THE UNIVERSITY OF MICHIGAN
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A METHOD FOR STUDYING THE BEHAVIOUR OF CUTTING FLUIDS IN WEAR OF TOOL MATERIALS

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It seems almost presumptious to lay claim to any new developments in this area in view of the vast amount of research that has been done in this complex field. While much has been done, there are many problems remaining to be solved, both fundamental and in application. It was an attempt to solve some of the problems with lubricants for metal processing operations that led to development of the apparatus described in this paper. More important than new features in apparatus, however, is the new type of information which these refinements have made possible. Thus the primary purpose of the paper is to discuss a new approach to lubrication and wear problems.

The new approach consists of observing and measuring the behaviour of lubricants at continuously varying load conditions in the presence of accelerated wear and substantial change in the geometry of the rubbing surfaces during a single test. Details of the method can best be discussed in connection with samples of test results but first it is advisable to review some aspects of the test apparatus.

A New Friction-Wear Machine

Figure 1 is a general view of the machine. It consists of a standard drill press which has been modified for the purpose. One specimen of a friction pair is mounted on the spindle and rotated. The other specimen is mounted on a carrier permitting straight line motion radially to the spindle. The specimen carrier and all of the loading mechanism are mounted on a square housing which in turn is mounted on ball bearings so that the entire assembly is free to rotate about the centerline of the spindle. The normal load between the friction pair is provided by dead-weights mounted on a table free to slide along two one-inch diameter horizontal rods.

When the table is in its innermost position the dead-weight loading mechanism is counterbalanced and the normal load between the specimens is equal to zero. The table is connected by a split nut to a lead screw rotated by a small synchronous motor. Thus in starting a test, the load can be increased linearly with time as the table travels outward from the balance point. Eventually, the table engages a preset limit switch which selectively either stops the table and holds the normal load at that value or reverses the synchronous motor causing the load to be reduced at the same rate it had increased. In the latter type of operation , the normal load can be made to oscillate between any preselected values of high and low load including a low load of zero.

Both the normal load and the torque or friction reaction are indicated continuously by the use of resistance-wire strain gages mounted on cantilever beams. A carrier-amplifier-recorder provides a continuous time chart of these important quantities. The load cell for the normal load lies between the specimen carrier and the heavier dead-weight loading system. This feature has two advantages; it limits the normal load variations resulting from run-out of the rotating specimen and it provides immediate indication of any undesirable alignment between specimens since the spindle is always operated above the resonant frequency of the dead-weight system.

A similar load cell is used to constrain the so-called stationary specimen against rotation about the centerline of the drill press spindle. The natural frequency of this system also is very low but the majority of its mass or inertia lies between the torque load cell and the point of torque application so that short duration changes in torque are greatly attenuated on the chart recording.

Figure 2 is a close-up picture of two typical test specimens mounted in place ready for a test. The specimens are submerged in a bath of lubricant contained in a glass dish. At the conclusion of the test, the quill is raised and the apparatus can be cleaned readily in preparation for the next test.

Geometry of Test Specimens

A variety of specimen shapes can be tested in this machine but they do not represent anything new that has not been tried before. Typical combinations are:

Combination	Rotating Specimen	Stationary Specimen
(1) Plane and sphere	Spherical	Flat Plant
(2) Plane and torus	Torus	"
(3) Crossed-Axes	Cylinder	Cylinder
(4) "	Torus (Convex)	"
(5) "	Torus (Concave)	"
(6) Special	Simulated Thread	Thread Tap

None of the above combinations are particularly new in wear studies since others have used them in different test situations. For example, Jannin(1) and Spindel(2) reported on tests with similar arrangements in 1922. Also, Brownsdon(3) reported on tests using this specimen configurations in 1936.

A major portion of the work done to date with this machine has been with the plane and sphere combination where the rotating specimen is a portion of a sphere and the so-called stationary specimen is a flat plane which is brought into tangential contact with the spherical surface during a test. This arrangement offers certain advantages for test purposes. Perhaps the principal advantage is that Hertzian equations can be applied to predict the stresses and minimum elastic contact areas in the early stages of test before significant wear has taken place. Thus if a test begins with gradual application of the normal load and if the rate of application of this load is slow enough in relation to rate of wear, then the most severe pressures will be encountered in the early stages thus making it possible to predict and control the upper limits of pressure and shear stress as they are related to the flow properties of the metals under test. Timoshenko(4) gives the following equations for the plane and sphere combination:

Maximum Pressure $q_o = 3N/2\pi\ a^2$ (I)

Maximum Shear $\tau_o = 0.31\ q_o$ (II)

Radius of Contact Area $a = [3\pi N(k_1 + k_2)\ R/4]^{1/3}$ (III)

Where $k_1 = (1 - \nu_1^2)\ /\pi E_1$ (IV)

And $k_2 = (1 - \nu_2^2)\ /\pi E_2$ (V)

ν_1, ν_2 = Poisson's Ratio for the Test Materials

E_1, E_2 = Modulus of Elasticity

These equations were used in planning the typical experiments which are reported in this paper.

Typical Test Results

Friction Records

Fig. 3 shows reproductions of the beginning portions of the recorder charts obtained for three different lubricants. The test specimens in this case consisted of an oxidized aluminum sphere and a high carbon steel flat plane. The steel specimen was quenched and tempered to a hardness of 37 -

39 Rockwell C-Scale hardness. The test began with zero normal load which was increased linearly with time until a peak value was reached and then oscillated between that value and the lower value shown in Fig. 3 for a total time of one hour. The individual cycles were 45 seconds in duration. The thrust or normal load record is shown at the bottom in Fig. 3. This, of course, was the same for the tests with all three lubricants.

