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EFFECT OF LONGITUDINAL SURFACE FINISH ON ELASTOHYDRODYNAMIC LUBRICATION

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16. Abstract
A rolling-disk apparatus was used to evaluate the effect of longitudinal-lay surface finish on elastohydrodynamic (EHD) film thickness and percentage of film between rolling disks in contact. Film thickness was measured by transmitted X-rays. Percentage of film was monitored by using an alternating-current continuity circuit. Disk finish was varied on both the crowned upper disk and the cylindrical lower disk over the range from polished to rough (0.025 to 0.56 μm centerline average (cla)). A type II ester and a synthetic paraffinic oil were used as lubricants. The experiments indicated that the roughness with longitudinal lay has a deleterious effect on both film thickness and percentage of film. Measured film thicknesses for the two lubricants were comparable at equivalent test conditions. The percentage of film where a change in surface topography was observed was approximately 20 percent for the synthetic paraffinic oil and 10 percent for the type II ester.

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EFFECT OF LONGITUDINAL SURFACE FINISH ON ELASTOHYDRO-DYNAMIC LUBRICATION

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SUMMARY

A rolling-disk apparatus was used to evaluate the effect of surface roughness with the lay in the longitudinal direction on elastohydrodynamic (EHD) film thickness and percentage of film between two disks in rolling contact. The film thickness was measured by using a calibrated X-ray technique. The percentage of film between disks was monitored by using an alternating-current continuity circuit. The percentage of film at conditions where a change in surface topography could be detected was determined. This is termed the critical percentage of film.

Disk temperature was varied from 339 to 422 K (150° to 300° F). The loading was such that the maximum Hertz stress on the disks ranged from 689 to 2070 MPa (100 000 to 300 000 psi). Shaft speeds of 5000 to 20 000 rpm resulted in surface speeds of 9.4 to 37.6 m/sec (370 to 1480 in./sec). Four levels of surface finish from polished to rough (0.025 to 0.56 μm (1 to 22 μin.) centerline average (cla)) were used, with the lay of the finish around the circumference of the disk. Two lubricants were used: an advanced type II ester and a synthetic paraffinic oil.

Measured film thicknesses with polished mating disks were similar to those reported in previous studies; and similar trends with speed, load, and temperature were observed. When the roughness of the upper or lower disk was increased, the measured film thickness decreased for equivalent operating conditions. Measured film thicknesses were comparable for the synthetic paraffinic oil and the type II ester for disks of similar roughness and equivalent test conditions.

The synthetic paraffinic oil generally showed a higher percentage of film for the same measured film thickness than did the type II ester. The percentage of films where changes in surface topography occurred were approximately 20 for the synthetic paraffinic oil and 10 for the type II ester.

Very thin EHD films and a low percentage of film were observed with the rough-on-rough disks, even for relatively mild operating conditions. At higher temperatures, the surface topography was drastically modified for even the mildest operating conditions.

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INTRODUCTION

Efforts to understand the lubrication of rolling-element bearings has led to the development of elastohydrodynamic (EHD) lubrication theory (refs. 1 and 2). The theoretical developments and the majority of the EHD film thickness measurements have been limited to studying the interaction of the lubricant with ideally smooth surfaces. However, real bearing and gear surfaces are not ideal. The height of asperities on the surfaces of bearings and gears can be of the same order of magnitude as the thickness of the EHD films separating the surfaces. Thus, asperity interaction is not uncommon in bearing and gear applications. The ratio of EHD film thickness to a composite surface roughness has become an acceptable indicator of the effectiveness of the lubricant film within the rolling-element contact zone. This ratio has been experimentally shown to influence the fatigue life of rolling-element bearings (refs. 3 and 4). The film thickness used in this ratio is generally a calculated value based on ideally smooth surfaces.

The effect of surface roughness on EHD film thickness is not presently understood. Theories such as that of reference 5 have been proposed to explain the interaction of asperities in an EHD-lubricated contact. Experimental measurements of these effects are lacking. The work of reference 6 was limited to sliding point contacts.

The research described herein was conducted to determine (1) the effect of surface finish on the EHD film thickness generated in rolling contact and (2) the level of surface contact (or percentage of film) where changes in surface topography were observed. Experiments were conducted on a lubricated rolling-contact disk apparatus. The disks were finished to various levels of surface roughness with the lay in the direction of rolling (longitudinal). The range of roughnesses studied was from polished to typical gear-tooth finishes.

EHD film thickness and percentage of film were measured for a broad range of test conditions. The technique used to measure film thickness involved passing X-rays through the contact zone and calibrating the pickup system in terms of the gap between the disks. The percentage of film between disks was measured by using an alternating-current (ac) continuity circuit. The maximum Hertz stress was varied from 689 to 2070 MPa (100 000 to 300 000 psi). Shaft speeds of 5000 to 20 000 rpm yielded surface speeds from 9.4 to 37.6 m/sec (370 to 1480 in./sec). Disk temperatures were varied from 339 to 422 K (150° to 300° F). Disk surface roughness (as measured in the axial direction) was varied from polished to rough (0.025 to 0.56 μm (1 to 22 μin.) cla). Two lubricants were studied: a type II ester and a synthetic paraffinic oil.

These tests were made in the U.S. customary system of units. Conversion to the International System of Units (SI) was for reporting purposes only.

APPARATUS AND PROCEDURE

Rolling-Disk Apparatus

The rolling-disk apparatus is shown in figure 1 and was initially described in detail in reference 7. The disks are driven by two variable-speed, high-frequency induction motors (fig. 1(a)). Each disk is mounted on an auxiliary shaft fitted into the end of the motor shaft and is held by a precision taper fit. Disks are loaded by means of a pivot arrangement in the support for the upper motor to which dead weights are applied. Micrometer adjustment on the orientation of the upper disk allows precise alinement of the gap with respect to the X-ray beam.

Lubricant for the disks is circulated by a pump submerged in the oil sump and is fed to the contact zone by an oil jet. Before entering the contact zone, the lubricant passes through a series of filters that remove particulate contaminants and which are heated to keep the lubricant at the specified test temperature. The disks are surrounded by an induction heater that is used to heat the disks to the test temperature.

In order to establish a reproducible series of experiments, a multiple-disk arrangement containing a range of surface finishes was designed for the lower disk. The arrangement of the mating disks is shown in figure 1(b). The lower drive motor was in an adjustable mount such that the appropriate lower disk specimen could be easily centered under the upper disk. This arrangement allowed the range of surface finishes to be run in sequence and provided for easy back-checking of different finishes.

Both upper and lower disks had a diameter of 3.6 cm (1.42 in.). The lower disks were cylindrical, and the upper disk had a crown radius of 14 cm (5.50 in.). The disk material was AISI M-50 steel having a Rockwell C hardness of 60 to 61.

Four levels of disk surface finish were used. These levels are defined in table I. Scanning electron micrographs of the four levels of surface finish are shown in figure 2. Because the disk roughness was generated by cylindrical grinding, the lay of the finish was in the longitudinal (circumferential) direction. The different levels of finish were a result of varying the following grinding parameters: the rate of dressing the grinding wheel, the relative speed of disk and grinding wheel, and the feed rate of the grinding process.

The EHD film thickness was measured by a calibrated X-ray system consisting of an X-ray source that was aimed at the contact zone between the disks (fig. 1(a)). Since the steel disks were essentially opaque to the X-rays and the lubricants were nearly transparent, the transmitted X-rays were detected by a scintillation tube calibrated for a direct reading of film thickness. The X-rays were masked by a narrow gate so that only the minimum film thickness at the centerline of contact was measured. This minimum thickness occurs at the trailing edge of the contact. Care was taken to aline the upper disk under dynamic conditions such that the gap was centered and parallel to the X-ray beam. The film-thickness measurements made by the X-ray technique were generally reproducible to within 10 percent of the measured value or 0.05 μm (2 μin.) - whichever was higher.

The percentage of film was measured by using an ac continuity circuit (ref. 8), shown in figure 3. A high-frequency ac signal was applied to the insulated upper disk. The lower disk was grounded. When static contact was made, the voltage was zero. When no contact was made, the signal was unchanged. Intermittent contact between surfaces under thin-film conditions modified the applied signal. This modified signal was amplified, rectified, and fed into a voltage-to-frequency converter that integrated and quantified the voltage reading. The resulting output was a number between 0 and 100 which was a measure of the percentage of time when one opposing surface was separated from the other by an electrically insulating lubricating film, in other words, the "percentage of film." The percentage of contact is 100 minus the percentage of film.

Test Lubricants

The lubricants chosen for this program are of interest for bearing and gear applications. Properties of the test lubricants are given in table II. Viscosity-temperature characteristics are shown in figure 4.

Advanced type II ester. - The lubricant is a 5×10^{-6}-m^2/sec (5-cS) neopentylpolyol (tetra) ester for which a substantial amount of test data (ref. 9) is available. It is a type II ester qualified under MIL-L-23699.

Synthetic paraffinic oil. - The synthetic paraffinic oil is a type that has been studied extensively both with and without an antiwear additive. The lubricant used in this investigation contained an antiwear additive. It is from the same class of fluids previously reported in reference 10 but with a shorter chain length and, hence, a lower viscosity. This lubricant has provided excellent results in bearing fatigue tests at 492 K (425° F) (ref. 11).

Experimental Procedure

The sequence of steps performed for each rolling-sliding experiment was as follows: The crowned upper disk containing the specified surface finish was brought into static contact with a cylindrical lower disk. The X-ray emitter was energized, and the magnitude of the radiation reaching the detector was recorded for each static loading condition. The background radiation levels represent the baseline from which the film thickness was measured at each load. The values of background radiation are reduced as the load is increased and are increased as the roughness of the disk is increased. The film thickness equivalent to the background radiation varied from 0.02 μm (1 μin.) for polished disks at high load to a high of 0.25 μm (10 μin.) for rough disks at low loads.

Dynamic film-thickness and percentage-of-film data were first taken at conditions which were expected to produce the largest EHD film; that is, a disk temperature of 339 K (150^{o} F), a shaft speed of 20 000 rpm, and a maximum Hertz stress of 689 MPa (100 000 psi). The speed was then lowered to 5000 rpm in three steps before the next load condition was imposed. The maximum Hertz stress was increased to 2070 MPa (300 000 psi) in three steps or until the film thickness and percentage of film indicated that damage to the mating surfaces had occurred.

The range of conditions studied were disk temperatures from 339 to 422 K (150^{o} to 300^{o} F), disk speeds from 5000 to 20 000 rpm, and maximum Hertz stresses from 689 to 2070 MPa (100 000 to 300 000 psi).

RESULTS AND DISCUSSION

Results of tests to evaluate the effect of surface finish (longitudinal lay) on EHD film thickness and percentage of film for two lubricants (a type II ester and a synthetic paraffinic oil) are given in tables III to V. The results shown in tables III and IV are for a polished upper disk mating with a lower disk of each of the four levels of surface finish. Table V contains data for tests with both the upper and lower disks roughened.

The observed film thickness between mating disks with other than ideally smooth surfaces warrants discussion. For example, consider the measured data for the type II ester lubricant at 366 K (200^{o} F), a maximum Hertz stress of 689 MPa (100 000 psi), and a shaft speed of 10 000 rpm for the polished upper disk and the smooth lower disk. Table III indicates the measured film thickness is 0.25 μm (10 μin.) and the percentage of film is 13. Since, for this case, the centerline average (cla) roughness is 0.15 μm (6 μin.) for the lower disk and 0.025 μm (1 μin.) for the upper disk, it does not seem that any contact (indicated by the percentage of film) would take place. However, the reported film thickness represents an average value for the irregular gap between the rough surfaces. The cla roughness represents an average peak height, but there are peak heights much higher than that average. Therefore, some areas of the apparent contact area are separated by a relatively thick film; but in other areas, asperities on the surfaces interact and result in less than perfect percentage of film.

Effect of Surface Finish on EHD Film Thickness

In order to delineate the trends in film thickness as a function of the experimental variables, a least-squares fitting technique was performed on the data in tables III and IV.

The data in table V were not included because tests of the roughened mating pairs provided too few data points for a valid assessment of the trends.

The form of the empirical relation selected is

$$h = C_1 \frac{u^\alpha \mu^\beta}{p_{Hz}^\gamma (cla)^\delta} \qquad (1)$$

where

h	film thickness, m (in.)
C_1	constant, $m^{1+\delta-\alpha} Pa^{\gamma-\beta} sec^{\alpha-\beta}$ ($in.^{1+\delta-\alpha-2(\gamma-\beta)} lb^{\gamma-\beta} sec^{\alpha-\beta}$)
u	disk surface speed, m/sec (in./sec)
μ	lubricant absolute viscosity at disk temperature, Pa-sec ($lb\text{-}sec/in.^2$)
p_{Hz}	maximum Hertz stress, Pa (psi)
cla	centerline average surface finish of lower disk, m (in.)
$\alpha, \beta, \gamma, \delta$	exponents

Values of these constants and exponents representing composites of all the data in tables III and IV are given in table VI for each of the two lubricants in both SI and U. S. customary units.

The effect of surface finish on film thickness at a temperature of 339 K (150° F) is shown in figures 5 and 6 as a function of maximum Hertz stress and disk speed for the type II ester and the synthetic paraffinic oil, respectively. The curves represent the empirical relation of equation (1). As the roughness of the lower disk was increased while mating with a polished upper disk, the measured film thickness was reduced from that measured under the same conditions for a polished mating pair.

