system reports the number of such replacements that took place.

The user specifies a frequency band f_1 and f_2 in units of cycles per linear distance and the data are then digitally filtered using a cascaded Butterworth filtering scheme described.

PRODOE then computes the values of m_0 and m_2 and m_4 using the filtered signal. It also compiles a histogram of the surface height distribution using a sub-sample of 300 points.

APPENDIX D

"EVALUATION OF THE LSI/11 ROUGHNESS

DATA PROCESSING SYSTEM"

LETTER REPORT

TO: L. D. Wedeven

REPORT NO: AT84D020L
PROJECT CODE: KPC744
DATE: 2 April 1984
FROM: J. I. McCool
COPIES TO: F. Morrison, B. Rhoads

TITLE: EVALUATION OF THE LSI/11 ROUGHNESS DATA PROCESSING SYSTEM

REFERENCE:

We have used a National Bureau of Standards precision diamond turned sinusoidal specimen to evaluate the LSI/11 computerized system for roughness data acquisition and processing. The sinewave used for this evaluation had a CLA value of 1 μm or 40 μin. and a period of 100 μm or 4000 μin. This surface was traced using the Talydata 1000 at a tracing speed of 0.00233 in/sec. This corresponds to a horizontal magnification of 100.

As part of the calibration procedure used within the data acquisition routine of the LSI/11 system, the stylus was first used to trace a step of 118 μin height. The digitized values of the two levels of the step were then equated to 118 μin within the program to derive a calibration factor of .0527 μin per digitized unit. The nominal calibration is computed knowing that at the vertical magnification used, (X10000) the full range of the Talysurf output corresponds to 200 μin. Dividing 200 μin by 4096 the full scale of the digitized values, gives a constant of .0488 μm per division.

At the tracing speed used, the sinewave frequency is .6 cycles/sec. The sampling frequency specified to the LSI/11 program was 6 cycles/sec. so that there were 10 samples taken per period of the sinusoidal surface. A total of 600 digitized values were taken corresponding to 60 periods or roughly 60 x .004 in. = .24 in. total profile length, typical of the total tracing length used in our production evaluations. The table below shows the measured values of the spectral moments m_0, m_2 and m_4 obtained with the LSI/11. Also shown are the theoreti al values of m_0, m_2 and m_4 based upon the nominal amplitude and frequency of the sinusoidal specimen. Finally, the values of m_0 and m_2 are computed from the ordinary Talydata output are shown. (The Talydata output does not include m_4 at this time).

	MEASURED LSI/11	(NOMINAL) THEORETICAL	TALYDATA
m_0	2297	1971.4	$1831.8 = (R_q)^2$
m_2	6.13E-3	4.87E-3	$5.37E\text{-}3 = [180/\pi\Delta_q]^2$
m_4	1.77E-8	1.20E-8	N/A

It is seen that there is an essential agreement regarding orders of magnitude with the LSI/11 values being higher than both the theoretical and the Talydata values. If one equates the value of m_0 measured on the LSI/11 and the theoretical value of m_0 it is possible to compute a modified calibration factor. Interestingly the computed value of this factor is 0.0488, the same as the nominal calibration. Using this factor as the calibration, and adjusting the LSI/11 values of m_2 and m_4 gives:

$m_2 = 5.26E\text{-}3$ $m_4 = 1.52E\text{-}8$

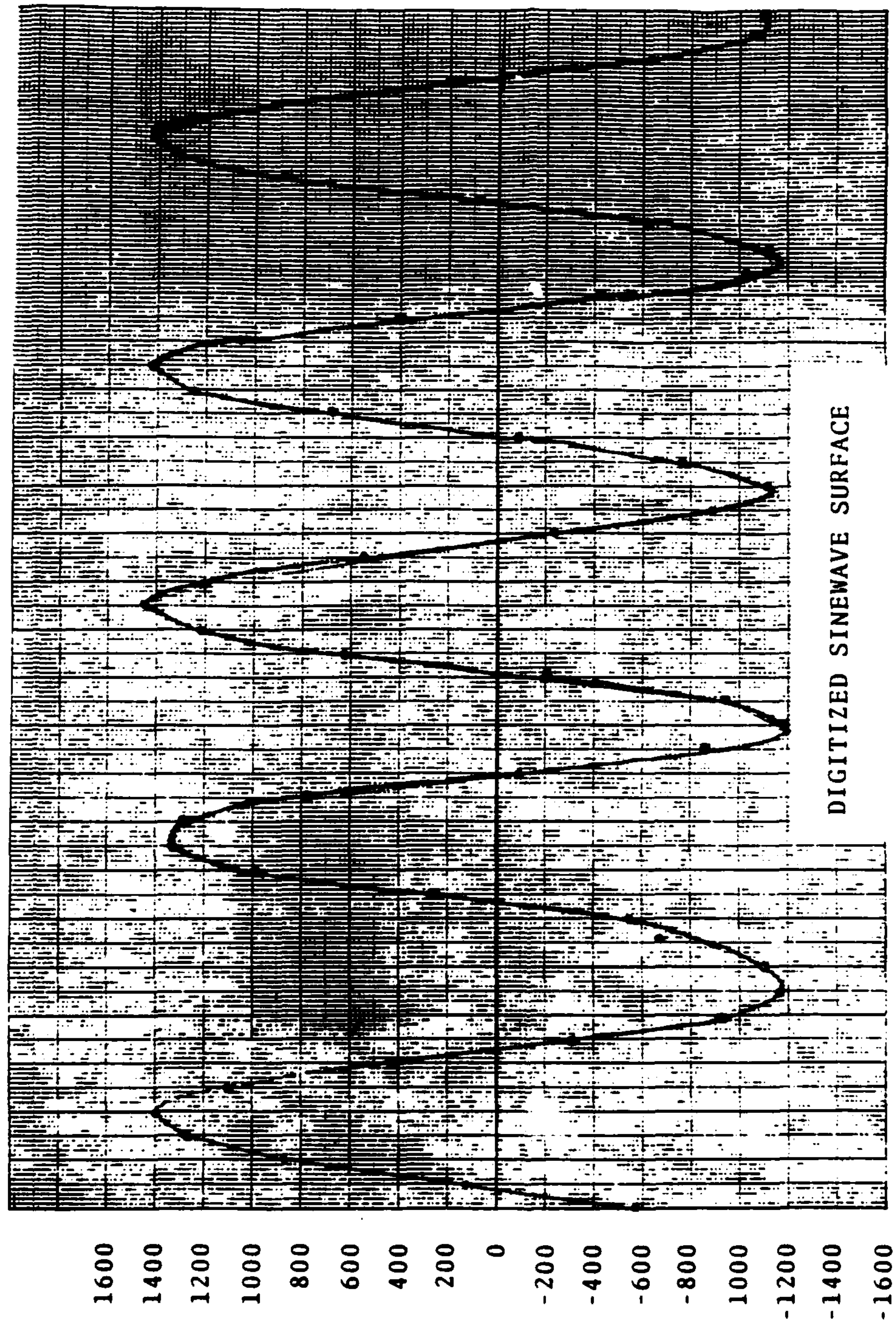
It is seen that the m_2 value thus adjusted is in good agreement with the Talydata value. The m_4 value remains higher than the theoretical m_4 value calculated based on the nominal amplitude and frequency. This amount of disagreement could, however, easily be due as much to the inaccuracy of the NBS specimen as to an error in processing. It is concluded that overall, the system is accurate but the use of the NBS sinewave specimen for calibration is probably preferable to using a step.

Figure 1 attached shows a plot of the digitized input to the LSI/11 with a freehand sketch connecting the points. Although some small inaccuracies are evident, the overall appearance is adequately sinusoidal and the sampling rate of 10 points per period seems exact.

John I. McCool

JIM/amh

REPORT NO: AT84D020L
CODE: KPC744
PAGE: 4



DIGITIZED SINEWAVE SURFACE

Figure D-1

APPENDIX E

"MICROCONTACT ANALYSIS OUTPUT FOR FIELD FAILURES"

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: ANGULAR CONTACT MAST BALL BEARING

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.00000 (MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.00000 (MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.18008 (MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.00000 (RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.00000 (RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.03701 (RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200 (MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000 (MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05 (N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000 (N/MM^2)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	1.91318 (NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	3.24300E-02 (MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	1.37000E-03 (NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	8.74000E-04 (MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	15.10140 (NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.10458 (MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	1.95402E+04 (MM^-2)
SUMMIT RADIUS	R =	2.24770E-02 (MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	1.74654E-01 (MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: ANGULAR CONTACT MAST BALL BEARING

EXPLANATION OF SYMBOLS

****

H = SEPARATION OF SURFACE MEAN PLANES (MUM)

SIG = STANDARD DEVIATION OF SURFACE HTS. (MUM)

N = CONTACT DENSITY (CONTACTS/MM^2)

AC/AO = REAL CONTACT AREA FRACTION

P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)

P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)

NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)