The corresponding torque or friction force records are shown above the thrust record in the figure. All of these likewise began at zero torque level. In any test, if the coefficient of friction were constant at all thrust loads then the torque versus time record would be an exact multiple of the thrust record. Thus any deviations from this ideal state constitute deviations of the coefficient of friction.

It will be noted that the torque record obtained for the straight mineral oil as shown on the top of Fig. 3 remains substantially constant or insensitive to the oscillating thrust load whereas the same mineral oil with an additive designated as additive A did respond sensitively to changes in the thrust load during the oscillating part of the cycle. The same mineral oil plus additive B demonstrated the same erratic behavior as the mineral oil alone but it did respond appreciably to the oscillating thrust. It was observed that the small, rapid variations in the torque records for the straight mineral oil and with additive B was accompanied by more or less rapid clouding up and discoloring of the bath of oil. This was determined to be due to very small particles of aluminum being sloughed off from the rotating specimen. Thus it would appear that the sudden changes in the corresponding torque records represented unstable seizure. It is significant or normal load was oscillated between zero and the maximum. However, it will be noted that the maximum was substantially less in this case than for the test represented by Figs. 3 to 5, inclusive. It will be noted that the straight mineral oil did produce a sensitive reaction to the oscillating thrust load for this lower level of load. However, it still demonstrated inability to prevent sloughing off of small particles of aluminum, thus producing cloudiness in the oil. Additive A, on the other hand, appeared to duplicate its performance with the high load range at the beginning of the test and changed rather little throughout the one hour run.

Fig. 7 and 8 are a repetition of the tests shown in Figs. 3 to 5, inclusive, except for the use of an aluminum specimen with a somewhat heavier layer of surface oxide. As long as the oxide remained on the surface, the straight mineral oil gave a torque record similar to those obtained with the use of additives. On the other hand, it would be noted in Fig. 8 that the small, rapid variations indicating sloughing off have appeared near the end of the one hour test.

Additives A and B reacted quite differently from the previous test made with the lighter oxide coating. Fig. 8 shows that the range of torque reactions actually decreased in contrast to the increase that occurred in the earlier tests. The reasons for these differences are not yet fully understood, but it is apparent that rates of wear, film strength, adhesiveness, etc. are combining in such a manner as to provide a sensitive distinction in the form of the torque records.

The wear scars produced in the high carbon steel specimens were substantially different for the three lubricant conditions. The area of the scar was measureably less for the straight mineral oil, but this appeared to be due to the inability of the oxide to remain on the aluminum specimen throughout the test with this oil. In addition, the scars obtained with the straight mineral oil were also streaked with relatively deep notches parallel to the rubbing direction. This appeared to be due either to gross seizure in localized regions or to the sloughed off particles which might have become reimbedded in the aluminum specimen because of continuour agitation of the lubricant bath. Such notches did not appear when additives A and B were used. Therefore, these additives acted in some manner to enable the oxides to remain intact at the same loads.

Wear Scars

Fig. 9 is a schematic reproduction of a typical wear scar. The sketch at "A" in this figure shows the general outline of the scars which have been obtained with a wide range of lubricants and specimen materials. The notches which have been referred to previously do not occur unless there is seizure or sloughing off of the rotating specimen. If the rotating specimen is very hard or for some reason does not wear, then the scar will be circular. On the other hand, if it does wear, then the scar will be longer in the direction designated as length (Fig. 9a) than in the other direction designated as width. In general, the width will be larger with a high rate of wear of the tool material. Others have used the ratio of the length to the width of the scar as a general parameter for comparing their results. A large value of this ratio can be the result of a rapidly wearing, rotating specimen for a given tool material or a higher wear resistance of the tool material for any constant rate of wear of the rotating specimen. However, it becomes necessary to consider both the length and width independently as well in order to describe the wear situation completely. Table I shows friction and size data of typical wear scars for a range of materials.

Fig. 9b shows a section of a typical scar parallel to the rubbing direction. The curvature has been exaggerated for the sake of illustration. Usually the scar obtained with the 1.5 inch diameter sphere is less than 0.001 inch deep at the midpoint and most of them are less than 0.0005 inches at the test conditions used so far.

Behavior of Specimen Contact Under Oscillating Normal Load

Fig. 10 shows schematic drawings of the two specimens in contact at the high and low normal loads during an oscillating load test. At "a," the rotating specimen is shown to be in full area contact with the scar at high normal load. At "b," for the low normal load, the rotating spherical specimen is shown to have relaxed elastically resulting in higher curvature in the contact area. Similarly, the stationary specimen, which contains the scar, also relaxes elastically resulting in less curvature with the net result that an open wedge appears near the perimeter of the scar, thus permitting the lubricant to create a different friction or lubricating condition providing it has the capacity to use this opportunity. The behavior with oscillating normal load cannot be described as simply as has just been stated since it is complicated by the fact that wear may be going on continuously but at a rate which varies gradually with the normal load. On the other hand, it is possible that wear practically ceases at the lower loads while it might progress very rapidly in the vicinity of the highest thrust load. Much more study needs to be given these properties before

BIBLIOGRAPHY

(1) "Nouvelle Methode D'Essai des Métaux à L'Usure," by M. L. Jannin, Revue de Metallurgie, vol. 19, 1922, p. 109.

(2) "Neues Prüfverfahren für den Abnutzungswiderstand von Eisenbahnmaterial," by M. Spindel. Zeit. V.D.I., vol. 66, 1922, pp. 1071-1072.

(3) "Metallic Wear," by H. W. Brownsdon, Journal of the Institute of Metals, vol. 58, no. 1, 1936, p. 15.