The effect of speed and temperature (lubricant viscosity) on measured film thickness is shown in figures 7 and 8 for the two lubricants. Least-squares lines are drawn through the data for each lower-disk surface finish. There is considerable scatter in the data for the rougher surfaces. Nevertheless, as roughness of the lower disk is increased, a trend is suggested toward a greater reduction in measured film thickness at lower values of the speed-viscosity parameter

$$\frac{\mu u}{E'R'}$$

where

E' $\left(\frac{1 - \nu_1^2}{\pi E_1} + \frac{1 - \nu_2^2}{\pi E_2}\right)^{-1}$, Pa (psi)

E_1, E_2 modulus of elasticity of elements 1 and 2, Pa (psi)

ν_1, ν_2 Poisson's ratio of elements 1 and 2

R' equivalent radius, $\left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$, m (in.)

R_1, R_2 radius of elements 1 and 2 in rolling direction, m (in.)

With the exception of the data at 1720 MPa (250 000 psi) with the synthetic paraffinic oil, the measured film thickness with the polished mating pair showed little scatter and agreed well with the trends of reference 12. The data of reference 12 were obtained with polished mating disks and a type II ester similar to the one used in this program.

The results of the experiments using equally roughened upper and lower disks are shown in table V. These data indicate that the EHD film thickness is very small for longitudinally roughened mating disks. For example, for the ester lubricant above 366 K (200° F), the EHD film was so small that a change in the texture of the surface finish would occur at even the mildest operating conditions (20 000 rpm and 689 MPa). The synthetic paraffinic oil behaved in a similar manner when used with roughened mating pairs.

Effect of Surface Finish on Percentage of Film

The measurements of percentage of film as a function of surface finish of the lower disk are presented in tables III and IV and plotted in figures 9 to 12 for each of the two lubricants. A least-squares curve-fitting technique was used with these data to determine an empirical relation between percentage of film, surface roughness, and calculated film thickness (from eq. (1)). As with the film thickness relation, the data of table V were not included because there were too few data points for a valid assessment of the trends. The form of this empirical relation is

$$f_p = \frac{200}{\pi} \arctan\left[C_2 \frac{h^{\epsilon}}{(cla)^{\zeta}}\right] \qquad (2)$$

where

f_p percentage of film

C_2 constant, $m^{\zeta-\epsilon}$ (in.$^{\zeta-\epsilon}$)

h film thickness (eq. (1)), m (in.)

cla centerline average surface finish of lower disk, m (in.)

ζ, ϵ exponents

Values of these constants and exponents representing composites of all the data in tables III and IV are given in table VII for each of the two lubricants in both SI and U. S. customary units.

Figures 9 and 10 show the relation of equation (2) to the measured values of percentage of film for various stresses and speeds at a disk temperature of 339 K (150° F). Percentage of film is decreased by increasing surface roughness, increasing stress, or decreasing speed. The calculated values from equation (2) are in better agreement with the measured values for the type II ester lubricant than for the synthetic paraffinic oil.

Figures 11 and 12 show the effect of disk temperature, and thus lubricant viscosity, on percentage of film. As lubricant viscosity was decreased at higher disk temperatures, the percentage of film decreased. At equal conditions of speed, stress, and lower-disk surface finish and for approximately equal viscosities (10.5 and 11.5 MPa-sec (1.52×10^{-6} and 1.67×10^{-6} lb-sec/in.^{2}) for the synthetic paraffinic oil and the type II ester, respectively), the synthetic paraffinic oil showed a consistently higher percentage of film than did the type II ester. This effect is more significant for the rougher surface conditions.

In addition, the synthetic paraffinic oil generally showed a higher percentage of film for the same measured film thickness than did the type II ester. Thus, the values of film percentage resulting from asperity interactions appear to be a function of lubricant and/or additive type. The two lubricants contain different additive packages, which possibly could have influenced this result.

The percentage-of-film measurements indicated a high degree of surface contact for longitudinally roughened mating disks, that is, when both upper and lower disks are roughened. This result would be expected since thin lubricant films were measured for these conditions. Thus, the effect of increasing the longitudinal-lay roughness of either the upper or lower disk is to decrease the EHD film thickness and to increase surface contact from that present when polished mating surfaces are used.

Very thin films and a low percentage of film were observed with roughened mating disks for relatively mild operating conditions. At higher temperatures, the surface topography was drastically modified for even the mildest operating conditions.

Changes in Surface Topography

By measuring the EHD film thickness and percentage of film and observing the surfaces after the test, the effect of surface asperity interaction on surface finish or changes in surface topography was evaluated. An objective of the research reported herein was to determine at what level of surface contact, or percentage of film, a change would occur in surface topography that could be detected by a measurable change in surface finish.

The type of surface topography change discussed can best be described as light scratching or polishing rather than severe scuffing, galling, or smearing. It is characterized on smooth surfaces as small markings or pits and on rougher surfaces as flattening of the surface ridges, along with small pits on these flat regions. This surface change is the very early stage of a type of surface damage described in reference 13 as glazing and is the result of surface interaction approaching that which causes glazing. The glazing phenomenon can lead to very short rolling-element bearing life (ref. 13).

Figure 13 shows micrographs and surface traces for the most severe condition that was run for a polished upper disk mating with a polished lower disk with the synthetic paraffinic oil. Here, the load is 2070 MPa (300 000 psi), the disks are rotating at 5000 rpm, and the disk temperature is 422 K (300° F). The film thickness was 0.05 μm (2 μin.), and the continuity circuit showed a reading of 60-percent film. Figure 13(a) shows the surface of the lower disk before the experiment. The surface is quite smooth with small random markings. Figure 13(b) shows the same surface after the experiment.

The most evident difference between these two micrographs are lines of indentations (or pockmarks) on the surface after the experiment. These pockmarks may be due to minimum amounts of contaminants in the lubricant. Their largest size is approximately 5 μm (200 μin.), which is the pore size of the filter elements. The surface traces shown in figures 13(c) and (d) for these polished disks show no change in surface finish as a result of the contact.

Tests with the equivalent disk surfaces run with the type II ester at 422 K (300° F) indicated zero-percent film and 0.1-μm (4-μin.) film thickness at 1720 MPa (250 000 psi) and 5000 rpm. However, the surface after that run was similar to that shown in figure 13(b).

Figure 14 shows micrographs and surface traces of a smooth lower disk (0.13 to 0.18 μm (5 to 7 μin.) cla) operating against a polished upper disk with the type II ester lubricant. Figure 14(a) shows the surface of the lower disk before the experiment. Figure 14(b) shows the same surface after operation at 1380 MPa (200 000 psi) and 5000 rpm. The disk temperature was 338 K (150° F). Some surface markings similar to those on the polished disks in figure 13(b) are seen in figure 14(b).

In addition to the surface markings, another change in the surface finish can be observed in figure 14(b). The sharp ridges of the original ground surface have been flattened, producing tongue-like tops on the ridges. This flattening also appears in a comparison of surface traces (figs. 14(c) and (d)). From these traces it is evident that some contact has occurred and that the finish of the surface has been changed. Table III shows that the measured film thickness in this case was 0.13 μm (5 μin.) and that the percentage of film was 4.

Figure 15 shows the results of experiments performed with a medium-rough lower disk (0.30 to 0.38 μm (12 to 15 μin.) cla). Figures 15(a) and (c) show the surface before the experiments. The resulting surface finish after operation at 689 MPa (100 000 psi), 10 000 rpm, and 339 K (150° F) with the type II ester lubricant is shown in figures 15(b) and (d). The micrographs show differences in surface topography similar to those indicated for the smooth lower disk (fig. 14). The tops of the ridges have been flattened by the contact with the upper disk. The surface traces also indicate that the surface topography has been changed. The peaks shown in figure 15(c) have been flattened, and the surface finish has been changed from 0.30 μm (12 μin.) to 0.28 μm (11 μin.), cla. Table III shows that the film conditions for this case were 0.30-μm (12-μin.) film thickness and 6-percent film. This example for a lower disk of medium surface roughness agrees with the result obtained from the experiments performed with a smooth-surface-finish lower disk. That is, a change in surface topography occurs when the percentage of film is less than 10 percent for the type II ester lubricant.

An example of an experiment performed with a rough lower disk (0.48 to 0.56 μm (19 to 22 μin.) cla) mated with a polished upper disk with the type II ester lubricant is shown in figure 16. The experiment was run at 689 MPa (100 000 psi), 10 000 rpm, and 339 K (150° F) disk temperature. The surface before the experiments is shown in figures 16(a) and (c) and after the experiments in figures 16(b) and (d). The micrographs show a distinct change in the surface before and after the experiments. This change exhibits itself as an apparent flattening of the ridges on the surface so that after the experiments the surface is characterized by the broad flat areas observed on the smooth and medium surfaces. The surface traces reinforce this conclusion. The sharp peaks of the original ground surface have been reduced by surface contact, and the surface finish has been changed from 0.52 μm (20.5 μin.) to 0.43 μm (17 μin.), cla. The measured film conditions for this experiment were 0.25-μm (10-μin.) film thickness and 4-percent film.

In general, all the different surface finishes yielded comparable values of the critical percentage of film, or the percentage of film where a change in surface topography occurs. These experiments have indicated that when the percentage of film is less than 10 for the type II ester lubricant, some change in surface topography will occur. Comparisons similar to figures 14 to 16 have been made for the synthetic paraffinic oil. The critical percentage of film with this lubricant is approximately 20. However, the operating conditions (speed, load, and disk temperature) which produced these surface changes were not significantly different for the two lubricants.

Since the observed critical percentage of film was different for the two lubricants, it appears to be a function of the lubricant and the boundary film formed by the lubricant or its additives.

Effects of Boundary Film

It is speculated that surface-to-surface interaction (percentage of film) was influenced by a boundary film that was dependent on lubricant and additive chemistry. The difference in percentage of film was most evident when conditions were such that only a very small EHD film was formed between the disks. For example, consider the case of 1380-MPa (200 000-psi) stress with a 339 K (150° F) disk temperature and a polished upper disk mating with a medium-rough lower disk. At 5000 rpm, the film thickness was measured to be 0.08 μm (3 μin.) for each lubricant. However, the ac continuity measurement indicated 32-percent film for the synthetic paraffinic oil and zero-percent film for the type II ester.

In order to further understand these results, the two lubricants were compared in rupture strength experiments. These experiments consisted of pressing a steel needle against a heated AISI M-50 steel plate flooded with lubricant and measuring the load required to make electrical contact through the lubricant. This technique is described in reference 14. This experiment is analogous to a rolling experiment where asperities are penetrating the EHD film. The pressure on the asperities will vary with their heights, so that only those asperities loaded above the rupture strength of the film will contribute to the electrical continuity measurement.

The results of these experiments, which are shown in table VIII, indicate that the rupture strength of the film formed with the synthetic paraffinic oil was consistently higher than that of the type II ester for temperatures of 394 K (250° F) and above. Hence, a higher load is required to rupture the film formed by the synthetic paraffinic oil than that formed by the ester. Therefore, identical film thicknesses should result in higher percentages of film for the paraffinic oil; that is, there will be fewer asperities exceeding the higher rupture strength of the synthetic paraffinic oil.

Sensitivity of Film Thickness to Hertz Stress

The empirical relation (eq. (1)), which is a statistical best fit of the experimental film thickness data, shows that film thickness is inversely proportional to maximum

Hertz stress to the 1.41 power for the type II ester and to the 1.30 power for the synthetic paraffinic oil. These exponents are much greater than would be predicted by classical elastohydrodynamic theories (e.g., 0.22 in ref. 15) and therefore, indicate a greater sensitivity to stress. Experimental film thickness measurements of references 10 and 12 also have shown this greater effect of stress on film thickness for a similar type II ester and three other lubricants. These data (refs. 10 and 12) were all obtained with polished disks (0.025 to 0.05 μm (1 to 2 μin.) cla) in the X-ray disk apparatus. An empirical formula based on these data with polished disk surfaces is presented in reference 16. This formula includes a high-contact-stress factor, which is a polynomial expression with maximum Hertz stress as a variable. The formula of reference 16 differs from equation (1) in that the formula predicts an effect of stress on film thickness that increases as stress increases. This effect is illustrated by the curves in figure 5 that are taken from reference 16 and show predicted film thickness for a similar type II ester. It appears that this form of empirical formula could show a better fit with the experimental data with further refinements, including effects of surface finish.

SUMMARY OF RESULTS

A rolling-disk apparatus was used to evaluate the effect of surface finish with the lay in the longitudinal direction on the elastohydrodynamic film thickness and percentage of film between rolling disks in contact. The film thickness was measured by using a calibrated X-ray technique, and the percentage of film between disks was monitored by an alternating-current continuity circuit. The critical percentage of film, or that percentage of film where a change in surface topography that could be detected by a change in surface finish occurred, was determined.

Disk temperature was varied from 339 to 422 K (150° to 300° F). The loading on the disks was such that the maximum Hertz stress ranged from 689 to 2070 MPa (100 000 to 300 000 psi). Shaft speeds of 5000 to 20 000 rpm resulted in surface speeds of 9.4 to 37.6 m/sec (370 to 1480 in./sec). Four levels of surface finish from polished to rough (0.025 to 0.56 μm (1 to 22 μin.) centerline average (cla)), were used, with the lay of the finish around the circumference of the disk. Two lubricants were used: a type II ester and a synthetic paraffinic oil. The results of these measurements were as follows:

1. Measured film thickness decreased with increasing roughness of the lower and/or upper disks at equivalent operating conditions.

