

MRC Bearings

**SKF**  
AEROSPACE BEARINGS

AD-A216 673

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

John I. McCool

MRC Bearings - SKF Aerospace  
402 Chandler Street  
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August, 1989

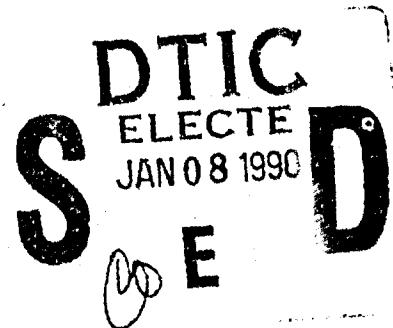
Final Report

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PREPARED FOR

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



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

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

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## 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.

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## 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:

| <u>Load<br/>Condition</u> | <u>Radial<br/>Force (lbs)</u> | <u>Axial<br/>Force (lbs)</u> | <u>Run<br/>Time (%)</u> |
|---------------------------|-------------------------------|------------------------------|-------------------------|
| 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  $h/\sigma$  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<br>(lbs) | Fa<br>(lbs) | %<br>Relative<br>Duration | $\sigma_{max}$<br>KSI | a<br>(in) | b<br>(in) | $V_{max}$<br>(in/sec) | $P_{max}$<br>(lb) | Life<br>(Hrs) | h<br>( $\mu$ in) |
|-------------|-------------|---------------------------|-----------------------|-----------|-----------|-----------------------|-------------------|---------------|------------------|
| 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:

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

The pressure angle is  $22.5^\circ$  for all gears. The lubricant (MIL-L-23699) operating temperature was given as  $180^\circ\text{F}$ . 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:

| <u>Percentage<br/>Of Time</u> | <u>Rotor Speed<br/>(RPM)</u> | <u>Horsepower</u> |
|-------------------------------|------------------------------|-------------------|
| 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  $180^\circ\text{F}$ .

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  $\mu$  inch rms for the surface roughness of the raceways and 4  $\mu$  inch rms minimum for the rollers, the composite surface roughness is approximately 9  $\mu$  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  $\delta$  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  $\omega$  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<br>HP |                            | NO. OF ROLLERS |       |       |       | (EXTRAPOLATED) |
|-------------|----------------------------|----------------|-------|-------|-------|----------------|
|             |                            | 36             | 38    | 40    | 42    |                |
| 1140        | Max. Load (Lbs)            | 2107           | 2006  | 1911  | 1820  |                |
|             | Film Thickness ( $\mu$ in) | 0.569          | 0.572 | 0.578 | 0.584 |                |
|             | Life (Hrs)                 | 61             | 70    | 79    | 88    |                |
| 1500        | Max. Load (Lbs)            | 2765           | 2639  | 2522  | 2402  |                |
|             | Film Thickness ( $\mu$ in) | 0.552          | 0.555 | 0.561 | 0.567 |                |
|             | Life (Hrs)                 | 23             | 26    | 29    | 32    |                |
| 1710        | Max. Load (LBs)            | 3158           | 3001  | 2870  | 2733  |                |
|             | Film Thickness ( $\mu$ in) | 0.544          | 0.547 | 0.553 | 0.559 |                |
|             | Life (Hrs)                 | 14             | 16    | 18    | 20    |                |
| 2090        | Max. Load (Lbs)            | 4274           | 4055  | 3854  | 3670  |                |
|             | Film Thickness ( $\mu$ in) | 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<br>(LBS) | $\sigma_{MAX}$<br>(ksi) | $\delta$<br>(in) | $V_{MAX}$<br>(in/sec) | S/R<br>(%) |
|------|------|---------------|-------------------------|------------------|-----------------------|------------|
| 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 inner 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  $22.5^\circ$  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  $\Delta x$  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  $22.5^\circ$  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  $\theta$  is expressible as:

TABLE 3.1  
Summary of Roughness Data

| DIRECTION       | SPECIMEN                 | $m_0(\mu\text{in}^2)$ | $m_2$   | $m_4(\mu\text{in})^2$ |
|-----------------|--------------------------|-----------------------|---------|-----------------------|
| AXIAL<br>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<br>GROOVE | ANGULAR CONTACT<br>INNER | 51.9                  | 1.37E-3 | 5.46E-7               |
| CROSS<br>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<br>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  $\theta$  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  $\theta$  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  $\theta$  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<br>CONTACT |
|----------|--------------------------------|----------|---------|----------|---------|--------------------|
| $m_{00}$ | $(\mu\text{in})^2 \times 10^3$ | 63.2     | (19.9)  | 334.0    | (235.0) | 51.9               |
| $m_{20}$ | $(\mu\text{in})^2 \times 10^3$ | 3.40     | (0.370) | 15.8     | (2.91)  | 1.37               |
| $m_{11}$ | $(\mu\text{in})^2 \times 10^3$ | -0.479   | (0.302) | -2.07    | (2.38)  | 0.0                |
| $m_{02}$ | $(\mu\text{in})^2 \times 10^3$ | 0.861    | (0.370) | 2.99     | (2.91)  | 1.37               |
| $m_{40}$ | $(\mu\text{in})^2 \times 10^7$ | 10.4     | (0.701) | 37.4     | (9.67)  | 5.46               |
| $m_{31}$ | $(\mu\text{in})^2 \times 10^7$ | -1.64    | (0.495) | -9.56    | (6.84)  | 0.0                |
| $m_{22}$ | $(\mu\text{in})^2 \times 10^7$ | 3.66     | (0.455) | 7.94     | (6.28)  | 1.82               |
| $m_{13}$ | $(\mu\text{in})^2 \times 10^7$ | 0.232    | (0.495) | 4.32     | (6.84)  | 0.0                |
| $m_{04}$ | $(\mu\text{in})^2 \times 10^7$ | 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  $h/\sigma = 1.5$  Isotropic With Cross Groove Parameters

| BEARING                                                         | CONTACT<br>MODEL | N<br>(in <sup>2</sup> ) | P/A <sub>o</sub><br>(lb/in <sup>2</sup> ) | A <sub>o</sub> /A <sub>c</sub> | P/A <sub>c</sub><br>(lb/in <sup>2</sup> ) | N <sub>p</sub><br>(in <sup>2</sup> ) | N <sub>p</sub> /N |
|-----------------------------------------------------------------|------------------|-------------------------|-------------------------------------------|--------------------------------|-------------------------------------------|--------------------------------------|-------------------|
| ANGULAR<br>CONTACT<br>MAST BEARING                              | ASPERSIM<br>GW   | 2.10E6<br>2.09E6        | 13250<br>115100                           | 0.0252<br>.0221                | 526000<br>566000                          | -<br>1.36E6                          | -<br>0.651        |
| PLANETARY<br>TRANSMISSION<br>CYLINDRICAL<br>BEARING<br>S/N 3922 | ASPERSIM<br>GW   | 2.59E6<br>2.64E6        | 17050<br>16582                            | 0.0244<br>0.0230               | 699000<br>720000                          | -<br>2.07E6                          | -<br>0.784        |
| PLANETARY<br>TRANSMISSION<br>CYLINDRICAL<br>BEARING<br>S/N 6065 | ASPERSIM<br>GW   | 1.91E6<br>1.94E6        | 41480<br>40817                            | 0.0241<br>0.0228               | 1.72E6<br>1.79E6                          | -<br>1.87E6                          | -<br>0.962        |

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 ( $\mu$  inch<sup>2</sup>) implying a range in  $R_q$  of 15-18  $\mu$  inch which seemed abnormally high. Several Talysurf V determinations, however, showed that the  $R_q$  value could be as high as 26  $\mu$  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                                                   | $m_0(\text{in})^2$ | $m_2(\text{non-dim})$ | $m_4(\text{in}^2)^{-1}$ |
|-----------------------------------------------------------|--------------------|-----------------------|-------------------------|
| ANGULAR CONTACT<br>MAST BEARING                           | 51.9E-12           | 1.37E-3               | 5.46E5                  |
| PLANETARY TRANSMISSION<br>CYLINDRICAL BEARING<br>S/N 3922 | 63.2E-12           | 3.4E-3                | 1.04E6                  |
| PLANETARY TRANSMISSION<br>CYLINDRICAL BEARING<br>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                                               | $h/\sigma$ | $N$<br>(in <sup>2</sup> ) | $P/A_c$<br>(lb/in <sup>2</sup> ) | $A_c/A_o$ | $P/A_c$<br>(lb/in <sup>2</sup> ) | $N_p$<br>(in <sup>2</sup> ) | $N_p/N$ |
|-------------------------------------------------------|------------|---------------------------|----------------------------------|-----------|----------------------------------|-----------------------------|---------|
| ANGULAR<br>CONTACT<br>MAST<br>BEARING                 | 0.262      | 7.93E6                    | 114,150                          | 0.138     | 8.18E5                           | 6.54E6                      | 0.824   |
| PLANETARY<br>TRANS-<br>MISSION<br>BEARING<br>S/N 3922 | 0.061      | 8.21E6                    | 235,300                          | 0.148     | 1.59E6                           | 7.59E6                      | 0.925   |
| PLANETARY<br>TRANS-<br>MISSION<br>BEARING<br>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.