(4) "Theory of Elasticity," by S. Timoshenko; McGraw-Hill Book Co., pp. 339-352.

TABLE-I

Typical Friction and Wear Results

Normal Load Oscillates Between 7.2 Pounds and 9.6 Pounds Reaching the Maximum
Value of 9.6 Pounds in 1.5 Minutes
Stationary Specimen: (18-4-1) High Speed Steel Flat (Hardness = 63 R_c except as noted)
Lubricant: 90% Mineral Oil Plus 10% of a Sulphur Additive

Spherical Specimen			Test Duration Min.	Scar		Coefficient of Friction
Material	Heat Treatment	Tool Hardness R_c		Width (Inches)	Length (Inches)	
Cast Iron	Plain (As Machined)		10.21	0.025	0.053	0.055 to 0.063
Cast Iron	16 hrs @ 950°F.		10.21	0.021	0.042	0.055 to 0.067
Titanium	16 hrs @ 950°F.		10.18	0.055	0.143	0.250 to 0.275
Bronze (85/5/5/5)	16 hrs @ 950°F.		10.28	0.018	0.048	0.057 to 0.066
Brass (70/30)	16 hrs @ 950°F.		10.25	0.014	0.027	0.055 to 0.063
Aluminum 5052	16 hrs @ 950°F.		0.50	0.022	0.031	.040
"	"		1.00	0.025	0.037	.062
"	"		1.50	0.027	0.040	.072
"	"		2.00	0.034	0.043	.060
"	"		5.65	0.036	0.045	.060
"	"		10.23	0.037	0.049	.056 to .069
"	"	63.0	10.00	0.0302	0.0609	0.052
"	"	59.5	"	0.0313	0.0673	0.052
* "	"	56.1	"	0.0294	0.0676	0.052
"	"	46.6	"	0.0273	0.0657	0.0541 to 0.0515
"	"	39.0	"	0.0241	0.0652	0.0515

* Normal load constant at 37 pounds after loading gradually from zero; time to reach peak load was 5.8 minutes.

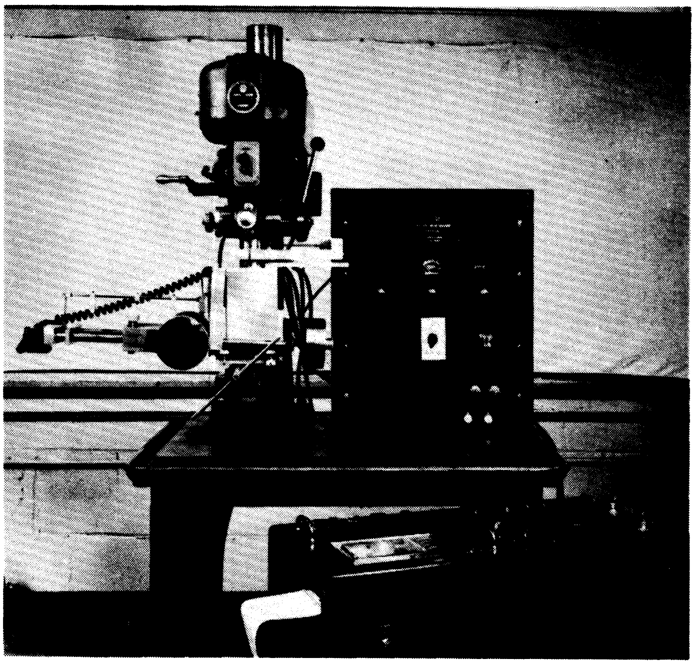


Figure 1: Friction-Wear Machine consists of standard drill press with all additional mechanism clamped to and pivoted about the quill. Test specimens are mounted on lower end and can be lowered into any suitable lubricant container.

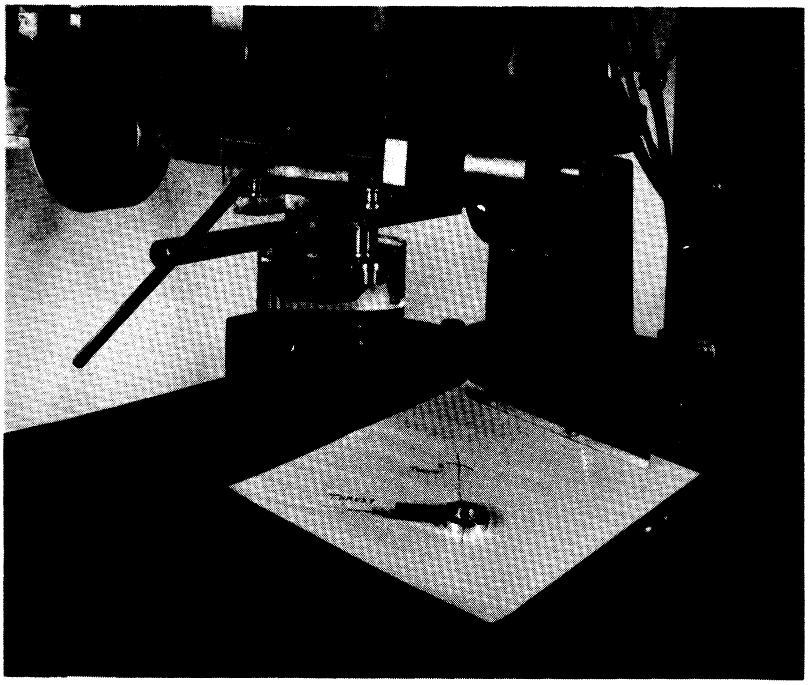


Figure 2: A close-up showing test specimens lowered into glass dish containing clear butyl stearate. Typical test specimens are shown on writing board.

