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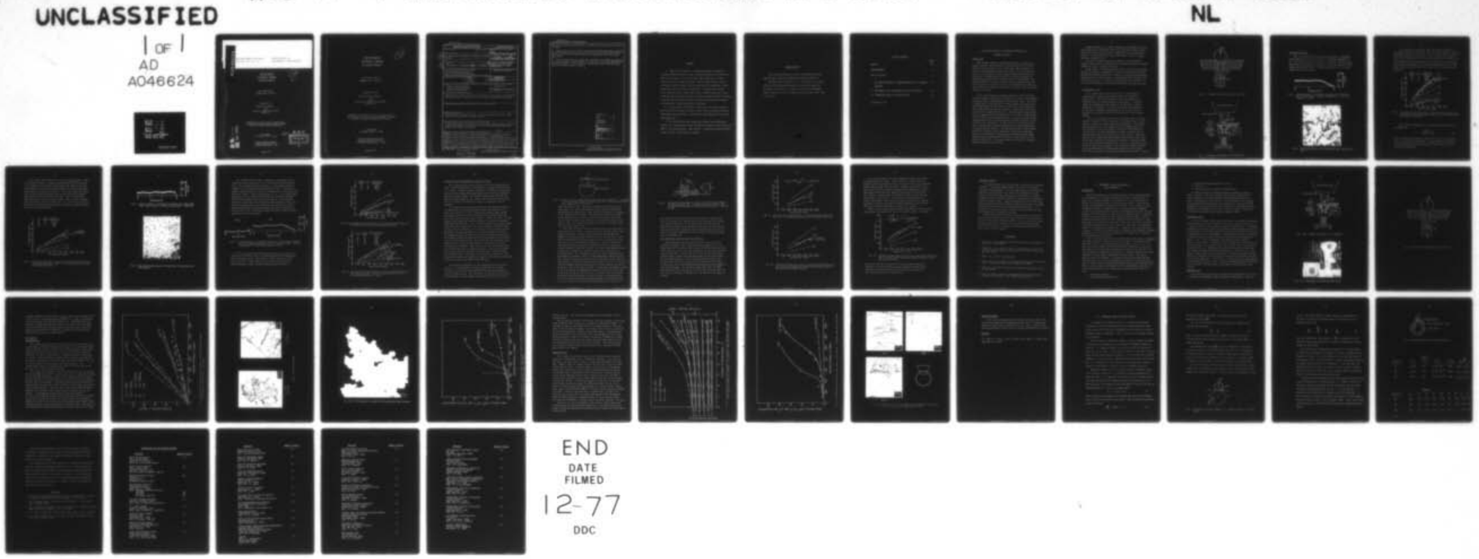

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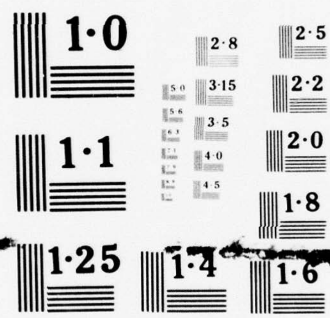

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WEAR MECHANISMS
FOR METALLIC SURFACES
IN SLIDING CONTACT

Third Annual Report
November 1976 - July 1977

Sponsored by the
Office of Naval Research
under
Contract No. N00014-67-A-0314-0025
NR 097-396

T. Shirakashi
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1. Under certain conditions, carbontetrachloride is found to be a negative boundary lubricant (gives a higher coefficient of friction than that of dry surfaces in air), while under other conditions, it lowers friction and gives a beneficial effect. Both of these situations are illustrated for heavily loaded sliding surfaces where the subsurface is undergoing gross plastic flow and an explanation is presented which appears to be consistent with all experimental facts. Carbontetrachloride is found to be more reactive chemically when the sliding surfaces are heavily strained or galled under high normal and shear

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stresses and containing microcracks, a situation that arises when cutting at low speed.

2. Initial results of frictional sliding under high normal pressure obtained with ATA and MoS_2 lubricants clearly show that the newly developed chalcogenides are more useful in reducing wear under high normal loads than under light loads.

3. The non-dimensional wear number (N_w) obtained using dimensional analysis to a limited system of wear quantity was found to be very useful parameter to the design engineer. More research is recommended towards obtaining values of N_w for a wide variety of systems.

ABSTRACT

1. Under certain conditions, carbontetrachloride is found to be a negative boundary lubricant (gives a higher coefficient of friction than that of dry surfaces in air), while under other conditions, it lowers friction and gives a beneficial effect. Both of these situations are illustrated for heavily loaded sliding surfaces where the subsurface is undergoing gross plastic flow and an explanation is presented which appears to be consistent with all experimental facts. Carbontetrachloride is found to be more reactive chemically when the sliding surfaces are heavily strained or galled under high normal and shear stresses and containing microcracks, a situation that arises when cutting at low speed.

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ACKNOWLEDGEMENTS

This work was sponsored by a grant from the Office of Naval Research under contract No. N00014-67-A-0314-0025, NR097-397.

The authors wish to thank Drs. R. S. Miller and K. E. Ellingsworth for many interesting discussions and valuable suggestions. The authors also thank Dr. A. Conte of the Naval Air Development Center, Warminister, PA, for supplying solid lubricants (ATA), used in this study.

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1. THE CONFLICTING ROLES OF CARBONTETRACHLORIDE AS A BOUNDARY LUBRICANT

INTRODUCTION

Under certain conditions, carbontetrachloride is found to be a negative boundary lubricant (gives a higher coefficient of friction than that of dry surfaces in air), while under other conditions, it lowers friction and gives a beneficial effect. Both of these situations are illustrated for heavily loaded sliding surfaces where the subsurface is undergoing gross plastic flow and an explanation is presented which appears to be consistent with all experimental facts. Carbontetrachloride is found to be more reactive chemically when the sliding surfaces are heavily strained or galled under high normal and shear stresses and containing microcracks, a situation that arises when cutting at low speed.

At low cutting speeds, carbontetrachloride is one of the most effective cutting fluids known from the point of view of the reduction of cutting forces, and improvement of the surface finish. Yet, when a cutting tool is slid back over a surface freshly cut using CCl_4 as the cutting fluid, the coefficient of friction of the clearance surface rubbing on the freshly cut surface is higher than with sliding in air under the same conditions (1). This observation suggests that CCl_4 is a good cutting fluid despite the fact it gives a high coefficient of friction as a boundary lubricant. A similar result has been reported using a friction apparatus that simulates conditions on the tool face of a cutting tool. In this test (2) a hard steel brinell ball is forced into a soft steel surface until a fully plastic zone is produced beneath the ball. The deformed specimen is then rotated relative to the ball and the coefficient of friction is measured. When such an experiment is performed on a surface wetted by carbontetrachloride, the coefficient of friction is high relative to the value obtained in air. This again suggests that CCl_4 is a negative boundary lubricant relative to air.

However, workers in Dr. Tabor's laboratory at Cambridge University have reported just the reverse role of CCl_4 (3) when a freshly turned surface was wetted with CCl_4 and a loaded slider was drawn across the surface. In these tests, CCl_4 gave a coefficient of friction lower than that obtained in air.

In order to further explore this paradox, a test arrangement similar to that used in reference 2 was constructed and used in further studies of CCl_4 as a boundary lubricant.

At the outset, it should be explained that this work was conducted on CCl_4 not because it represents an important boundary lubricant but because the phenomenon explored is thought to exist with other boundary lubricants but to a lesser degree. Carbontetrachloride cannot be used in practice because it is very toxic and under certain conditions, it is too active leading to chemical corrosion and an increased wear rate.

EXPERIMENTAL SET-UP

Fig. 1 shows the principle of the test. A hard sphere is loaded against a softer test specimen until the subsurface is fully plastic. Then, with the normal load still applied, the deformed surface is rotated relative to the sphere. In order to remove the singularity at the center of the specimen, a hole of diameter d_1 is employed. It has been found that the coefficient of friction is essentially independent of the size of the hole employed in the range of 1/16 to 1/8 inch for a 1/2 inch diameter sphere.

Fig. 2 is a schematic view of the arrangement used. The hard sphere is mounted in a chuck attached to a standard brinell testing machine by means of a strain gage torque dynamometer. The spheres used are standard 1/2 inch diameter AISI 51100 bearing balls. The soft specimen is a one inch diameter cylinder of AISI 1018 steel, 1/2 inch high. The lower cylindrical specimen is provided with a central hole ranging in diameter from 1/16 to 1/8 inch. After the vertical load is applied to the hardness tester and the lower specimen has been indented, the cylindrical specimen is rotated by means of the motor and gear arrangement shown in Fig. 2. Rotational speeds from 2 to 1000 rpm are possible. This arrangement enables friction to be measured when one of the mating surfaces is fully plastic. The frictional torque is continuously monitored using a chart recorder.

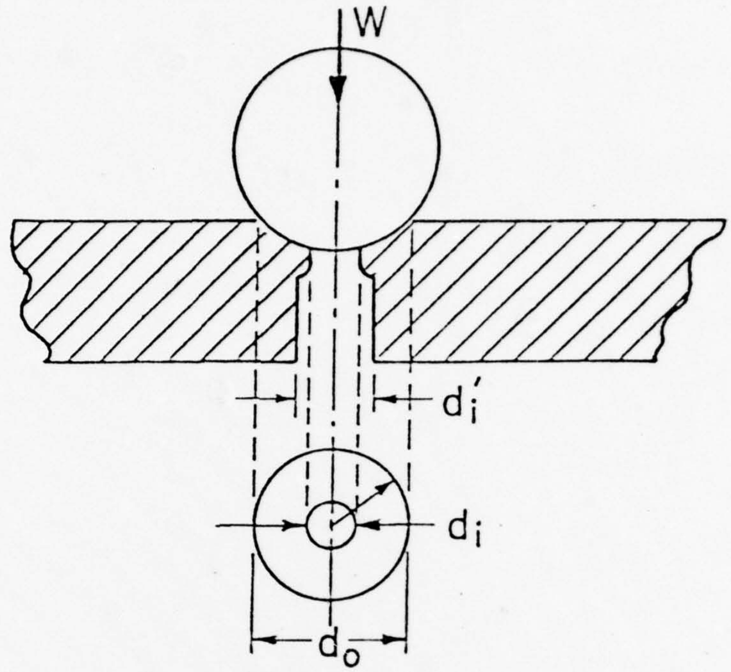


Fig. 1. Principle of Fully Plastic Friction Test.