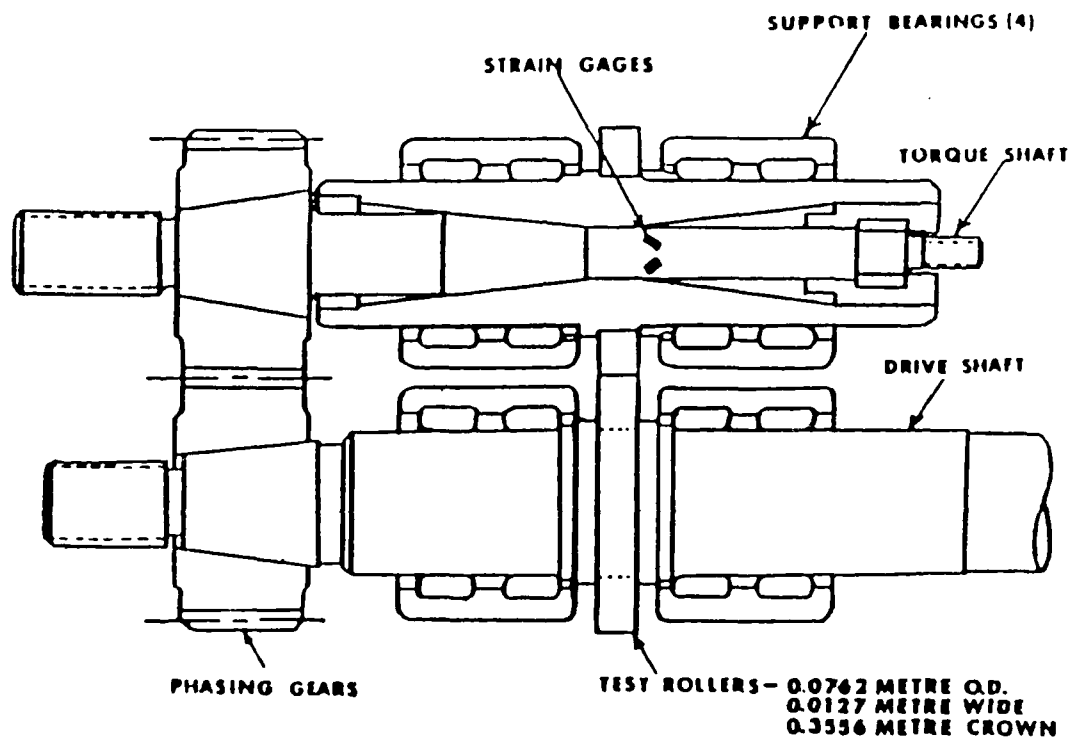


Figure 4.1  
Geared Roller Test Machine Schematic

TABLE 4.1  
Test Matrix For Micropitting Tests

| INVESTIGATION OF FINISH, LUBE AND MATERIAL<br>EFFECTS DURING LOW-FILM OPERATION |               |                    |                   |  |
|---------------------------------------------------------------------------------|---------------|--------------------|-------------------|--|
|                                                                                 |               | F1<br>( POLISHED ) | F2<br>(TUMBLLED ) |  |
| M1<br>(9310)                                                                    | 01<br>-23699  |                    |                   |  |
|                                                                                 | 02<br>( 555 ) |                    |                   |  |
| M2<br>(MSX)                                                                     | 01<br>-23699  |                    |                   |  |
|                                                                                 | 02<br>( 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)

|                     | Life at 1250 lbs                | Life at 2151 lbs                | Equivalent Life                        |
|---------------------|---------------------------------|---------------------------------|----------------------------------------|
| <u>Specimen No.</u> | <u><math>L_1</math> (hours)</u> | <u><math>L_2</math> (hours)</u> | <u><math>L_1 + 6L_2</math> (hours)</u> |
| 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.

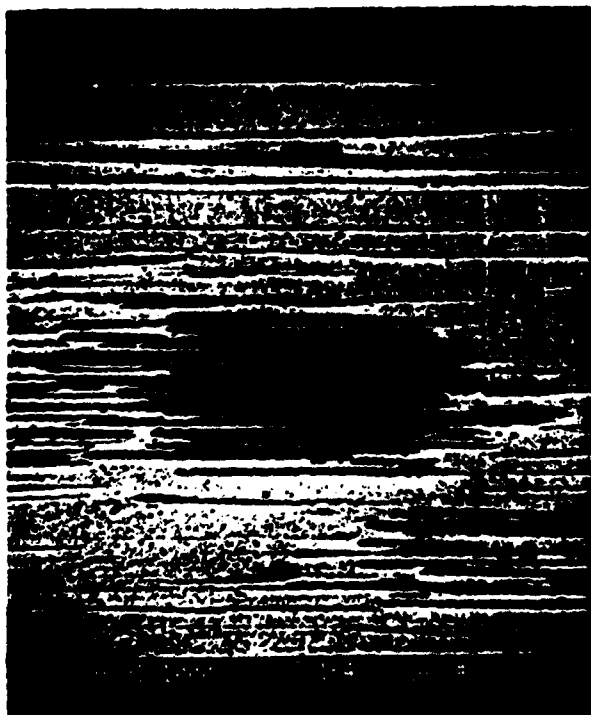
Photographs (c) and (d) are specimens V11 and V15. Both are tumbled M50. V11 was tested with Shell 555 and V15 with MIL-L-23699. Both show damage suggestive of the incursion of hard particle.



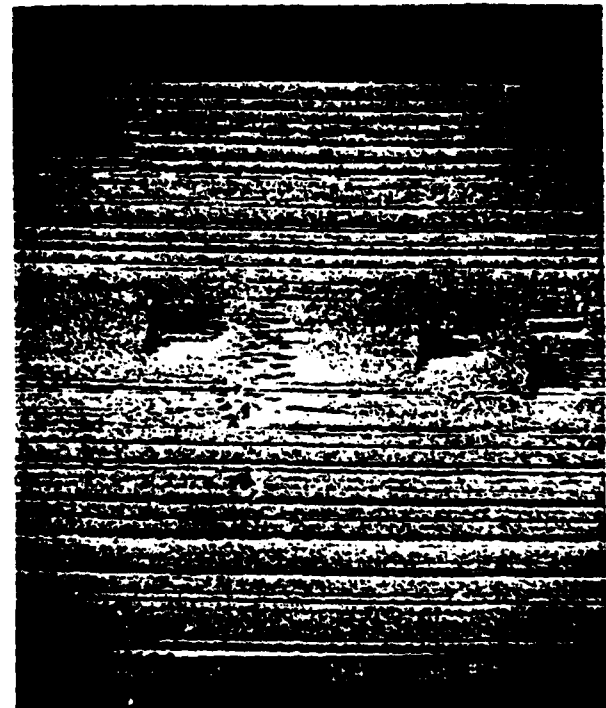
(a)



(b)



(c)

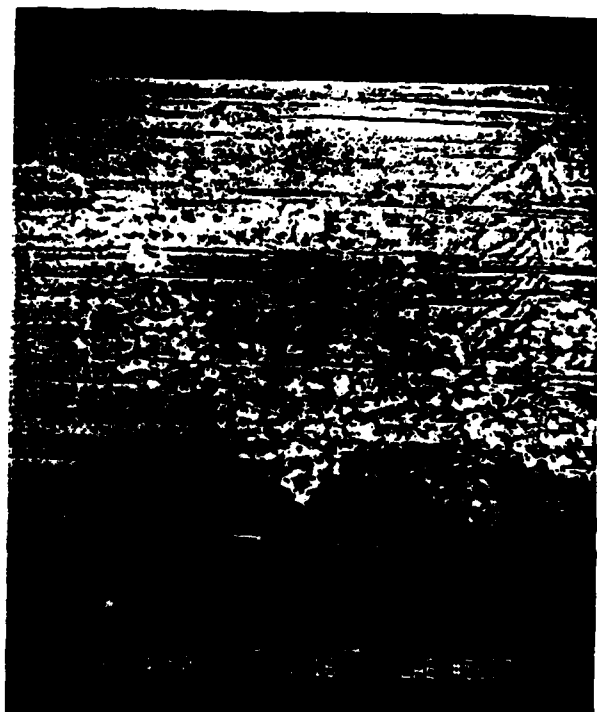


(d)

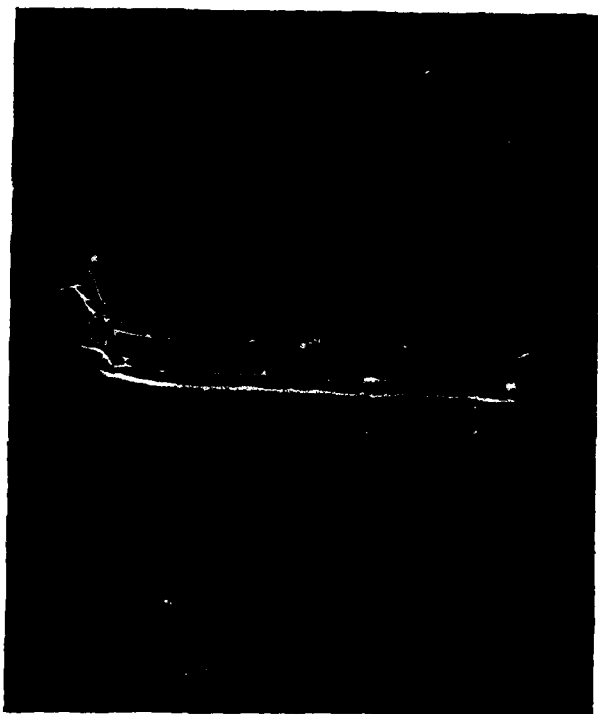
Figure 5.1  
9310 Specimen



(a)



(b)



(c)



(d)

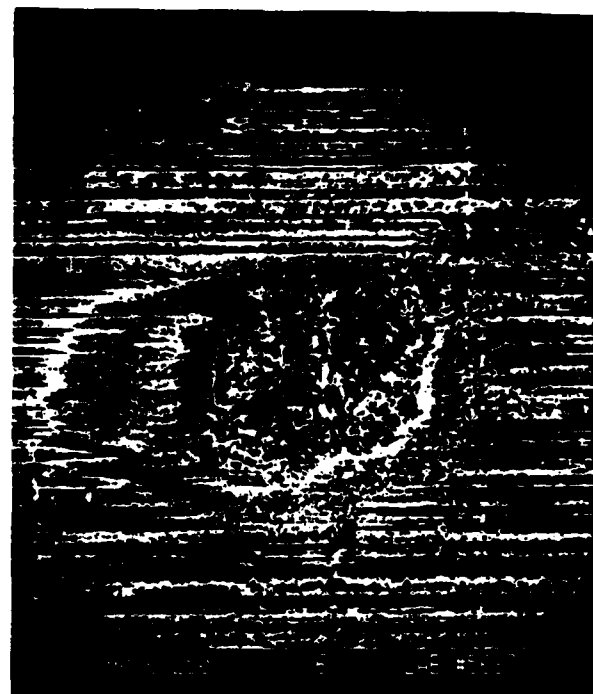
Figure 5.2  
M50 Specimen

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.