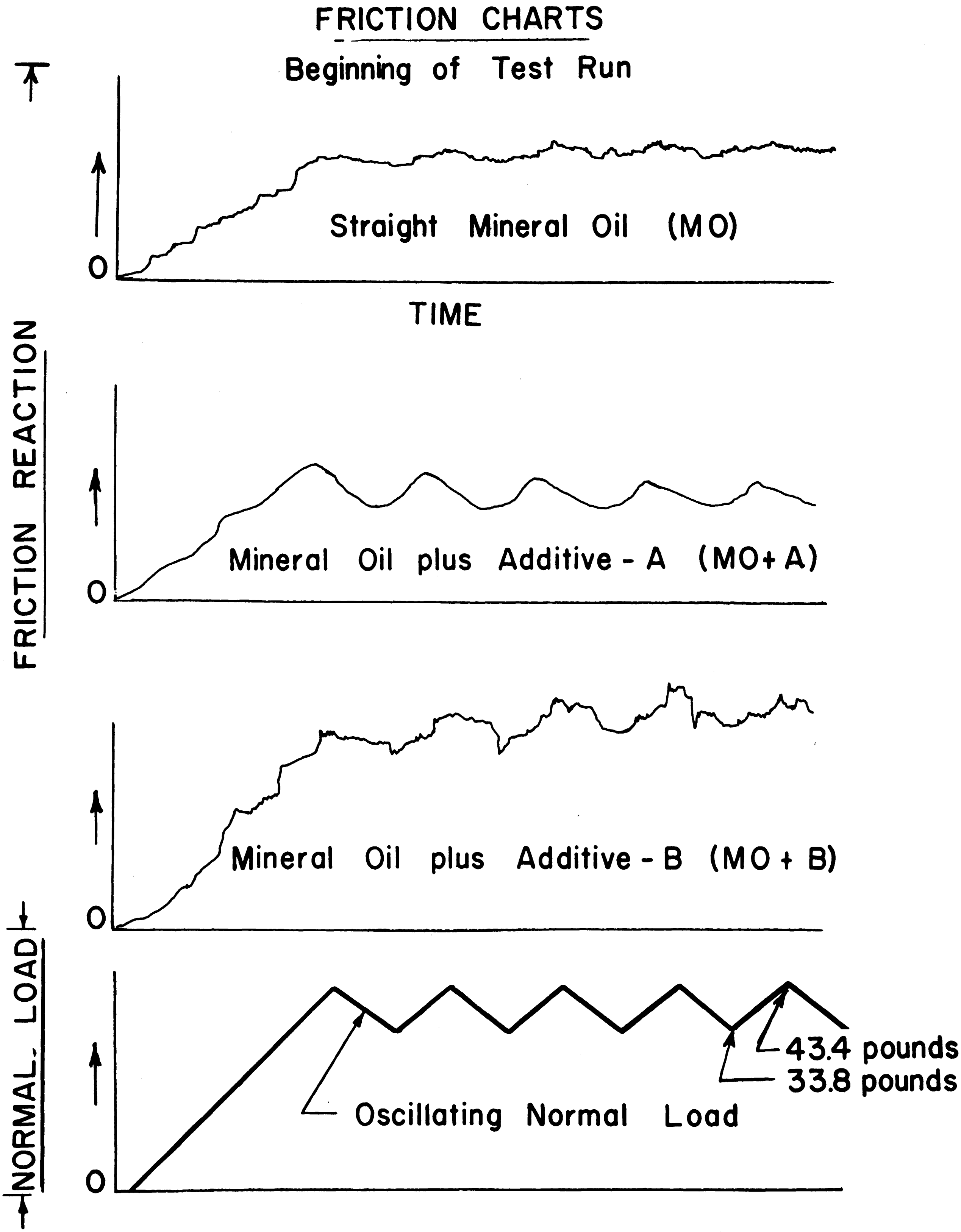


Figure 3: Reproduced chart records for the first few cycles of a one hour test run. Cycle period is 45 seconds. Normal load reaches initial peak in 74 seconds. Spindle speed 493 rpm; 5052 aluminum specimen with light oxide rubbing on 37-39 R_c steel flat.

