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FRICTIONAL RESISTANCE, HEATING AND WEAR AT HIGH SLIDING SPEEDS

BY

W. W. SHUGARTS, JR.
H. C. RIPPEL

PREPARED FOR

BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND

DEPARTMENT OF THE ARMY CONTRACT NO. DA-36-034-ORD-1634 RD
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THE FRANKLIN INSTITUTE
LABORATORIES FOR RESEARCH AND DEVELOPMENT
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ABSTRACT

A broad outline is presented of an investigation of solid material sliding on gun steel at high speeds. Reference is made to previous reports for detailed information. However, the work done since the last report is covered in detail.

The results of additional tests of copper and shell steel prods run against the gun steel disk complete the picture of the friction and wear characteristics of these materials. The tests of shell steel against gun steel were made to exploit the formation of a martensitic layer ("altered" layer) as a clue to the rate of heat penetration. The variation of the "altered" layer with the rate of heat generation (up to 30,000 ft-lb/sec) is shown.

A summary of the theoretical work is presented with some recent calculations that treat the problem of a molten layer at the friction interface. The expressions relating frictional resistance, load carrying ability and film thickness from hydrodynamic lubrication theory were unable to describe the complex phenomenon taking place at the friction interface. Apparently, a combination of a fluid film and some solid contact exists at the interface.

Suggestions are made for the continuation of both the theoretical and experimental work.

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1. INTRODUCTION

More than two years ago, The Franklin Institute undertook the investigation of the frictional phenomena that occur when small samples of solid materials slide on gun steel at high speeds. The work, which included a theoretical phase and an experimental phase, was essentially fundamental in nature. The eventual use of this information will be for problems in interior ballistics, but could include also high-speed aircraft engines, rocket-driven sleds, and other problems involving high-speed sliding contact. If a satisfactory theory can be found and correlated with the experimental evidence, the solution to problems at both higher and lower speeds also may be possible.

Details that have been presented in previous reports will not be repeated in this final report. Instead, a broad outline of the work will include a summary of the work previously reported and the details of work accomplished since the last interim report.

The theoretical study involved a survey of the literature to learn whether a satisfactory theory had been evolved to explain the phenomena occurring at the interface between two rubbing materials. Soon after the survey was started, it became apparent that a knowledge of the properties of materials at high temperatures was involved. Therefore, a search was made of high-temperature properties, particularly thermal properties, of copper and gun steel. These materials were selected because the commercially pure copper was not "contaminated" by alloying agents, and because the gun steel was the material in the disk of the friction machine.

In approaching the theory, a few approximate calculations at the beginning were followed by a comparison of the more significant versions of the theory of the transfer of heat away from a friction interface. None of these considered the possibility of melting occurring, and none accounted for wear. Time did not permit any further work on this phase. However, references are given to published works that do consider melting and wear, and suggestions are presented concerning the future path for a continuation of this study.

The experimental phase of the work centers around the high-speed friction machine[1,2*]. A steel disk two feet in diameter is rotated at speeds up to 20,000 rpm. Small samples of materials are applied to the rim of the disk in such a manner as to traverse the rim, and travel of up to 40 feet is possible without retracking. By variations in the load or size of sample, or both, contact pressures over the range 300 to 30,000 psi may be obtained. Instrumentation with relatively high frequency response (down 10% at 35 kc) records normal load, frictional force, and temperature during tests which often last only 10 milliseconds.

Previous work has established the feasibility of using the sample (prod) and the disk as a thermocouple in order to measure interfacial temperature[2]. This procedure was used throughout the present investigation. An important phase of the work was the calibration of copper <u>vs</u>. gun steel at temperatures up to 2400°F.

Friction tests were made using copper prods to provide empirical data for comparison with theory. In addition, tests were conducted using steel from a 105mm artillery shell. The data from the latter tests were to provide a means of estimating the unbalance forces that cause the body engraving of a shell as its traverses a gun tube. One very interesting phase of the work was the discovery that an "altered" layer of martensite was produced on the worn surface of a prod during a test. This phenomenon of a high surface temperature followed by very rapid cooling is well known in Ordnance. It occurs on the bore surface of artillery weapons, and has received considerable study in the past. In the present work, it provided a clue as to the rate of heat penetration. Consequently, additional tests were made specifically to exploit this valuable feature.