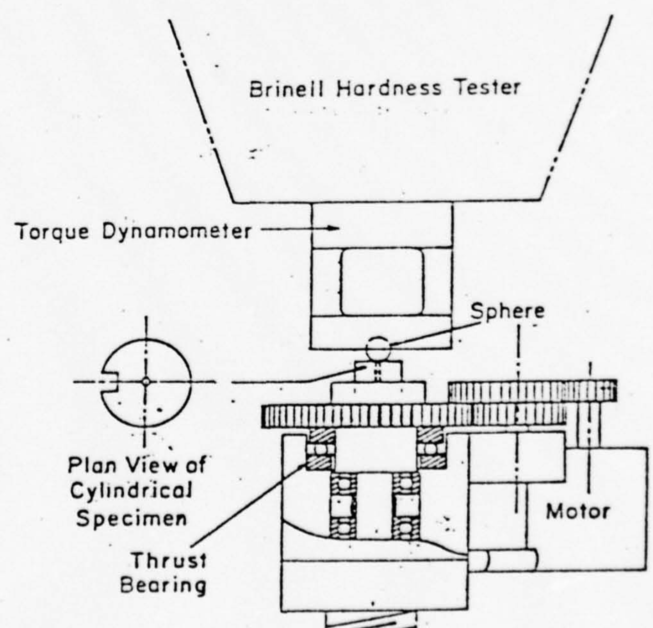


Fig. 2. Schematic Arrangement of Test Apparatus.

TEST RESULTS ON STEEL

Fig. 3 is a typical friction torque (inch pounds) vs. rotational displacement (rev) curve for sliding in air following indentation in air. The initial torque is very low ($\simeq$ 8 in. lb) but rises to a value of about 50 in lbs during one revolution. During this period of rising torque, the rotating surface is severely galled and Fig. 4 is a plan view of such a galled surface.

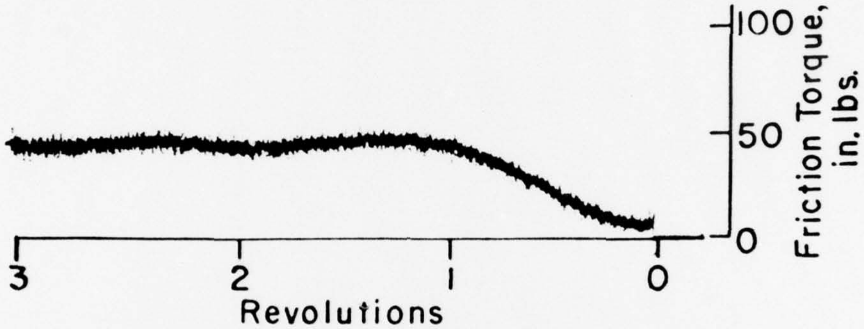


Fig. 3. Friction torque vs. Rotational Displacement for Sliding in Air. Load on sphere = 1000 kg, sliding speed = 2 rpm, hole diameter = 0.125 in.

Fig. 4. Galled Surface After Three Revolutions Under Conditions of Fig. 3.

If dry sliding is interrupted after the initial transition to the steady state, the steady state value of friction torque is obtained immediately without any transition. This is because the surface was fully galled during the initial transition and after that, there is no further deterioration of the surface even when motion is interrupted. Fig. 5 shows the variation of the mean frictional stress (τ) vs. mean normal stress (σ) when sliding in air under initial and steady state conditions.

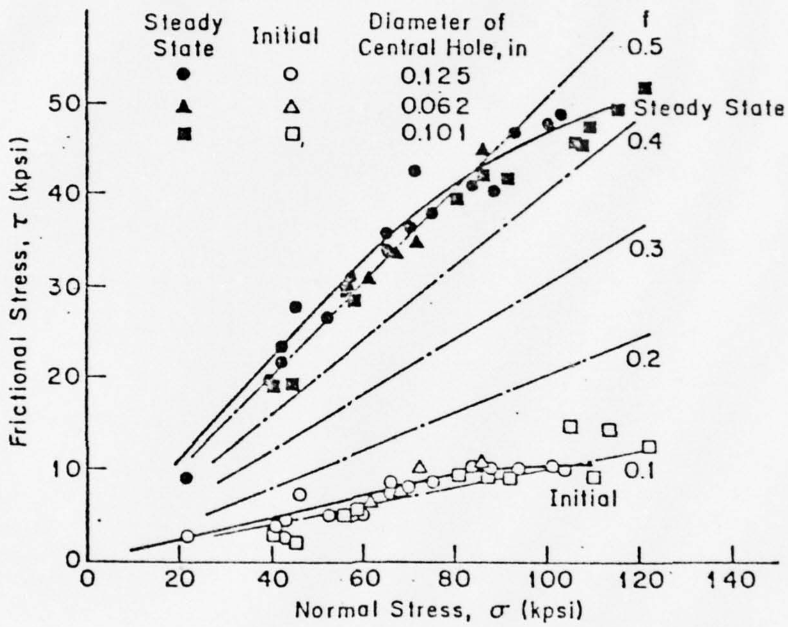


Fig. 5. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for Sliding in Air Under Initial (Open Points) and Steady State (Solid Points) Conditions.

The frictional torque (M) is converted to mean shear stress (τ) as follows (2)

$$\tau = \frac{12\,M}{\pi\,(d_0^{\;3} - d_1^{\;3})} \tag{1}$$

Lines of constant coefficient of friction ($f = \frac{\tau}{\sigma}$) are also shown in Fig. 5. for purposes of reference. The coefficient of friction is initially about 0.1 for the dry case but rises to about 0.5 under steady state conditions.

Fig. 6 shows the variation of τ with σ for CCl_4 and Fig. 7 shows the frictional torque vs. rotational displacement for the same case. It is evident that frictional torque reaches the steady state value instantaneously in this case and consequently the initial and steady state values are the same as in Fig. 6. Also, the initial and steady state friction coefficients with CCl_4 are the same (0·28) compared with the 0·5 for the dry steady state case. Fig. 8 is plan view photomicrograph of the CCl_4 surface which is seen to be far smoother and crack free than the air surface (Fig. 4). A thin film of material was present on the surface that had been indented and rubbed with CCl_4 which was indentified as $FeCl_3$.

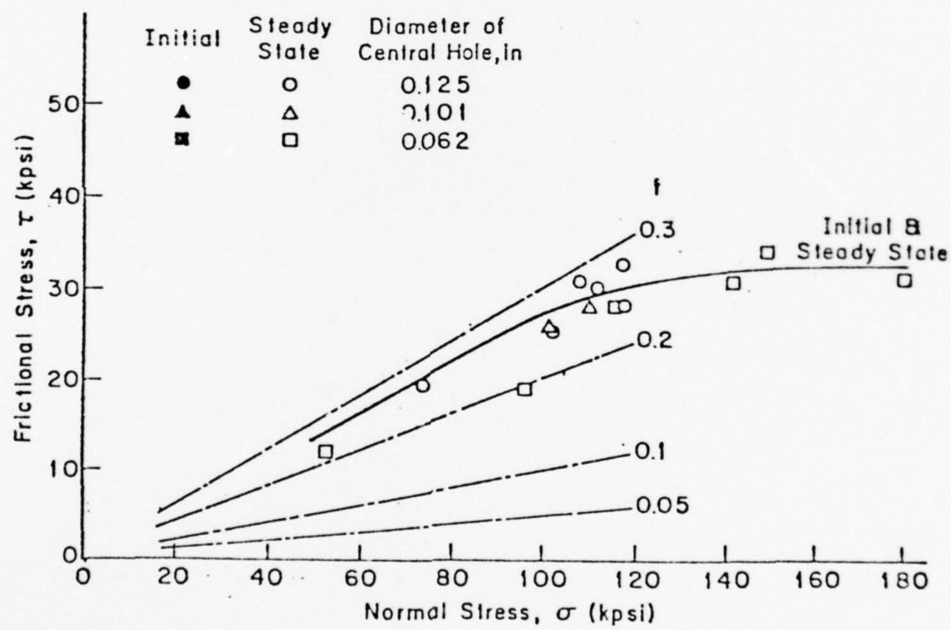


Fig. 6. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for Sliding with CCl_4. There is no difference between initial and Steady State Values.

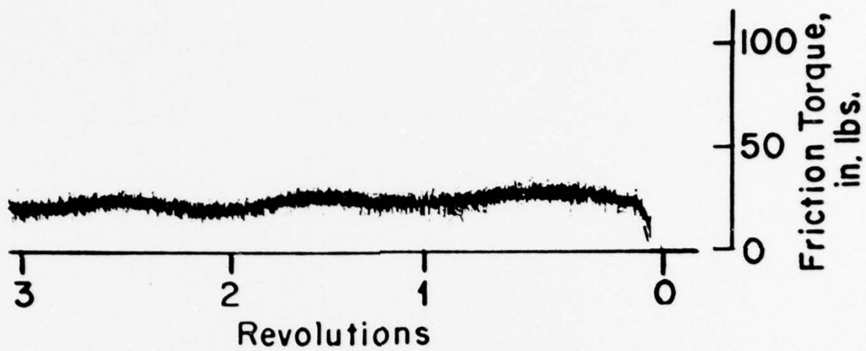


Fig. 7. Friction Torque vs. Rotational Displacement for Sliding with CCl_4. Load on sphere = 1000 kg, sliding speed = 2 rpm, hole

Fig. 8. Plan View Photomicrograph of Surface After 3 Revolutions with CCl_4 present.

In a further series of tests, indentation and rotation to the steady state were carried out in air followed by the application of CCl_4. Fig. 9 shows the friction torque vs. displacement traces for rotation in air followed by the application of CCl_4. The friction torque is seen to drop to a very low value when CCl_4 is applied to the galled air surface. Fig. 10 shows values of τ vs. σ for indentations produced in air and rotated until galling occurred (3 revolutions). Then CCl_4 was applied to the cavity and values of τ were measured. The values marked initial were those measured immediately before the CCl_4 had an opportunity to react with the surface while the values marked steady state are those pertaining after three revolutions in the presence of CCl_4. The latter values are nearly an order of magnitude lower than the former ones.