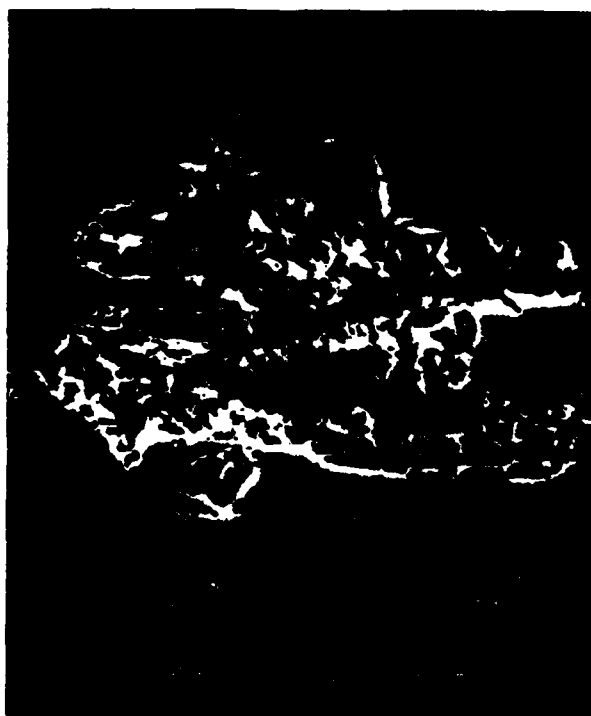
Other than the visual difference between polished and tumbled specimens, the SEM photos were too varied to suggest systematic behavioral differences due to the differences in material and lubricants.



(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:

| <u>Factor</u> | <u>-</u>    | <u>+</u>  |
|---------------|-------------|-----------|
| 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.

| <u>Effect Name</u> | <u>Effect Value</u> |
|--------------------|---------------------|
| 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 O 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.

|             |             |            |
|-------------|-------------|------------|
|             | <u>9310</u> | <u>M50</u> |
| 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.

|                  |              |            |
|------------------|--------------|------------|
|                  | <u>23699</u> | <u>555</u> |
| Material Effect: | -264         | -2.25      |

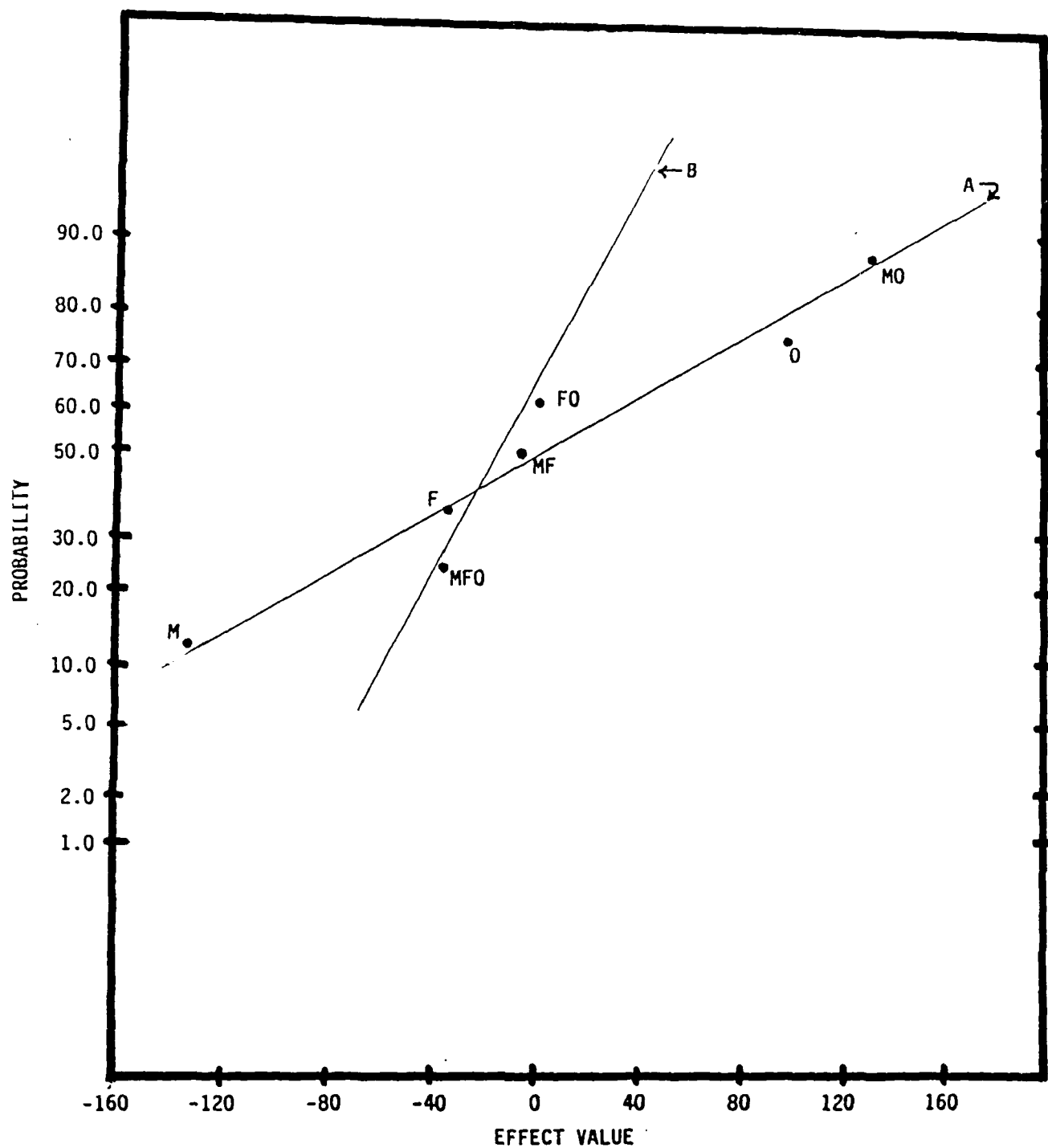


FIGURE 6.1  
Data Analysis of Micropitting Test Results

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  $\Delta_q$  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  $\Delta_q$  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  $\mu$  inch range. The other specimens vary over the 10-16  $\mu$  inch range.

TABLE 7.1

Averages of Six Axial and Circumferential Readings of  $R_q$  and  $\Delta_q$  for  
Micropitting Specimens Prior to Test

| SPECIMEN<br>NUMBER | MATERIAL | FINISH      | AXIAL               |                        | CIRCUMFERENTIAL     |                        |
|--------------------|----------|-------------|---------------------|------------------------|---------------------|------------------------|
|                    |          |             | $R_q(\mu\text{in})$ | $\Delta_q(\text{deg})$ | $R_q(\mu\text{in})$ | $\Delta_q(\text{deg})$ |
| 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  $R_q$  and  $\Delta q$  for Micropitting Specimens  
After Test

| SPECIMEN<br>NUMBER | MATERIAL | OIL   | FINISH   | AXIAL               |            |
|--------------------|----------|-------|----------|---------------------|------------|
|                    |          |       |          | $R_q(\mu\text{in})$ | $\Delta q$ |
| 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  $\Delta_q$  using the methodology 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  $h/\sigma$ .

TABLE 7.3  
Ruffian Output for Unrun Specimens

| SPECIMEN<br>NUMBER | MATERIAL | FINISH   | P /Ac<br>(ksi) | N <sub>p</sub><br>(in <sup>-2</sup> ) | N <sub>p</sub> /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  $h/\sigma$ ,  $N_p/N$  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  $h/\sigma$ . 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 (KSI) | N <sub>P</sub> (10 <sup>6</sup> ) | N/N <sub>P</sub> | 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        |