AP/AO = AREA FRACTION OF PLASTIC CONTACTS

H/SIG	N	NP	NP/N	AC/AO	AP/AO	AP/AC	P/AO	P/AC
2.62000E-01	1.22983E+04	1.01305E+04	8.23731E-01	1.39576E-01	1.80081E+01	1.29020E+02	7.87245E+02	5.64027E+03
3.62000E-01	1.15181E+04	9.32664E+03	8.09736E-01	1.25052E-01	1.24014E-01	9.91701E-01	6.60398E+02	5.28098E+03

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: CYLINDRICAL ROLLER BEARING FOR PLANETARY TRANSMISSION S/N 3922

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.00000	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.00000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.19875	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.00000	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.00000	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.05831	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	1.69747	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	3.95000E-02	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	3.40000E-03	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.66000E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	5.67215	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.18833	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	1.49544E+04	(MM^-2)
SUMMIT RADIUS	R =	1.63095E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	1.82359E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: CYLINDRICAL ROLLER BEARING FOR PLANETARY TRANSMISSION S/N 3922

EXPLANATION OF SYMBOLS
****

H = SEPARATION OF SURFACE MEAN PLANES (MUM)
SIG = STANDARD DEVIATION OF SURFACE HTS. (MUM)
N = CONTACT DENSITY (CONTACTS/MM^2)
AC/AO = REAL CONTACT AREA FRACTION
P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)
P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)
NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)
AP/AO = AREA FRACTION OF PLASTIC CONTACTS

H/SIG	N	NP	NP/N	AC/AO	AP/AO	AP/AC	P/AO	P/AC
6.10000E-02	1.27323E+04	1.17747E+04	9.24786E-01	1.47979E-01	1.85628E+02	1.25442E+03	1.62281E+03	1.09665E+04
7.10000E-02	1.26799E+04	1.17203E+04	9.24321E-01	1.46777E-01	1.77751E+02	1.21102E+03	1.59295E+03	1.08528E+04

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: CYLINDRICAL ROLLER BEARING FOR PLANETARY TRANSMISSION S/N 6065

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.00000 (MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.00000 (MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.57735 (MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.00000 (RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.00000 (RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.14107 (RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200 (MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000 (MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05 (N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000 (N/MM^2)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	1.80930 (NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	3.33330E-01 (MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	1.99000E-02 (NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	7.71000E-03 (MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	6.48967 (NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.51146 (MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	1.18670E+04 (MM^-2)
SUMMIT RADIUS	R =	7.56777E-03 (MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	5.35973E-01 (MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: CYLINDRICAL ROLLER BEARING FOR PLANETARY TRANSMISSION S/N 6065

EXPLANATION OF SYMBOLS
****

H = SEPARATION OF SURFACE MEAN PLANES (MUM)
SIG = STANDARD DEVIATION OF SURFACE HTS. (MUM)
N = CONTACT DENSITY (CONTACTS/MM^2)
AC/AO = REAL CONTACT AREA FRACTION
P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)
P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)
NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)
AP/AO = AREA FRACTION OF PLASTIC CONTACTS

H/SIG	N	NP	NP/N	AC/AO	AP/AO	AP/AC	P/AO	P/AC
2.10000E-02	9.97144E+03	9.85259E+03	9.88081E-01	1.55930E-01	3.37875E+02	2.16684E+03	4.16700E+03	2.67235E+04
3.10000E-02	9.93018E+03	9.81116E+03	9.88015E-01	1.54551E-01	3.23700E+02	2.09445E+03	4.09121E+03	2.64715E+04

APPENDIX F

"FAILURE ANALYSIS OF GEARED ROLLER TEST SPECIMENS FROM INITIAL TESTS"

MATERIALS SECTION RESULTS REPORT

TO: J. I. McCool

LABORATORY NO.: 4496

PROJECT CODE: LC744

TITLE: Characterization of Surface Condition on Geared Roller Test Specimens, S181 and S182

DATE: 11/21/85

FROM: R. E. Maurer

REFERENCE:

COPIES TO: A. DiGiorgio
W. Ferguson
D. Wensing
Laboratory

Data Requested:

Identify the nature of the micro-characteristics on the contact tracks of a mating pair of geared roller specimens.

Results:

The contact surfaces of specimens S181 and S182 were examined via scanning electron microscopy. All surface indications appeared to be associated with debris denting. No indications of mircopitting were observed.

The most frequently observed denting feature is typified in Figure 1 (a). This feature is characterized by a smooth-bottomed, circular impression at one end, with a "tail" of roughened material extending from one side. The "tails" are oriented at an angle of 40° from the circumferential direction. The surrounding region was heavily stippled. Figure 1 (b) is a higher magnification view of the circular region in Figure 1 (a). Figures 1 (c) and 1 (d) are higher magnification views of the stippled patch in the lower left corner of Figure 1 (a).

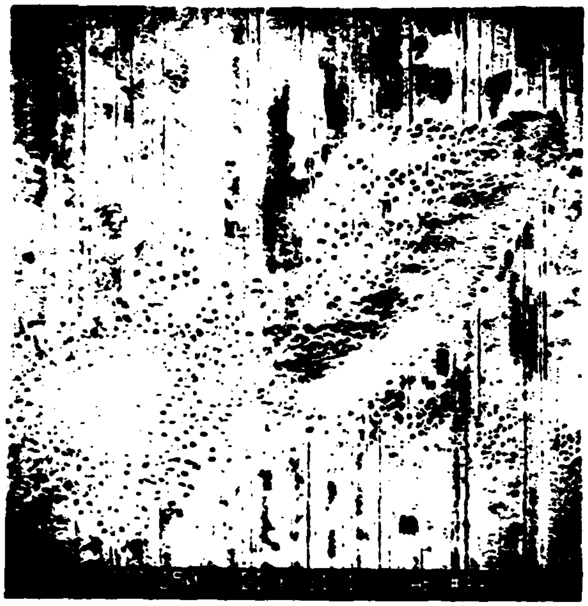
Figure 2 (a) shows another example of the characteristic denting on S181, and Figure 2 (b) shows a similar manifestation on S182.

Figure 3 contains SEM micrographs of another frequently observed characteristic on these specimens. These appear to be regions in which a very shallow surface layer has been removed. The appearance is very similar to that resulting from acid etching.

Figure 4 (a) is an SEM micrograph of a region very close to the edge of S181. Circular regions similar to those in Figure 3 are indicated. Figure 4 (b) is a region on S181 closer to the center of the contact surface showing adherent, nonmetallic material that remained through specimen cleaning prior to examination. It appears that this material may have been associated with both the stippled appearance [top of center in 4 (b)] and the smooth circular regions [just below center in 4 (b)].

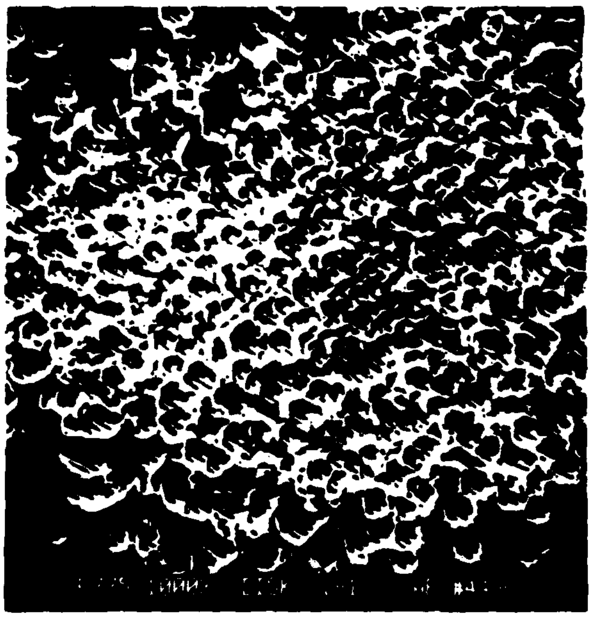
This material, which was not identified, may have participated chemically in the formation of the surface characteristics shown in Figure 3 and 4 (b).

Figure 5 shows curiously arranged patterns of stippled dents, as well as larger debris dents on S182.