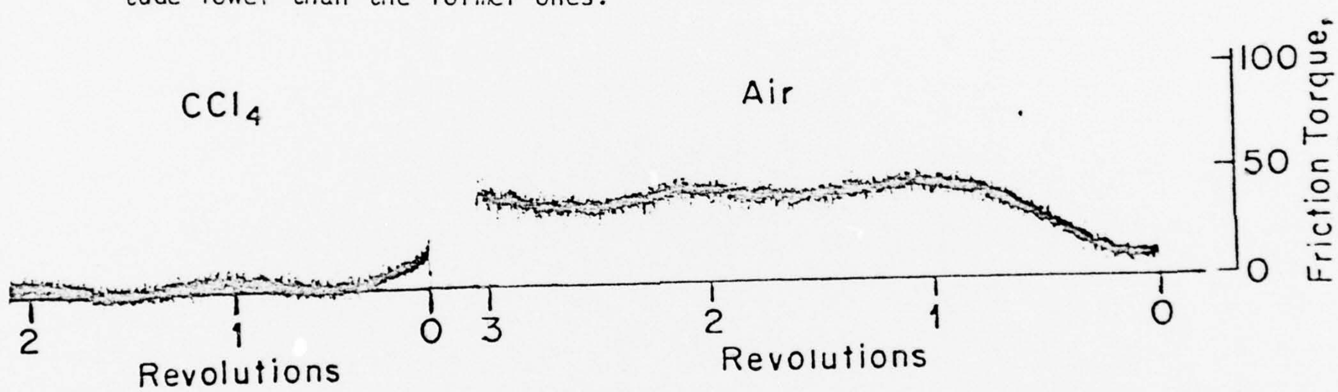


Fig. 9. Friction Torque vs. Rotational Displacement for Sliding Initially in Air Followed by Application of CCl_4. Load on sphere = 1000 kg, sliding speed = 2 rpm, hole diameter = 0.125 in.

Fig. 11 shows values of shear and normal stress obtained for surfaces having different values of surface roughness before indentation when lubricated by CCl_4. While there is little difference in the initial values of f with roughness, the steady state values show a large difference, rougher surfaces yielding lower values of f.

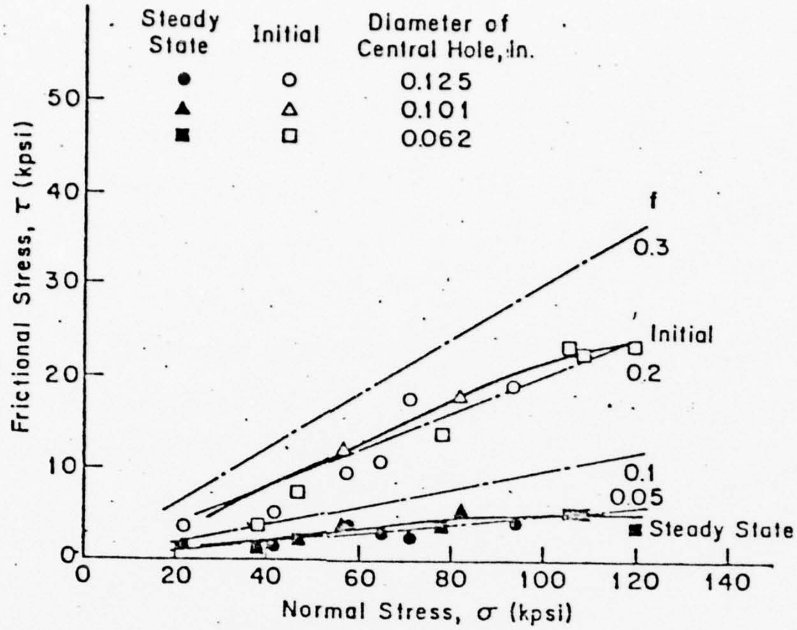


Fig. 10. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for Sliding in Air Followed by Sliding with CCl_4.

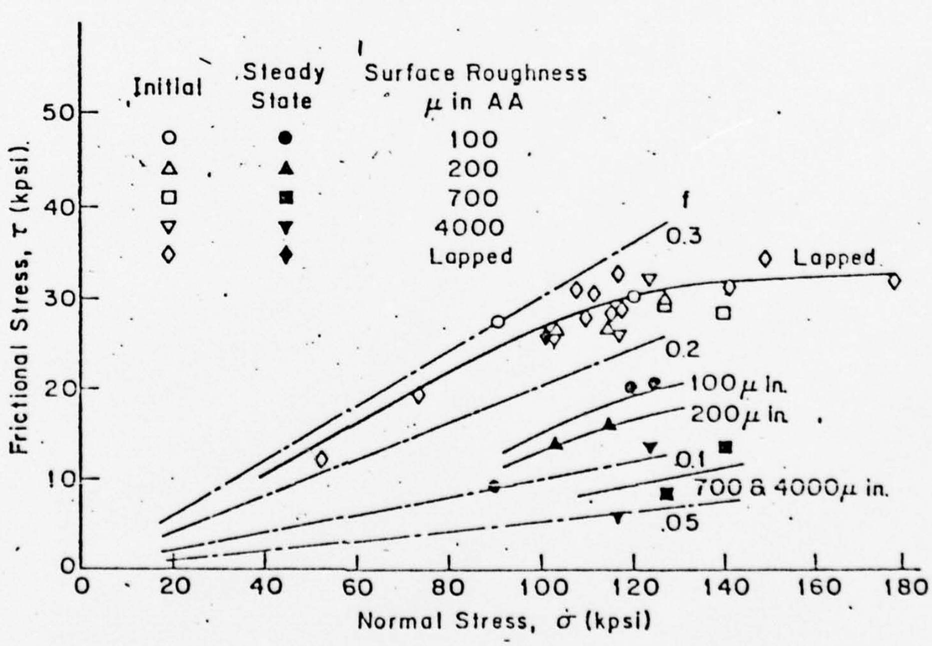


Fig. 11. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for Sliding with CCl_4 when the Initial Surface Roughness has Different Values in μ in, AA.

DISCUSSION AND INTERPRETATION OF RESULTS ON STEEL

The foregoing results are consistent with the following explanation. Carbontetrachloride is ineffective as a boundary lubricant and is, in fact, a negative boundary lubricant if it does not react chemically with the surface being lubricated to form a brittle compound in the case of steel ($FeCl_3$). The negative action comes from the fact that it excludes oxygen in air. Since metal oxides are somewhat beneficial in lowering frictional resistance, the presence of air is important.

It is well known that surface asperities are merely flattened by an indenter but not removed completely unless the indenter is slid across the surface (4). This is because the plastic zones beneath each asperity grow as they are flattened under increased load, but only until adjacent plastic zones interact. After that, there is gross plastic flow beneath the indenter instead of localized flow beneath individual asperities (5). Fig. 12 shows schematically a rough surface before and after indentation. For a given material, the mean stress at the surface of asperities will increase as the spacing of adjacent asperities increases and hence as the surface roughness increases. The tendency for CCl_4 to react with iron will increase with pressure. For a smooth surface, the pressure will be insufficient to cause CCl_4 to react to form $FeCl_3$ and the role of CCl_4 will be to exclude oxygen which, in turn, results in high friction. This explains why the friction was so high when a tool used to cut steel or aluminum using CCl_4 was slid back over a freshly cut surface. The surface produced was so smooth that the CCl_4 did not react to form a metal chloride on the backward pass. The values of f recorded in reference 2 were initial ones rather than steady state values. This explains why sliding in air was so much lower than sliding with CCl_4.

The foregoing explanation is also consistent with the results of Fig. 11. The pressure is too low on asperities of a smooth surface to cause CCl_4 to react and hence its role is the negative one of excluding oxygen. The experiments at Cambridge University (3) were conducted on a much rougher turned surface than that of experi-

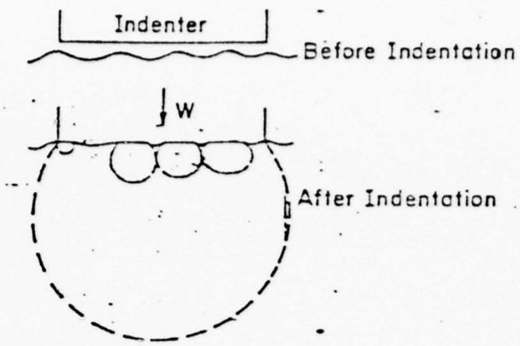


Fig. 12 Schematic view of rough surface before and after indentation. The dashed line is the elastic-plastic boundary under entire indentor when plastic zones beneath asperities join up.

ments described in ref. 1 which were produced by a shaving cut made using CCl_4. As a result, the pressure on the Cambridge asperities was sufficient to cause CCl_4 to react and this resulted in a reduction in the coefficient of friction. The results of Fig. 10 are similar to the Cambridge ones in that a surface first rotated in air gives rise to a galled surface and pressures are sufficiently high to cause CCl_4 to react. This causes the steady state values of friction with CCl_4 to be lower than in air.

Having said all this, the role played by CCl_4 on the tool face in metal cutting is not clear. In fact, it may act as both positive and negative lubricant - positive very close to the cutting edge and negative as the chip proceeds farther up the face of the tool. From the well established concentrated shear model of cutting and the fact that strain is not uniformly distributed in a metal but occurs on relatively widely spaced planes, fracture must occur at the ends of lamellae adjacent to the tool tip (Fig. 13). The most probable direction of fracture is along AD for a ductile material but along AE for a brittle material. Fig. 13 shows the slip line field suggested by Lee and Shaffer (6) together with the corresponding Mohr's Circle diagram. This analytical approach to metal cutting arbitrarily assumes that the shear plane is in the direction of maximum shear stress (i.e. on plane S). The most probable fracture direction for a brittle material will be at an angle $\theta = 45°$ to the plane of shear. In any case, the bottom surfaces of the lamellae will be jagged when freshly generated at the tool tip. As the chip proceeds up the tool face, its surface will be burnished. During the burnishing process, the role of CCl_4 in reducing friction will be a positive one if the pressure generated is sufficiently high to cause a reaction to occur with the metal being cut. However, as

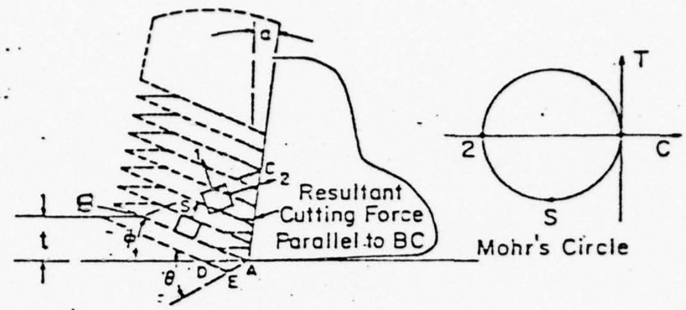


Fig. 13. Concentrated Shear Model of Cutting with Mohr's Circle Diagram for Slip Line Field ABC. Fracture Surface at Tool Tip = AD for Ductile Material but AE for Brittle Material (AE is parallel to BC).

the burnished surface of the chip proceeds further along the tool face, the pressure will drop and the role of CCl_4 may shift to that of a negative lubricant. On the other hand, the metal chloride generated during the initial burnishing action may be sufficient to have a positive effect during the post burnishing contact period in which case we must conclude that the net effect of CCl_4 on the tool face is a positive one.