2. Measured film thicknesses were comparable for the synthetic paraffinic oil and the type II ester lubricant for disks of similar surface finish at equivalent operating conditions.

3. The synthetic paraffinic oil generally showed a higher percentage of film for the same measured film thickness than did the type II ester. The percentages of film where changes in surface topography occurred were approximately 20 for the synthetic paraffinic oil and 10 for the type II ester.

4. Very thin EHD films and low percentages of film were observed with the rough-on-rough disks at relatively mild operating conditions. At higher temperatures the surface topography was drastically modified at even the mildest operating conditions.

Lewis Research Center,
National Aeronautics and Space Administration,
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TABLE I. - SURFACE FINISH

DEFINITIONS

[Longitudinal lay.]

Designation	Range of surface finish (centerline average)[a]	
	μm	μin.
Polished	0.025 - 0.05	1 - 2
Smooth	.13 - .18	5 - 7
Medium rough	.30 - .38	12 - 15
Rough	.48 - .56	19 - 22

[a]Centerline average from profilometer measured perpendicular to longitudinal lay.

TABLE II. - LUBRICANT PROPERTIES

Property	Lubricant	
	Type II ester	Synthetic paraffinic oil
Additives	Antiwear; oxidation inhibitor; antifoam	Antiwear; oxidation inhibitor
Kinematic viscosity, m^2/sec (cS):		
At 311 K (100° F)	28.5×10^{-6} (28.5)	60×10^{-6} (60)
At 372 K (210° F)	5.2×10^{-6} (5.2)	8.9×10^{-6} (8.9)
At 477 K (400° F)	1.3×10^{-6} (1.3)	1.9×10^{-6} (1.9)
Flashpoint, K; °F	533; 500	538; 510
Firepoint, K; °F	Unknown	575; 575
Autoignition temperature, K; °F	694; 800	645; 700
Pour point, K; °F	214; -75	225; -55
Volatility (6.5 hr at 477 K (400° F)), wt %	3.2	Unknown
Specific heat, J/(kg)(K); Btu/(lb)(°F)		
At 311 K (100° F)	1920; 0.458	2080; 0.498
At 372 K (210° F)	2060; 0.493	2560; 0.612
At 422 K (300° F)	2160; 0.515	2650; 0.632
At 477 K (400° F)	2260; 0.539	2690; 0.642
Thermal conductivity, J/(m)(sec)(K); Btu/(ft)(hr)(°F)		
At 311 K (100° F)	0.162; 0.0939	0.138; 0.080
At 372 K (210° F)	0.152; 0.0876	0.133; 0.077
At 422 K (300° F)	0.143; 0.0827	0.130; 0.075
At 477 K (400° F)	0.134; 0.0772	0.126; 0.073
Specific gravity		
At 311 K (100° F)	0.976	0.824
At 372 K (210° F)	0.931	0.788
At 422 K (300° F)	0.893	0.758
At 477 K (400° F)	0.847	0.723

TABLE III. - RESULTS OF EXPERIMENTS USING A TYPE II ESTER LUBRICANT AND A POLISHED, CROWNED UPPER DISK

Maximum Hertz stress		Lower-disk surface[a]															
		Polished				Smooth				Medium rough				Rough			
		Disk speed, rpm															
MPa	psi	20 000	15 000	10 000	5000	20 000	15 000	10 000	5000	20 000	15 000	10 000	5000	20 000	15 000	10 000	5000
		Film thickness, μm/Percentage of film (Film thickness, μin.)															
Disk temperature, 339 K (150° F); lubricant absolute viscosity, 11.5 mPa-sec[b] (1.67×10^{-6} lb-sec/in.^{2})																	
689	100 000	0.91/97 (36)	0.71/97 (28)	0.58/98 (23)	0.46/95 (18)	0.79/67 (31)	0.53/49 (21)	0.33/29 (13)	0.18/10 (7)	0.76/25 (30)	0.64/13 (25)	0.30/6 (12)	0.18/0 (7)	1.02/20 (40)	0.69/7 (27)	0.25/4 (10)	0.15/0 (6)
1380	200 000	0.58/90 (23)	0.53/85 (21)	0.43/80 (17)	0.33/55 (13)	0.41/50 (16)	0.36/32 (14)	0.25/17 (10)	0.13/4 (5)	0.23/15 (9)	0.20/13 (8)	0.15/5 (6)	0.08/0 (3)	0.18/5 (7)	0.15/4 (6)	0.10/3 (4)	0.05/0 (2)
1720	250 000	0.51/80 (20)	0.43/74 (17)	0.41/69 (16)	0.25/55 (10)	0.33/30 (13)	0.18/25 (7)	0.15/8 (6)	0.08/0 (3)	0.15/12 (6)	0.13/10 (5)	0.08/9 (3)	0.05/0 (2)	-------	-------	-------	-------
2070	300 000	0.46/48 (18)	0.41/26 (16)	0.38/19 (15)	0.25/6 (10)	0.10/30 (4)	0.10/17 (4)	0.08/2 (3)	-------	0.10/-- (4)	0.08/7 (3)	0.05/2 (2)	0.02/0 (1)	-------	-------	-------	-------
Disk temperature, 366 K (200° F); lubricant absolute viscosity, 5.5 mPa-sec (0.80×10^{-6} lb-sec/in.^{2})																	
689	100 000	0.81/87 (32)	0.66/85 (26)	0.36/81 (14)	0.18/57 (7)	0.94/74 (37)	0.61/40 (24)	0.25/13 (10)	0.15/7 (6)	0.56/25 (22)	0.25/5 (10)	0.18/5 (7)	0.10/3 (4)	0.69/25 (27)	0.41/6 (16)	0.25/4 (10)	0.18/5 (7)
1380	200 000	0.41/75 (16)	0.41/70 (16)	0.25/61 (10)	0.18/30 (7)	0.15/48 (6)	0.13/24 (5)	0.08/10 (3)	0.02/8 (1)	0.15/12 (6)	0.10/7 (4)	0.08/5 (3)	0.05/3 (2)	0.08/15 (3)	0.05/7 (2)	0.02/3 (1)	0.02/0 (1)
1720	250 000	0.30/66 (12)	0.23/58 (9)	0.20/46 (8)	0.13/18 (5)	0.15/56 (6)	0.08/30 (3)	0.02/15 (1)	0.02/7 (1)	-------	-------	-------	-------	-------	-------	-------	-------
2070	300 000	0.25/24 (10)	0.25/18 (10)	0.15/11 (6)	0.10/5 (4)	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Disk temperature, 422 K (300° F); lubricant absolute viscosity, 2.3 mPa-sec (0.33×10^{-6} lb-sec/in.^{2})																	
689	100 000	0.66/65 (26)	0.38/40 (15)	0.23/12 (9)	0.15/5 (6)	0.71/20 (28)	0.51/10 (20)	0.13/5 (5)	0.08/0 (3)	0.81/17 (32)	0.43/14 (17)	0.08/7 (3)	0.05/0 (2)	0.46/7 (18)	0.23/4 (9)	0.20/0 (8)	0.13/0 (5)
1380	200 000	0.30/65 (12)	0.25/35 (10)	0.20/10 (8)	0.13/5 (5)	0.10/9 (4)	0.10/8 (4)	0.10/0 (4)	0.08/0 (3)	-------	-------	-------	-------	-------	-------	-------	-------
1720	250 000	0.23/50 (9)	0.18/20 (7)	0.13/4 (5)	0.10/0 (4)	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
2070	300 000	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

[a]See table I for definition of surface finishes.

[b]1 mPa-sec = 1 centipoise.

TABLE IV. - RESULTS OF EXPERIMENTS USING A SYNTHETIC PARAFFINIC OIL LUBRICANT AND A POLISHED, CROWNED UPPER DISK

Maximum Hertz stress		Lower-disk surface[a]															
		Polished				Smooth				Medium rough				Rough			
MPa	psi	Disk speed, rpm															
		20 000	15 000	10 000	5000	20 000	15 000	10 000	5000	20 000	15 000	10 000	5000	20 000	15 000	10 000	5000
		Film thickness, μm/Percentage of film (Film thickness, μin.)															
Disk temperature, 339 K (150° F); lubricant absolute viscosity, 23 mPa-sec[b] (3.33×10^{-6} lb-sec/in.^{2})																	
689	100 000	1.78/97 (70)	0.71/97 (28)	0.53/97 (21)	0.38/93 (15)	1.42/99 (56)	0.76/99 (30)	0.46/99 (18)	0.28/94 (11)	0.25/97 (10)	0.18/97 (7)	0.10/94 (4)	0.05/80 (2)	-------	0.68/56 (27)	0.20/33 (8)	0.10/21 (4)
1380	200 000	0.58/96 (23)	0.38/96 (15)	0.30/96 (12)	0.15/93 (6)	0.43/99 (17)	0.30/94 (12)	0.23/94 (9)	0.10/85 (4)	0.18/96 (7)	0.13/93 (5)	0.10/84 (4)	0.08/32 (3)	0.15/55 (6)	0.08/30 (3)	0.02/20 (1)	-------
1720	250 000	0.51/96 (20)	0.41/96 (16)	0.33/96 (13)	0.20/92 (8)	0.36/97 (14)	0.23/97 (9)	0.15/94 (6)	0.08/70 (3)	0.13/93 (5)	0.08/85 (3)	0.05/72 (2)	0.02/20 (1)	-------	-------	-------	-------
2070	300 000	0.43/97 (17)	0.43/96 (17)	0.36/95 (14)	0.25/87 (10)	0.30/94 (12)	0.20/90 (8)	0.18/75 (7)	0.10/30 (4)	-------	-------	-------	-------	-------	-------	-------	-------
Disk temperature, 366 K (200° F); lubricant absolute viscosity, 10.5 mPa-sec (1.52×10^{-6} lb-sec/in.^{2})																	
689	100 000	1.40/98 (55)	0.74/97 (29)	0.43/94 (17)	0.28/85 (11)	1.19/90 (47)	0.38/88 (15)	0.28/75 (11)	0.18/27 (7)	1.37/91 (54)	0.28/85 (11)	0.08×60 (3)	0.02/17 (1)	1.27/78 (50)	0.36/29 (14)	0.25/11 (10)	0.05/7 (2)
1380	200 000	0.43/97 (17)	0.36/97 (14)	0.30/95 (12)	0.20/80 (8)	0.28/82 (11)	0.20/67 (8)	0.08/41 (3)	0.05/28 (2)	-------	-------	-------	-------	-------	-------	-------	-------
1720	250 000	0.33/96 (13)	0.15/96 (6)	0.10/91 (4)	0.05/70 (2)	0.15/80 (6)	0.08/65 (3)	0.08/34 (3)	0.02/9 (1)	-------	-------	-------	-------	-------	-------	-------	-------
2070	300 000	0.36/96 (14)	0.28/94 (11)	0.23/90 (9)	0.13/67 (5)	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
Disk temperature, 422 K (300° F); lubricant absolute viscosity, 3.5 mPa-sec (0.51×10^{-6} lb-sec/in.^{2})																	
689	100 000	0.64/99 (25)	0.25/97 (10)	0.23/94 (9)	0.15/80 (6)	0.56/75 (22)	0.28/60 (11)	0.18/20 (7)	0.10/14 (4)	0.61/43 (24)	0.20/40 (8)	0.13/12 (5)	0.10/12 (4)	0.58/30 (23)	0.13/30 (5)	0.13/10 (5)	0.05/10 (2)
1380	200 000	0.30/99 (12)	0.20/95 (8)	0.18/91 (7)	0.10/74 (4)	0.18/56 (7)	0.13/37 (5)	0.13/20 (5)	0.05/15 (2)	-------	-------	-------	-------	-------	-------	-------	-------
1720	250 000	0.30/97 (12)	0.20/95 (8)	0.13/70 (5)	0.10/50 (4)	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
2070	300 000	0.23/90 (9)	0.15/90 (6)	0.13/75 (5)	0.05/60 (2)	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

[a]See table I for definition of surface finishes.

[b]1 mPa-sec = 1 centipoise.

TABLE V. - RESULTS OF EXPERIMENTS WITH UPPER AND LOWER DISKS OF EQUAL ROUGHNESS WITH LONGITUDINAL LAY

Maximum Hertz stress		Disk temperature		Absolute viscosity		Mating surfaces[a]							
						Smooth				Medium rough			
						Disk speed, rpm							
						20 000	15 000	10 000	5000	20 000	15 000	10 000	5000
MPa	psi	K	°F	mPa-sec	lb-sec/in.^{2}	Film thickness, μm/Percentage of film (Film thickness, μin.)							
						Type II ester							
689	100 000	339	150	11.5	1.67×10^{-6}	0.09/57 (3.5)	0.07/30 (2.7)	0.02/2.5 (1)	0/5 (0)	0.13/50 (5)	0.08/50 (3)	0.02/12 (1)	0/3 (0)
1380	200 000	339	150	11.5	1.67	0.11/33 (4.3)	0.08/25 (3)	0.05/7 (2)	---	-------	-------	-------	---
689	100 000	366	200	5.5	.80	0.24/10 (9.3)	0.07/8 (2.7)	0.05/6 (1.9)	---	0.05/2 (2)	-------	-------	---
1380	200 000	366	200	5.5	.80	0.05/7 (1.9)	-------	--------	---	-------	-------	-------	---
689	100 000	422	300	2.3	.33	0.13/5 (5)	0.02/2 (1)	--------	---	0/2 (0)	-------	-------	---
						Synthetic paraffinic oil							
689	100 000	339	150	23.0	3.33×10^{-6}	0.72/45 (28.5)	0.28/20 (11)	--------	---	0.24/30 (9.6)	0.08/20 (3.3)	-------	---
		366	200	10.5	1.52	0.44/30 (17.5)	0.15/15 (6)	--------	---	0.10/7 (4)	-------	-------	---
		422	300	3.5	.51	0.34/20 (13.5)	-------	--------	---	0/3 (0)	-------	-------	---

[a]See table I for definition of surface finishes.