1 (a)

1 (b) Circular Region in 1 (a)

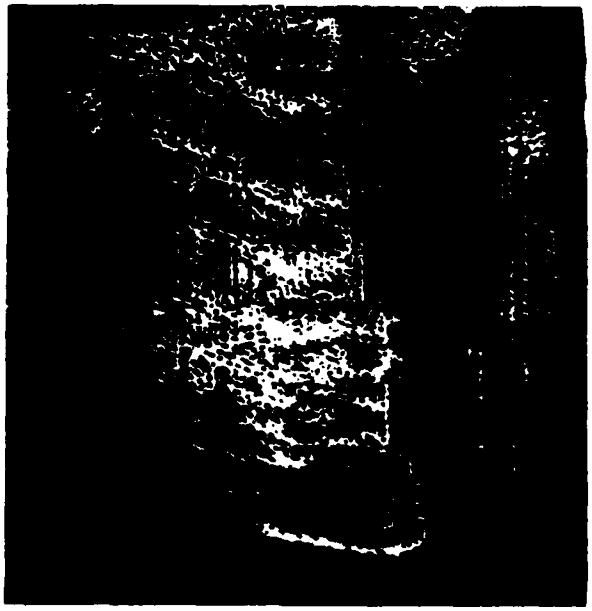


1 (c) Stippled Patch in Lower Left Corner of 1 (a)

1 (d) Higher Magnification of 1 (c)

Figure F-1
Most Frequent Debris Denting Manifestation

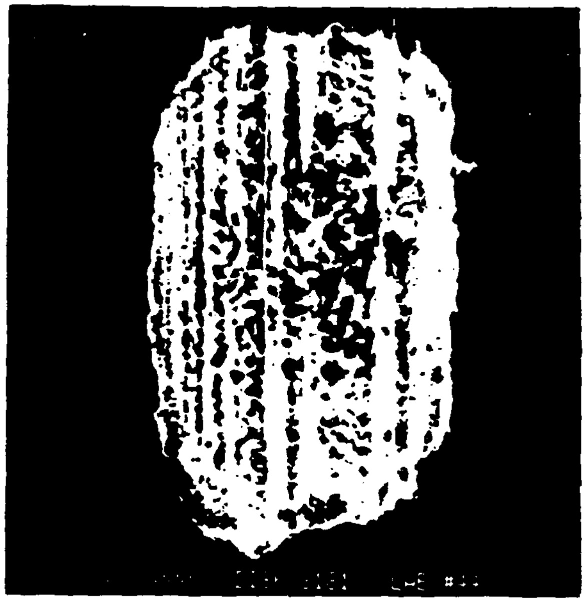
2 (a)



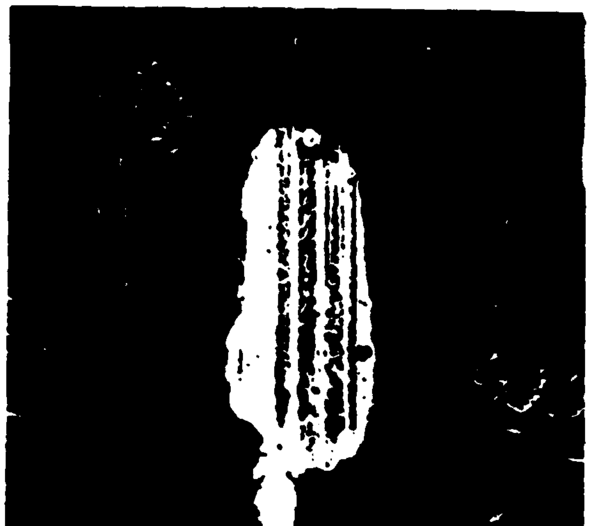
2 (b)

Figure F-2
Additional Examples of Most Frequent Debris Denting Manifestations

3 (a)

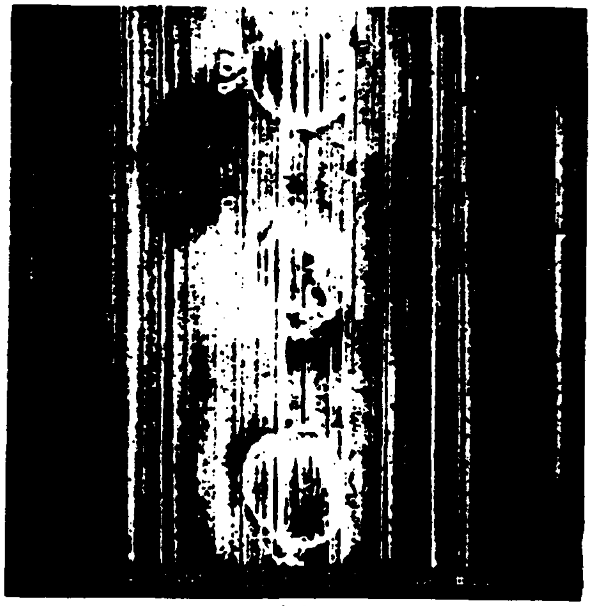


3 (b) Higher Magnification of Region in 3 (a)

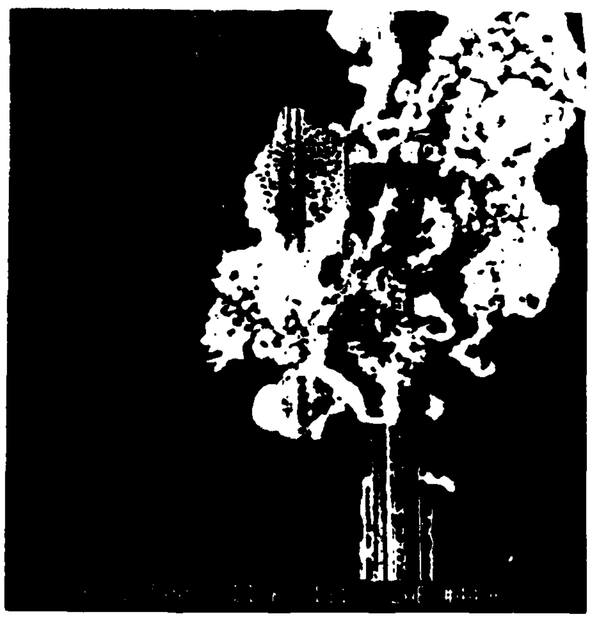


3 (c) Higher Magnification of Region in 1 (a)

Figure F-3
Localized Removal of Shalow Surface Layer Appearing Similar to Acid Etching



4 (a)



4 (b) Adherent Nonmetallic Material on Surface of S181. Possible Association with Stippled Dents and Circular Regions in 4 (a)

Figure F-4

Circular Indication and Possible Association with Nonmetallic Contaminant

5 (a)

5 (b)

Figure F-5
Irregularly Shaped Arrays of Stippled Dents

APPENDIX G

"RUFFIAN OUTPUT FOR MICROPITTING SPECIMENS"

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S151/152,9310,TUMBLED,UNRUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.27000	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.30000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.40361	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.02180	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.02570	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.03370	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.46309	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.62900E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	1.13573E-03	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.61217E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	203.60190	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.06383	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.34785E+04	(MM^-2)
SUMMIT RADIUS	R =	1.65497E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	4.02719E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S151/152,9310,TUMBLED,UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.13724E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.20965E-01
AC/A0	REAL CONTACT AREA FRACTION	.38440E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.31155E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.81048E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.22103E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.20539E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.37808E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.92924E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.98357E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.10724E+05
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.19688E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.87555E+04
AC	REAL CONTACT AREA (MM^2)	.13232E+01

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S173/174, 9310, TUMBLED, UNRUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.30800	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.32000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.44414	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.02910	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.03140	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.04281	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35550E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.37141	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.97264E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	1.83277E-03	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	2.87146E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	168.62990	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.07719	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.79881E+04	(MM^-2)
SUMMIT RADIUS	R =	1.24006E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	4.42962E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S173/174, 9310, TUMBLED, UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24414E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40622E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26972E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66399E+01	
CONTACT ELLIPSE AREA	AREA =	.34422E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29320E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60697E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.12471E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.49204E-01
AC/A0	REAL CONTACT AREA FRACTION	.35899E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.36029E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.10036E+05
N	CONTACT DENSITY (CONTACTS/MM^2)	.24936E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.23760E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.36197E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.95281E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.10083E+01
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.12402E+05
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.24409E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.99609E+04
AC	REAL CONTACT AREA (MM^2)	.12357E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V11/V12, M50, TUMBLED,UNRUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.21700	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.25600	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.33560	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01950	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.02790	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.03404	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.33955	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.12625E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	1.15866E-03	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.87332E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	157.15700	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.06041	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.95215E+04	(MM^-2)
SUMMIT RADIUS	R =	1.53529E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	3.34638E-01	(MUM)

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V11/V12, M50, TUMBLED,UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMAO =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.16505E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.15008E-01
AC/A0	REAL CONTACT AREA FRACTION	.33568E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.25627E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.76344E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.25057E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.23070E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.32798E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.92067E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.97707E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.88214E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.10805E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.77409E+04
AC	REAL CONTACT AREA (MM^2)	.11555E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S169/170, 9310, POLISHED, UNRUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.36000	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.34300	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.49724	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.04710	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.03890	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.06109	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.22169	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	2.47249E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	3.73162E-03	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	6.71123E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	119.16320	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.10280	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	5.50863E+04	(MM^-2)
SUMMIT RADIUS	R =	8.11136E-03	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	4.95367E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S169/170, 9310, POLISHED, UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMAO =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.11140E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.95698E-01
AC/A0	REAL CONTACT AREA FRACTION	.31541E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.42819E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.13575E+05
N	CONTACT DENSITY (CONTACTS/MM^2)	.29646E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.28857E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.54747E+02
NP/N	FRACTION OF PLASTIC CONTACTS	.97340E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.17357E+03
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.14739E+05
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.28819E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.11858E+05
AC	REAL CONTACT AREA (MM^2)	.10857E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V5/6, M50, POLISHED, UNRUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.14200	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.15300	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.20874	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01830	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01870	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.02616	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.20951	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	4.35730E-02	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	6.84580E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.24365E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	115.62950	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.04381	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	5.56434E+04	(MM^-2)
SUMMIT RADIUS	R =	1.88428E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	2.07930E-01	(MUM)