TEST RESULTS ON LEAD AND THEIR INTERPRETATION

Some additional tests were performed with lead as the soft cylindrical specimen. Fig. 14 shows tests performed in air. The initial value of friction coefficient was low (~0.18) but after a few revolutions, the shear stress corresponded to the bulk shear strength of lead (~1000 psi). This is due to the fact the oxide initially present tends to prevent the lead from bonding to the steel sphere, thus preventing galling. As the oxide originally present is displaced, clean lead on steel gives rise to high values of friction. To check this, tests were performed using hydrogen peroxide (H_2O_2) as the source of oxygen. The results of these tests (Fig. 15) show final values of friction equal to initial values since the oxide surface layer was replaced as rapidly as it was displaced when H_2O_2 was present.

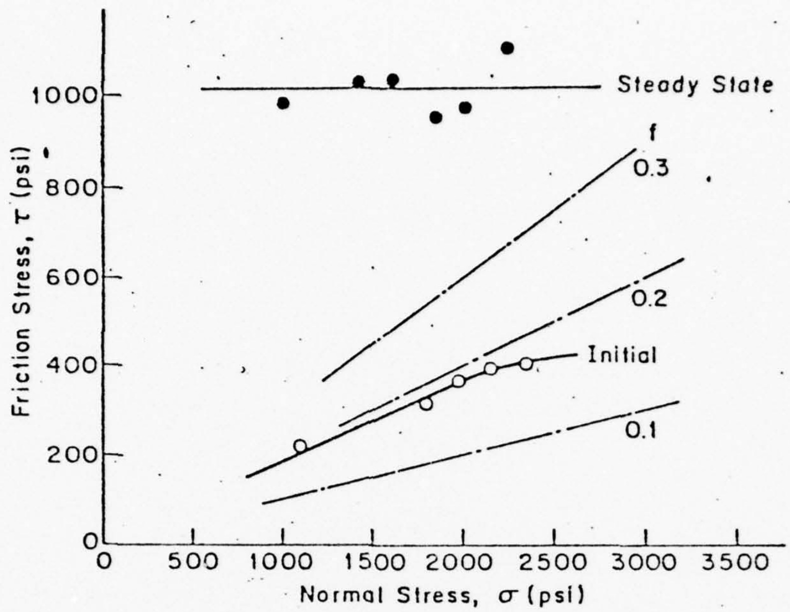


Fig. 14. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for a 1/2 in. diameter Hard Steel Sphere Sliding on Lead in Air.

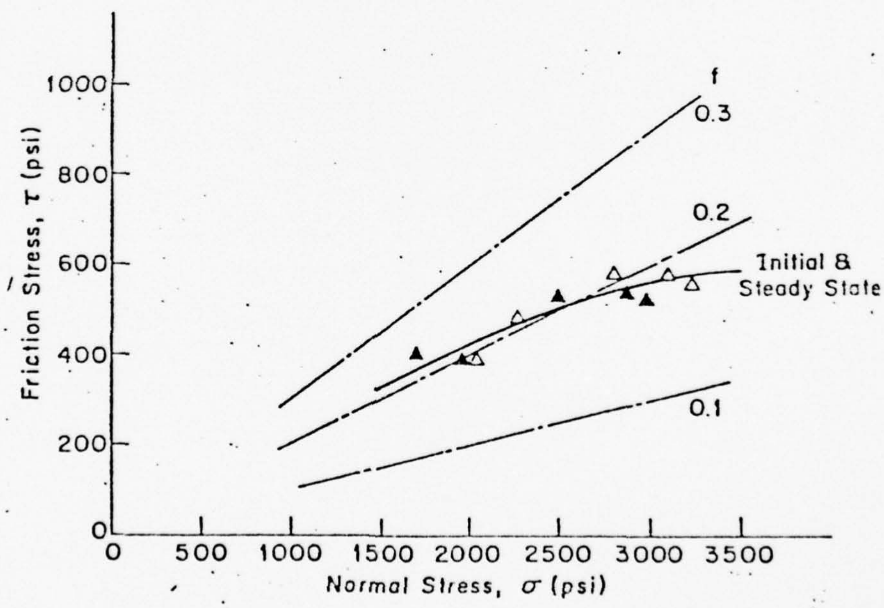


Fig. 15. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for a 1/2 inch diameter Hard Steel Sphere Sliding on Lead in the Presence of Hydrogen Peroxide.

Fig. 16 gives results for lead indentations made in the presence of CCl_4 followed by sliding. Initial values of friction were only slightly higher than those for the dry case since Pb Cl_3 has a slightly higher shear strength than lead oxide. However, what is more important, the Pb Cl_3 film initially produced during indentation is brittle and ruptures during sliding, exposing clean lead to the steel ball. This results in final values of friction with CCl_4 that are the same as the final values for air. In both cases, the high values of f result from galling. Thus, CCl_4 is a negative lubricant for lead due primarily to the fact that the film formed chemically on the surface (Pb Cl_3) is brittle, exposing clean lead as it fractures.

Lead is about the only metal for which CCl_4 does not reduce cutting forces below those obtained in air at low cutting speeds. The reason

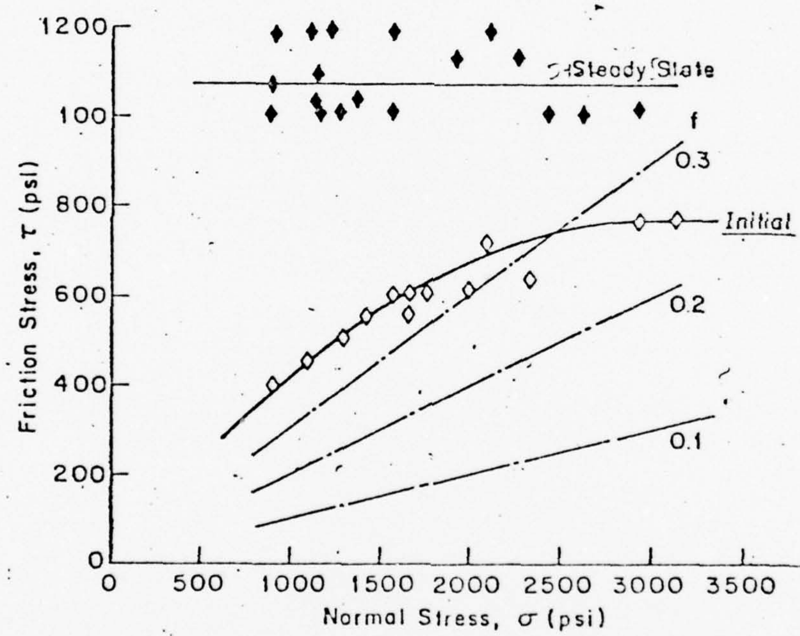


Fig. 16. Variation of Mean Shear Stress (τ) with Mean Normal Stress (σ) for a 1/2 inch diameter Hard Steel Sphere Sliding on Lead in the presence of CCl_4.

for this is that the lead chloride initially formed during chip formation is brittle, fractures during subsequent sliding of the chip up the face of the tool and thus exposes clean lead to the tool face which results in high friction.

CONCLUDING REMARKS

This study reveals that CCl_4 can have a dual role as a boundary lubricant. It can give higher friction than air, if it does not react, by excluding oxygen. Or it can give low values of friction if conditions are such that it can react. The tendency for a steel surface to react with CCl_4 increases with an increase in surface roughness since the resulting increase in pressure on the asperities promotes chemical action. Carbontetrachloride is most effective on very rough galled surfaces (highly strained) and results in a surface burnishing action that is part chemical and part physical. It is believed that extreme pressure lubricants generally perform in this way although not as dramatically as CCl_4.

Carbontetrachloride is believed to be a negative cutting fluid (gives higher cutting forces than when cutting in air) for lead not so much for the reason generally stated - i.e. due to lead chloride having a higher shear strength than lead itself but because lead chloride is so brittle it ruptures on sliding, exposing clean lead which in turn leads to galling.

REFERENCES

1. Shaw, M.C. "On the Action of Metal Cutting Fluids at Low Speeds", Wear 2 No.3, 217 (1959).

2. Shaw, M.C., A. Ber and P.A. Mamin, "Friction Characteristics of Sliding Surfaces Undergoing Subsurface Plastic Flow", Trans. ASME 82, 342, (1960).

3. Doyle, E.D., private communication.

4. Bowden, F.P. and D. Tabor, "The Friction and Lubrication of Solids", Part I, Oxford University Press, London, p.21 (1950).

5. Shaw, M.C. "The Role of Friction in Deformation Processing", Wear, 6, 140, (1963).

6. Lee, E.H. and B.W. Shaffer, "The Theory of Plasticity Applied to a Problem of Machining", Trans. ASME, 72, 405, (1951).

II. PERFORMANCE OF NEW CHALCOGENIDES AS SOLID LUBRICANTS

INTRODUCTION

There are many bearings in engineering practice that cannot be designed to be hydrodynamic. Such bearings perform well when a solid lubricant is applied to the bearing surfaces. The function of a solid lubricant is to prevent the contacting surfaces from welding which result in high friction, and wear and roughening of surfaces due to galling. Solid lubricants are advantageous with heavily loaded bearings or bearings designed to operate at speeds below that necessary to establish a hydrodynamic film.The important property of solid lubricants is their ability to adhere strongly to a bearing surface so that they cannot be readily displaced during sliding. Graphite and Molybdenum disulfide are the most commonly used solid lubricants. While these materials perform well in many applications they have their limitations. For example, graphite requires minute amounts of water vapor or hydrocarbons present in the atmosphere to perform well. Graphite is not a good lubricant in vacuum.It also fails to lubricate above a moderately high temperature ($\approx 900^{\circ}F$). Molybdenum disulfide does perform satisfactorily in vacuum and is usable to higher temperatures than graphite.