TABLE VI. - VALUES FOR CONSTANTS AND EXPONENTS IN EQUATION (1)

Lubricant	Constant, C_1		Exponent			
	$m^{1+\delta-\alpha} Pa^{\gamma-\beta} sec^{\alpha-\beta}$	$in.^{1+\delta-\alpha-2(\gamma-\beta)} lb^{\gamma-\beta} sec^{\alpha-\beta}$	α	β	γ	δ
Type II ester	1.4×10^{3}	2.1	0.91	0.47	1.41	0.40
Synthetic paraffinic oil	4.1	3.4×10^{-3}	1.16	.35	1.30	.51

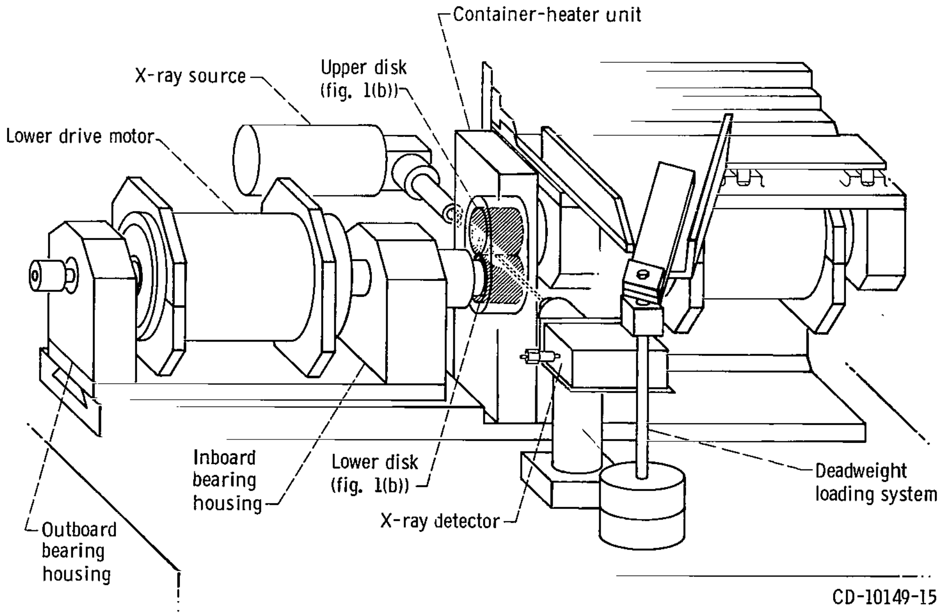
TABLE VII. - VALUES FOR CONSTANTS AND EXPONENTS IN EQUATION (2)

Lubricant	Constant, C_2		Exponent	
	$m^{\zeta-\epsilon}$	$in.^{\zeta-\epsilon}$	ϵ	ζ
Type II ester	8.7×10^{5}	2.2×10^{4}	1.53	0.53
Synthetic paraffinic oil	3.6×10^{5}	2.2×10^{4}	1.20	.44

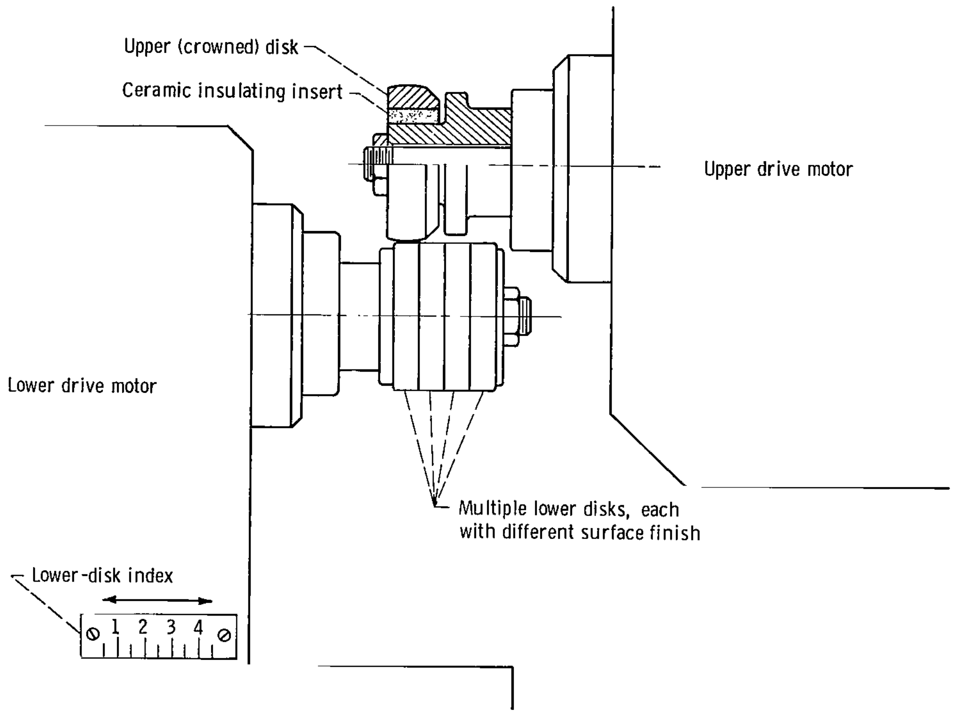
TABLE VIII. - RESULTS OF EXPERIMENTS MEASURING BOUNDARY-FILM RUPTURE STRENGTH

Plate temperature		Lubricant	
		Type II ester	Synthetic paraffinic oil
K	^{o}F	Load required to rupture film,[a] N(lb)	
366	200	0.05 (0.011)	0.040 (0.009)
394	250	0	0.046 (0.010)
422	300	0.042 (0.010)	0.104 (0.024)
450	350	0.033 (0.007)	0.121 (0.027)

[a]Average of three tests.

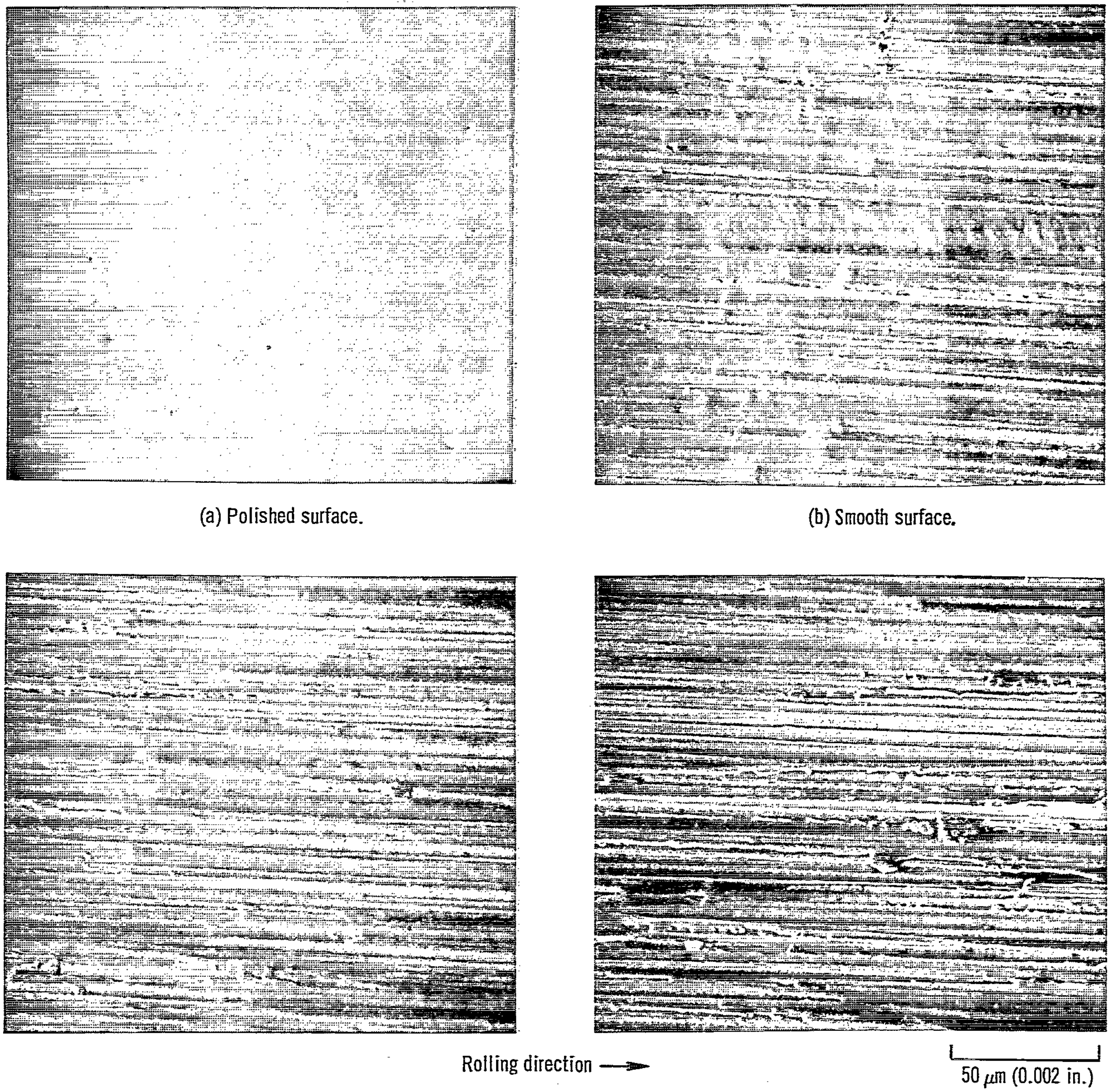


(a) Schematic.



(b) Arrangement of disks.

Figure 1. - Rolling-disk apparatus.



(a) Polished surface.

(b) Smooth surface.

(c) Medium-rough surface.

(d) Rough surface.

Figure 2. - Comparative longitudinal roughness of disk surfaces. (See table I for surface finish definitions.)

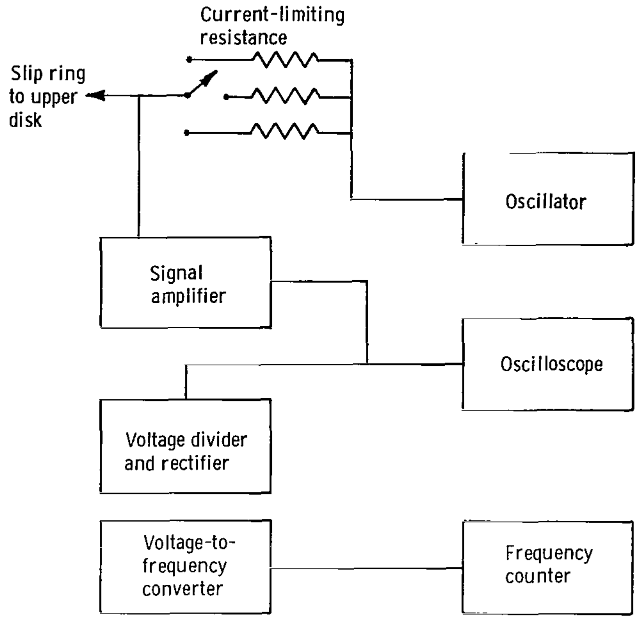


Figure 3. - Block diagram of instrumentation for contact conductivity measurements of percentage of film.

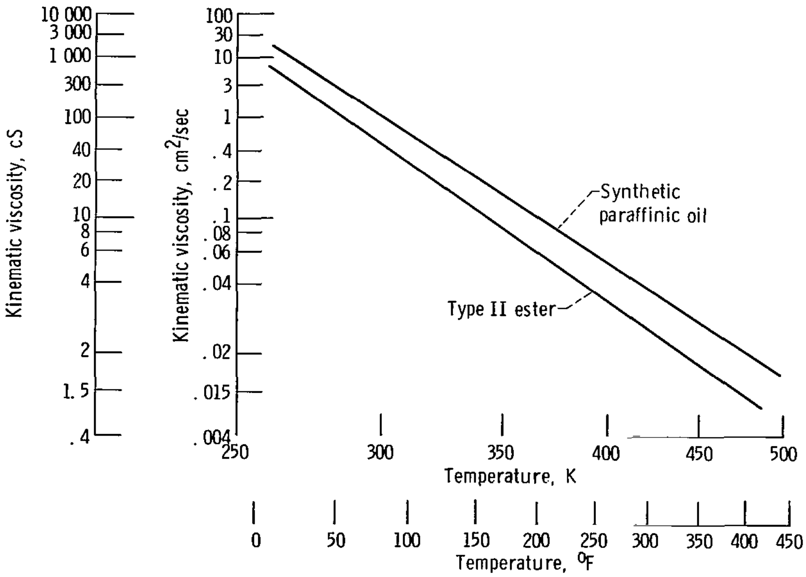


Figure 4. - ASTM chart of lubricant kinematic viscosity as a function of temperature.