* All superscript numerals refer to Bibliography at the end of text.

The early tests showed some indication that melting occurred at the interface at high speeds. To substantiate this, the physical appearances of worn prods and the wear track on the disk were examined in great detail. Both the light microscope and the electron microscope were used in the search for a typical melted appearance.

One characteristic of these experiments is that oscillations occur during tests over a portion of the speed range of the friction machine. The exact cause of these is unknown. This phenomenon is studied in an attempt to determine its cause and, if possible, either learn its quantitative effect on the friction results or eliminate it.

An attempt is made to correlate the experimental data with the theoretical work and, in a final section of this report, suggestions for future work are made.

2. THEORETICAL WORK

Observations of sliding friction by various investigators, including ourselves, have shown that, at high speeds, high surface temperatures and probably melting of at least one of the materials occur. Hence, the present study was planned to treat the case where a continuous molten film separates the materials. Moreover, the study was an attempt to develop a theory that will relate wear, frictional heating and temperature distribution to sliding speed, normal load and material properties. The effort has been directed toward reviewing the appropriate theories, accumulating data on material properties, and then applying this knowledge to the friction problem.

2.1 Literature and Material Properties Survey

The references obtained in the literature survey are listed in the Appendix of a previous report, with some comment about each that had been reviewed[3]. Several additional references were located, but time did not permit their review; these are listed separately in the same report. Since that time, other related work has been published. While no extensive survey has been made recently, several papers are mentioned in this report that show promise for future work.

The material properties that are important in heat transfer are density, specific heat and thermal conductivity. Data were accumulated on materials of primary interest in the friction testing. These are pure copper, electrolytic-tough-pitch (ETP) copper, and two steels similar to that in the friction disk. The data were plotted to show more clearly the variation with increasing temperature, and particularly to point up the change at both the melting point of copper and the transformation temperature of steel where the data are known.

Since an application of hydrodynamic theory to the problem was anticipated because of the molten film, a search was made for data on the viscosity of molten copper. Some data were found, but the effects of pressure and rate of shear have not been determined; hence the data have limited usefulness.

2.2 Heat Transfer Calculations

The first objective in this work was to develop a theory applicable to the friction machine. This particular theory could then be modified later to fit the physical situation in a gun or any other sliding contact application. In the friction machine, the physical system consists of a stationary slider (prod) which is pressed against a moving surface (disk). These are assumed to be separated by a molten film of prod material. Both heat and mass transfer occur between these parts. Heat is generated by viscous shear in the film and conducted away through the prod and the disk. At the same time, the prod melts and thus supplies material to the film, which in turn loses material to the disk. It appears that this phenomenon could be described through use of the basic theories of heat transfer and film hydrodynamics.

The above statement of the problem in broad terms neglects many of the factors that make the search for an explicit solution rather difficult. When these are disregarded and we neglect details of melting in the prod and the actions taking place in the film, solutions of the equations describing the heat transfer into the prod and disk are obtained. However, the value of the solutions is decreased by the number of qualifying conditions used in obtaining them. More specific details concerning these difficulties may be found in two previous reports[3,5].

Several authors have published heat transfer solutions that approach the true physical situation when the prod and disk are considered separately. At the heated surface, a non-uniform distribution of heat or temperature, or both, is shown to exist. The problem is to make the individual solutions compatible at the interface between the prod and the disk. The various methods used by these authors are covered in a previous report[5]. Most of those considered resulted in essentially the same theoretical expression. However, a comparison of the theory with the experimental data left much to be desired. The temperature at the friction interface, for copper on steel at high speeds, appears to be at or above the melting point of copper according to the experimental data. The theory predicts that the interfacial temperature will increase with increasing speed. However, when a correction is made for the decrease of the coefficient of friction with speed, the theoretical temperature decreases well below the melting point of copper. The difference between the theory and experiment may be due to the fact that the theory has not considered melting and has not paid much attention to exactly how or where the heat is formed. In addition, the theories treated thus far have not considered wear. Any future work should consider these aspects of the problem.