There is need for improved solid lubricants other than graphite or Molybdenum disulfide, particularly under high loads or low speed This need was clearly identified recently in the Naval Aircraft applications in the U.S. A. The Naval Air Systems Command initiated and sponsored a program by the Naval Air Development Center and Pennwalt Corporation to synthesize and evaluate a new class of complex chalcogenide solid lubricants. They have prepared over twenty compounds including $AsSbS_4$, $FeMoS_4$,$SbSbS_4$, and Ce_2 (MoS_4) . They found a number of them to be amorphous. As extreme pressure and antiwear additives they found almost all of the chalcogenides to be superior to simple sulfides. However, research work was mainly concentrated on arsenic thio antimonate (ATA). There is need to study the performance of other chalcogenides, which are not yet fully characterized, over a wide range of speeds and loads relative to their:

1. Frictional properties.
2. Wear prevention characteristics.

3. Surface refining characteristics (run-in).
4. Film life.
5. Fretting, corrosion prevention characteristics.

A friction and wear test apparatus recently developed at Carnegie-Mellon University is ideal for studying solid lubricant characteristics since it operates in the high load region where the subsurface of the softer sliding member is fully plastic. In the following, initial results on the performance of MoS_2 and ATA solid lubricants in sliding AISI 52100 (hardened) ball on AISI 1018 steel and stainless steel involving subsurface deformation are presented which clearly inidcate the superior performance of ATA under high normal pressure only as compared to MoS_2.

EXPERIMENTAL SETUP

In order to achieve sliding under bulk plastic flow conditions a modified Brinnel hardness test set up is used. This set up as shown in Fig. 1(a) is an improved version of that reported by Shaw, Ber and Mamin [1]. The specimen is mounted on the table of the Brinnel hardness tester supported by radial and thrust bearings. The torque required to rotate the specimen against the ball is measured by means of a dynamometer. The necessary bulk flow is accomplished by making an ordinary Brinnel indentation before rotating the specimen by a motor . Fig. 1 (b) is a photograph of the modified Brinnel Hardness tester for wear studies. In order to avoid the singularity that exists at the pole in the case of an ordinary Brinnel test, a central hole in the specimen is provided (Fig. 2). Experiments with different sized holes for the same ball diameter revealed no significant differences so far as friction is concerned. However, when the size of the hole is too small and normal load too high due to collapse of the hole and side flow of the metal the hole was found to fill almost completely. To avoid such a situation and to provide geometric similarity the d_i/d_o ratio in Fig. 2 is maintained approximately constant (≈ 2.5) in all the tests. Friction force is continuously monitored using a chart recorder.

MATERIALS USED

Solid lubricants used in this study were kindly provided by Dr. A. Conte of the Naval Air Development Center, Warminister, Pennsylvania. They are

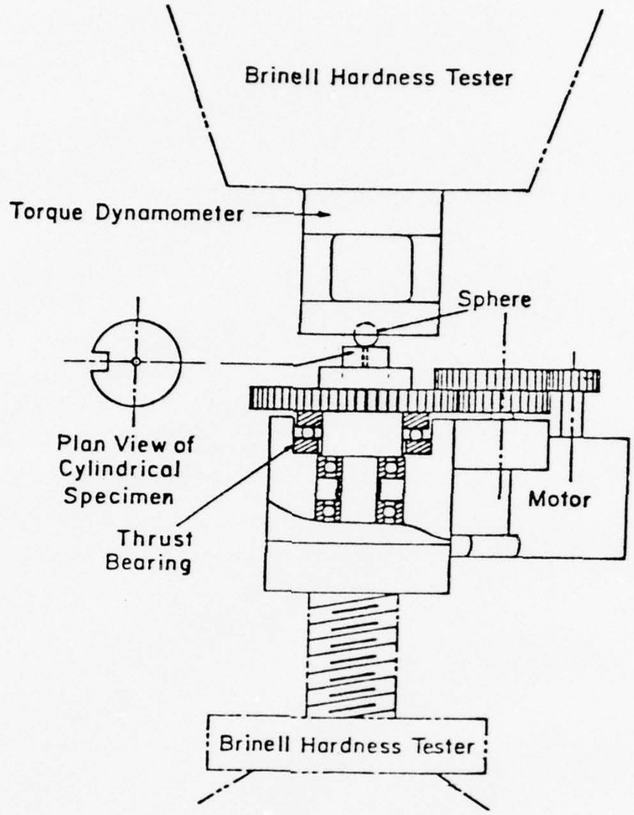


Fig. 1 (a). Schematic Arrangement of Test Apparatus.

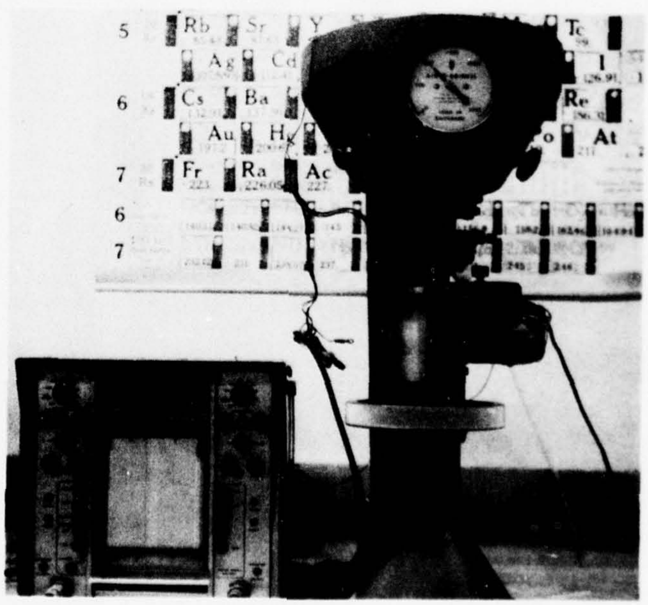


Fig. 1 (b). Photograph of the CMU's New Wear Tester.

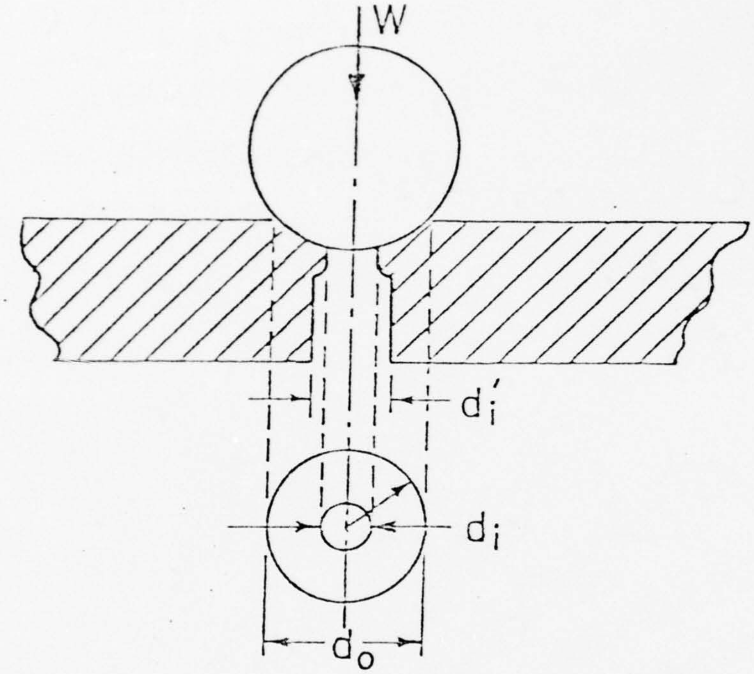


Fig. 2. Area of Contact Between Ball and Impression.

straight Molybdenum disulfide (MoS_2), straight arsenic thio antimonate (ATA) 5 wt.% of ATA in lubricating grease (LS1-5ATA), 5 wt.% MoS_2 in lubricating grease (LS1-5 MoS_2) and lubricating grease (LS1). AISI 52100 steel ball was used for indentation and the surface of 1 inch (AISI 1018) low carbon steel and stainless steel cylinders were used as the sliders. Lubrication pockets were provided on the indentation as otherwise the lubricant was found to extrude out due to normal pressure.

TEST RESULTS

LOW CARBON STEEL

Fig. 3 shows the variation of frictional stress (τ) with normal stress for ATA, MoS_2, LS1-5ATA, LS1-5MoS_2 and LS1 grease. Lines of constant coefficient of friction (μ), which is the ratio of frictional stress to the normal stress, are also drawn in the figure. It can be seen that the frictional coefficient is high for straight ATA (μ = 0·225) followed by straight MoS_2 ($\mu \approx 0{\cdot}09$). The high friction of straight ATA can be due to the fact that the surface is covered with an ATA film. Figs. 4(a) & (b) are SEM's. Fig 4(c) is a TEM of platelets of ATA showing sheet type structure. The friction coefficients for straight grease, grease with either MoS_2 or ATA are very low (μ = 0·05) and about the same.

Fig. 5 shows the variation of wear rate with normal stress for straight grease, LSi-5MoS_2 and LS1-5ATA. It can be seen that up to about 45 kpsi there is no significant difference in the wear rate. However, above this normal pressure, the wear rate of AISI 1018 steel covered with LS1 grease increases, possibly due to film breakage. A much higher normal pressure ($\approx$ 65 kpsi) is required before the wear rate of AISI 1018 steel surface coated with LS1-MoS_2 starts increasing rapidly. The wear rate of steel with LS1-5ATA increases gradually up to 130 kpsi and the second stage of rapid wear rate was not reached. If one compares the wear rates of AISI steel covered with grease, LS1-5MoS_2 and LS1-5ATA, one can clearly notice a 5 fold increase in wear rate with straight grease and a 3 fold increase with LS1-5MoS_2 as compared to LS1-5ATA. This clearly varifies the superior performance of ATA chalcogenides under high normal pressure as compared to MoS_2. Again from this figure one would not notice much difference in the wear rate when the normal