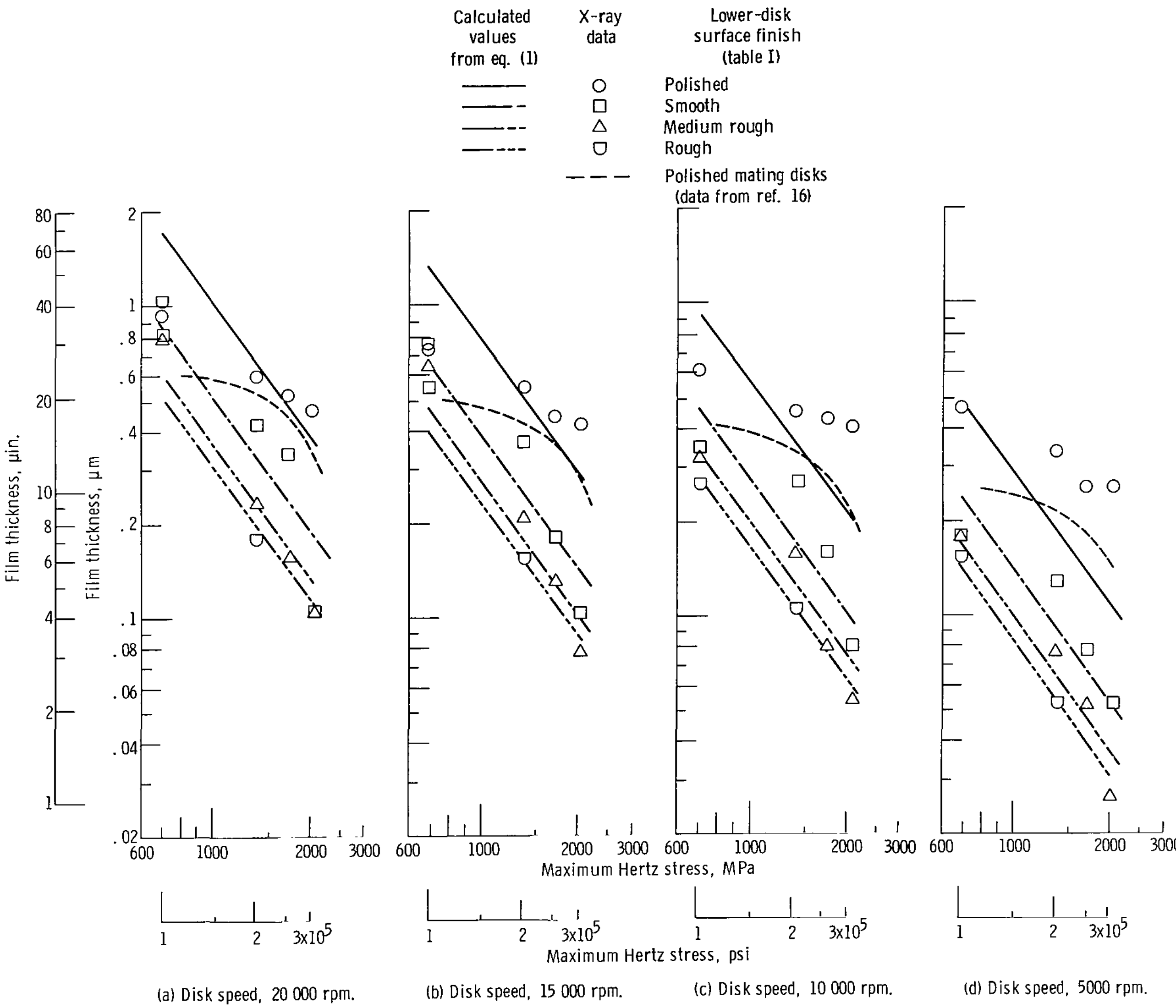


Figure 5. - Elastohydrodynamic film thickness as function of maximum Hertz stress for four lower-disk surface finishes with type II ester lubricant. Disk temperature, 339 K (150° F); lubricant absolute viscosity, 11.5 mPa-sec (1.67×10^{-6} lb-sec/in.^{2}).

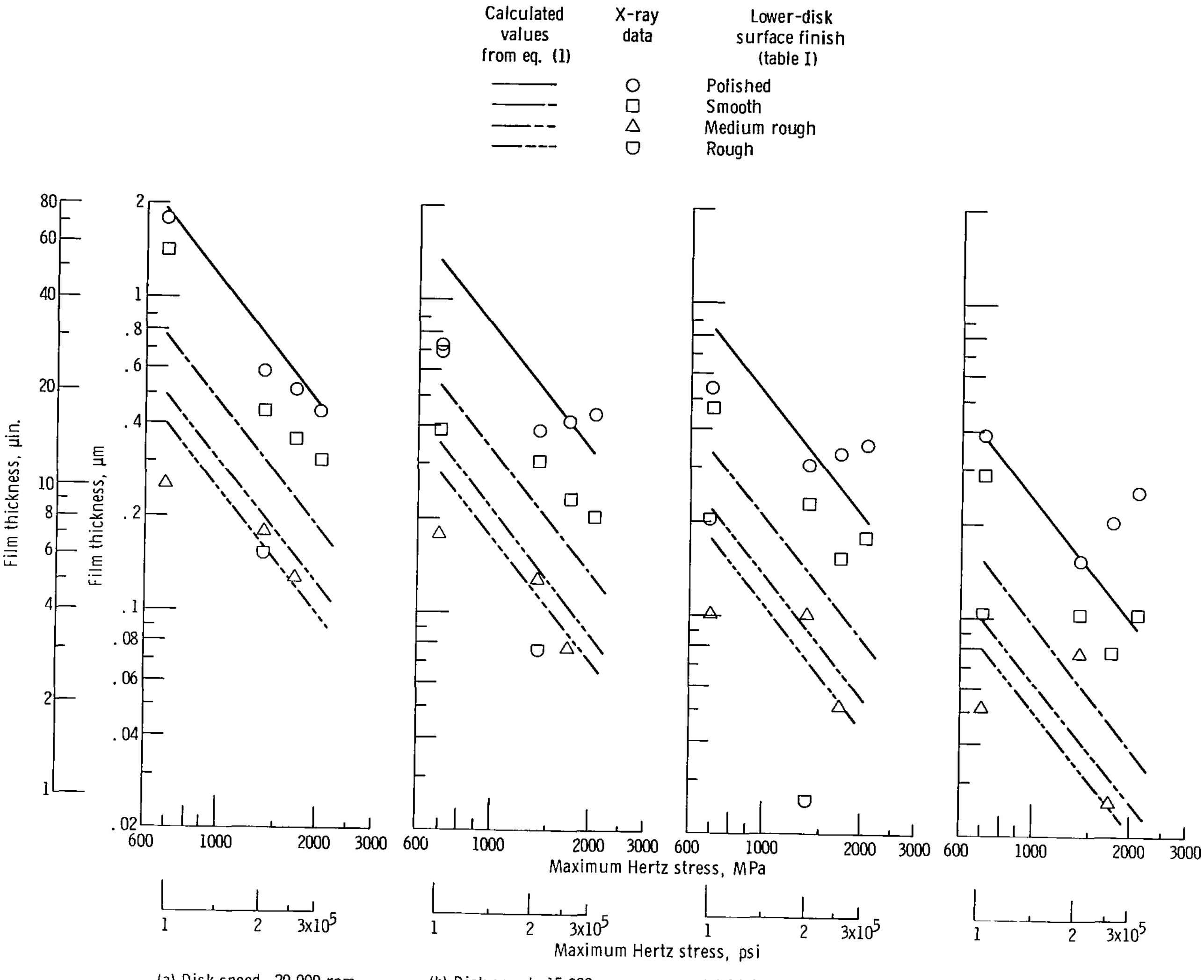
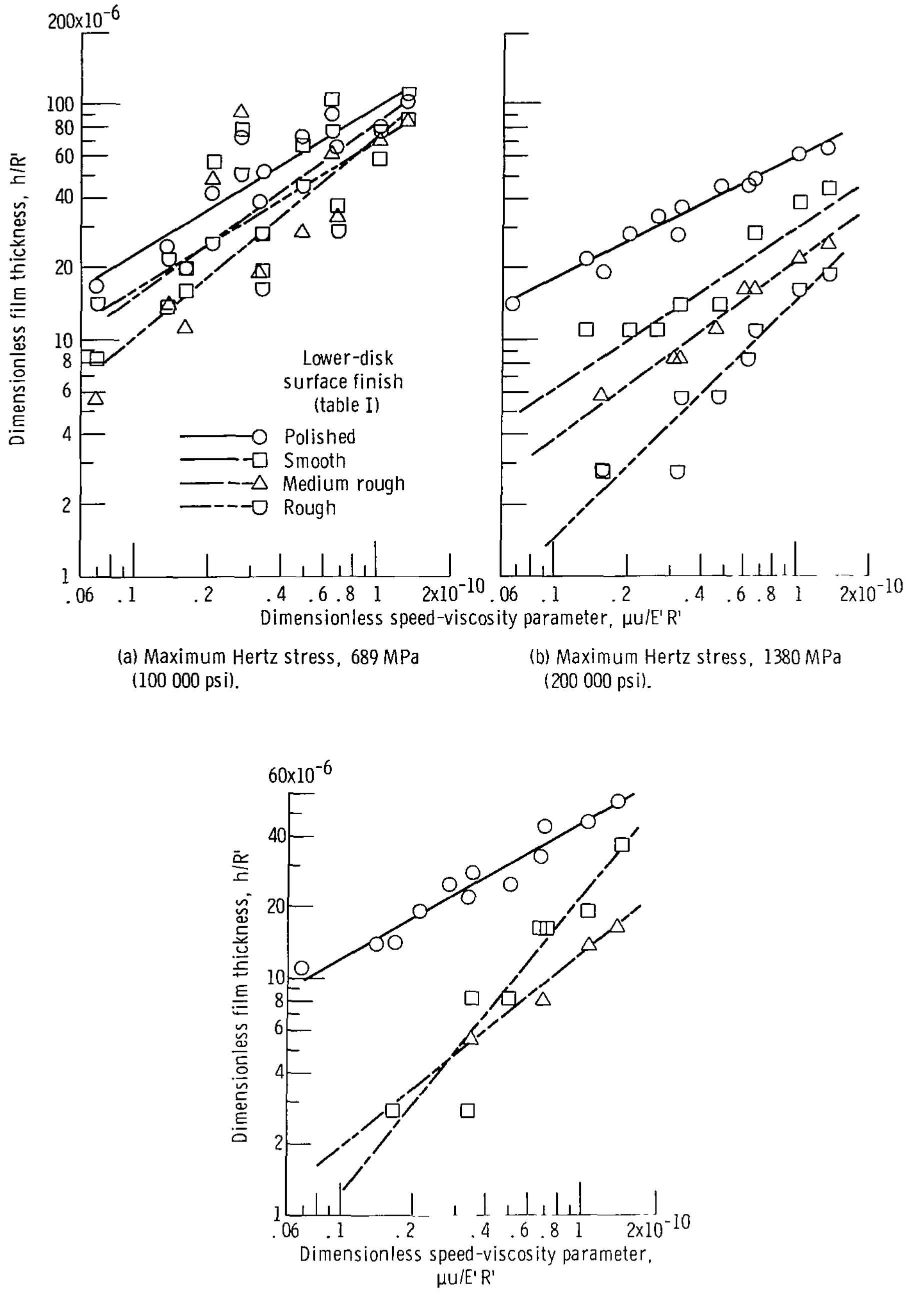


Figure 6. - Elastohydrodynamic film thickness as function of maximum Hertz stress for four lower-disk surface finishes with synthetic paraffinic oil lubricant. Disk temperature, 339 K (150° F); lubricant absolute viscosity, 23.0 mPa-sec (3.33×10^{6} lb-sec/in.^{2}).