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V5/6, M50, POLISHED, UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.26536E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.55705E-01
AC/A0	REAL CONTACT AREA FRACTION	.26060E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.13851E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.53150E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.26585E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.22231E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.24661E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.83621E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.94633E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.47678E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	.21752E+03
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.49853E+04
AC	REAL CONTACT AREA (MM^2)	.89706E+00

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S159/160, 9310, 23699, TUMBLED

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.27000	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.27000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.38184	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.02080	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01900	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.02817	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.54475	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.45800E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	7.93640E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.02112E-03	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	236.36810	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.05605	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	3.94088E+04	(MM^-2)
SUMMIT RADIUS	R =	2.07949E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	3.81113E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S159/160, 9310, 23699, TUMBLED

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.14507E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.17259E-02
AC/A0	REAL CONTACT AREA FRACTION	.40719E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.28201E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.69257E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.19732E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	[illegible]7853E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	[illegible]
NP/N	FRACTION OF PLASTIC CONTACTS	.90479E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.96414E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.97075E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.16715E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.80360E+04
AC	REAL CONTACT AREA (MM^2)	.14017E+01

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V11/12,M50, 555, TUMBLED, RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.26300	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.30000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.39896	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01100	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01130	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.01577	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	3.03246	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.59169E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	2.48690E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	1.38092E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	355.39300	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.04776	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	1.70078E+04	(MM^-2)
SUMMIT RADIUS	R =	5.65473E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	3.98456E-01	(MUM)

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V11/12,M50, 555, TUMBLED, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.13884E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.19154E-01
AC/A0	REAL CONTACT AREA FRACTION	.48444E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.20705E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.42741E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.83739E+04
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.63010E+04
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.43963E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.75246E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.90750E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.71274E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.73870E+03
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.63887E+04
AC	REAL CONTACT AREA (MM^2)	.16676E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V15/16, M50,23699, TUMBLED, RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.34500	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.30500	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.46049	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01400	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01260	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.01884	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	3.00013	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	2.12050E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	3.54760E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	2.11397E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	356.17860	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.05506	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	1.82517E+04	(MM^-2)
SUMMIT RADIUS	R =	4.57031E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	4.59909E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V15/16, M50,23699, TUMBLED, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.12029E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.71123E-03
AC/A0	REAL CONTACT AREA FRACTION	.49887E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.25562E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.51240E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.91207E+04
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.75453E+04
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.46591E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.82728E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.93395E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.87990E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.15946E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.72044E+04
AC	REAL CONTACT AREA (MM^2)	.17172E+01

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V5/6, M50, 23699, POLISHED

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.14900	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.14500	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.20791	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01220	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.00890	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.01510	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.55528	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	4.32260E-02	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	2.28050E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	2.89501E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	240.62220	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.03025	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	3.88829E+04	(MM^-2)
SUMMIT RADIUS	R =	3.90544E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	2.07521E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V5/6, M50, 23699, POLISHED

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.26642E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.12116E+00
AC/A0	REAL CONTACT AREA FRACTION	.34077E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.12427E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.36466E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.17566E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.11533E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.30235E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.65656E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.88726E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.42776E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	.45149E+03
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.47291E+04
AC	REAL CONTACT AREA (MM^2)	.11730E+01

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V7/8, M50, 555, POLISHED,RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.32300	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.13500	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.35008	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.02510	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01050	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.02721	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.51014	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	1.22554E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	7.40260E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	9.94038E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	222.31160	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.05299	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.11299E+04	(MM^-2)
SUMMIT RADIUS	R =	2.10763E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	3.49370E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: V7/8, M50, 555, POLISHED,RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.15823E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.68827E-02
AC/A0	REAL CONTACT AREA FRACTION	.39012E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.25629E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.65694E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.20452E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.18287E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.37455E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.89413E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.96009E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.88220E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.12560E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.75660E+04
AC	REAL CONTACT AREA (MM^2)	.13429E+01

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S143/144, 9310, 555, TUMBLED, RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.28000	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.40000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.48826	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01270	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01937	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.02316	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED

------- -- ----- ----- ---

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.87027	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	2.38400E-01	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	5.36487E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	4.15259E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	343.95890	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.05941	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	2.37082E+04	(MM^-2)
SUMMIT RADIUS	R =	3.26089E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	4.87625E-01	(MUM)

DOE - ECUT

<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S143/144, 9310, 555, TUMBLED, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMAO =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAUO =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	ZO =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.11345E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	-.82482E-02
AC/AO	REAL CONTACT AREA FRACTION	.49436E+00
P/AO	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.31091E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.62892E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.11932E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.10548E+05
AP/AO	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.47430E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.88400E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.95943E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.10702E+05
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	-.25211E+04
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.81812E+04
AC	REAL CONTACT AREA (MM^2)	.17017E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S146/145, 9310, 23699, POLISHED, RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.18700	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.14000	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.23360	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01820	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01540	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.02384	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.33568	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	5.45690E-02	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	5.68400E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	9.22459E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	155.80620	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.04223	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.97086E+04	(MM^-2)
SUMMIT RADIUS	R =	2.18787E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	2.32927E-01	(MUM)

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S146/145, 9310, 23699, POLISHED, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.23712E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.56486E-01
AC/A0	REAL CONTACT AREA FRACTION	.30245E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.15787E+04
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.52198E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.23734E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.19706E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.28563E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.83026E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.94438E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.54344E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	.50852E+02
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.54852E+04
AC	REAL CONTACT AREA (MM^2)	.10411E+01

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S163/164, 9310, 555, POLISHED, RUN

INPUT DATA:

ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 1	RQ1 =	.13100	(MUM)
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2	RQ2 =	.10800	(MUM)
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT	RQ =	.16978	(MUM)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1	DELQ1 =	.01080	(RADIANS)
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2	DELQ2 =	.01010	(RADIANS)
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE	DELQ =	.01479	(RADIANS)
LOWER FREQUENCY LIMIT	F1 =	.00200	(MUM^-1)
UPPER FREQUENCY LIMIT	F2 =	.40000	(MUM^-1)
MODIFIED ELASTIC MODULUS	EPRIME =	1.11785E+05	(N/MM^2)
TENSILE YIELD STRENGTH	Y =	2070.0000	(N/MM^2)

CONTACT ANALYSIS INPUT DATA:

RADIUS OF CURVATURE OF BODY 1 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 1 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
RADIUS OF CURVATURE OF BODY 2 - ROLLING DIRECTION	=	.19050E+02	(MM)
RADIUS OF CURVATURE OF BODY 2 - TRANSVERSE DIRECTION	=	.35560E+03	(MM)
CONTACT LOAD	=	.56025E+04	(N)

CONTACT IS FLUID LUBRICATED
------- -- ----- ----------

LUBRICANT DYNAMIC VISCOSITY	=	.50000E+01	(CENTIPOISE)
LUBRICANT PRESSURE VISCOSITY INDEX	=	.10300E-01	(MM^2/N)
ROLLING VELOCITY	=	.14500E+01	(M/SEC)

CALCULATED ROUGHNESS PARAMETERS

SPECTRAL EXPONENT	K =	2.43593	(NON-DIM)
ZERO-TH ORDER SPECTRAL MOMENT	M0 =	2.88250E-02	(MUM^2)
2-ND ORDER SPECTRAL MOMENT	M2 =	2.18650E-04	(NON-DIM)
4-TH ORDER SPECTRAL MOMENT	M4 =	3.19911E-04	(MUM^-2)
BANDWIDTH PARAMETER	ALPHA =	192.88570	(NON-DIM)
SEPARATION OF SUMMIT AND SURFACE MEAN PLANES	ZS =	.02759	(MUM)

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY	DSUM =	4.48145E+04	(MM^-2)
SUMMIT RADIUS	R =	3.71518E-02	(MM)
STANDARD DEVIATION OF SUMMIT HTS.	SIGMAS =	1.69384E-01	(MUM)

DOE - ECUT
<<< ROUGH INTERFACE ANALYSIS >>>

SPECIMEN ID: S163/164, 9310, 555, POLISHED, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

MAXIMUM CONTACT STRESS	SIGMA0 =	.24413E+04	(N/MM^2)
CONTACT ELLIPSE SEMIAXIS IN ROLLING DIRECTION	A =	.40621E+00	(MM)
CONTACT ELLIPSE SEMIAXIS IN TRANSVERSE DIRECTION	B =	.26974E+01	(MM)
CONTACT ELLIPSE ASPECT RATIO (B/A)	KAPPA =	.66404E+01	
CONTACT ELLIPSE AREA	AREA =	.34423E+01	(MM^2)
CONTACT TOTAL ELASTIC APPROACH	DELTA =	.29319E-01	(MM)
MAXIMUM ORTHOGONAL SHEAR STRESS	TAU0 =	.60695E+03	(N/MM^2)
DEPTH TO MAXIMUM ORTHOGONAL SHEAR STRESS	Z0 =	.19980E+00	(MM)

CALCULATED FILM THICKNESS AND GREENWOOD-WILLIAMSON PARAMETERS:

HCF	CENTRAL FILM THICKNESS (MUM)	.55391E-01
H/SIG	FILM THICKNESS / COMPOSITE SURFACE ROUGHNESS	.32626E+00
D/SIGMAS	STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE	.16414E+00
AC/A0	REAL CONTACT AREA FRACTION	.28554E+00
P/A0	MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM^2)	.95737E+03
P/AC	MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM^2)	.33528E+04
N	CONTACT DENSITY (CONTACTS/MM^2)	.19486E+05
NP	DENSITY OF PLASTIC CONTACTS (CONTACTS/MM^2)	.11620E+05
AP/A0	AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA	.24723E+00
NP/N	FRACTION OF PLASTIC CONTACTS	.59636E+00
AP/AC	AREA OF PLASTIC CONTACTS PER UNIT REAL AREA	.86585E+00
PEL	TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)	.32955E+04
PF	TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)	.65874E+03
PASP	TOTAL LOAD CARRIED BY ASPERITIES (N)	.39543E+04
AC	REAL CONTACT AREA (MM^2)	.98291E+00

DISTRIBUTION LIST

COMPANY:	ALLISON GAS TURBINE DIVISION GENERAL MOTORS CORPORATION
ATTENTION:	LIBRARY S5
ADDRESS:	POST OFFICE BOX 420
CITY/STATE/ZIP:	INDIANAPOLIS, INDIANA 46206-0420
NO. OF COPIES:	1
COMPANY:	ALLISON GAS TURBINE DIVISION GENERAL MOTORS CORPORATION
ATTENTION:	E.E. PFAFFENBERGER S48A
ADDRESS:	POST OFFICE BOX 420
CITY/STATE/ZIP:	INDIANAPOLIS, INDIANA 46206-0420
NO. OF COPIES:	1
COMPANY:	AVCON-ADVANCED CONTROLS TECH., INC.
ATTENTION:	MR. CRAWFORD R. MEEKS
ADDRESS:	19151 PARTHENIA STREET #G
CITY/STATE/ZIP:	NORTHRIDGE, CALIFORNIA 91324-3637
NO. OF COPIES:	1
COMPANY:	AVIATION APPLIED TECHNOLOGY DIRECTORATE
ATTENTION:	SAVRT-TY-ATP, MR. CLAY AMES
ADDRESS:	AVSCOM
CITY/STATE/ZIP:	FORT EUSTIS, VIRGINIA 23604-5577
NO. OF COPIES:	1
COMPANY:	BATTELLE COLUMBUS DIVISION ENGINEERING SYSTEMS DEPARTMENT
ATTENTION:	DR. JERRY KANNEL
ADDRESS:	505 KING AVENUE
CITY/STATE/ZIP:	COLUMBUS, OHIO 43201-2693
NO. OF COPIES:	1
COMPANY:	BELL AEROSPACE TEXTRON/TECHNICAL LIBRARY
ATTENTION:	LESTER M. BRESLAUER
ADDRESS:	POST OFFICE BOX 1
CITY/STATE/ZIP:	BUFFALO, NEW YORK 14240
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	BELL HELICOPTER TEXTRON, INC. ENGINEERING TECHNICAL LIBRARY
ATTENTION:	MAIL ZONE 012681-2
ADDRESS:	POST OFFICE BOX 482
CITY/STATE/ZIP:	FORT WORTH, TEXAS 76101-0482
NO. OF COPIES:	1
COMPANY:	BOEING AEROSPACE COMPANY
ATTENTION:	DR. THOMAS S. LUHMAN, 73-09
ADDRESS:	POST OFFICE BOX 3999
CITY/STATE/ZIP:	SEATTLE, WASHINGTON 98124
NO. OF COPIES:	1
COMPANY:	BOEING HELICOPTERS
ATTENTION:	J.W. LENSKI, (MS P32-09)
ADDRESS:	POST OFFICE BOX 16858
CITY/STATE/ZIP:	PHILADELPHIA, PENNSYLVANIA 19142-0858
NO. OF COPIES:	1
COMPANY:	BORG-WARNER CORPORATION ROY C. INGERSOLL RESEARCH CENTER
ATTENTION:	RESEARCH LIBRARY
ADDRESS:	WOLF ALGONQUIN ROADS
CITY/STATE/ZIP:	DES PLAINES, ILLINOIS 60018
NO. OF COPIES:	1
COMPANY:	CARPENTER TECHNOLOGY/CARPENTER STEEL DIVISION
ATTENTION:	RD CENTER LIBRARY
ADDRESS:	POST OFFICE BOX 14662
CITY/STATE/ZIP:	READING, PENNSYLVANIA 19612-4662
NO. OF COPIES:	1
COMPANY:	CATERPILLAR INC./TECHNICAL CENTER - E
ATTENTION:	MR. DAVID WEISS
ADDRESS:	POST OFFICE BOX 1875
CITY/STATE/ZIP:	PEORIA, ILLINOIS 61656-1875
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	CHARLES STARK DRAPER LABORATORY, INC. TECHNICAL INFORMATION CENTER
ATTENTION:	JOYCE L. GEVIRTZMAN MAIL STOP #74
ADDRESS:	555 TECHNOLOGY SQUARE
CITY/STATE/ZIP:	CAMBRIDGE, MASSACHUSETTS 02139-3539
NO. OF COPIES:	1
COMPANY:	CHEVRON RESEARCH COMPANY
ATTENTION:	MR. H.S. MACKINNON
ADDRESS:	POST OFFICE BOX 1627
CITY/STATE/ZIP:	RICHMOND, CALIFORNIA 94802
NO. OF COPIES:	1
COMPANY:	CLEVITE INDUSTRIES INC./ENGINE PARTS DIVISION
ATTENTION:	DOUG TORGENT
ADDRESS:	9200 AIRPORT ROAD
CITY/STATE/ZIP:	MORRISVILLE, NORTH CAROLINA 27560-9645
NO. OF COPIES:	1
COMPANY:	COMMUNICATIONS SATELLITE CORPORATION
ATTENTION:	JAMES SIMPSON
ADDRESS:	22300 COMSAT DRIVE
CITY/STATE/ZIP:	CLARKSBURG, MARYLAND 20871
NO. OF COPIES:	1
COMPANY:	COORDINATING RESEARCH COUNCIL
ATTENTION:	A. ZENGEL
ADDRESS:	219 PERIMETER CENTER PARKWAY
CITY/STATE/ZIP:	ATLANTA, GEORGIA 30346
NO. OF COPIES:	1
COMPANY:	CRUCIBLE MATERIALS CORPORATION/ CRUCIBLE RESEARCH CENTER
ATTENTION:	PAT ADUCCI
ADDRESS:	POST OFFICE BOX 88
CITY/STATE/ZIP:	PITTSBURGH, PENNSYLVANIA 15230-0088
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY: DEFENSE TECHNICAL INFORMATION CENTER
ATTENTION: FDAC
ADDRESS: CAMERON STATION
CITY/STATE/ZIP: ALEXANDRIA, VIRGINIA 22304-6145
NO. OF COPIES: 2

COMPANY: DEPARTMENT OF TRANSPORTATION
LIBRARY SERVICE DIVISION
ATTENTION: FOB-10A, M494.6
ADDRESS: 800 INDEPENDENCE AVENUE, SOUTHWEST
CITY/STATE/ZIP: WASHINGTON, DC 20591
NO. OF COPIES: 1

COMPANY: E.I. DUPONT DE NEMOURS COMPANY
ATTENTION: PERRY POLSS
ADDRESS: 609 PETROLEUM LABORATORY
CITY/STATE/ZIP: WILMINGTON, DELAWARE 19898
NO. OF COPIES: 1

COMPANY: EG & G SEALOL
ATTENTION: DR. ADMITAVA DATTA
ADDRESS: 15 PIONEER AVENUE
CITY/STATE/ZIP: WARWICK, RHODE ISLAND 02888
NO. OF COPIES: 1

COMPANY: EMERY CHEMICALS/SYNTHESIZED LUBRICANTS GROUP
ATTENTION: JACK B. BOYLAN
ADDRESS: 4900 ESTE AVENUE
CITY/STATE/ZIP: CINCINNATI, OHIO 45232
NO. OF COPIES: 1

COMPANY: EXXON RESEARCH ENGINEERING COMPANY,
PRODUCT RESEARCH DIVISION
ATTENTION: M.J. WISOTSKY/AVIATION LUBS
ADDRESS: POST OFFICE BOX 51
CITY/STATE/ZIP: LINDEN, NEW JERSEY 07036-0051
NO. OF COPIES: 1

COMPANY: FAG BEARING CORPORATION
ATTENTION: R.M. BIROSCAK
ADDRESS: 118 HAMILTON AVENUE/POST OFFICE BOX 811
CITY/STATE/ZIP: STAMFORD, CONNECTICUT 06094-0811
NO. OF COPIES: 1