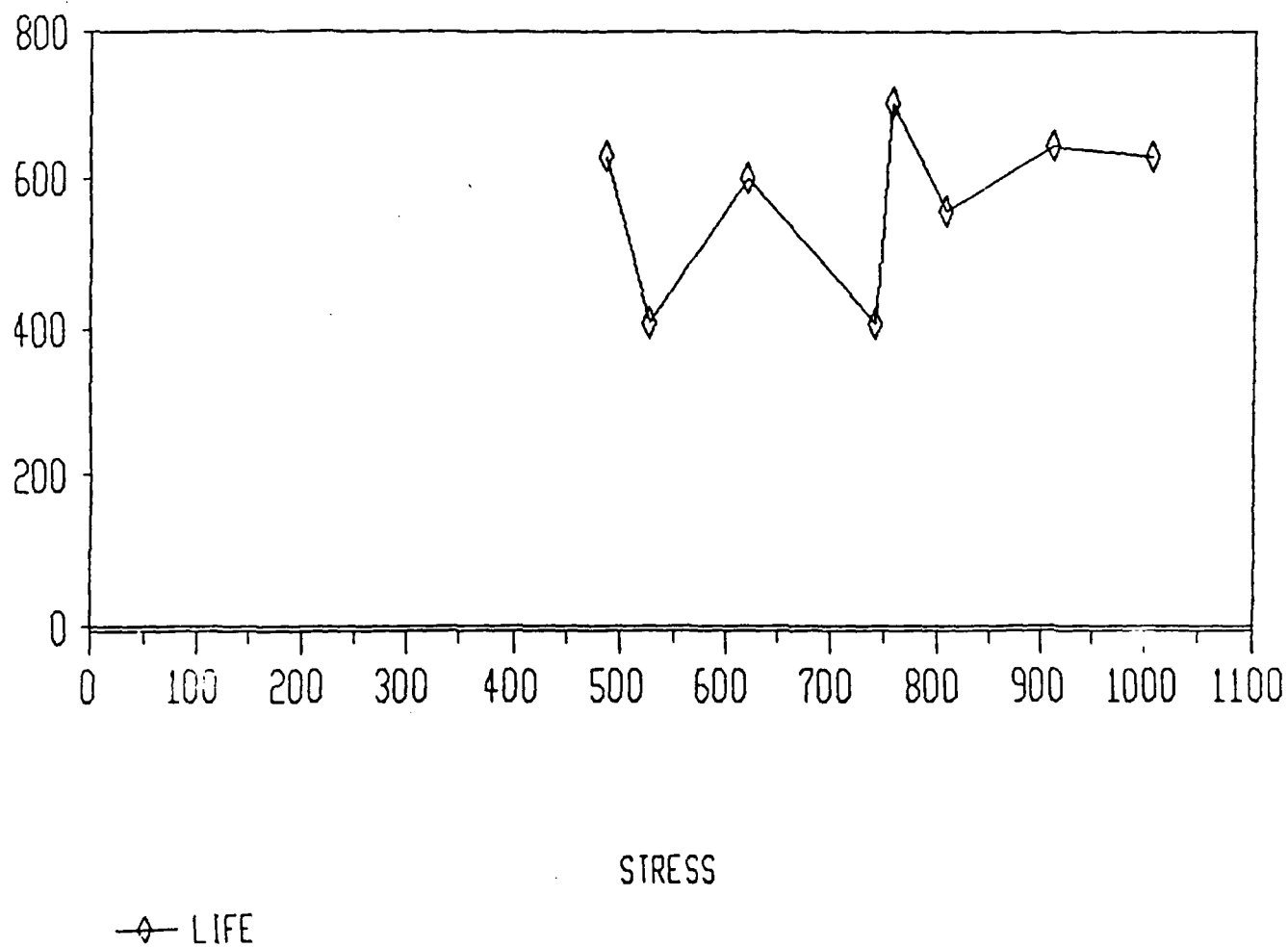


FIGURE 7.1  
Geared Roller Life Vs. Mean Real Stress

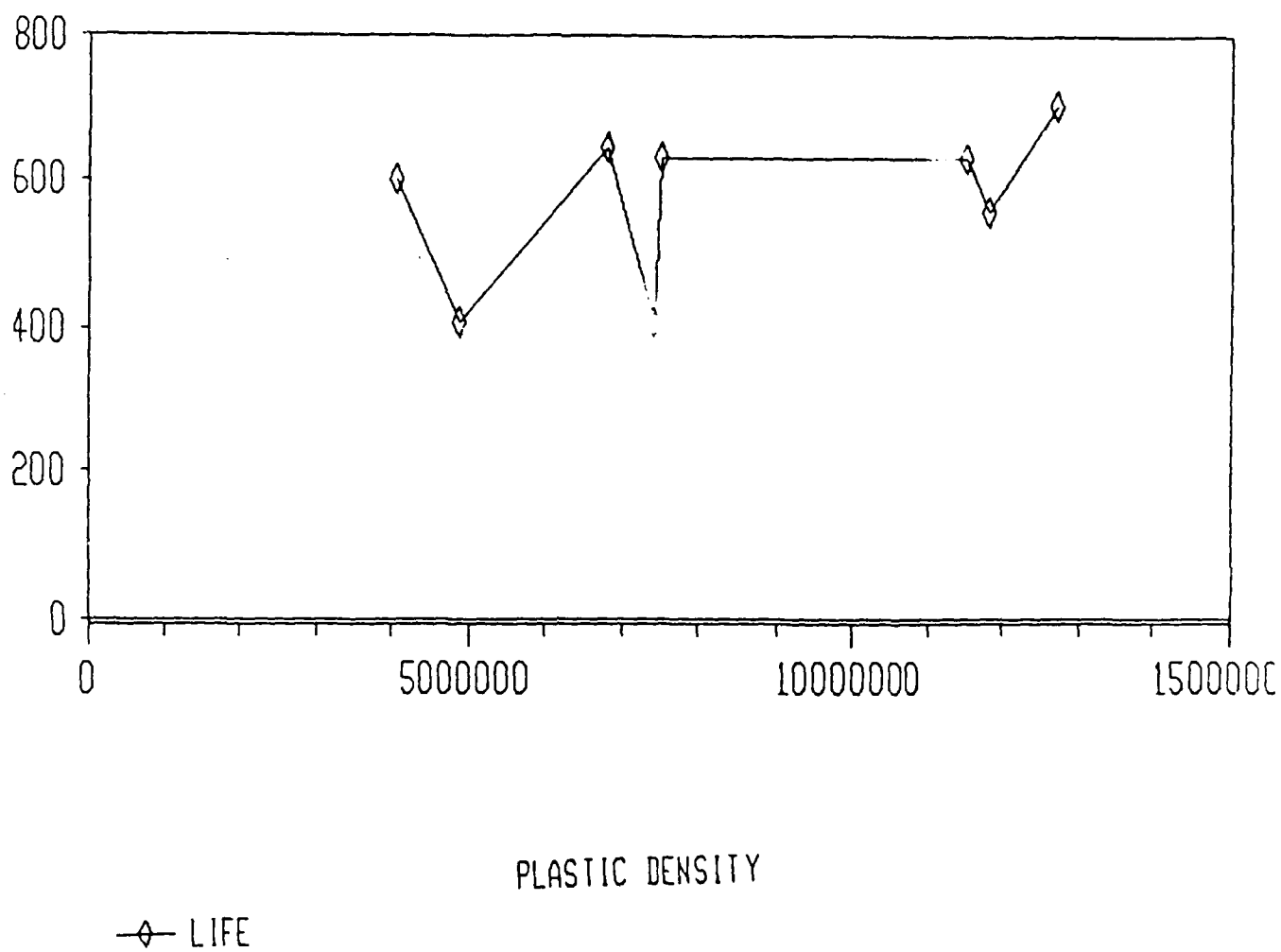


FIGURE 7.2  
Geared Roller Life Vs. Plastic Density

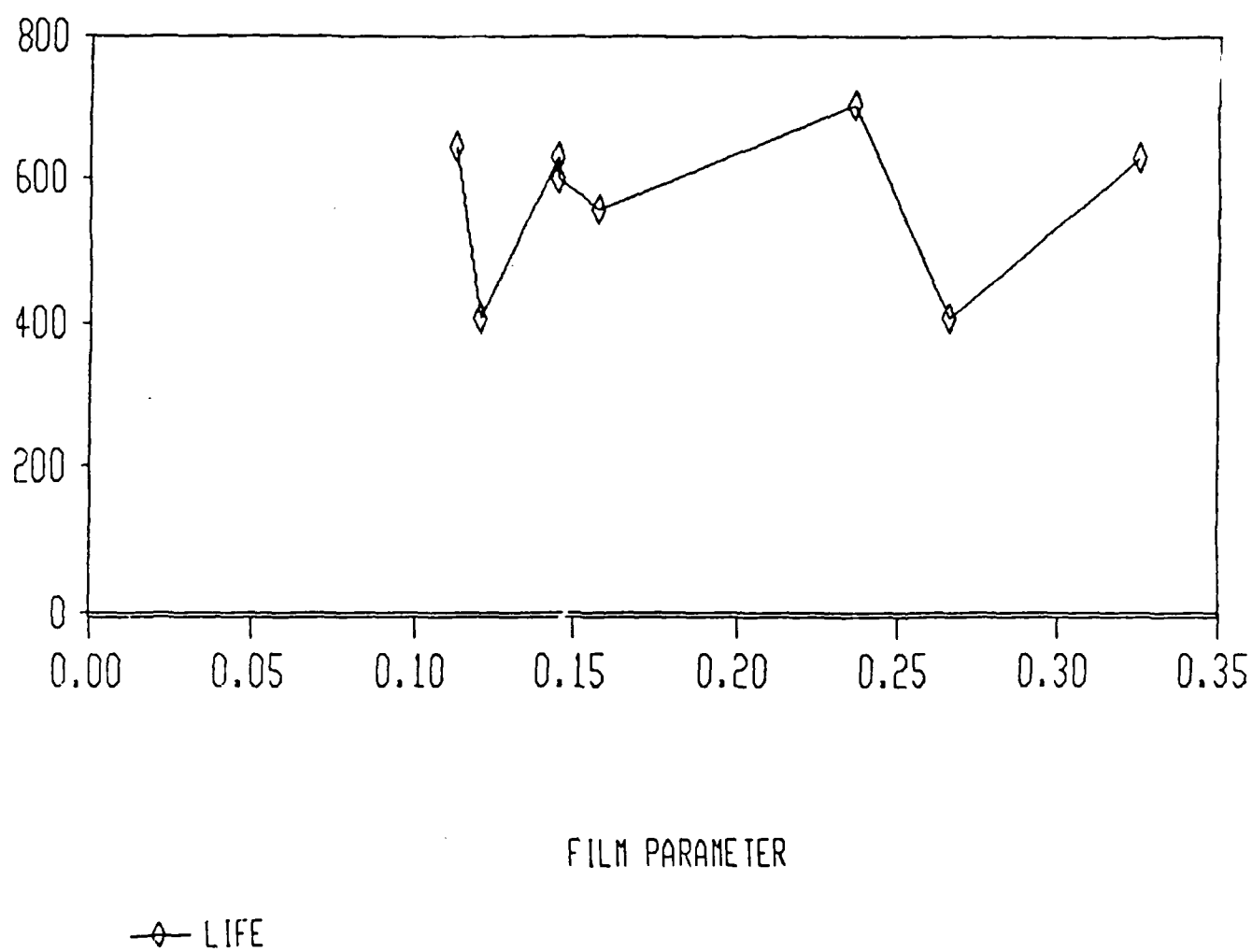


FIGURE 7.3  
Geared Roller Life Vs. Film Parameter

| <u>Effect</u> | <u>P/A<sub>c</sub></u> | <u>N<sub>p</sub>/N</u> | <u>N<sub>p</sub></u> |
|---------------|------------------------|------------------------|----------------------|
| 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<sub>c</sub> 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 understand the 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.

| <u>Response<br/>Variable</u> | <u>23699</u> | <u>555</u> |
|------------------------------|--------------|------------|
| $P/A_c$                      | -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  $P/A_c$ ,  $N_p/N$  and  $N_p$ . 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 than 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.

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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

TITLE: Failed M-50 Alloy Helicopter  
Rotor Bearing

REFERENCE: Lab No. 1497

REPORT NO: AT83M003L  
PROJECT CODE: L0914  
DATE: January 5, 1985  
FROM: A. S. DiGiorgio  
COPIES TO: J. Phinney  
F. Morrison  
G. Baile  
Laboratory  
Library

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.

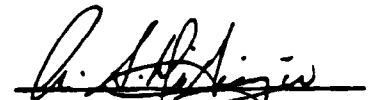
The split inner ring sustaining the lower load displayed adhesive wear 360° around the bottom half of the side face. Seized particles were evident, probably resulting by sliding contact against another metallic component during operation (see Figure 3).

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.