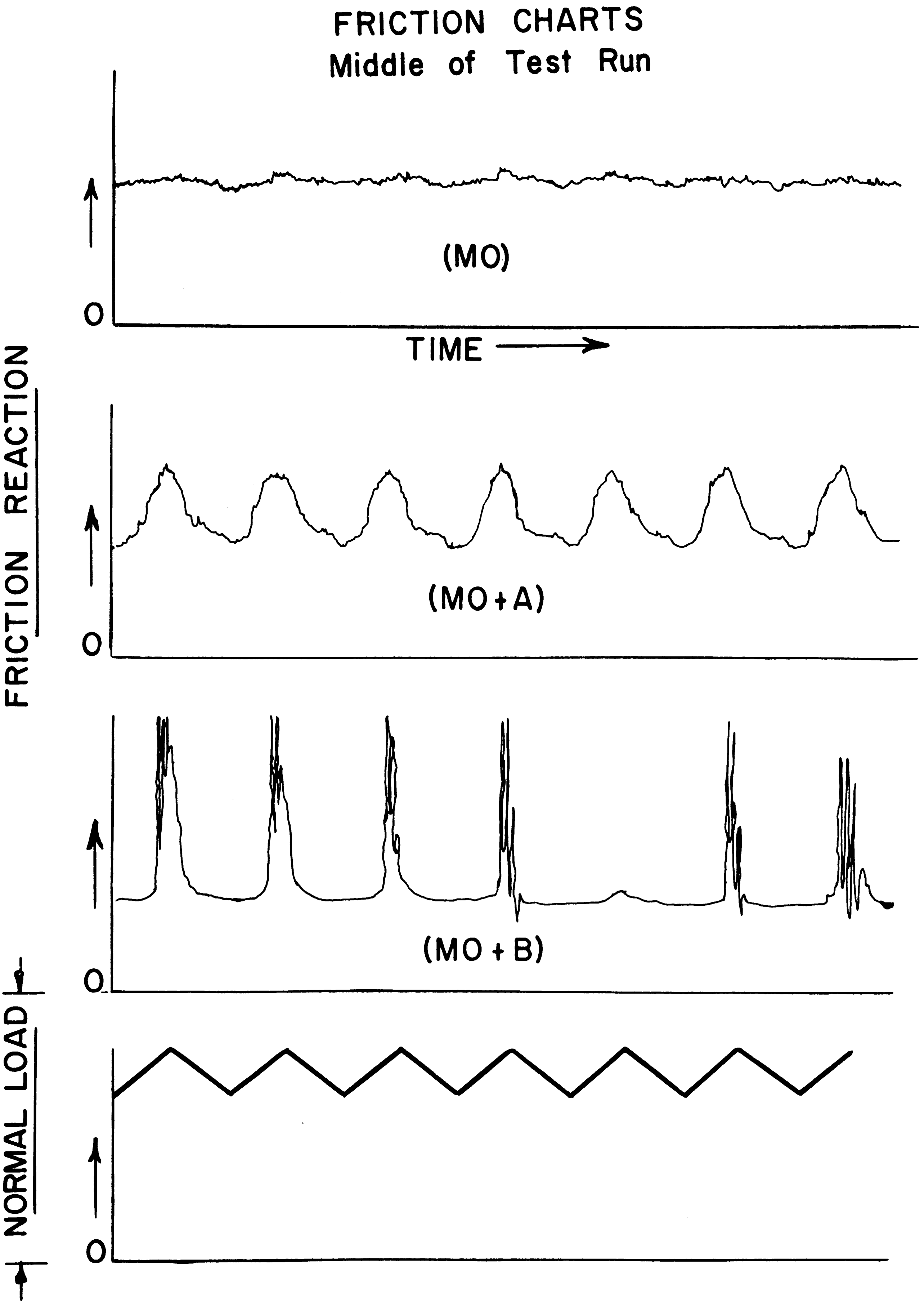


Figure 4: Chart records for middle of test runs. Accumulated running time about 30 minutes. Note change in shape of friction reaction curves for (MO + A) and (MO + B) compared to corresponding curves in Figure 3.