DISTRIBUTION LIST
- Continued -

COMPANY:	FORD MOTOR COMPANY ENGINEERING RESEARCH LIBRARY
ATTENTION:	H. SCHNEIDER
ADDRESS:	POST OFFICE BOX 1602
CITY/STATE/ZIP:	DEARBORN, MICHIGAN 48121
NO. OF COPIES:	1
COMPANY:	FTD/TQTR
ATTENTION:	BRUCE BURNS
CITY/STATE/ZIP:	WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433
NO. OF COPIES:	1
COMPANY:	GARRETT ENGINE DIVISION
ATTENTION:	D. BIRNBAUM/LIBRARIAN, 503-1L
ADDRESS:	111 SOUTH 34TH STREET/POST OFFICE BOX 5217
CITY/STATE/ZIP:	PHOENIX, ARIZONA 85010-5217
NO. OF COPIES:	1
COMPANY:	GARRETT ENGINE DIVISION
ATTENTION:	KEN DIRKS 93-337-503-4K
ADDRESS:	111 SOUTH 34TH STREET/POST OFFICE BOX 5217
CITY/STATE/ZIP:	PHOENIX, ARIZONA 85010-5217
NO. OF COPIES:	1
COMPANY:	GENERAL DYNAMICS CONVAIR DIVISION
ATTENTION:	ROBERT E. ARNDAL/CHIEF LIBRARIAN MAIL ZONE 40-6540
ADDRESS:	POST OFFICE BOX 85357
CITY/STATE/ZIP:	SAN DIEGO, CALIFORNIA 92138-5357
NO. OF COPIES:	1
COMPANY:	GENERAL DYNAMICS/FORT WORTH DIVISION
ATTENTION:	M.M. MERRIMAN/CHIEF LIBRARIAN MAIL ZONE 2246
ADDRESS:	POST OFFICE BOX 748
CITY/STATE/ZIP:	FORT WORTH, TEXAS 76101-9990
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	GENERAL ELECTRIC COMPANY AIRCRAFT ENGINE BUSINESS GROUP
ATTENTION:	NELSON POPE/A305
ADDRESS:	1 NEUMANN WAY
CITY/STATE/ZIP:	CINCINNATI, OHIO 45215-6301
NO. OF COPIES:	10
COMPANY:	GENERAL ELECTRIC COMPANY AIRCRAFT ENGINE BUSINESS GROUP
ATTENTION:	MR. JOHN CLARK/MD-J40
ADDRESS:	1 NEUMANN WAY
CITY/STATE/ZIP:	CINCINNATI, OHIO 45215-6301
NO. OF COPIES:	1
COMPANY:	GENERAL ELECTRIC COMPANY
ATTENTION:	TECHNICAL INFORMATION CENTER 24001
ADDRESS:	1000 WESTERN AVENUE
CITY/STATE/ZIP:	LYNN, MASSACHUSETTS 01910-0001
NO. OF COPIES:	1
COMPANY:	GENERAL ELECTRIC COMPANY AIRCRAFT BUSINESS GROUP
ATTENTION:	MR. E. ATKINSON/MD-A305RGS9
ADDRESS:	1 NEUMANN WAY, POST OFFICE BOX 156301
CITY/STATE/ZIP:	CINCINNATI, OHIO 45215-6301
NO. OF COPIES:	1
COMPANY:	GENERAL MOTORS CORPORATION/RESEARCH LABS
ATTENTION:	MR. FRED ROUNDS
ADDRESS:	12 MILE AND MOUND ROADS
CITY/STATE/ZIP:	WARREN, MICHIGAN 48090-9055
NO. OF COPIES:	1
COMPANY:	GENERAL MOTORS RESEARCH LABS FLUID MECHANICS DEPARTMENT
ATTENTION:	PAWAN GOENKA
ADDRESS:	GENERAL MOTORS TECHNICAL CENTER
CITY/STATE/ZIP:	WARREN, MICHIGAN 48090-9055
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF MECHANICAL ENGINEERING
ATTENTION:	DR. W.O. WINER
CITY/STATE/ZIP:	ATLANTA, GEORGIA 30332-0405
NO. OF COPIES:	1
COMPANY:	HATCO CORPORATION
ATTENTION:	C.A. LYNCH
ADDRESS:	KING GEORGE POST ROAD
CITY/STATE/ZIP:	FORDS, NEW JERSEY 08863-0601
NO. OF COPIES:	1
COMPANY:	HUGHES AIRCRAFT COMPANY
ATTENTION:	B.W. CAMPBELL BUILDING E1, MAIL STATION E110
ADDRESS:	POST OFFICE BOX 902
CITY/STATE/ZIP:	EL SEGUNDO, CALIFORNIA 90245
NO. OF COPIES:	1
COMPANY:	INDUSTRIAL TECTRONICS, INC./BEARINGS DIVISION
ATTENTION:	H. SIGNER, DIRECTOR OF ENGINEERING/RD
ADDRESS:	18301 SOUTH SANTA FE AVENUE
CITY/STATE/ZIP:	COMPTON, CALIFORNIA 90221-4879
NO. OF COPIES:	1
COMPANY:	KAYDON RING AND SEAL, INC. SHAFT SEAL ENGINEERING SECTION
ATTENTION:	MR. W.K. MOSLEYHMAN, 73-09
ADDRESS:	POST OFFICE BOX 626
CITY/STATE/ZIP:	BALTIMORE, MARYLAND 21203-0626
NO. OF COPIES:	1
COMPANY:	LITTON/GUIDANCE CONTROL SYSTEMS
ATTENTION:	ROBERT A. WESTERHOLM MAIL STOP 87
ADDRESS:	5500 CANOGA AVENUE
CITY/STATE/ZIP:	WOODLAND HILLS, CALIFORNIA 91367-6698
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	MARTIN MARIETTA DENVER AEROSPACE
ATTENTION:	MR. FRANK M. KUSTA/B3085
ADDRESS:	POST OFFICE BOX 179
CITY/STATE/ZIP:	DENVER, COLORADO 80201-0179
NO. OF COPIES:	1
COMPANY:	MASSACHUSETTS INSTITUTE OF TECHNOLOGY MATERIALS SCIENCE/ENGINEERING
ATTENTION:	PROFESSOR AVERBACH ROOM 8-409
ADDRESS:	77 MASSACHUSETTS AVENUE
CITY/STATE/ZIP:	CAMBRIDGE, MASSACHUSETTS 02139-9910
NO. OF COPIES:	1
COMPANY:	MECHANICAL TECHNOLOGY INC.
ATTENTION:	DR. HOOSHANG HESHMAT
ADDRESS:	968 ALBANY-SHAKER ROAD
CITY/STATE/ZIP:	LATHAM, NEW YORK 12100-0729
NO. OF COPIES:	1
COMPANY:	MOBIL RESEARCH DEVELOPMENT CORPORATION
ATTENTION:	MR. FRANK FEINBERG
CITY/STATE/ZIP:	PAULSBORO, NEW JERSEY 08066-0480
NO. OF COPIES:	1
COMPANY:	MONSANTO RESEARCH GROUP
ATTENTION:	LIBRARY
ADDRESS:	STATION B, BOX 8
CITY/STATE/ZIP:	DAYTON, OHIO 45407
NO. OF COPIES:	1
COMPANY:	MPB CORPORATION COMPANY
ATTENTION:	C.G. BEECHER
ADDRESS:	PRECISION PARK
CITY/STATE/ZIP:	KEENE, NEW HAMPSHIRE 03431
NO. OF COPIES:	1
COMPANY:	MRC BEARINGS
ATTENTION:	ANTHONY GALBATO
ADDRESS:	MAROCO ROAD
CITY/STATE/ZIP:	FALCONER, NEW YORK 14733
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY: MRC BEARINGS
ATTENTION: DR. BRUCE G. BUNTING, P.E.
ADDRESS: MAROCO ROAD
CITY/STATE/ZIP: FALCONER, NEW YORK 14733
NO. OF COPIES: 1

COMPANY: NAS PENSACOLA
ATTENTION: ROBERT HAMMAN/JOAP/TSC
ADDRESS: BUILDING 780
CITY/STATE/ZIP: PENSACOLA, FLORIDA 32508-5300
NO. OF COPIES: 1

COMPANY: NASA-LEWIS RESEARCH CENTER
ATTENTION: ERWIN V. ZARETSKY, MAIL STOP 49-6
ADDRESS: 21000 BROOKPARK ROAD
CITY/STATE/ZIP: CLEVELAND, OHIO 44135-3191
NO. OF COPIES: 1

COMPANY: NASA-LEWIS RESEARCH CENTER
ATTENTION: DR. DAVID FLEMING, MAIL STOP 23-3
ADDRESS: 21000 BROOKPARK ROAD
CITY/STATE/ZIP: CLEVELAND, OHIO 44135-3139
NO. OF COPIES: 1

COMPANY: NASA-LEWIS RESEARCH CENTER
MATERIALS DIVISION
ATTENTION: WILLIAM LOOMIS/MAIL STOP 23-2
MATERIALS DIVISION
ADDRESS: 21000 BROOKPARK ROAD
CITY/STATE/ZIP: CLEVELAND, OHIO 44135-3191
NO. OF COPIES: 1