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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  $\leq 1/2$ . 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

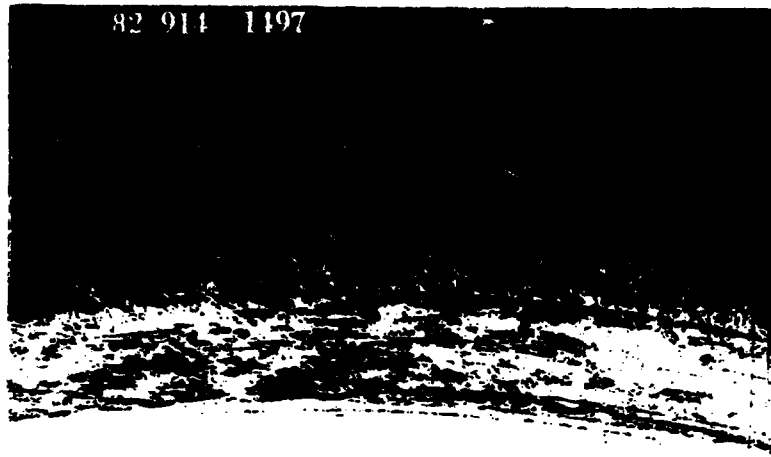


Figure A-3 Inner ring side face displaying seized metallic particles due to adhesion.  
Mag.: 5X



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. Micro-cracks are evident emanating from micro-spalls. The black features are oil residue. Mag.: 1000X



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



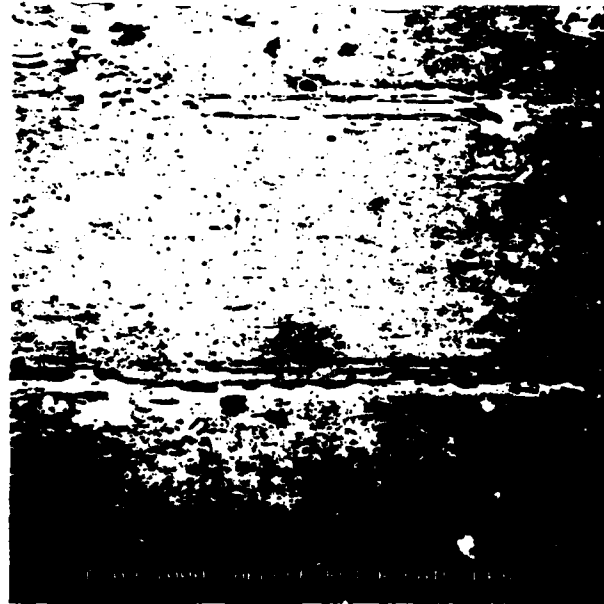


Figure A-7 Same as Figure 4. Surface finish near the opposite edge of the load zone showing remnants of grinding furrows. White particles on surface identified as silver (shown in the Figure 8). Magn.: 1000X

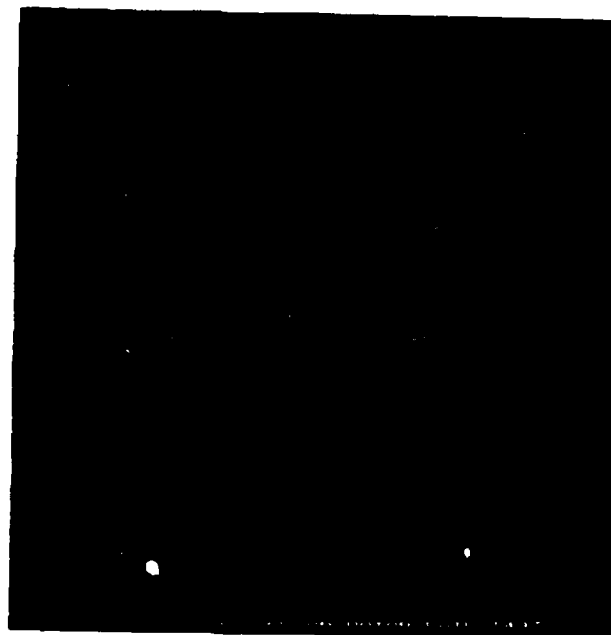


Figure A-8 SEM microprobe displays x-ray map showing silver concentrations. Mag.: 1000X



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

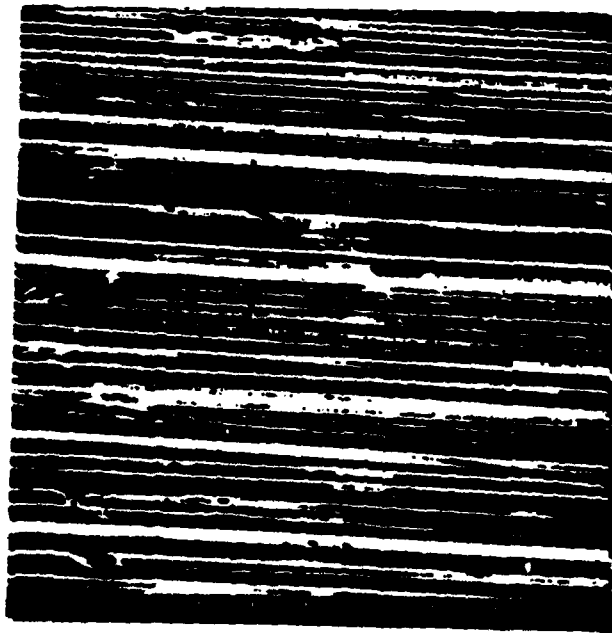


Figure A-10 Raceway of the inner ringsustaining the light load. Surface finish near the land contains unaffected grinding furrows.  
Mag.: 1000X



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

TITLE: Failed Helicopter Transmission  
Bearings

REFERENCE: Lab. No. 2401

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

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 appear 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.

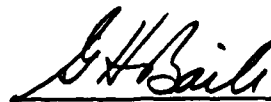
Scanning Electron Microscope (SEM) examination of the roller paths of both inner rings was conducted. The surface of S/N 3922 shows wide spread and generalized surface distress typical of rather heavy interaction of the surface asperities on the rings and rolling elements. As shown in Figures 3 and 4 many of the fine finishing lines have been obliterated by a cold working of the surface leaving only the

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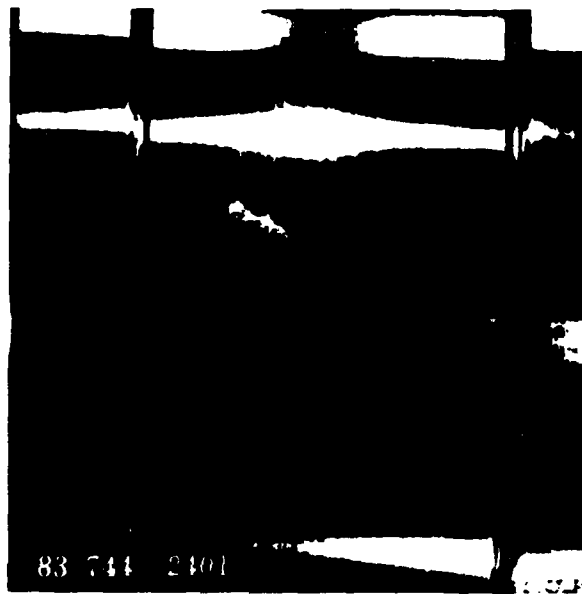
heavier finishing lines still visible. This condition is evident both at a distance from the highly distressed area as typified by Figure 3 as well as in the load zone typified by Figure 4. It can also be seen within the distressed area the surface is virtually covered with small superficial spalls. 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  $360^\circ$  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



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.



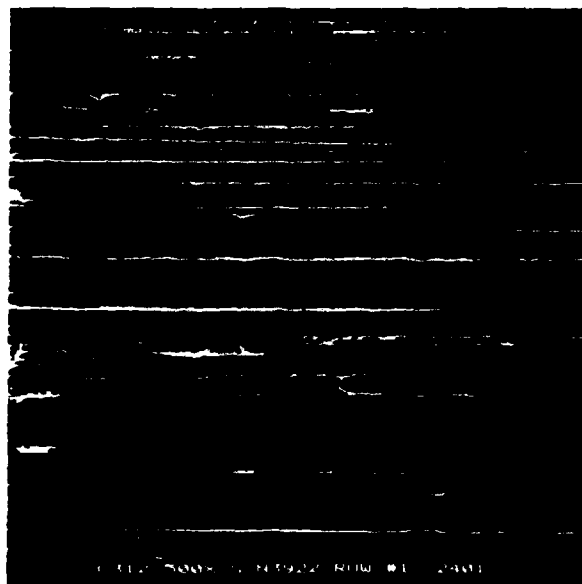


Figure B-3

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

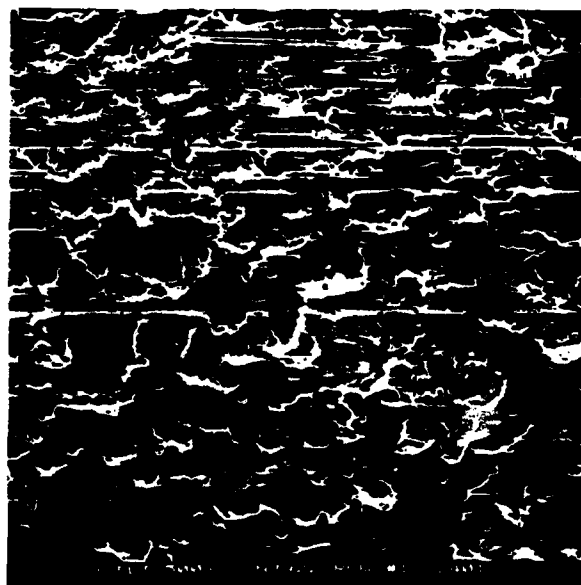


Figure B-4

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.