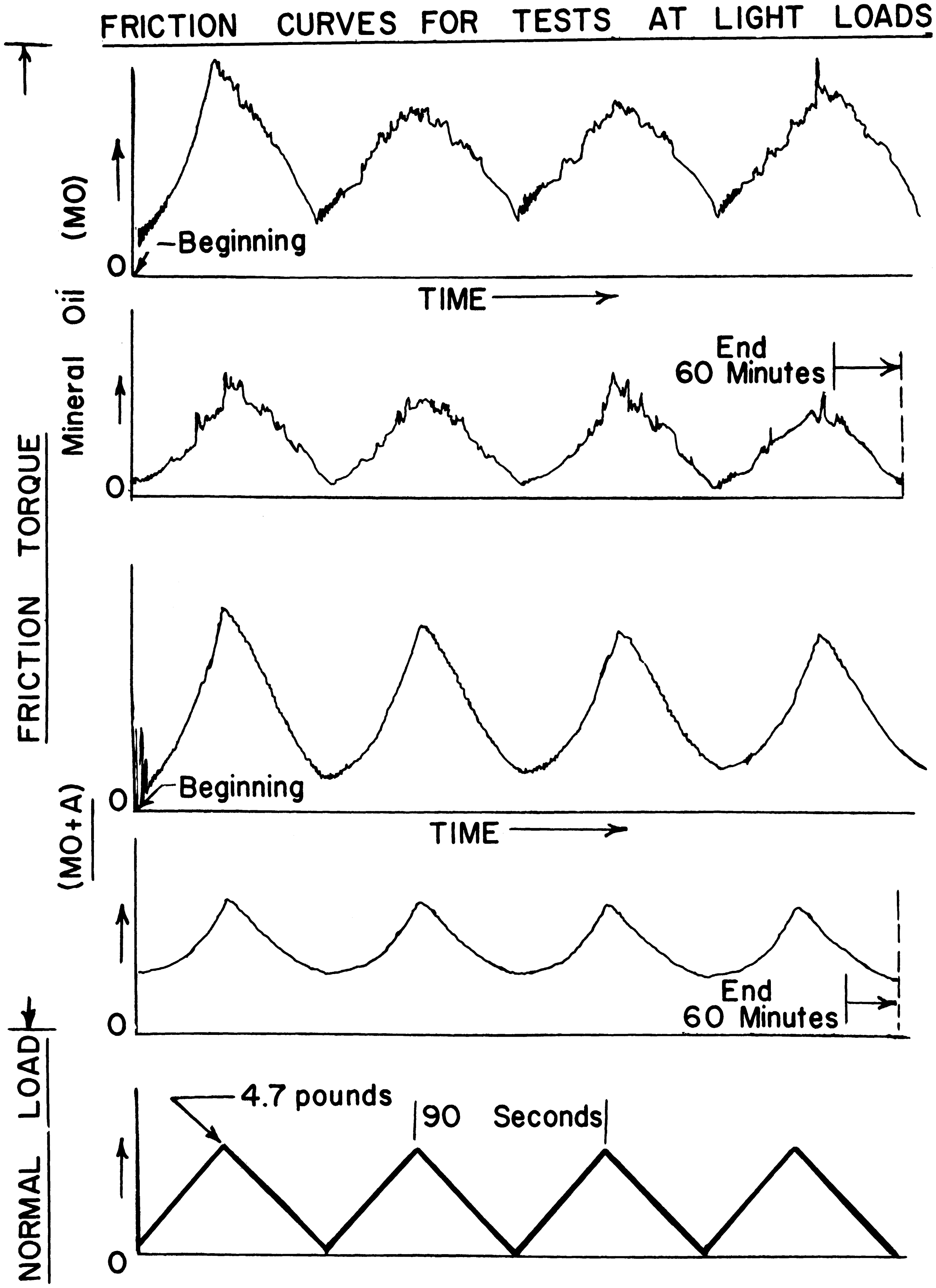


Figure 6: Lighter normal load permits usual reaction to oscillation. (Compare with top curves in Figs. 3, 4, and 5.)

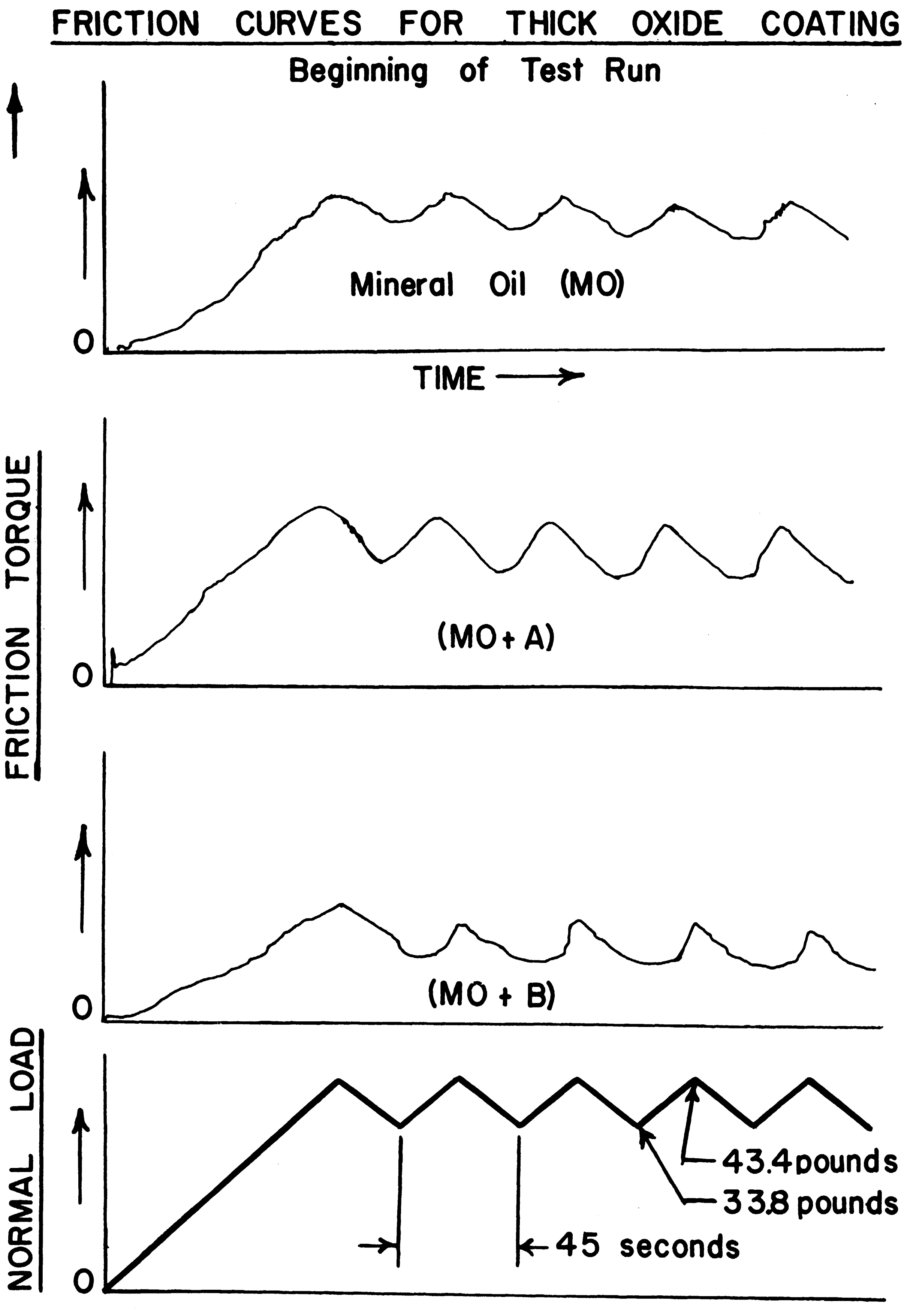


Figure 7: Comparable to Fig. 3 except that the rotating 5052 Aluminum specimen was given thicker oxide surface coating. Note effect with lubricants (MO) and (MO + B) compared to performance in Fig. 3.