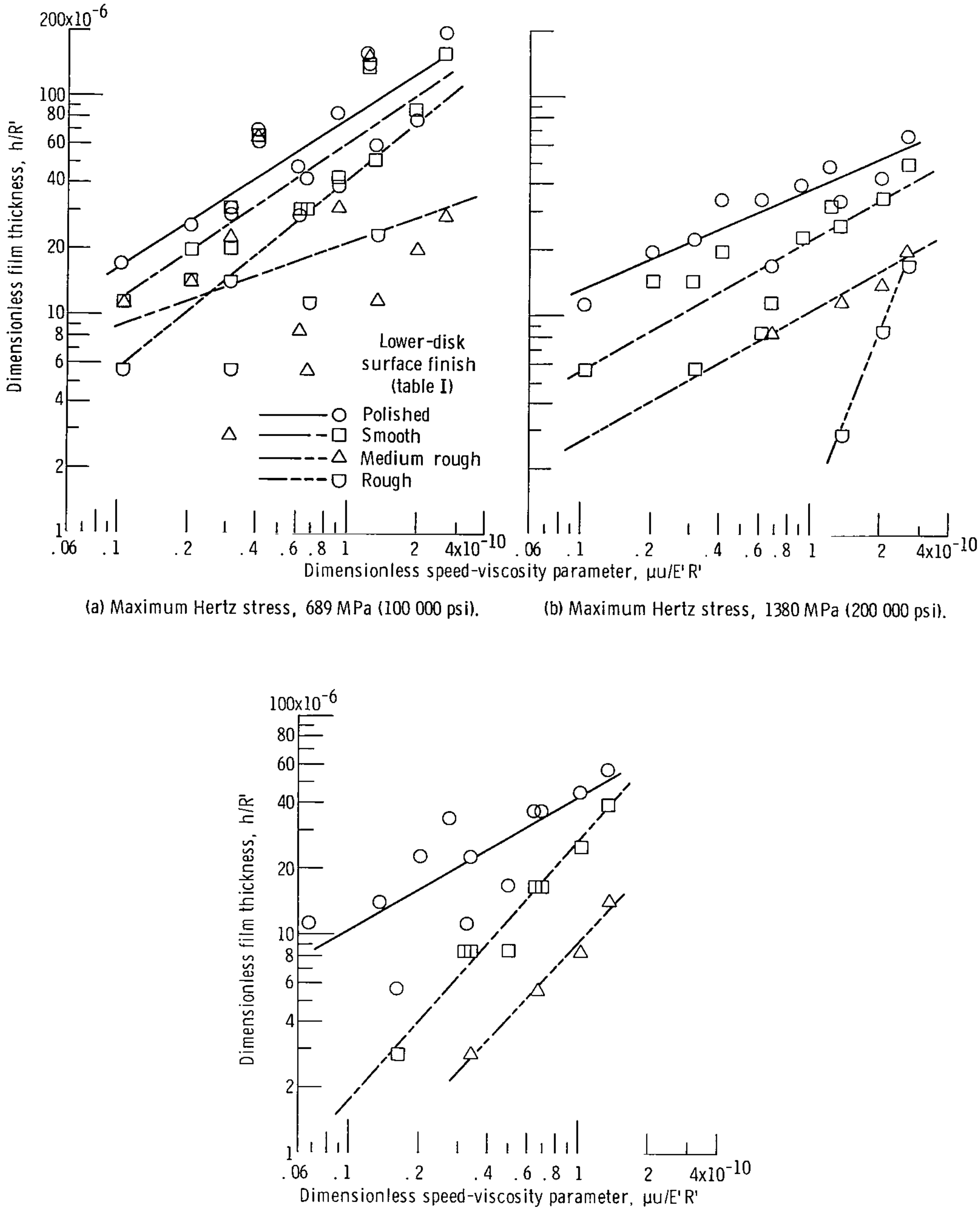


(a) Maximum Hertz stress, 689 MPa (100 000 psi).

(b) Maximum Hertz stress, 1380 MPa (200 000 psi).

(c) Maximum Hertz stress, 1720 MPa (250 000 psi).

Figure 7. - Elastohydrodynamic film thickness as function of speed-viscosity parameter for four lower-disk surface finishes with type II ester lubricant.

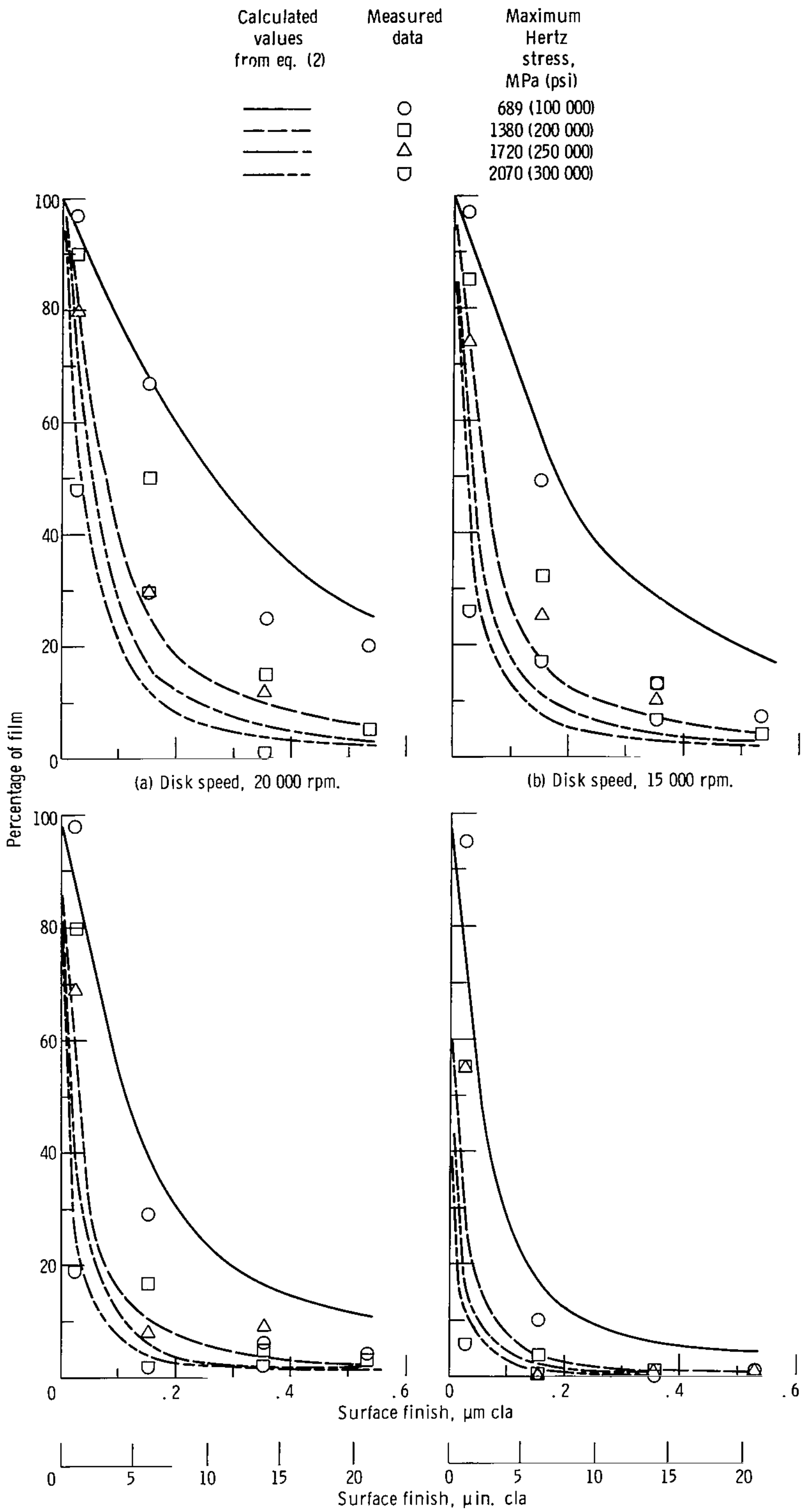


(a) Maximum Hertz stress, 689 MPa (100 000 psi).

(b) Maximum Hertz stress, 1380 MPa (200 000 psi).

(c) Maximum Hertz stress, 1720 MPa (250 000 psi).

Figure 8. - Elastohydrodynamic film thickness as function of speed-viscosity parameter for four lower-disk surface finishes with synthetic paraffinic oil lubricant.



(c) Disk speed, 10 000 rpm.

(d) Disk speed, 5000 rpm.

Figure 9. - Percentage of film as function of lower-disk surface finish with type II ester lubricant, at disk temperature of 339 K (150° F) and lubricant absolute viscosity of 11.5 mPa-sec (1.67×10^{-6} lb-sec/in.^{2}), for four maximum Hertz stresses.

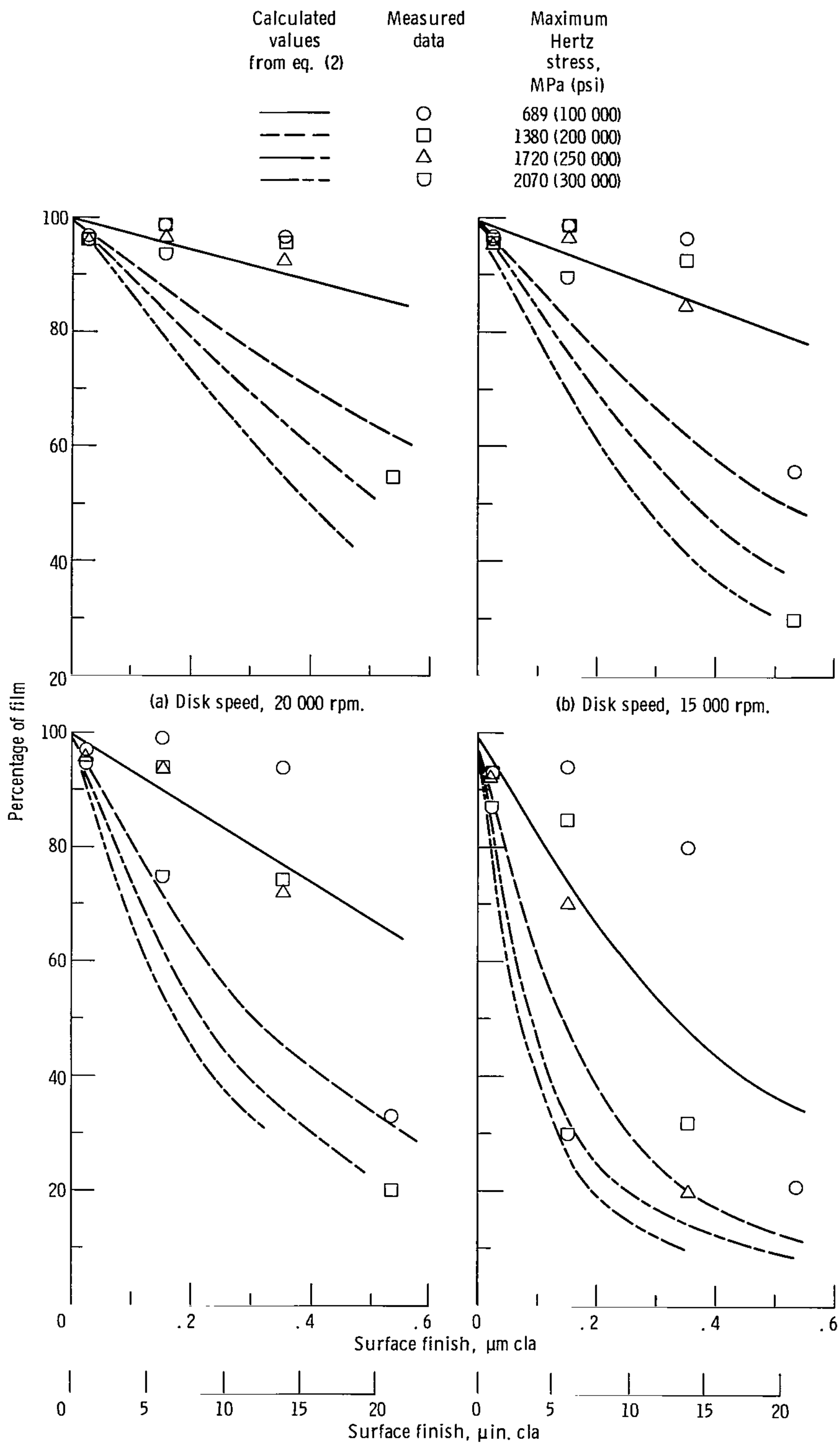


Figure 10. - Percentage of film as function of lower-disk surface finish with synthetic paraffinic oil lubricant, at disk temperature of 339 K (150° F) and lubricant absolute viscosity of 23.0 mPa-sec (3.33×10^{-6} lb-sec/in.^{2}), for four maximum Hertz stresses.