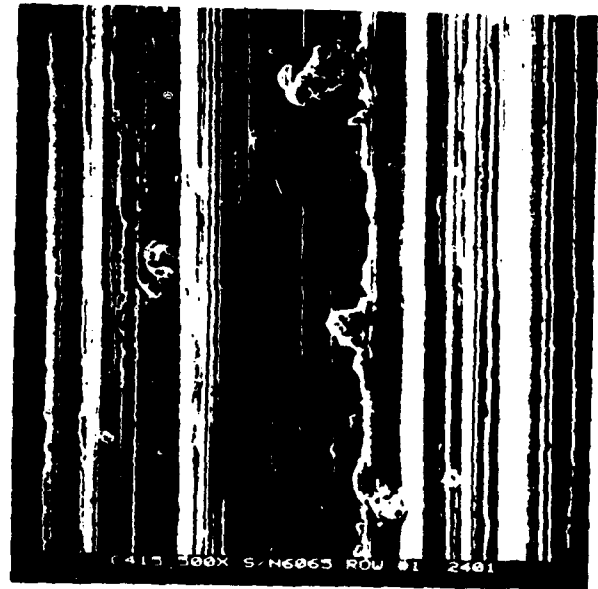
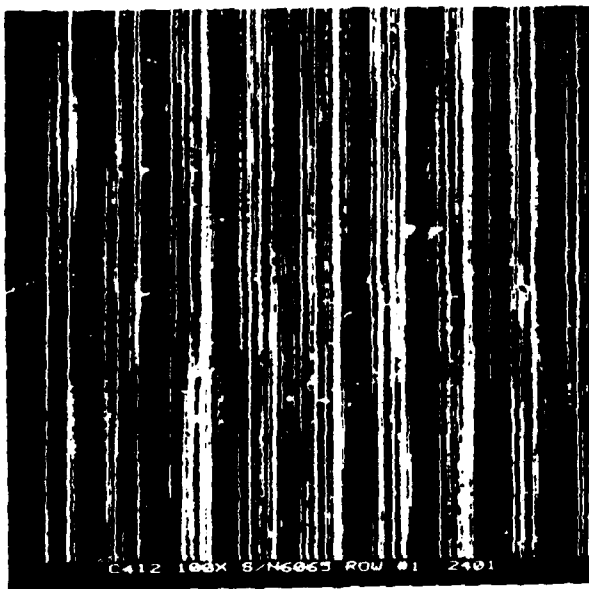


Figure B-5

SEM Photograph at Two Magnifications of Inner Ring  
Rolling Path (S/N # 65) Away From Distressed Area  
Showing Occasional Small Spall and Slightly Deformed  
Surface Material.

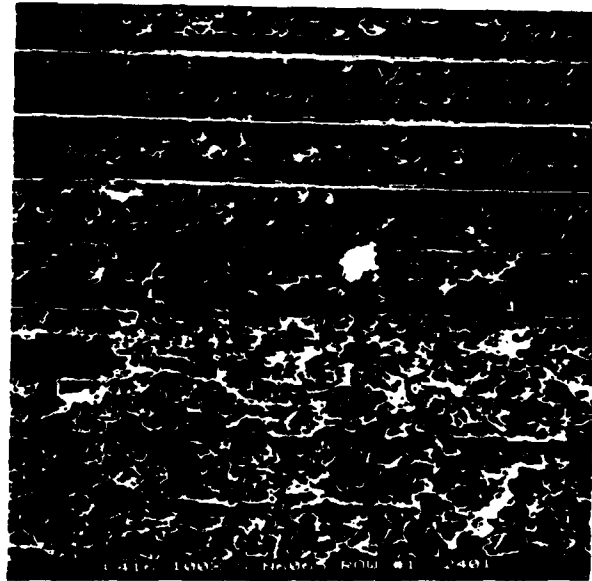


Figure B-6

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

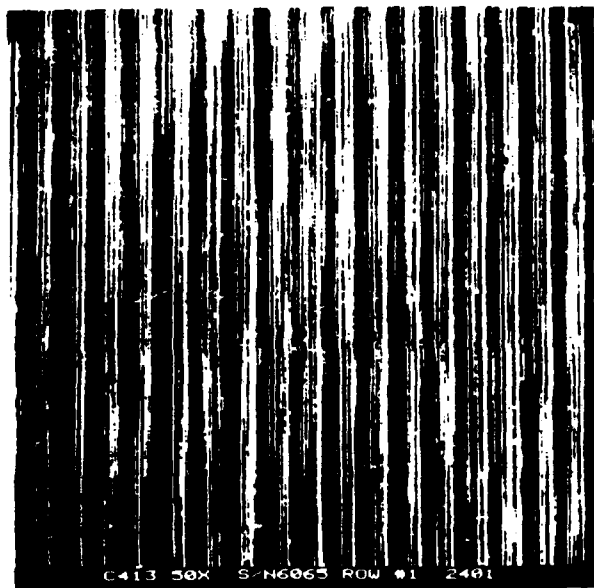


Figure 3-7

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".

P-4185C-1-1-81100

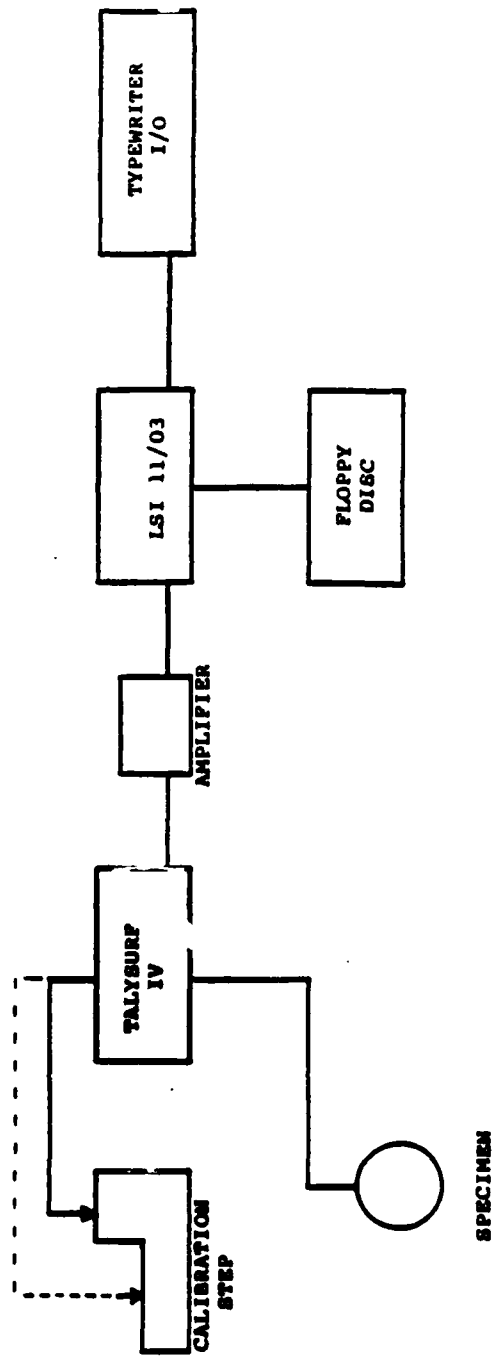


Figure C-1 ROUGHNESS DATA ACQUISITION SYSTEM



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 change 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

8-0105C-1-8100

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 dif-

ference 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.

P-4183C-1-8100

APPENDIX D

"EVALUATION OF THE LSI/11 ROUGHNESS

DATA PROCESSING SYSTEM"

## LETTER REPORT

TO: L. D. Wedeven

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

REFERENCE:

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

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  $\mu\text{m}$  or 40  $\mu\text{in.}$  and a period of 100  $\mu\text{m}$  or 4000  $\mu\text{in.}$  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  $\mu\text{in}$  height. The digitized values of the two levels of the step were then equated to 118  $\mu\text{in}$  within the program to derive a calibration factor of .0527  $\mu\text{in}$  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  $\mu\text{in.}$  Dividing 200  $\mu\text{in}$  by 4096 the full scale of the digitized values, gives a constant of .0488  $\mu\text{m}$  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

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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  $60 \times .004 \text{ in.} = .24 \text{ in.}$  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 theoretical 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).

|       | <u>MEASURED</u><br><u>LSI/11</u> | <u>(NOMINAL)</u><br><u>THEORETICAL</u> | <u>TALYDATA</u>                  |
|-------|----------------------------------|----------------------------------------|----------------------------------|
| $m_0$ | 2297                             | 1971.4                                 | $1831.8 = (R_q)^2$               |
| $m_2$ | $6.13E-3$                        | $4.87E-3$                              | $5.37E-3 = [180/\pi \Delta q]^2$ |
| $m_4$ | $1.77E-8$                        | $1.20E-8$                              | 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:

$$m_2 = 5.26E-3 \quad m_4 = 1.52E-8$$

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*

---

John I. McCool

JIM/amh

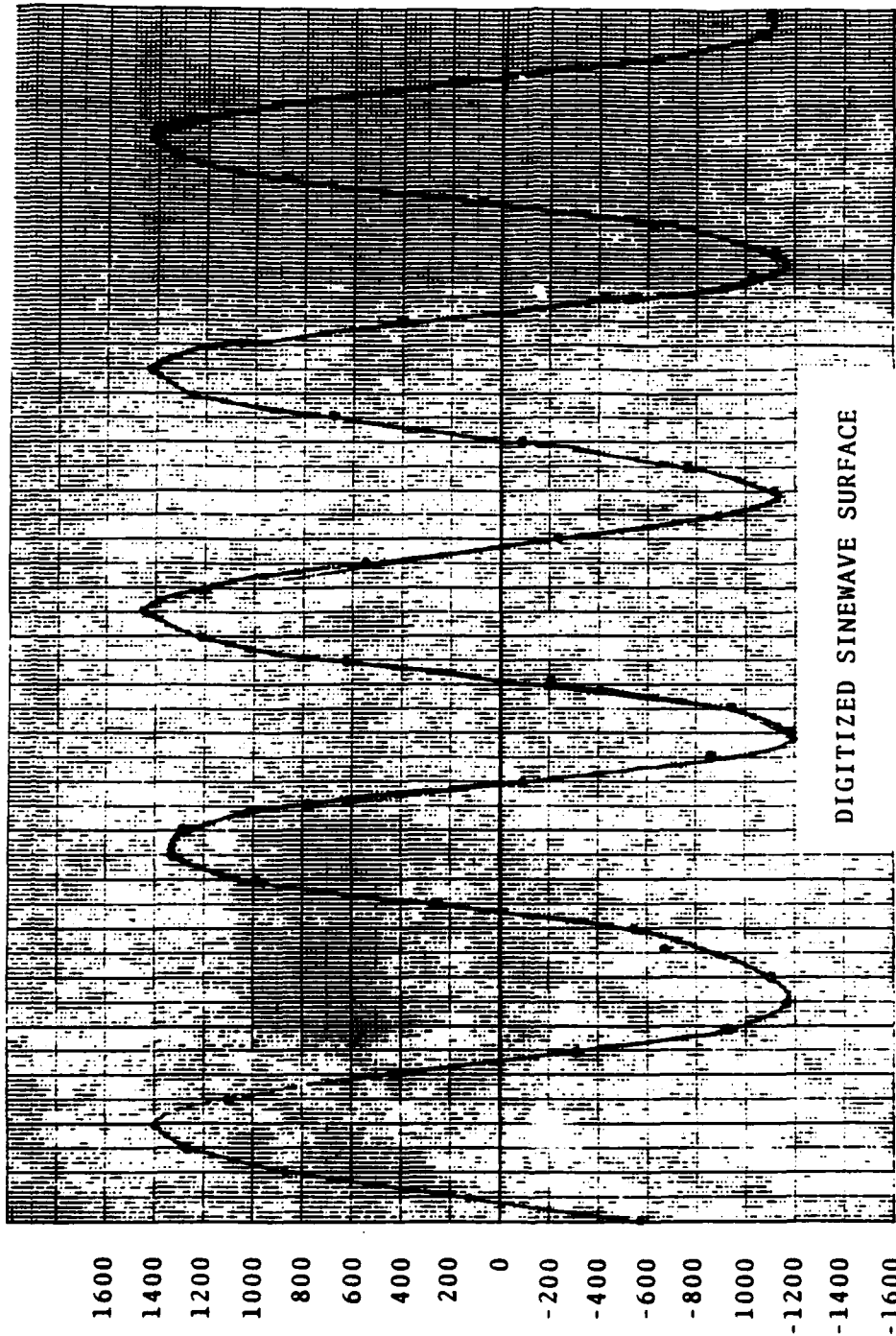


Figure D-1



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 (RADIAN\$)                |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .00000 (RADIAN\$)                |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .03701 (RADIAN\$)                |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

CALCULATED ROUGHNESS PARAMETERS

|                                              |         |                                  |
|----------------------------------------------|---------|----------------------------------|
| SPECTRAL EXPONENT                            | K =     | 1.91318 (NON-DIM)                |
| ZERO-TH ORDER SPECTRAL MOMENT                | M0 =    | 3.24300E-02 (MUM <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 1.37000E-03 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 8.74000E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| SUMMIT RADIUS                     | R =      | 2.26770E-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<sup>2</sup>)  
 AC/AO = REAL CONTACT AREA FRACTION  
 P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER  
 UNIT NOMINAL AREA (N/MM<sup>2</sup>)  
 P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD  
 PER UNIT REAL CONTACT AREA (N/MM<sup>2</sup>)  
 NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM<sup>2</sup>)  
 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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .00000 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .05831 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

CALCULATED ROUGHNESS PARAMETERS

|                                              |         |                                  |
|----------------------------------------------|---------|----------------------------------|
| SPECTRAL EXPONENT                            | K =     | 1.69747 (NON-DIM)                |
| ZERO-TH ORDER SPECTRAL MOMENT                | M0 =    | 3.95000E-02 (MUM <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 3.40000E-03 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.66000E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| SUMMIT RADIUS                     | R =       | 1.63095E-02 (MM)                |
| STANDARD DEVIATION OF SUMMIT HTS. | SIGMA S = | 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<sup>2</sup>)  
 AC/AO = REAL CONTACT AREA FRACTION  
 P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER  
 UNIT NOMINAL AREA (N/MM<sup>2</sup>)  
 P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD  
 PER UNIT REAL CONTACT AREA (N/MM<sup>2</sup>)  
 NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM<sup>2</sup>)  
 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 (NUM)  
ROOT MEAN SQUARE SURFACE HEIGHT OF BODY 2 RQ2 = .00000 (NUM)  
COMPOSITE ROOT MEAN SQUARE SURFACE HEIGHT RQ = .57735 (NUM)  
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 1 DELQ1 = .00000 (RADIAN)  
ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2 DELQ2 = .00000 (RADIAN)  
COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE DELQ = .14107 (RADIAN)  
LOWER FREQUENCY LIMIT F1 = .00200 (NUM<sup>-1</sup>)  
UPPER FREQUENCY LIMIT F2 = .40000 (NUM<sup>-1</sup>)  
MODIFIED ELASTIC MODULUS EPRIME = 1.11785E+05 (N/MM<sup>2</sup>)  
TENSILE YIELD STRENGTH Y = 2070.0000 (N/MM<sup>2</sup>)

CALCULATED ROUGHNESS PARAMETERS

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

CALCULATED CONTACT MODEL PARAMETERS:

CONTACT DENSITY DSUM = 1.18670E+04 (MM<sup>-2</sup>)  
SUMMIT RADIUS R = 7.56777E-03 (MM)  
STANDARD DEVIATION OF SUMMIT HTS. SIGMAS = 5.35973E-01 (NUM)

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<sup>2</sup>)
- AC/AO = REAL CONTACT AREA FRACTION
- P/AO = NOMINAL PRESSURE:MEAN CONTACT LOAD PER  
UNIT NOMINAL AREA (N/MM<sup>2</sup>)
- P/AC = TRUE AVERAGE PRESSURE:MEAN CONTACT LOAD  
PER UNIT REAL CONTACT AREA (N/MM<sup>2</sup>)
- NP = DENSITY OF PLASTIC CONTACTS (CONTACTS/MM<sup>2</sup>)
- 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 *RB*

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 micropitting 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).

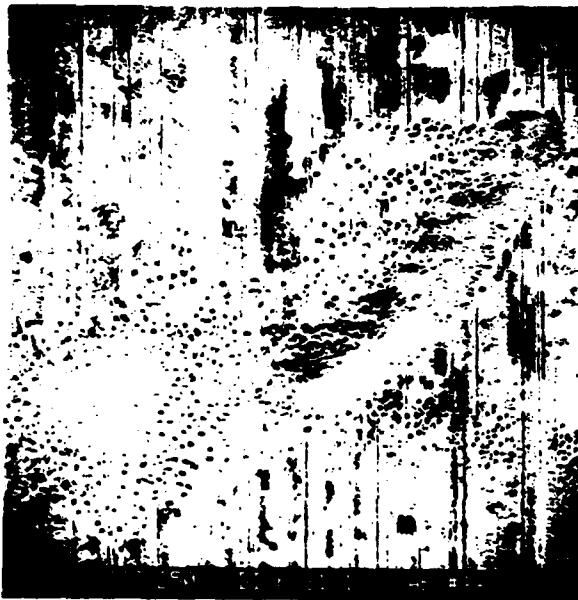
Figure 2 (a) shows another example of the characteristic denting on S181, and Figure 2 (b) shows a similar manifestation on S182.

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).

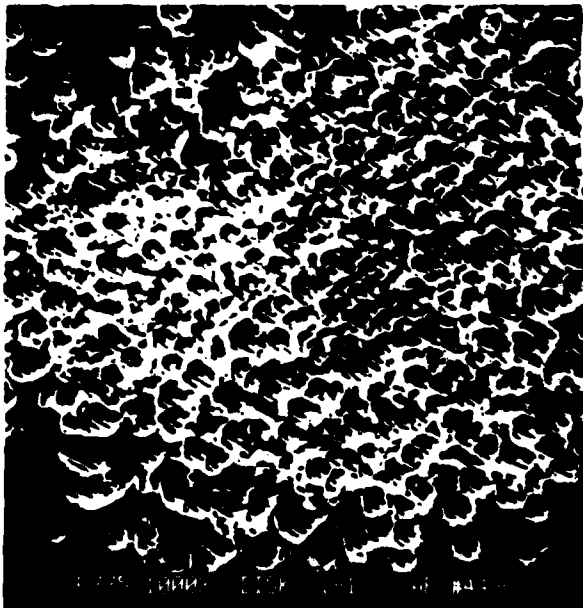
Figure 5 shows curiously arranged patterns of stippled dents, as well as larger debris dents on S182.



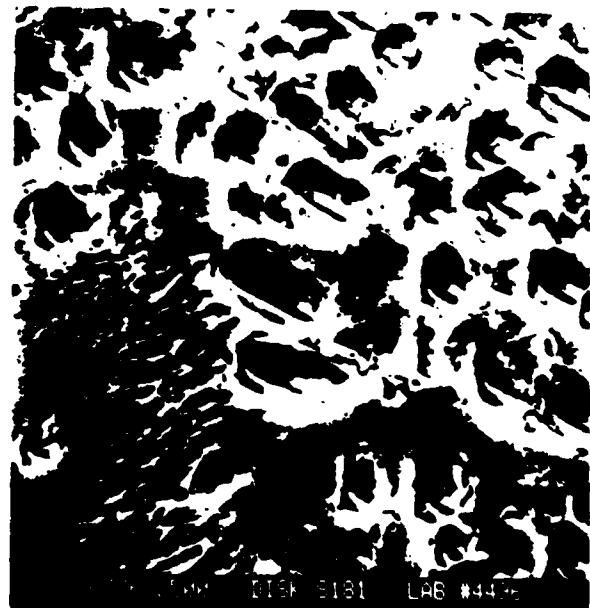
1 (a)



1 (b) Circular Region  
in 1 (a)



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

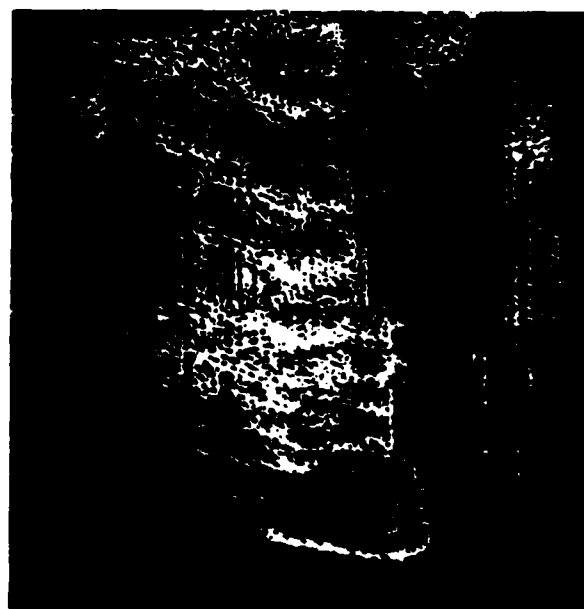


1 (d) Higher Magnification  
of 1 (c)