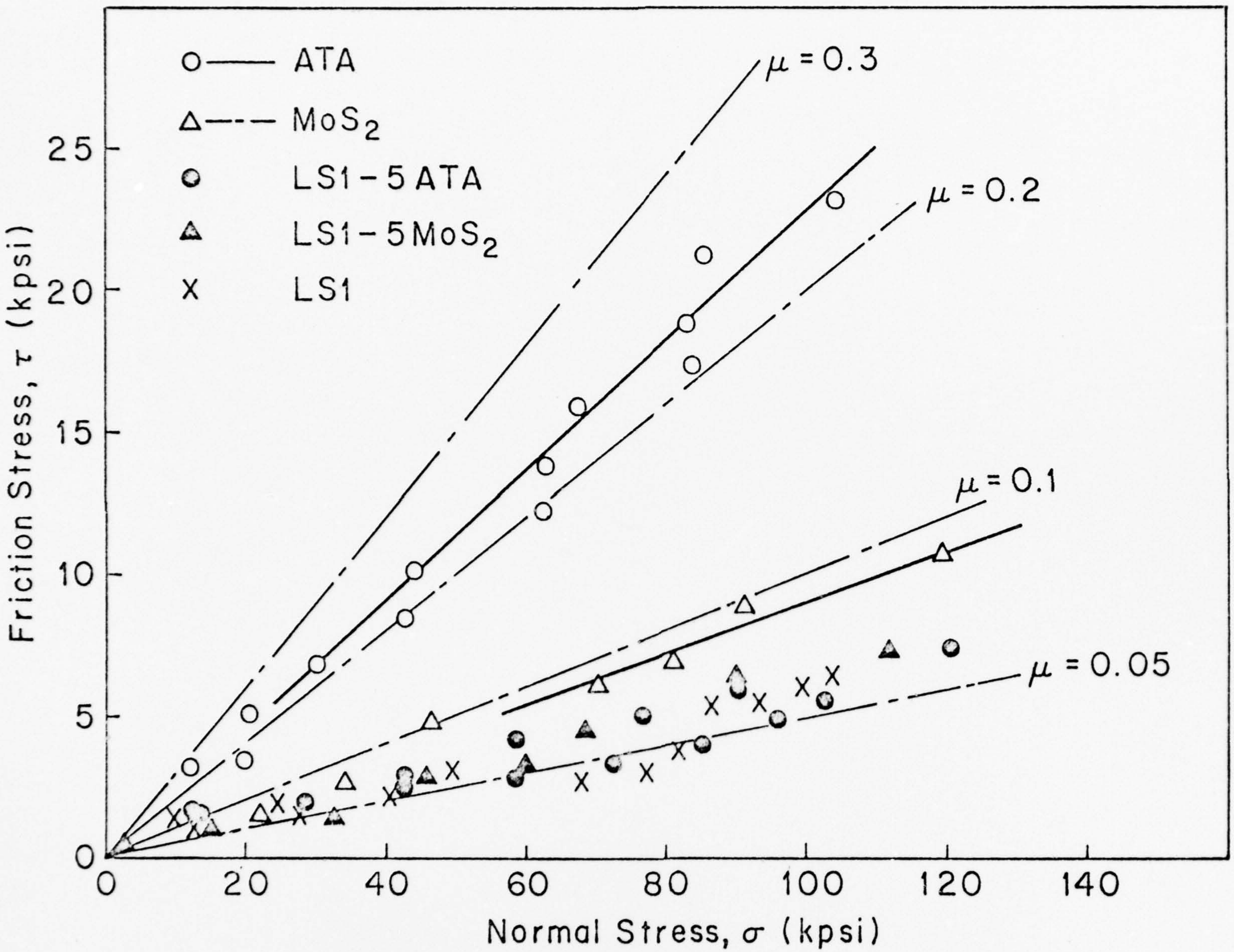
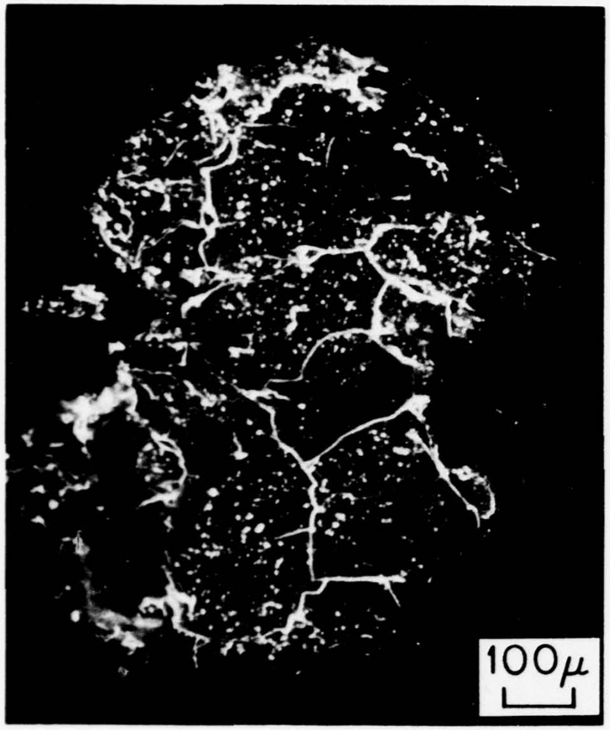


Fig. 3 Variation of frictional stress with normal stress for various lubricants.
Work material: AISI 1018, Ball: AISI 52100



(a)
Mag: X100

(b)
Mag: X300

Fig. 4. SEM of ATA Platelets.

Fig. 4(c) TEM micrograph of a sample of ATA showing layer type structure.

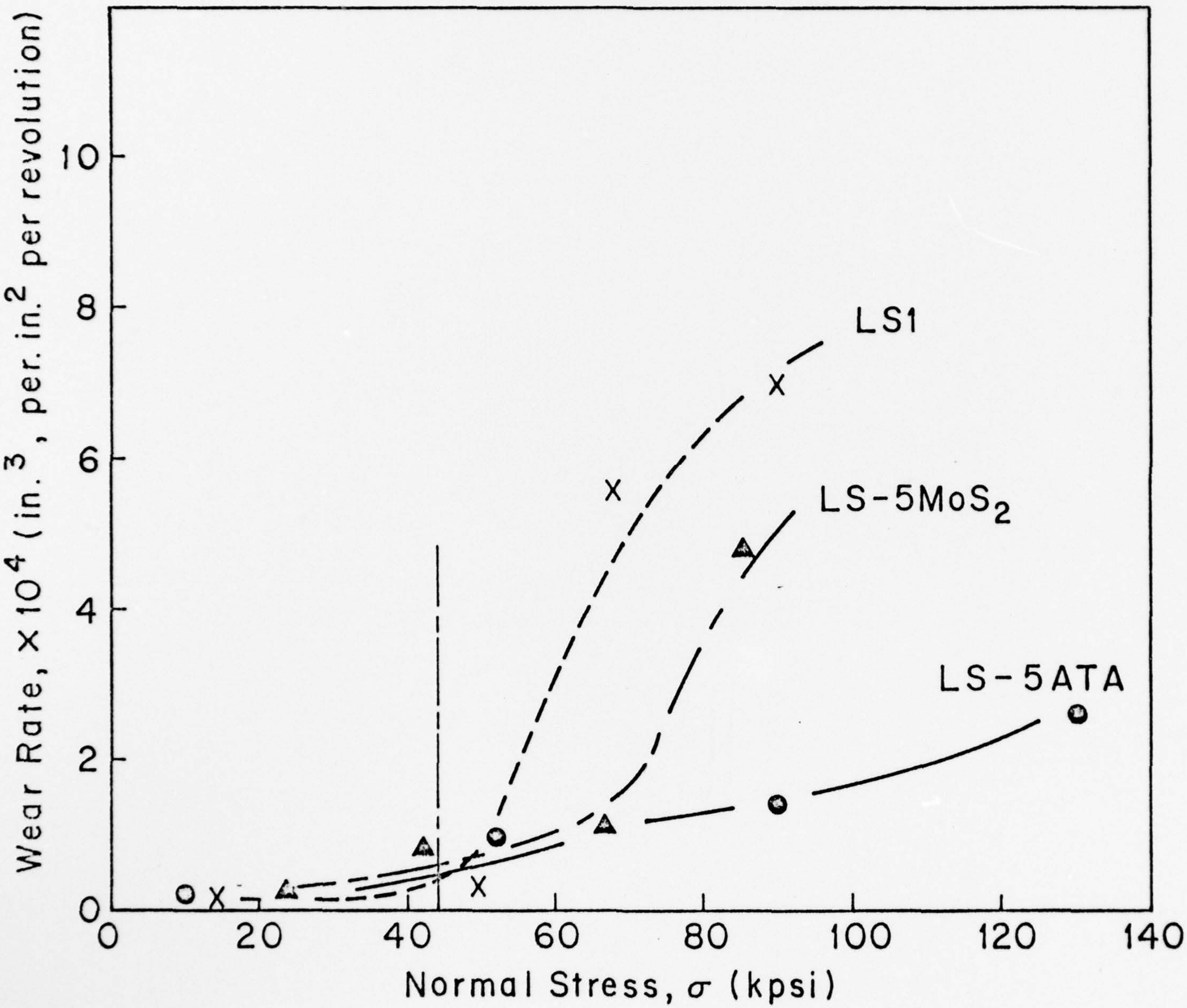


Fig. 5 Variation of wear rate with normal stress for LSI grease, LSI-5MoS$_2$ and LSI-5ATA. Work material: AISI 1015, Ball: AISI 52100

pressures are low. This also clearly demonstrates the usefulness of CMU's new wear tester.

Fig. 6 shows the variation of frictional stress with number of revolutions under different normal stresses for LS1 grease, LS1-5ATA and LS1-5MoS_2. It can again be seen from this figure that at low normal pressure ($\sigma \stackrel{\sim}{\sim} 45$ kpsi) there is no noticeable difference in frictional stress or friction coefficient for the three lubricants. However, as the normal stress is increased above 55 kpsi differences in the frictional stress (and consequently the friction coefficient) are very high for LS1 grease, followed by LS1-5MoS_2 and LS1-5ATA. The high frictional stress with LS1 grease under high normal pressure is due to film breakage and galling of the sliding surfaces. The sliding surfaces were covered with MoS_2 and ATA although some galling is observed with MoS_2 due to partial film removal.

STAINLESS STEELS

Fig. 7 shows the variation of wear rate of stainless steel with normal stress for straight grease (LS1), LS1-5MoS_2 and LS1-5ATA. It can again be seen that up to about 45 kpsi there is no significant difference in the wear rate. However, above this normal pressure, the wear rate of stainless steel covered with LS1 grease increases rapidly, possibly due to film breakage. A much higher normal pressures ($\stackrel{\sim}{\sim}$ 60 kpsi) is required before the wear rate of stainless steel surface coated with LS1-5MoS_2 starts increasing rapidly. It can also be seen that the wear rate of stainless steel with LS1-5ATA is increasing only gradually and the second stage of rapid wear was not reached yet even upto 120 kpsi. If we were to compare the wear rates of stainless steel surface covered with grease, LS1-5MoS_2 and LS1-5ATA, we can clearly notice an 8 fold increase with straight grease at $\stackrel{\sim}{\sim}$ 100 kpsi normal pressure and a similar increase with ATA-5MoS_2 at $\stackrel{\sim}{\sim}$ 130 kpsi normal pressure as compared to LS1-5ATA. Similar to the tests with low carbon steel, the tests with stainless steel clearly show the superior performance of ATA chalcogenides under high normal pressure as compared to MoS_2. As can be noted one would not notice much difference in the wear rate at low normal pressures (< 40 kpsi).