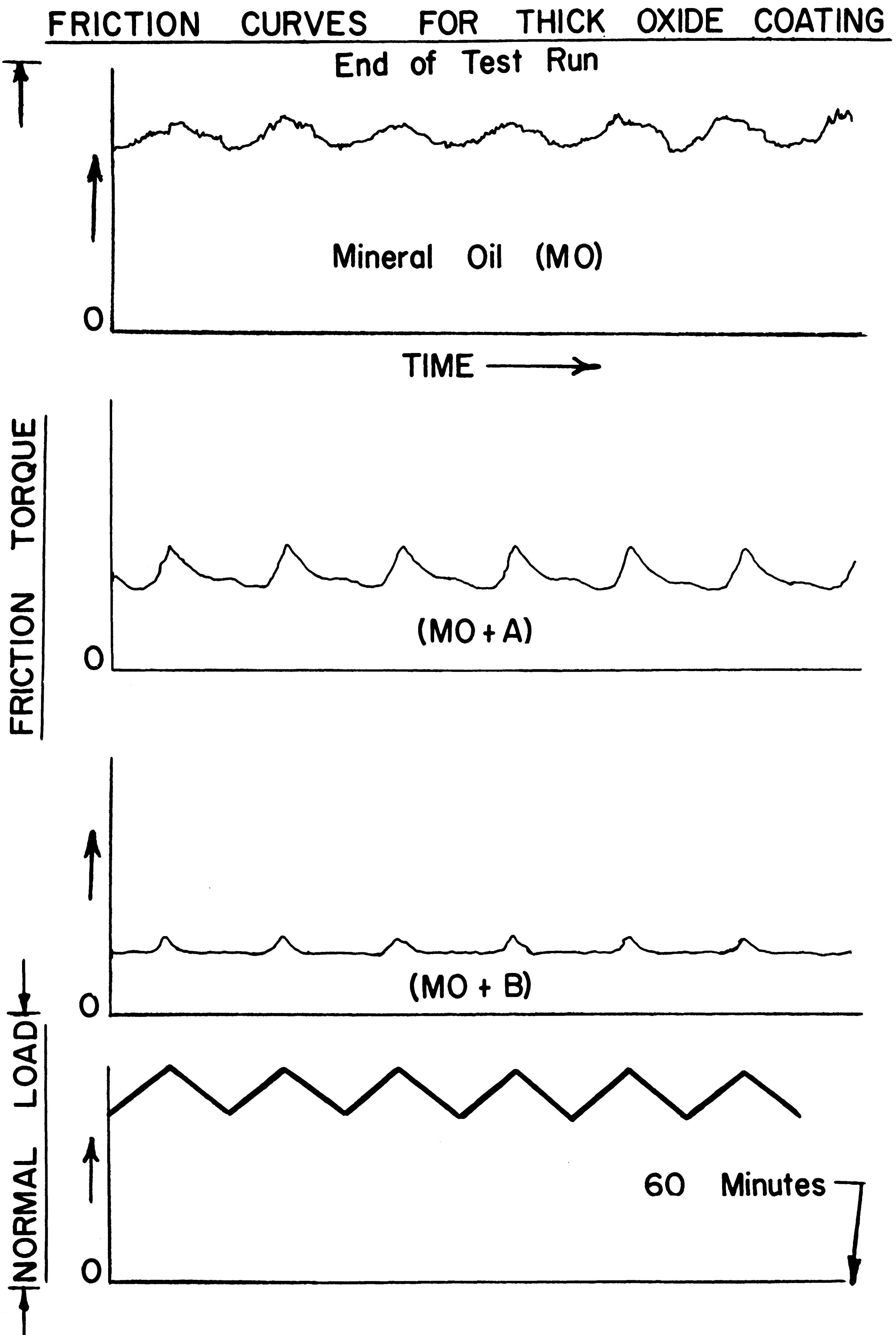
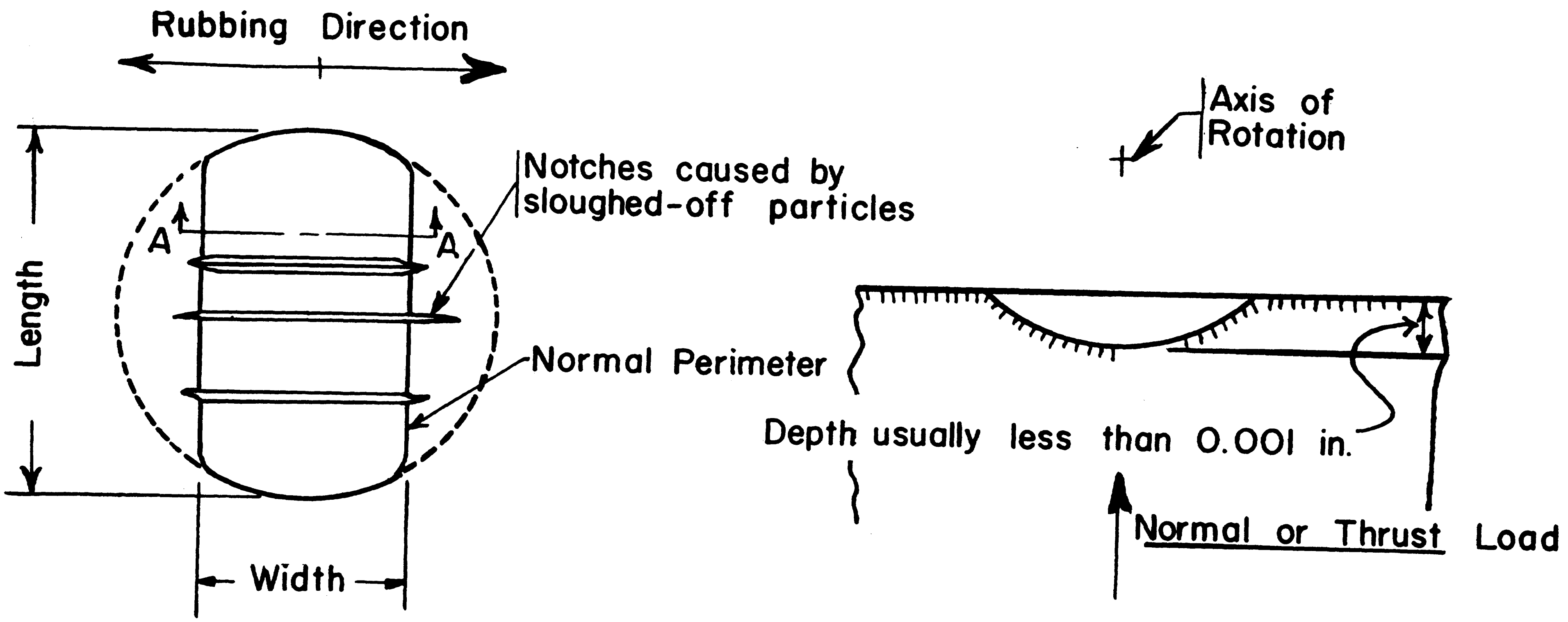