COMPANY: NATIONAL RESEARCH COUNCIL
ATTENTION: JACQUES MASOUNAUE
ADDRESS: 7421 CHAMBOIS
CITY/STATE/ZIP: MONTREAL, QUEBEC, CANADA
NO. OF COPIES: 1

COMPANY: NAVAL AIR DEVELOPMENT CENTER
ATTENTION: MR. NEAL REBUCK, CODE 60612
CITY/STATE/ZIP: WARMINSTER, PENNSYLVANIA 18974-5000
NO. OF COPIES: 1

DISTRIBUTION LIST
- Continued -

ATTENTION:	MR. MITCHELL WEISS
ADDRESS:	HANGAR 6, CODE 92731
CITY/STATE/ZIP:	LAKEHURST, NEW JERSEY 08733-5107
NO. OF COPIES:	1
COMPANY:	NAVAL AIR PROPULSION CENTER
ATTENTION:	P. MANGIONE/PE-32
ADDRESS:	POST OFFICE BOX 7176
CITY/STATE/ZIP:	TRENTON, NEW JERSEY 08628-0176
NO. OF COPIES:	1
COMPANY:	NAVAL AIR PROPULSION CENTER
ATTENTION:	A. D'ORAZIO/PE33
ADDRESS:	POST OFFICE BOX 7176
CITY/STATE/ZIP:	TRENTON, NEW JERSEY 08628-0176
NO. OF COPIES:	1
COMPANY:	NAVAL AIR PROPULSION CENTER
ATTENTION:	D. POPGOSHEV/PE32
ADDRESS:	POST OFFICE BOX 7176
CITY/STATE/ZIP:	TRENTON, NEW JERSEY 08628-0176
NO. OF COPIES:	25
COMPANY:	NAVAL AIR PROPULSION CENTER
ATTENTION:	DY D. LE/PE32
ADDRESS:	POST OFFICE BOX 7176
CITY/STATE/ZIP:	TRENTON, NEW JERSEY 08628-0176
NO. OF COPIES:	10
COMPANY:	NAVAL AIR PROPULSION CENTER
ATTENTION:	JAMES O'DONNELL/PE32
ADDRESS:	POST OFFICE BOX 7176
CITY/STATE/ZIP:	TRENTON, NEW JERSEY 08628-0176
NO. OF COPIES:	1
COMPANY:	NAVAL AIR SYSTEM COMMAND
ATTENTION:	AIR-931A
CITY/STATE/ZIP:	WASHINGTON, DC 20361-9310
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	NAVAL AVIONICS CENTER MATERIALS LABORATORY CONSULTANTS
ATTENTION:	DIV., F. GAHIMER, D/7133-09
ADDRESS:	6000 EAST 21ST STREET
CITY/STATE/ZIP:	INDIANAPOLIS, INDIANA 46219-2189
NO. OF COPIES:	1
COMPANY:	NAVAL POST GRADUATE SCHOOL DEPARTMENT OF MECHANICAL ENGINEERING
ATTENTION:	PROFESSOR T. MCNELLEY 73-09
CITY/STATE/ZIP:	MONTEREY, CALIFORNIA 93945-5000
NO. OF COPIES:	1
COMPANY:	NAVAL RESEARCH LABORATORY MATERIALS MOD ANALYSIS BRANCH
ATTENTION:	DR. F.A. SMIDT/CODE 4670-09
CITY/STATE/ZIP:	WASHINGTON, DC 20375-5000
NO. OF COPIES:	1
COMPANY:	NORTHEASTERN UNIVERSITY DEPARTMENT OF CHEMISTRY
ATTENTION:	DR. T.R. GILBERT
ADDRESS:	360 HUNTINGTON AVENUE
CITY/STATE/ZIP:	BOSTON, MASSACHUSETTS 02115
NO. OF COPIES:	1
COMPANY:	NORTHROP CORPORATION/AIRCRAFT DIVISION
ATTENTION:	LIBRARY 3360-82
ADDRESS:	ONE NORTHROP AVENUE
CITY/STATE/ZIP:	HAWTHORNE, CALIFORNIA 90250
NO. OF COPIES:	1
COMPANY:	NORTHWESTERN UNIVERSITY THE TECHNOLOGY INSTITUTE
ATTENTION:	H.S. CHENG
ADDRESS:	219 CATALYSIS
CITY/STATE/ZIP:	EVANSTON, ILLINOIS 60201-0000
NO. OF COPIES:	1

COMPANY:	PENN STATE GREAT VALLEY
ATTENTION:	J. MCCOOL
ADDRESS:	30 EAST SWEDES FORD ROAD
CITY/STATE/ZIP:	MALVERN, PENNSYLVANIA 19355-0000
NO. OF COPIES:	1
COMPANY:	PENNSYLVANIA STATE UNIVERSITY DEPARTMENT OF CHEMICAL ENGINEERING
ATTENTION:	DR. E.E. KLAUS
ADDRESS:	108 FENSKE LABORATORY
CITY/STATE/ZIP:	UNIVERSITY PARK, PENNSYLVANIA 16802
NO. OF COPIES:	1
COMPANY:	PRADEEP K. GUPTA, INC.
ATTENTION:	DR. P.K. GUPTA
ADDRESS:	117 SOUTHBURY ROAD
CITY/STATE/ZIP:	CLIFTON PARK, NEW YORK 12065-7714
NO. OF COPIES:	1
COMPANY:	PRATT & WHITNEY
ATTENTION:	P.A. WARNER, MAIL DROP 72204
ADDRESS:	POST OFFICE BOX 109600
CITY/STATE/ZIP:	WEST PALM BEACH, FLORIDA 33410-9600
NO. OF COPIES:	1
COMPANY:	PRATT & WHITNEY
ATTENTION:	LIBRARIAN
ADDRESS:	POST OFFICE BOX 109600
CITY/STATE/ZIP:	WEST PALM BEACH, FLORIDA 33410-9600
NO. OF COPIES:	1
COMPANY:	PRATT & WHITNEY
ATTENTION:	MR. E.M. BEVERLY
ADDRESS:	POST OFFICE BOX 109600, MAIL STOP 715-91
CITY/STATE/ZIP:	WEST PALM BEACH, FLORIDA 33410-9600
NO. OF COPIES:	1
COMPANY:	PRATT & WHITNEY
ATTENTION:	MR. BILL POOLE, MAIL STOP 715-91
ADDRESS:	POST OFFICE BOX 109600
CITY/STATE/ZIP:	WEST PALM BEACH, FLORIDA 33410=9600
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	PRATT & WHITNEY/COMMERCIAL PRODUCTS DIVISION
ATTENTION:	MR. PAUL F. BROWN/MAIL STOP 163-05
ADDRESS:	400 MAIN STREET
CITY/STATE/ZIP:	EAST HARTFORD, CONNECTICUT 06108-0969
NO. OF COPIES:	1
COMPANY:	PRATT & WHITNEY/COMMERCIAL PRODUCTS DIVISION
ATTENTION:	LIBRARY, M.E. DONNELLY
ADDRESS:	400 EAST MAIN STREET
CITY/STATE/ZIP:	EAST HARTFORD, CONNECTICUT 06108-000
NO. OF COPIES:	1
COMPANY:	PURDUE UNIVERSITY SCHOOL OF MECHANICAL ENGINEERING
ATTENTION:	DR. FARSHID SADEGHI
CITY/STATE/ZIP:	WEST LAFAYETTE, INDIANA 47907
NO. OF COPIES:	1
COMPANY:	PVO INTERNATIONAL, INC.
ATTENTION:	MR. DON MATTHEWS
ADDRESS:	416 DIVISION STREET
CITY/STATE/ZIP:	BOONTON, NEW JERSEY 07005
NO. OF COPIES:	1
COMPANY:	RENSSELAER POLYTECHNIC INSTITUTE DEPARTMENT OF MECHANICAL ENGINEERING
ATTENTION:	DR. F.F. LING
CITY/STATE/ZIP:	TROY, NEW YORK 12180-3590
NO. OF COPIES:	1
COMPANY:	RENSSELAER POLYTECHNIC INSTITUTE DEPARTMENT OF MECHANICAL ENGINEERING
ATTENTION:	J.J. LAUER
ADDRESS:	5040 JONSSON ENGINEERING CENTER
CITY/STATE/ZIP:	TROY, NEW YORK 12128
NO. OF COPIES:	1
COMPANY:	ROCKWELL INTERNATIONAL CORPORATION ROCKETYDYNE DIVISION
ATTENTION:	JULIA KEIM, MANAGER, BA29
ADDRESS:	6633 CANOGA AVENUE
CITY/STATE/ZIP:	CANOGA PARK, CALIFORNIA 91303-2790
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY: ROYAL LUBRICANTS COMPANY, INC.
ATTENTION: D.B. CLARKE
ADDRESS: POST OFFICE BOX 518, RIVER ROAD
CITY/STATE/ZIP: EAST HANOVER, NEW JERSEY 07936-0518
NO. OF COPIES: 1