Figs.8 (a) to (c) are micrographs of the stainless steel surfaces with straight grease, 5% MoS_2 and 5% ATA respectively. The surfaces covered with grease and MoS_2 show considerable galling while that covered with 5% ATA shows a smooth surface.

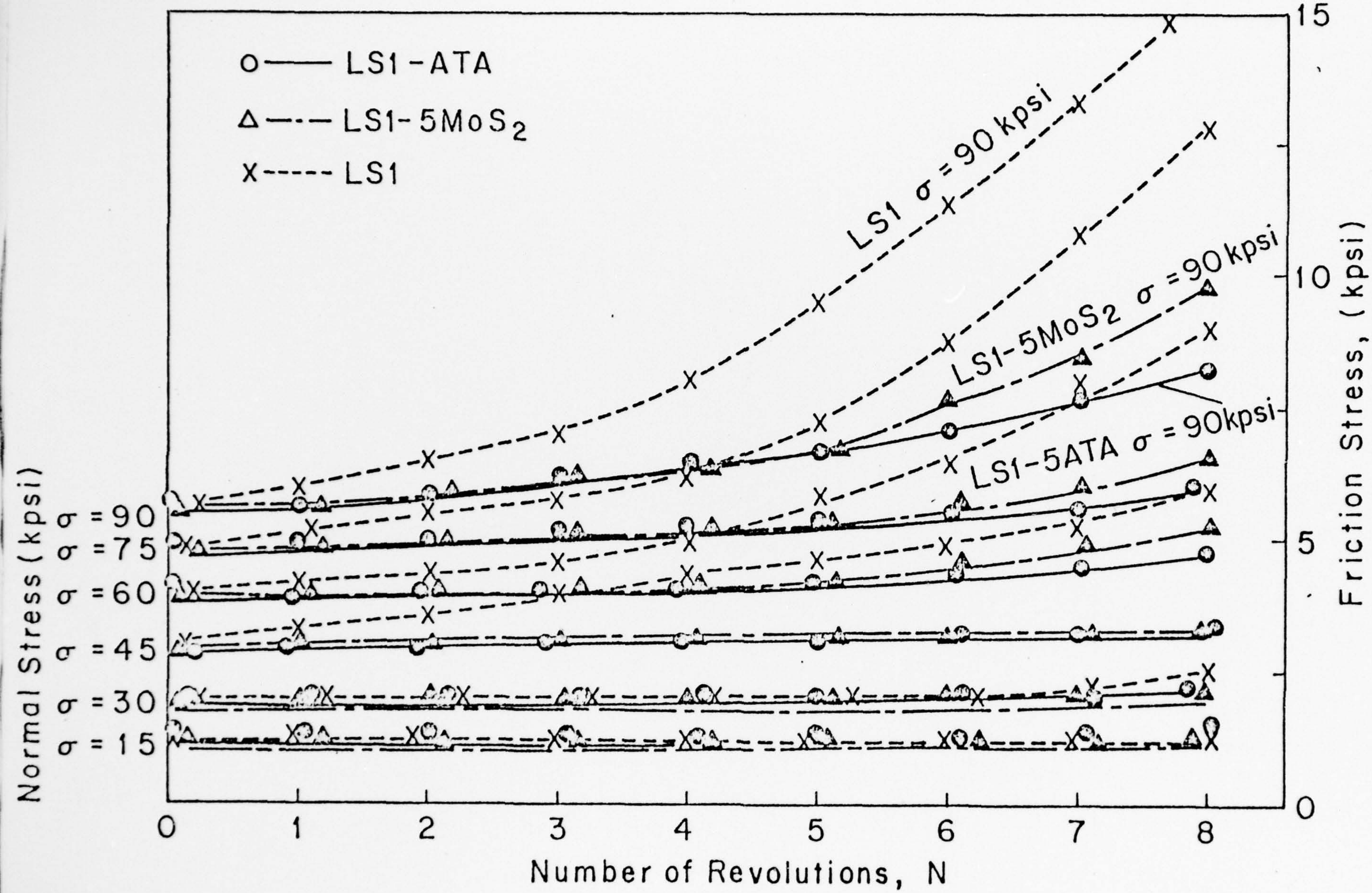


Fig. 6 Variation of frictional stress with number of revolutions under different normal stresses for LSI grease, LSI-5ATA and LSI-5MoS$_2$. Work material: AISI 1018, Ball: AISI 52100

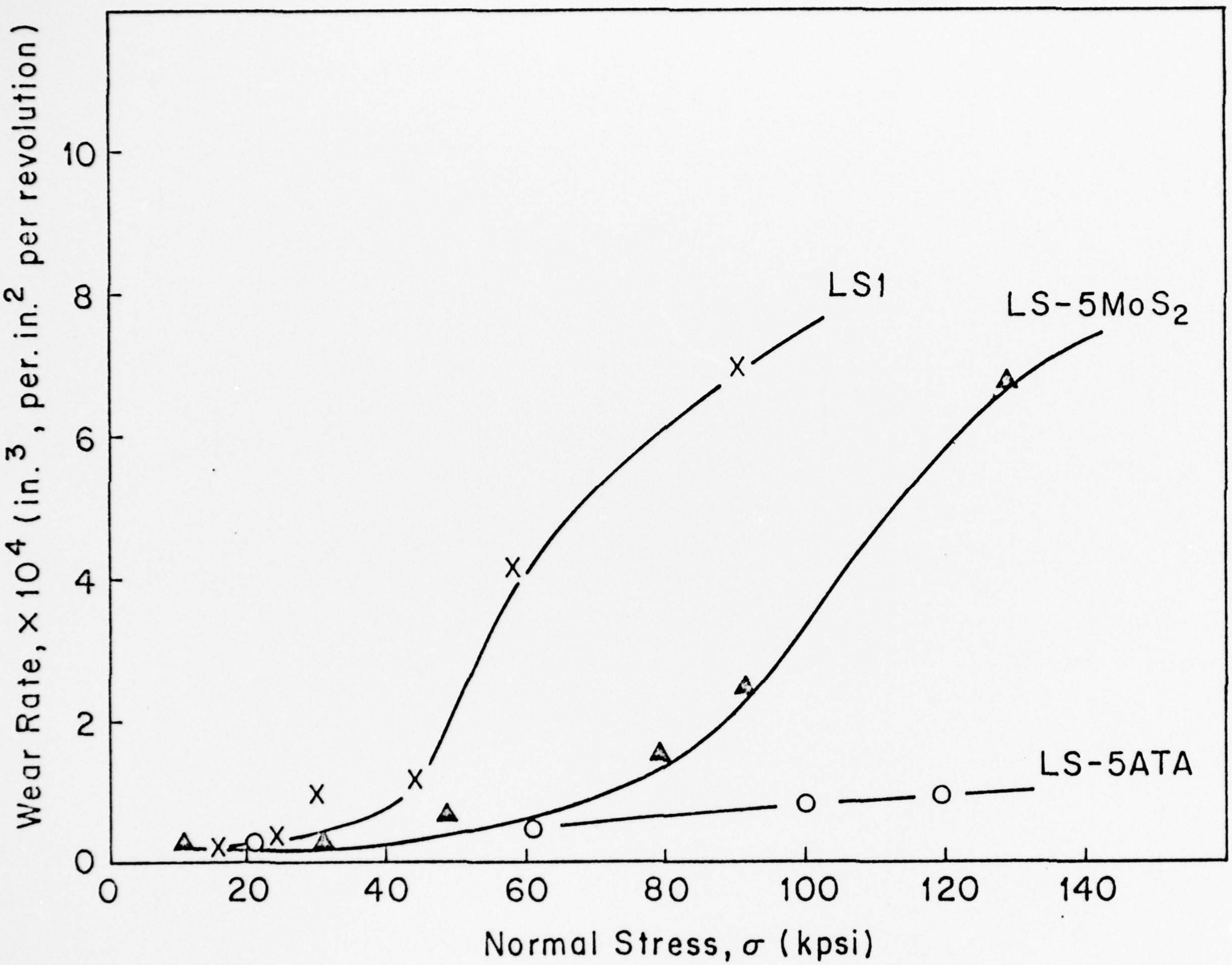
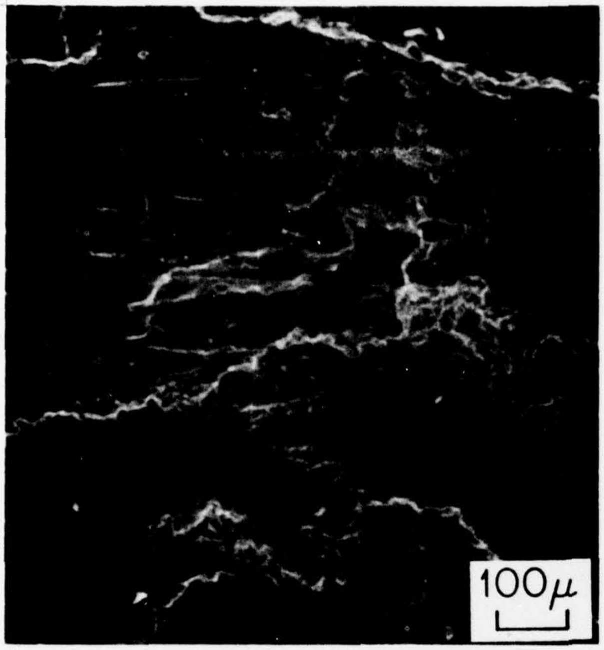
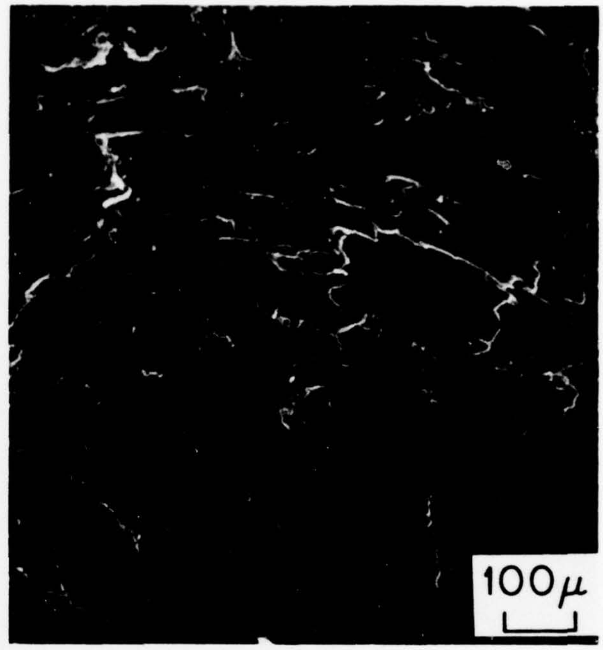