Figure 8: Compare with Fig. 5. Note absence of seizure when additives were used. Also note lower friction with Additive-B.

TYPICAL WEAR SCAR

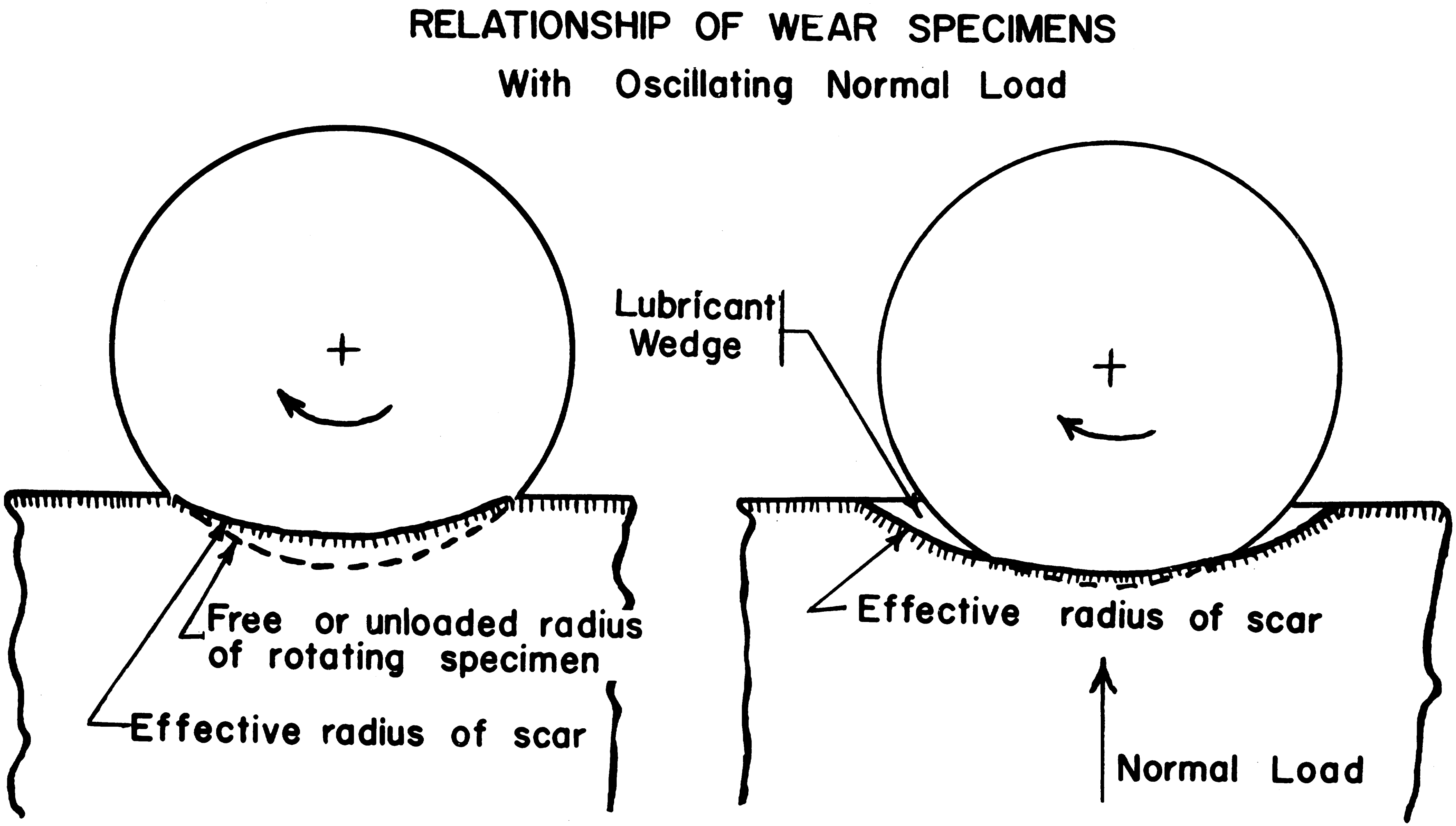
Rotating Sphere on Flat Plane



(a)PLAN VIEW

(b) SECTION AT A-A

Figure 9: Length of scar is measured in direction parallel to axis of rotating specimen. Section of scar at (b) will not be true circle but will approach this condition at high wear rates.



(a) AT HIGH NORMAL LOAD

(b) AT LOW NORMAL LOAD

Figure 10: A lubricant wedge forms between rotating specimen and the wear scar as the normal load is reduced. Many shapes of the scar section are possible as the result of different rates of wear.