Figure F-1  
Most Frequent Debris Denting Manifestation



2 (a)

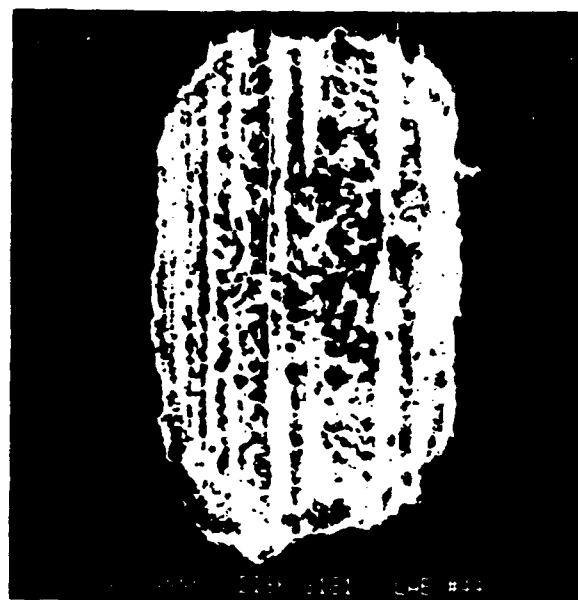


2 (b)

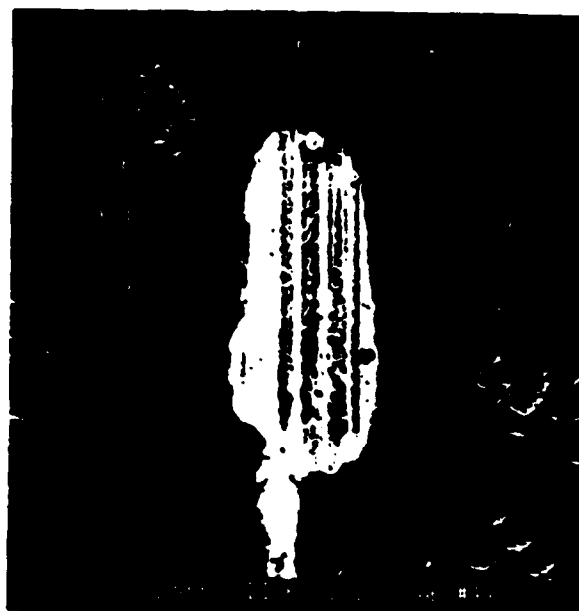
Figure F-2  
Additional Examples of Most Frequent Debris Denting Manifestations



3 (a)

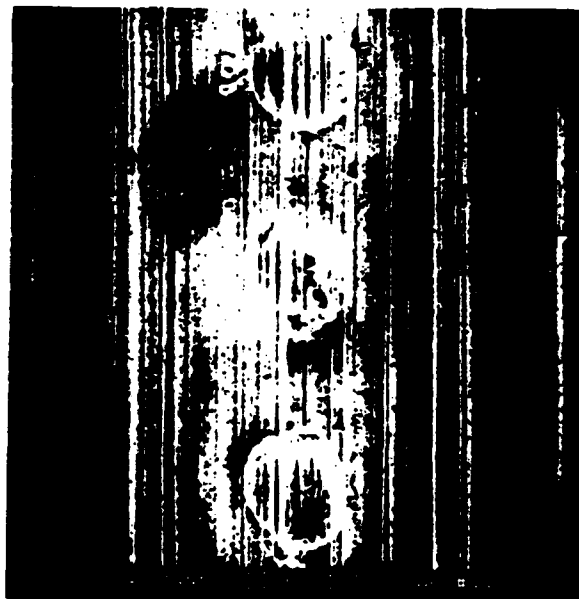


3 (b) Higher Magnification  
of Region in 3 (a)



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

Figure F-3  
Localized Removal of Shallow 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,TUMBLER,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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .02570 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .03370 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 1.13573E-03 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.61217E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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,TUMBLLED,UNRUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

|                                                  |          |                                 |
|--------------------------------------------------|----------|---------------------------------|
| MAXIMUM CONTACT STRESS                           | SIGMA0 = | .24413E+04 (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .31155E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .81048E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .22103E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .03140 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .04281 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 1.83277E-03 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 2.87146E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29320E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60697E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .36029E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .10036E+05  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .24936E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .02790 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .03404 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 1.15866E-03 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.87332E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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                           | SIGMA0 = | .24413E+04 (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .25627E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .76344E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .25057E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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      | (RADIAN)             |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .03890      | (RADIAN)             |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .06109      | (RADIAN)             |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200      | (MUM <sup>-1</sup> ) |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000      | (MUM <sup>-1</sup> ) |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 | (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000   | (N/MM <sup>2</sup> ) |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 3.73162E-03 | (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 6.71123E-03 | (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAUO =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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                      | .11140E+00  |
| D/SIGMAS | STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE                    | -.95698E-01 |
| AC/AO    | REAL CONTACT AREA FRACTION                                        | .31541E+00  |
| P/AO     | MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM <sup>2</sup> )      | .42819E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .13575E+05  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .29646E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .28857E+05  |
| AP/AO    | 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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01870 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .02616 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 6.84580E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.24365E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .13851E+04 |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .53150E+04 |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .26585E+05 |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01900 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .02817 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>-2</sup> ) |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 7.93640E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.02112E-03 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .28201E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .69257E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .19732E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .7853E+05   |
| AP/A0    | AREA OF PLASTIC CONTACTS PER UNIT NOMINAL AREA                    | .90479E+00  |
| NP/N     | FRACTION OF PLASTIC CONTACTS                                      | .96414E+00  |
| AP/AC    | AREA OF PLASTIC CONTACTS PER UNIT REAL AREA                       | .97075E+04  |
| PEL      | TOTAL LOAD TO ELASTICALLY DEFORM ASPERITIES (N)                   | -.16715E+04 |
| PF       | TOTAL LOAD DUE TO FLUID PRESSURE AT ASPERITIES (N)                | .80360E+04  |
| PASP     | TOTAL LOAD CARRIED BY ASPERITIES (N)                              | .14017E+01  |
| AC       | REAL CONTACT AREA (MM <sup>2</sup> )                              |             |

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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01130 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .01577 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 2.48690E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 1.38092E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .20705E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .42741E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .83739E+04  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01260 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .01884 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 3.54760E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 2.11397E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .25562E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .51240E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .91207E+04  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .00890 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .01510 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 2.28050E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 2.89501E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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                           | SIGMAO = | .24413E+04 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAUO =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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                      | .26642E+00 |
| D/SIGMAS | STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE                    | .12116E+00 |
| AC/AO    | REAL CONTACT AREA FRACTION                                        | .34077E+00 |
| P/AO     | MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM <sup>2</sup> )      | .12427E+04 |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .36466E+04 |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .17566E+05 |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .11533E+05 |
| AP/AO    | 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 <sup>2</sup> )                              | .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      | (RADIAN)             |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01050      | (RADIAN)             |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .02721      | (RADIAN)             |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200      | (MUM <sup>-1</sup> ) |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000      | (MUM <sup>-1</sup> ) |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 | (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000   | (N/MM <sup>2</sup> ) |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 7.40260E-04 | (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 9.94038E-04 | (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .25629E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .65694E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .20452E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01937 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .02316 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 5.36487E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 4.15259E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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, TUMBLER, RUN

CALCULATED HERTZIAN CONTACT PARAMETERS:

|                                                  |          |            |                      |
|--------------------------------------------------|----------|------------|----------------------|
| MAXIMUM CONTACT STRESS                           | SIGMA0 = | .24413E+04 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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                      | .11345E+00  |
| D/SIGMAS | STANDARDIZED SEPARATION FROM SUMMIT MEAN PLANE                    | -.82482E-02 |
| AC/A0    | REAL CONTACT AREA FRACTION                                        | .49436E+00  |
| P/A0     | MEAN CONTACT LOAD PER UNIT NOMINAL AREA (N/MM <sup>2</sup> )      | .31091E+04  |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .62892E+04  |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .11932E+05  |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .10548E+05  |
| AP/A0    | 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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01540 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .02384 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 5.68400E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 9.22459E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .15787E+04 |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .52198E+04 |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .23734E+05 |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .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 (RADIAN)                  |
| ROOT MEAN SQUARE PROFILE SLOPE OF BODY 2  | DELQ2 =  | .01010 (RADIAN)                  |
| COMPOSITE ROOT MEAN SQUARE PROFILE SLOPE  | DELQ =   | .01479 (RADIAN)                  |
| LOWER FREQUENCY LIMIT                     | F1 =     | .00200 (MUM <sup>-1</sup> )      |
| UPPER FREQUENCY LIMIT                     | F2 =     | .40000 (MUM <sup>-1</sup> )      |
| MODIFIED ELASTIC MODULUS                  | EPRIME = | 1.11785E+05 (N/MM <sup>2</sup> ) |
| TENSILE YIELD STRENGTH                    | Y =      | 2070.0000 (N/MM <sup>2</sup> )   |

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 <sup>2</sup> /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 <sup>2</sup> )  |
| 2-ND ORDER SPECTRAL MOMENT                   | M2 =    | 2.18650E-04 (NON-DIM)            |
| 4-TH ORDER SPECTRAL MOMENT                   | M4 =    | 3.19911E-04 (MUM <sup>-2</sup> ) |
| 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 <sup>-2</sup> ) |
| 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 <sup>2</sup> ) |
| 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 <sup>2</sup> )   |
| CONTACT TOTAL ELASTIC APPROACH                   | DELTA =  | .29319E-01 | (MM)                 |
| MAXIMUM ORTHOGONAL SHEAR STRESS                  | TAU0 =   | .60695E+03 | (N/MM <sup>2</sup> ) |
| 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 <sup>2</sup> )      | .95737E+03 |
| P/AC     | MEAN CONTACT LOAD PER UNIT REAL CONTACT AREA (N/MM <sup>2</sup> ) | .33528E+04 |
| N        | CONTACT DENSITY (CONTACTS/MM <sup>2</sup> )                       | .19486E+05 |
| NP       | DENSITY OF PLASTIC CONTACTS (CONTACTS/MM <sup>2</sup> )           | .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 <sup>2</sup> )                              | .98291E+00 |

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