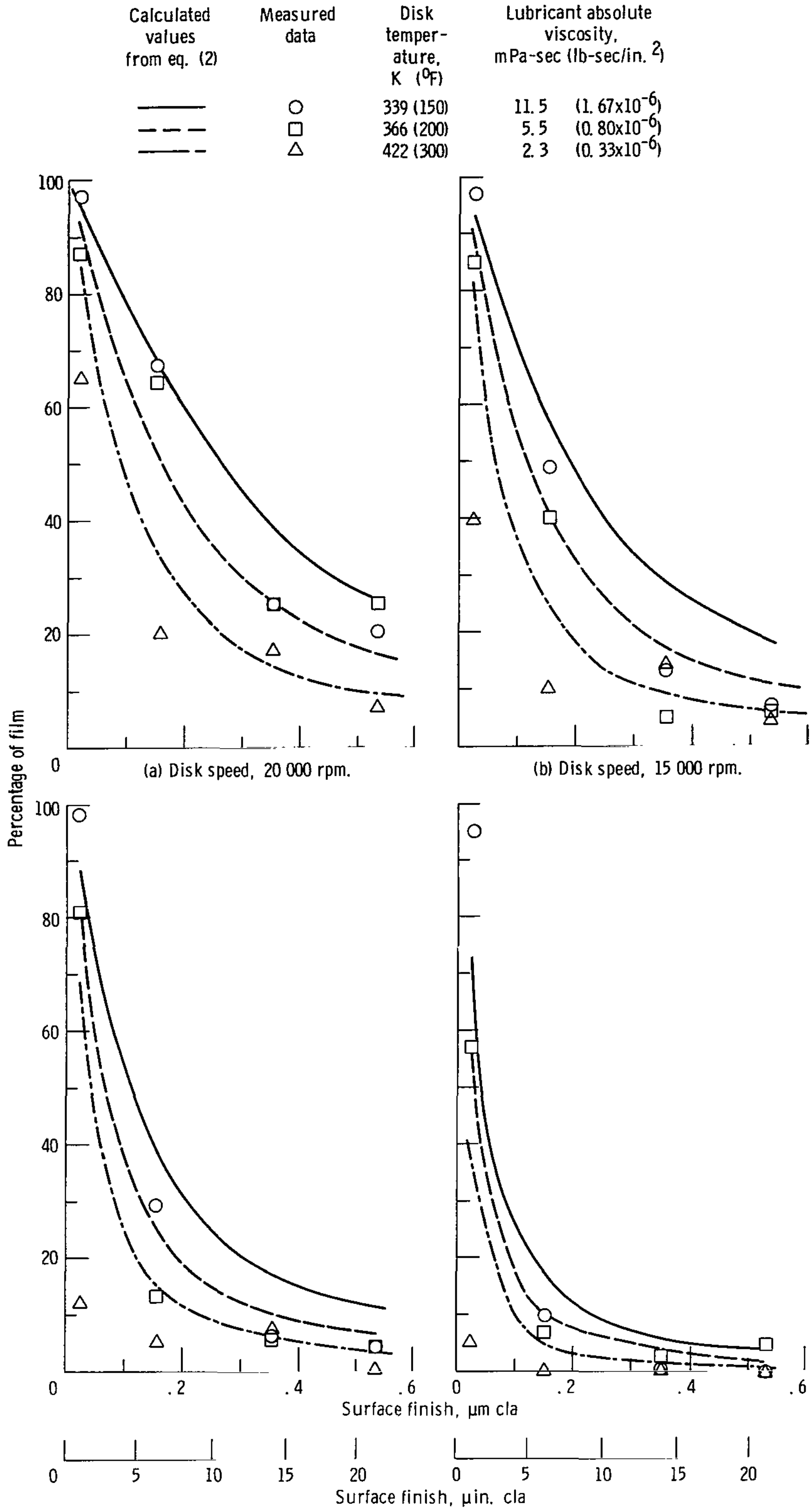


Figure 11. - Percentage of film as function of lower-disk surface finish for three viscosities of the type II ester lubricant. Maximum Hertz stress, 689 MPa (100 000 psi).

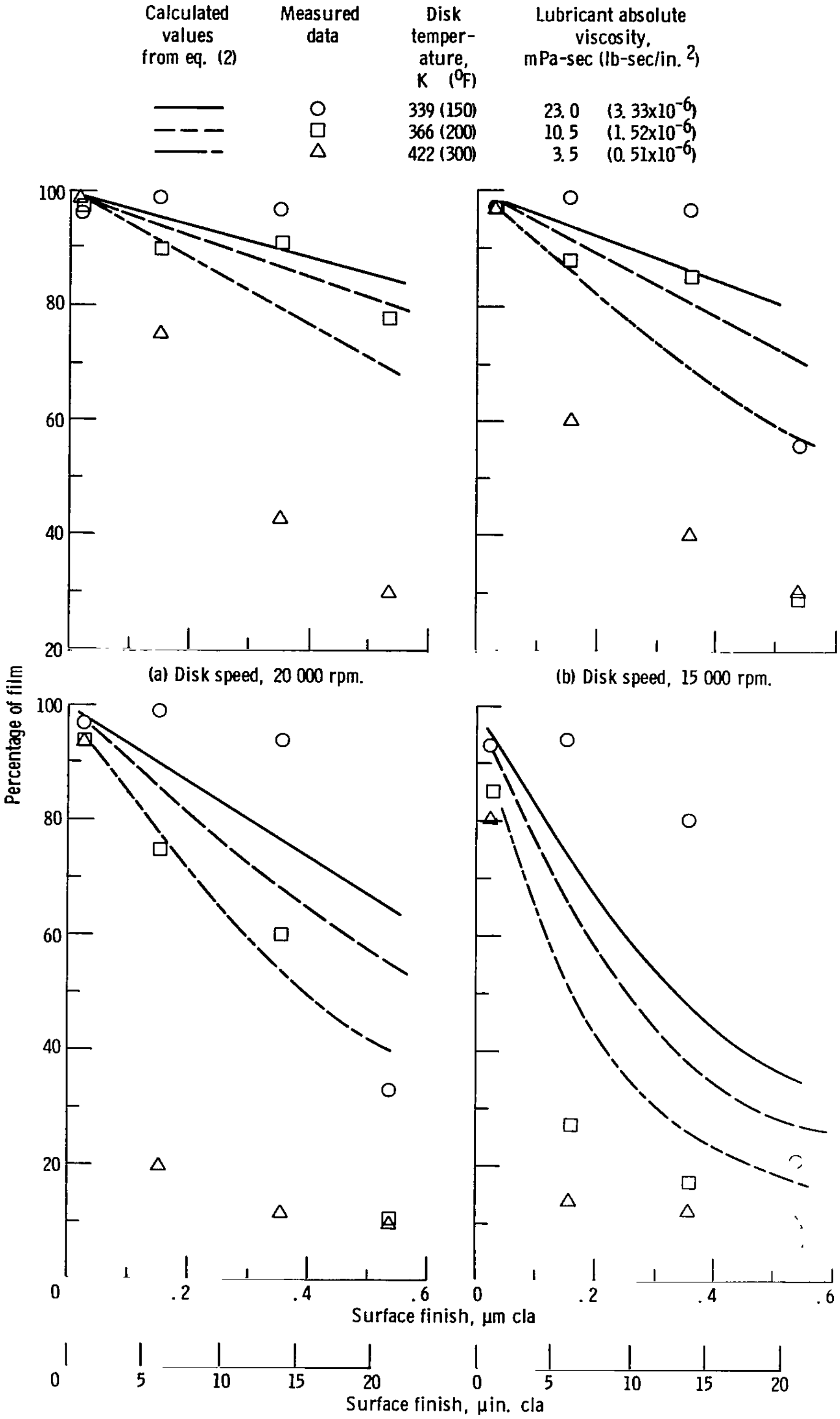
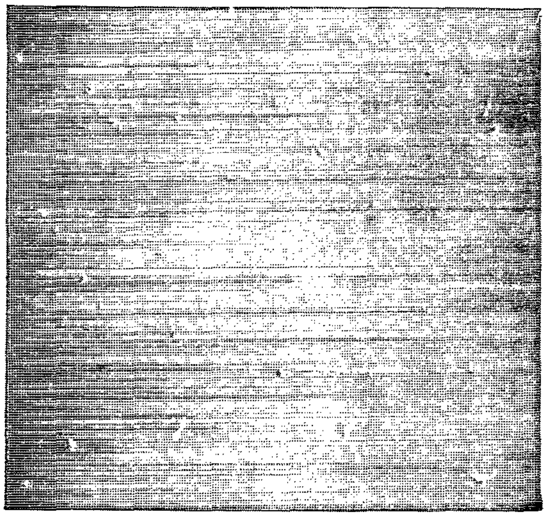
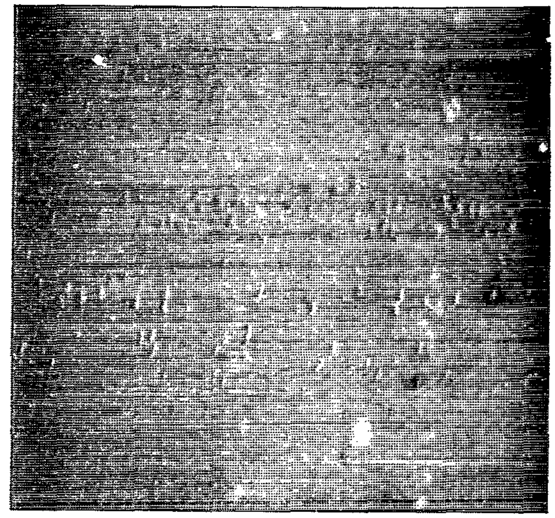


Figure 12. - Percentage of film as function of lower-disk surface finish for three viscosities of the synthetic paraffinic oil lubricant. Maximum Hertz stress, 689 MPa (100 000 psi).



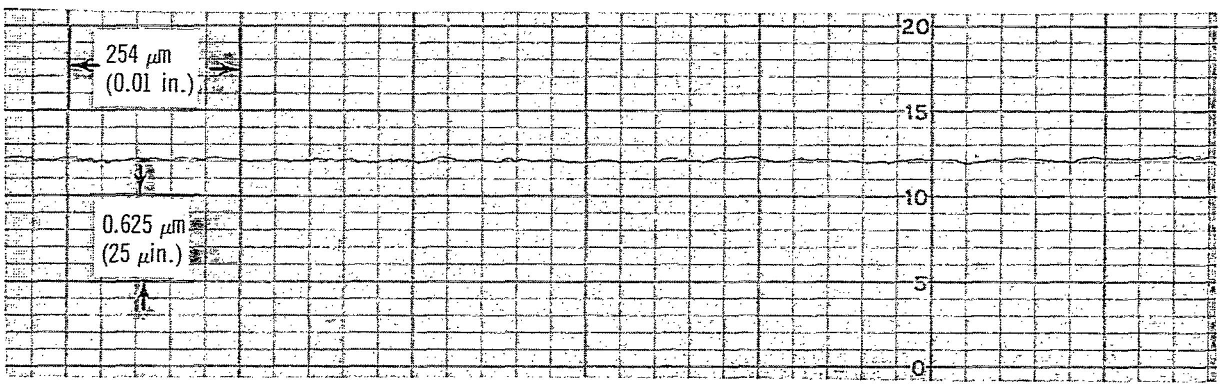


Rolling direction →

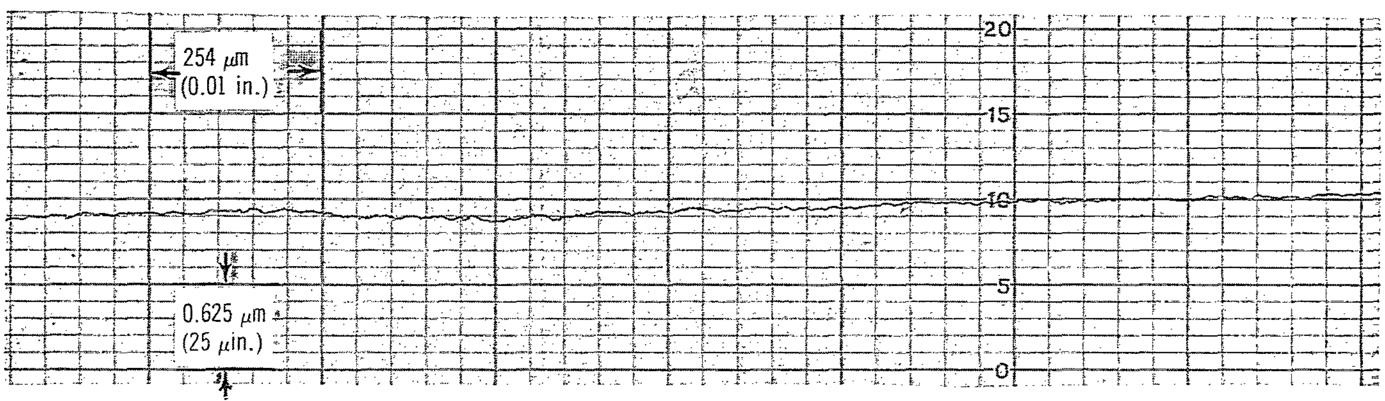
50 μm (0.002 in.)

(a) Surface before experiment.

(b) Surface after experiment.