COMPANY: SATCON TECHNOLOGY CORPORATION
ATTENTION: DAVID B. EISENHAUER
ADDRESS: 71 ROGERS STREET
CITY/STATE/ZIP: CAMBRIDGE, MASSACHUSETTS 02142
NO. OF COPIES: 1

COMPANY: SHELL DEVELOPMENT COMPANY
WESTHOLLOW RESEARCH CENTER
ATTENTION: LIBRARY (E.M. ANDO)
ADDRESS: POST OFFICE BOX 1378
CITY/STATE/ZIP: HOUSTON, TEXAS 77001
NO. OF COPIES: 1

COMPANY: SOLAR TURBINES INC.
ATTENTION: GEORGE D. HALL
ADDRESS: 2200 PACIFIC HALL
POST OFFICE BOX 85376
CITY/STATE/ZIP: SAN DIEGO, CALIFORNIA 92138-5376
NO. OF COPIES: 1

COMPANY: SOUTHWEST RESEARCH INSTITUTE
ATTENTION: ROBERT D. ARMOR/LIBRARIAN
ADDRESS: POST OFFICE BOX 28510
CITY/STATE/ZIP: SAN ANTONIO, TEXAS 78284-2901
NO. OF COPIES: 1

COMPANY: SOUTHWEST RESEARCH INSTITUTE
ATTENTION: B.B. BABER
ADDRESS: POST OFFICE DRAWER 28510
6220 CULEBRA ROAD
CITY/STATE/ZIP: SAN ANTONIO, TEXAS 78284-2901
NO. OF COPIES: 1

DISTRIBUTION LIST
- Continued -

COMPANY:	SPLIT BALL BEARING DIVISION OF MPB CORPORATION
ATTENTION:	MR. C.A. GRIFFITHS
ADDRESS:	HIGHWAY FOUR
CITY/STATE/ZIP:	LEBANON, NEW HAMPSHIRE 03766
NO. OF COPIES:	1
COMPANY:	SPLIT BALL BEARING DIVISION OF MPB CORPORATION
ATTENTION:	JOHN P. CARR
ADDRESS:	HIGHWAY FOUR
CITY/STATE/ZIP:	LEBANON, NEW HAMPSHIRE 03766
NO. OF COPIES:	1
COMPANY:	STEIN SEAL COMPANY
ATTENTION:	GEORGE T. HUNT
ADDRESS:	WAMBOLD ROAD AND INDUSTRIAL BOULEVARD
CITY/STATE/ZIP:	KULPSVILLE, PENNSYLVANIA 19443-0316
NO. OF COPIES:	1
COMPANY:	SUN REFINING MARKETING COMPANY
ATTENTION:	DR. LEWIS HALL
ADDRESS:	POST OFFICE BOX 1135
CITY/STATE/ZIP:	MARCUS HOOK, PENNSYLVANIA 19061-0835
NO. OF COPIES:	1
COMPANY:	SUNDSTRAND POWER SYSTEMS
ATTENTION:	G. HOSANG
ADDRESS:	4400 RUFFIN ROAD POST OFFICE BOX 85757
CITY/STATE/ZIP:	SAN DIEGO, CALIFORNIA 92138-5757
NO. OF COPIES:	1
COMPANY:	TELEDYNE CAE
ATTENTION:	G. HAMBURG
ADDRESS:	1330 LASKEY ROAD
CITY/STATE/ZIP:	TOLEDO, OHIO 43612
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	TELEDYNE CAE ENGINEERING LIBRARY
ATTENTION:	MARLENE DOWDELL
ADDRESS:	1330 LASKEY ROAD
CITY/STATE/ZIP:	TOLEDO, OHIO 43612-0971
NO. OF COPIES:	1
COMPANY:	TEXAXO, INC.
ATTENTION:	J.F. HILLARD
ADDRESS:	POST OFFICE BOX 509
CITY/STATE/ZIP:	BEACON, NEW YORK 12508-0509
NO. OF COPIES:	1
COMPANY:	TEXTRON LYCOMING
ATTENTION:	GEORGE T. MILO/LSB14
ADDRESS:	550 SOUTH MAIN STREET
CITY/STATE/ZIP:	STRATFORD, CONNECTICUT 06497-2452
NO. OF COPIES:	1
COMPANY:	THE BARDEN CORPORATION
ATTENTION:	HAROLD BERGLUND, DEPARTMENT 76
ADDRESS:	200 PARK AVENUE
CITY/STATE/ZIP:	DANBURY, CONNECTICUT 06813-2449
NO. OF COPIES:	1
COMPANY:	THE FRANKLIN INSTITUTE RESEARCH LABS ME LABORATORY
ATTENTION:	HARRY C. RIPPEL
ADDRESS:	20TH AND RACE STREETS
CITY/STATE/ZIP:	PHILADELPHIA, PENNSYLVANIA 19103
NO. OF COPIES:	1
COMPANY:	THE TIMKEN COMPANY RESEARCH/PRODUCT DEVELOPMENT/BEARINGS
ATTENTION:	MR. PETE ORVOS/GENERAL MANAGER
ADDRESS:	1835 DEUBER AVENUE, SOUTHWEST
CITY/STATE/ZIP:	CANTON, OHIO 44706-2798
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	THE TIMKEN COMPANY RESEARCH LIBRARY
ATTENTION:	P. CASEY
CITY/STATE/ZIP:	CANTON, OHIO 44706
NO. OF COPIES:	1
COMPANY:	THE TORRINGTON COMPANY ADVANCED TECHNOLOGY CENTER
ATTENTION:	WILLIAM J. CHMURA
ADDRESS:	59 FIELD STREET
CITY/STATE/ZIP:	TORRINGTON, CONNECTICUT 06790-4942
NO. OF COPIES:	1
COMPANY:	TRIBOLOGY SYSTEMS INC.
ATTENTION:	LEWIS B. SIBLEY
ADDRESS:	504 FOXWOOD LANE
CITY/STATE/ZIP:	PAOLI, PENNSYLVANIA 19301
NO. OF COPIES:	1
COMPANY:	UNIVERSITY OF DAYTON RESEARCH INSTITUTE
ATTENTION:	DR. COSTANDY SABA
ADDRESS:	300 COLLEGE PARK
CITY/STATE/ZIP:	DAYTON, OHIO 45469-0001
NO. OF COPIES:	1
COMPANY:	UNIVERSITY OF VIRGINIA
ATTENTION:	RALPH A. LOWRY
ADDRESS:	A109 THORNTON HALL, MCCORMICK ROAD
CITY/STATE/ZIP:	CHARLOTTISVILLE, VIRGINIA 22903-2442
NO. OF COPIES:	1
COMPANY:	UNIVERSITY OF VIRGINIA DEPARTMENT OF MATERIALS SCIENCE
ATTENTION:	FRANKLIN B. WAWNER, JR.
CITY/STATE/ZIP:	CHARLOTTISVILLE, VIRGINIA 22901
NO. OF COPIES:	1
COMPANY:	VOUGHT MISSILE ADVANCED PROGR DLTV AERO DEFENSE COMPANY
ATTENTION:	MR. L.E. BOSWELL, M/S EM-18
ADDRESS:	POST OFFICE BOX 650003
CITY/STATE/ZIP:	DALLAS, TEXAS 75265-0003
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	WEDEVEN ASSOCIATES, INC.
ATTENTION:	DR. L.D. WEDEVEN
ADDRESS:	P.O. BOX 646 508A WEST CHESTER PIKE
CITY/STATE/ZIP:	EDGMONT, PENNSYLVANIA 19028
NO. OF COPIES:	1

COMPANY:	WESTINGHOUSE ELECTRIC CORPORATION AERO ELECTRICAL DIVISION
ATTENTION:	A.E. KING
ADDRESS:	POST OFFICE BOX 989
CITY/STATE/ZIP:	LIMA, OHIO 45802
NO. OF COPIES:	1

COMPANY:	WILLIAMS INTERNATIONAL
ATTENTION:	MR. H. SCHEIFELE
ADDRESS:	POST OFFICE BOX 200
CITY/STATE/ZIP:	WALLED LAKE, MICHIGAN 48088-0200
NO. OF COPIES:	1

COMPANY:	WILLIAMS INTERNATIONAL
ATTENTION:	MR. JACK ORTIZ
ADDRESS:	5100 SPRINGFIELD PIKE, SUITE 520
CITY/STATE/ZIP:	DAYTON, OHIO 45431-1261
NO. OF COPIES:	1

COMPANY:	WILLIAMS INTERNATIONAL
ATTENTION:	LIBRARY
ADDRESS:	POST OFFICE BOX 200
CITY/STATE/ZIP:	WALLED LAKE, MICHIGAN 48088-0200
NO. OF COPIES:	1

COMPANY:	WRDC/MLBT
ATTENTION:	B.D. MCCONNELL
CITY/STATE/ZIP:	WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533
NO. OF COPIES:	1

COMPANY:	WRDC/MLBT
ATTENTION:	LOIS GSCHWENDER
CITY/STATE/ZIP:	WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533
NO. OF COPIES:	1

DISTRIBUTION LIST
- Continued -

COMPANY:	WRDC/POSL
CITY/STATE/ZIP:	WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533
NO. OF COPIES:	2