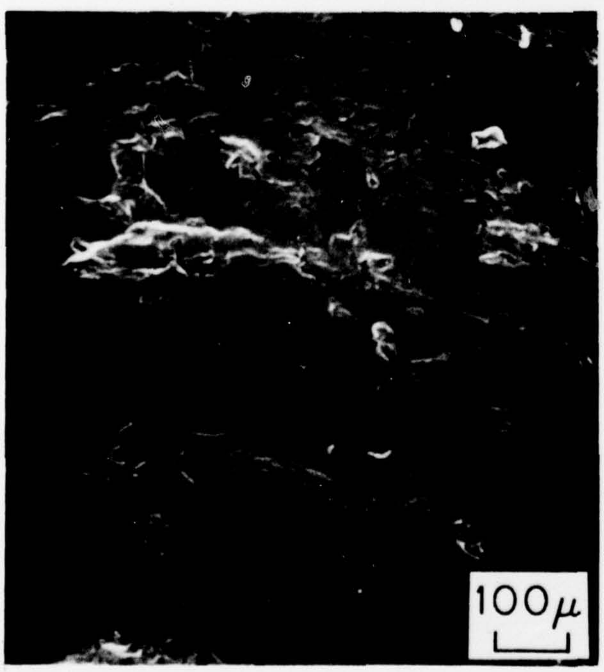
Fig. 7 Variation of wear rate with normal stress. Work material: Stainless steel, Ball: AISI 52100.



(a)



(b)



(c)

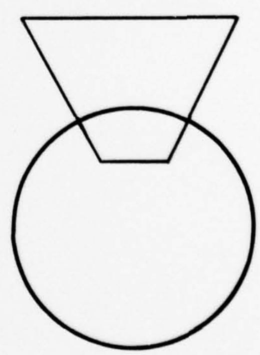


Fig. 8 Micrographs of part of the stainless steel deformed surfaces with, a) straight greases, b) 5% MoS_2 and c) 5% ATA.

CONCLUDING REMARKS

Initial results obtained with ATA and MoS_2 lubricants clearly show that the newly developed chalcogenides are more useful in reducing wear under high normal loads than under light loads. Also to evaluate their relative performance a setup similar to the one described here is required.

REFERENCE

[1]. Shaw, M. C., Ber, A. and P.A. Mamin, Trans. ASME, J. of Basic Engs., June 1960, pp. 342-346.

III. DIMENSIONAL ANALYSIS FOR WEAR SYSTEMS

In a recent issue of Wear [1], Prof. D. C. Drucker discussed wear from the point of view of dimensional analysis and concluded that "dimensional analysis falls far short of providing familiar results for the most elementary theory or experiment". This is only true if the problem tackled is too ambitious.

The main feature of dimensional analysis is that it enables the number of variables to be reduced by up to the number of fundamental dimensions involved. For a dynamics problem, such as that involved in friction and wear, this will be three. If the scope of a problem is such that it involves seven variables before dimensional analysis, it will involve four variables afterward. This still leaves a complex functional relationship to be evaluated. It is preferable to limit the scope of the problem and in doing so, reduce the final number of variables to two or preferably, only one.

Instead of considering the most general case for a frictional slider, let us consider the behavior of a single pair of metals operating with a given lubricant. It is reasonable to assume that for this limited problem, the volume worn away (B) will depend upon the sliding distance (ℓ), the applied load (W), the hardness of the softer member of the pair (H), and the sliding velocity (V). That is, we should expect

$$B = \psi(\ell, W, H, V) \tag{1}$$

where ψ stands for some function of the quantities within the parentheses. There are thus five variables at this point. After performing a dimensional analysis, we obtain

$$\frac{BH}{\ell W} = \text{const} = K \tag{2}$$

The velocity drops out and there is now only one variable (the non-dimensional quantity $(\frac{BH}{\ell W})$.

This is a familiar result since it corresponds to Archard's equation [2] when rearranged:

$$\frac{B}{\ell W} = \frac{K}{H} \qquad (3)$$

There is a host of empirical data in support of equation (3) and the fact that sliding speed (V) plays a minor role in the normal range of speeds encountered.

The nondimensional group $(\frac{BH}{\ell W})$ is just as fundamental to wear theory as Reynold's number is to fluid mechanics. And, just as it is convenient to interpret Reynold's number as a quantity proportional to the ratio of inertia to viscous forces acting on a fluid particle, it is equally useful to interpret the wear number in terms of two volumes as explained below.

Fig. 1 (dotted line) shows the elastic-plastic boundary under a loaded indentor [3]. The hardness is W/A_1 where A_1 is the area of contact of the indentor with the plastic material. Plastic area A_2 is proportional to area

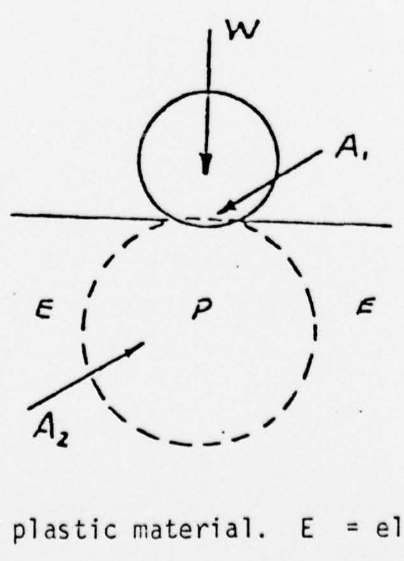


Fig. 1 Indentation of plastic material. E = elastic region, P = plastic region.

A_1 and if the loaded indentor is moved a distance ℓ perpendicular to the paper, the plastically deformed volume will be $A_2\ell$ which is proportional to $A_1\ell$. But

$$\frac{BH}{\ell W} = \frac{B\frac{W}{A_1}}{\ell W} = \frac{B}{\ell A_1} \sim \frac{B}{\ell A_2} \qquad (4)$$

Thus, the nondimensional wear number $N_W = \frac{BH}{\ell W}$ is proportional to the volume worn away to the volume that is plastically deformed when sliding through the same distance.

The value of N_W will depend upon the metal pair in sliding contact, the lubricant or environment, the geometry of the test arrangement and the intensity of loading. If the load intensity is low, attritious wear will be predominant, but if the load intensity is high or hard abrasive particles are present, abrasive wear will be predominant. It has been shown that equation [3] holds for either attritious or abrasive wear [4]. However, the value of N_W will be different for the two wear regimes, N_W being much larger for abrasive wear than for attritious wear.

A variety of test arrangements may be used to determine relative values of N_W for different wear resistant materials. For example, the Stellite Division of the Cabot Corporation uses the Dow-Corning Friction and Wear Test machine shown diagramatically in Fig. 2. The test specimen is a stationary block loaded against a rotating ring of AISI 4620 steel. A test is normally run without lubricant for 25 minutes at a sliding speed of 28.8 fpm (0.146 m/s) under a load of 30 pounds (134N). Table 1 gives representative results for three Stellite Alloys having the compositions given in Table 2.

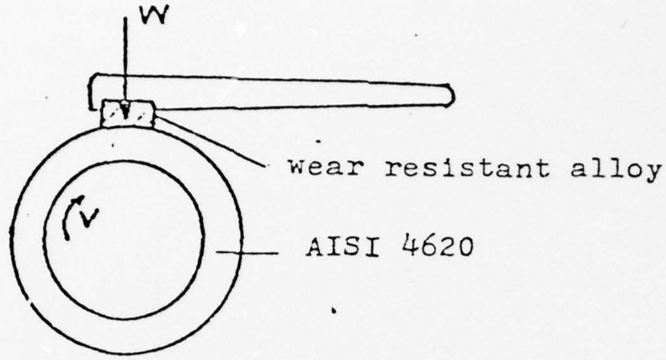


Fig. 2 Dow-Corning Friction and Wear Test Machine.

Table 1

Alloy No.	W,N	ℓ,m	B,m^3	H, MP_a	$N_w = \frac{BH}{\ell W}$
25	133.6	213	0.285×10^{-9}	2558	2.56×10^{-5}
6B	133.6	213	0.293×10^{-9}	3685	3.79×10^{-5}
6K	133.6	213	0.453×10^{-9}	4087	6.51×10^{-5}

Table 2

Alloy No.	Co	Ni	Si	Fe	Mn	Cr	Mo	W	C
25	BAL	3.0	2.0*	3.0*	2.0*	30	1.5*	4.5	~1.2
6B	BAL	3.0	2.0*	3.0*	2.0*	30	1.5*	4.5	~1.6
6K	BAL	10	1.0*	3.0*	1.5	30	-	15	~.10

*max

Under these test conditions, alloy 25 is the most wear resistant of the group. Different relative results will be obtained for different intensities of loading, in the presence of different lubricants or when abrasive particles are present.

The nondimensional wear number (N_W) that is obtained when dimensional analysis is applied to a limited system of wear is a useful quantity for use by the design engineer and more research should be directed toward obtaining values of N_W for a wide variety of systems. It is gratifying to note that the Lubrication Division of the American Society of Mechanical Engineers have plans for publishing a handbook of values of N_W covering a wide variety of situations [5].

References

1. D. C. Drucker, "Elementary Results of Dimensional Analysis for Friction and Wear in Steady State Sliding", Wear 40, p. 129-133 (1976).
2. J. F. Archard, "Contact and Rubbing of Flat Surfaces", J. Appl. Phys., 24, p. 981-988 (1953).
3. M. C. Shaw and G. J. DeSalvo, "The Role of Elasticity in Hardness Testing", Metals Engineering Quarterly, 12, p. 1-7 (1972).
4. M. C. Shaw, "Fundamentals of Wear", Chem. Tech., July, 1971 pp. 432-439.
5. D. F. Hays, "Proposal for A Wear Control Handbook", ASME Research Committee on Lubrication, 1976.

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