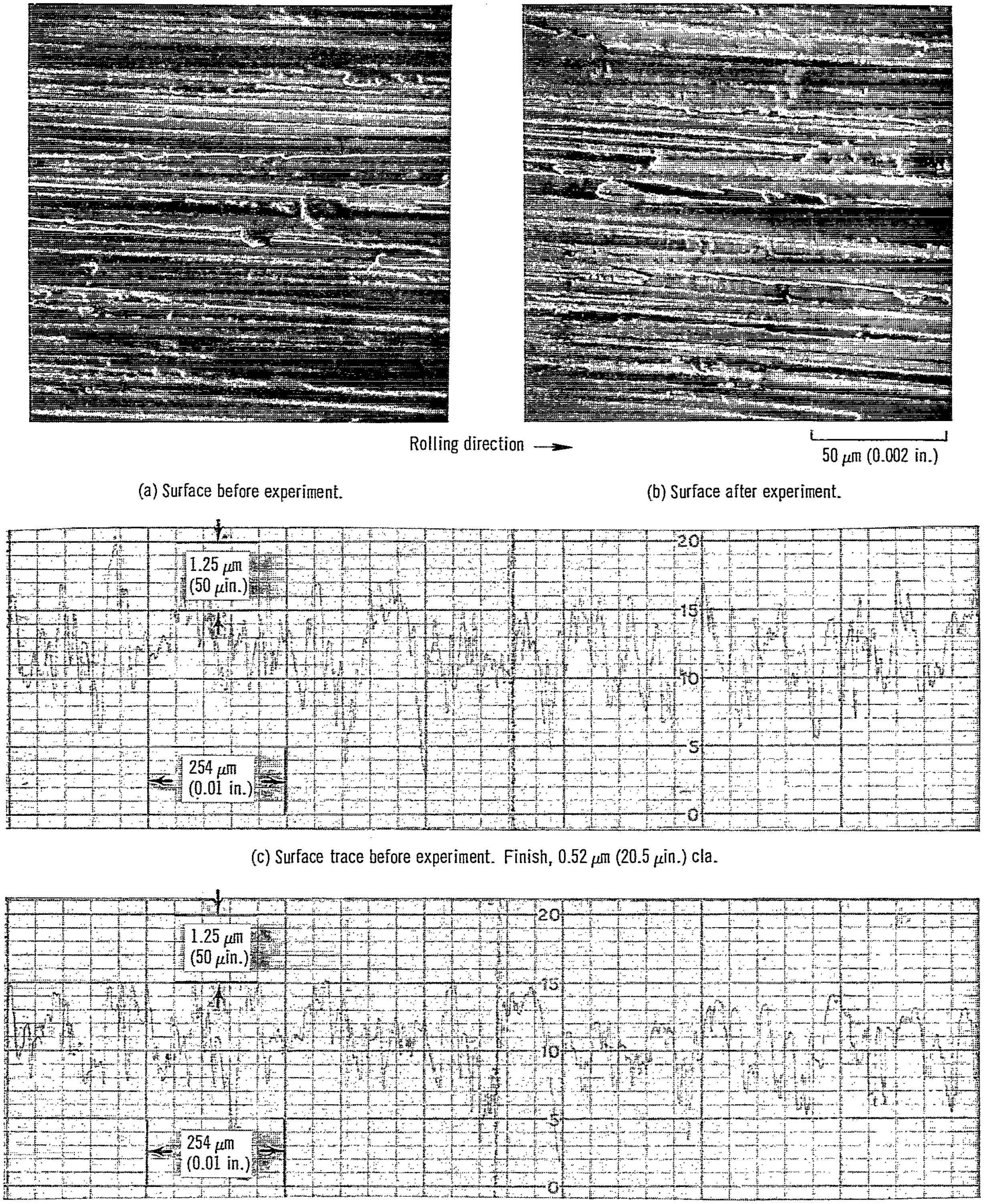


(c) Surface trace before experiment. Finish, 0.025 μm (1 $\mu in.$) cla.



(d) Surface trace after experiment. Finish, 0.025 μm (1 $\mu in.$) cla.

Figure 13. - Scanning electron micrographs and surface traces of polished lower-disk surface before and after operation at 2070 MPa (300 000 psi) and 5000 rpm with disk temperature of 422 K (300° F) and synthetic paraffinic oil lubricant.



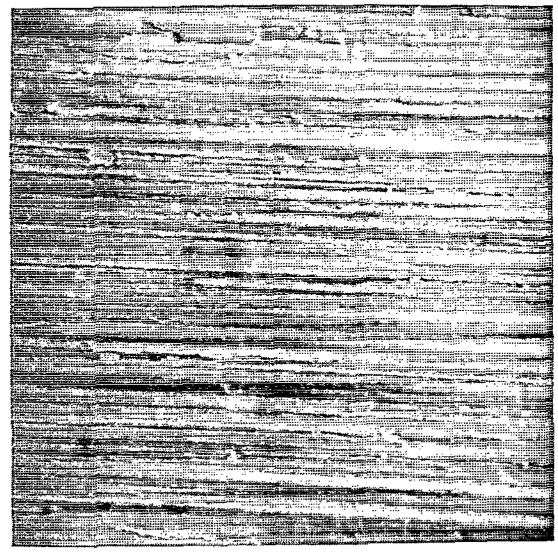
(a) Surface before experiment.

(b) Surface after experiment.

(c) Surface trace before experiment. Finish, 0.52 μm (20.5 μin.) cla.

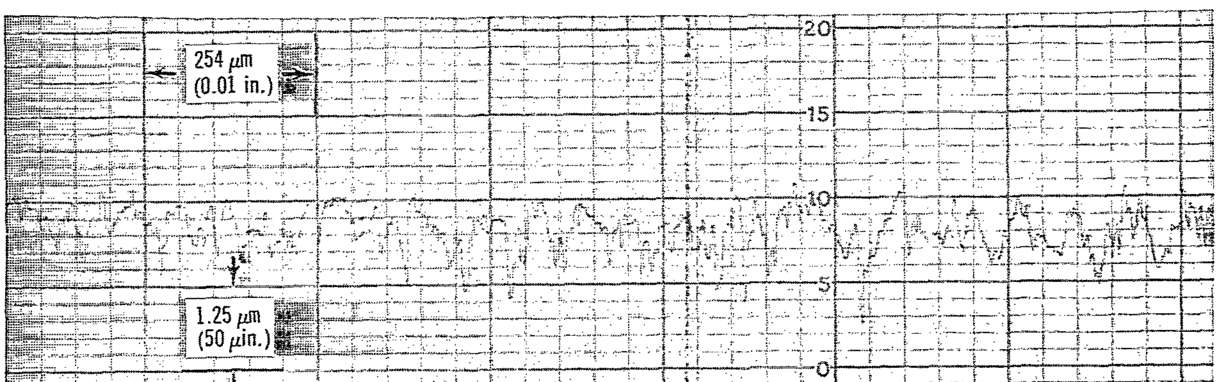
(d) Surface trace after experiment. Finish, 0.43 μm (17 μin.) cla.

Figure 16. - Scanning electron micrographs and surface traces of rough lower-disk surface before and after operation at 689 MPa (100 000 psi) and 10 000 rpm with disk temperature of 339 K (150° F) and type II ester lubricant.

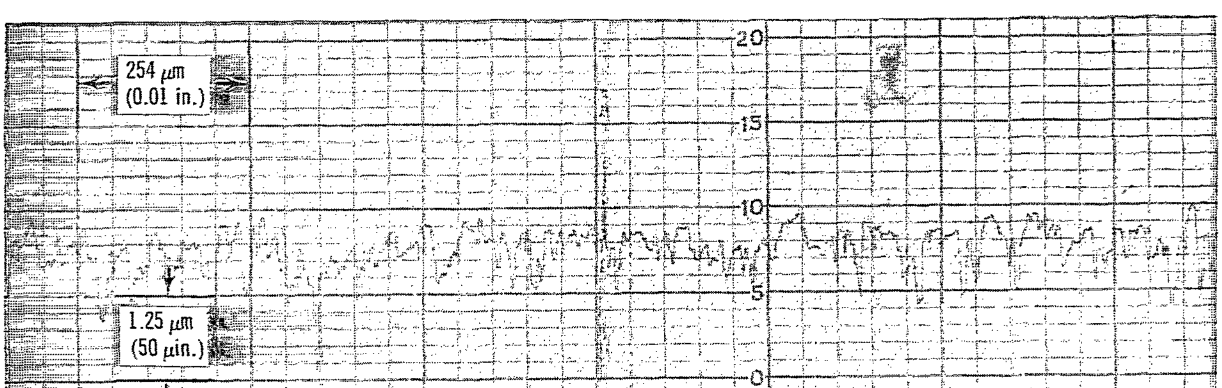


(a) Surface before experiment.

(b) Surface after experiment.

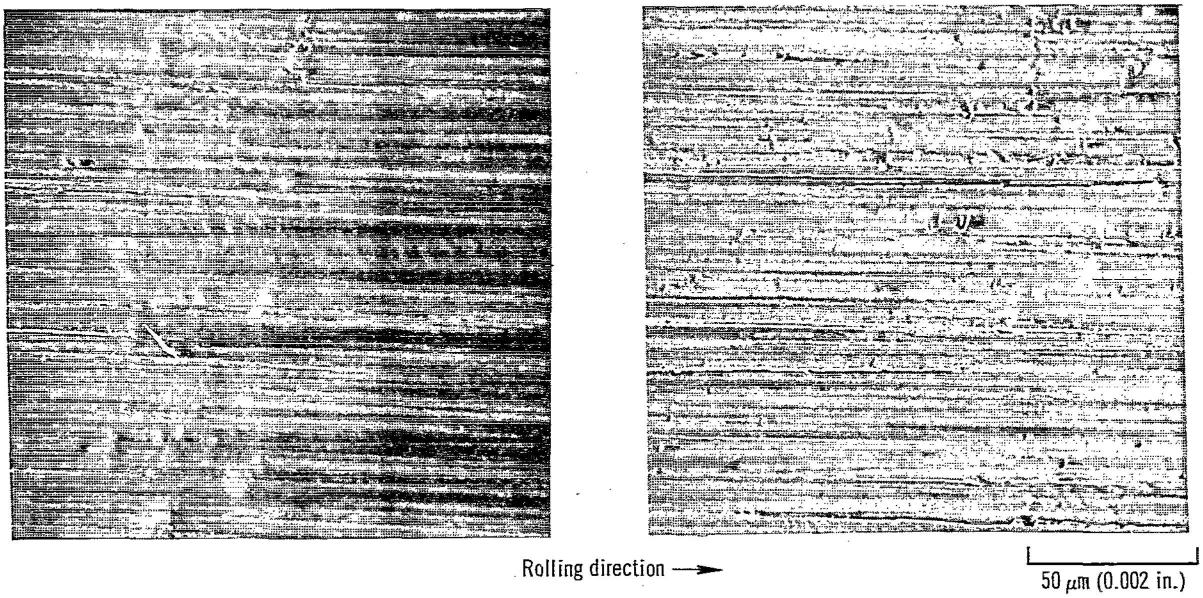


(c) Surface trace before experiment. Finish, 0.30 μm (12 μin.) cla.



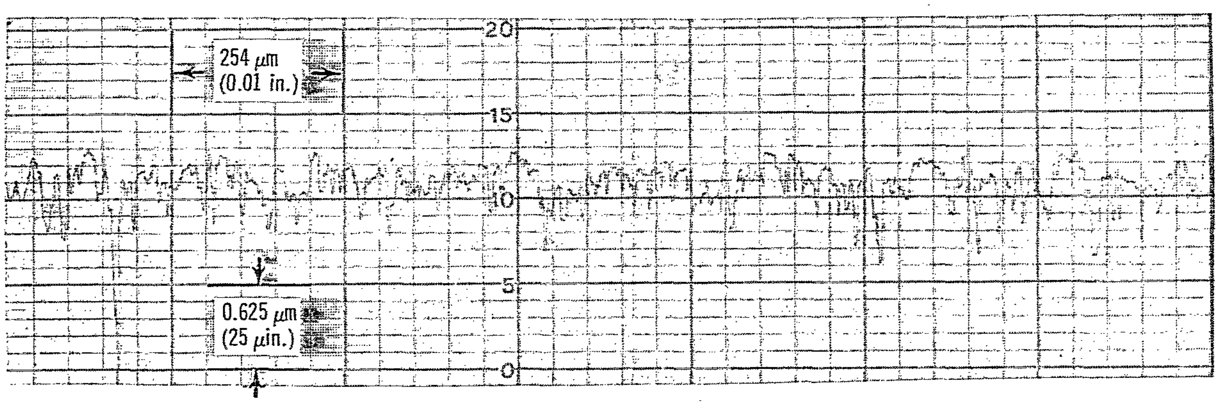
(d) Surface trace after experiment. Finish, 0.28 μm (11 μin.) cla.

Figure 15. - Scanning electron micrographs and surface traces of medium-rough lower disk surface before and after operation at 689 MPa (100 000 psi) and 10 000 rpm with disk temperature of 339 K (150° F) and type II ester lubricant.

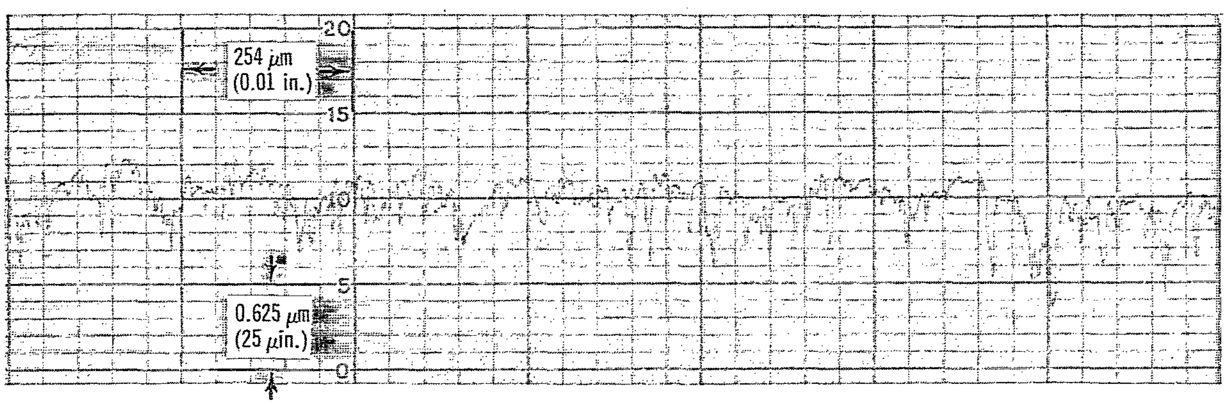


(a) Surface before experiment.

(b) Surface after experiment.



(c) Surface trace before experiment. Finish, 0.13 μm (5 μin.) cla



(d) Surface trace after experiment. Finish, 0.114 μm (4.5 μin.) cla.

Figure 14. - Scanning electron micrographs and surface traces of smooth lower-disk surface before and after operation at 1380 MPa (200 000 psi) and 5000 rpm with disk temperature of 339 K (150° F) and type II ester lubricant.