2.3 Hydrodynamic Calculations

Hydrodynamic theory shows the relation between frictional resistance, film thickness and speed to be[6].

$$F = \mu b \ell \frac{v}{h_o} \times K ,$$

where:

μ = viscosity of fluid.

b & ℓ = width and length of slider (prod).

K = coefficient depending upon the slope and clearance of the "tilted" slider, and whether the frictional force on the slider or on the runner is being considered (for most cases, $0.4 < K < 1$).

Based on a viscosity of molten copper of 3.3 centipoise (at 1100°C), a typical test might yield a calculated film thickness of 3 µin. ($F = 12$ lb, $b\ell = 0.005$ in^2, $v = 14{,}400$ ips and $K = 1$). The wear rate for this test was approximately 1.6 ips (lineal change of dimension of the prod). This would indicate a rate of deposition of prod material of 0.56×10^{-6} cu. in./in. of travel or a uniform thickness of 9 µin. deposited on the disk. That the deposited thickness even should be within a factor of three times the calculated film thickness is rather surprising and, possibly, accidental.

The surface of the disk has a roughness of between 2 and 5 µin. (rms) in the direction of travel, and between 4 and 7 µin. (rms) in the radial direction. These values of roughness imply that peaks greater in height than 10 µin. exist on the surface. It is not realistic to treat the material worn from the prod as being a uniformly thick layer spread over such a rough surface. Such being the case, the above formula, based on a full-fluid film separating the mating parts, would not be applicable.

Another expression derived from lubrication theory relates the load-carrying ability of a film to the speed, bearing area, and film thickness as follows:

$$W = \frac{6\mu v \, A \ell \, N}{h_o^2} \times K_p ,$$

where:

N = modification to account for side leakage, for round prod can use 0.44.

K_p = coefficient depending on the slope and clearance, average value of 0.026 can be used.

Then, for the test cited previously (using W = 60 lb, v = 14,400 ips, and ℓ = 0.08 in.), a film thickness of 56.2 µin. is calculated. The latter value does not agree with either the calculated value of film thickness obtained previously or the thickness of prod material deposited on the disk due to wear.

It is, perhaps, too much to expect of the hydrodynamic theory of lubrication that it describe, by rather simple expressions, the complex phenomenon taking place at the friction interface. By some means, heat is created at the interface. It could result from viscous shear of molten material, breaking of physically interlocked joints, or the separating of atoms after they have been brought in closer proximity. If it is assumed that only solid materials are in contact at the leading edge of the prod because there has not been time enough to heat prod material to a molten state, then the film of molten prod material would not extend entirely across the prod face. In that case, a combination of metal-to-metal contact and full-fluid lubrication exists, hence the discrepancies shown above between calculations of full-fluid lubrication and the experimentally determined wear deposits.

3. EXPERIMENTAL WORK

3.1 Friction and Wear Tests

3.1.1 Introduction

During a friction test, small samples (prods) of test material are applied to both faces of the rim of a rotating steel disk two feet in diameter. They are moved radially with just enough speed to make them follow a non-overlapping spiral path on successive revolutions of the disk. The load is applied to the prod holders (arms) by means of air pressure acting through a combination of pistons and cams. The prod arms ride on the cams except while traversing the rim of the disk, when they are let down at one edge of the rim and picked up as they reach the other edge. For this test period, the prod arms ride free and transmit the full load from the air pressure to the prods.

The frictional and normal forces on the prod are observed electrically by means of wire strain gages bonded to the prod arm. The temperature at the interface, when recorded, is measured by the thermoelectric emf generated during test by the prod and the disk. Measurements of wear are obtained by measuring the loss of length and weight of the prod. The instrumentation for recording the variables during test has been described in another report[1].

Variations in surface cleanliness have a great effect on frictional force and wear. In our tests, it is the disk surface that is of major importance. A reproducible surface is obtained by sanding the disk with 120 grit emery to remove a previous wear track, swabbing the disk with acetone, sanding with 240 grit emery, and finally, dusting the surface with clean, dry cheesecloth.

To reduce windage losses, tests were run at reduced pressure in the test chamber. The chamber pressure was always between 0.2 and 1.6 in. of mercury absolute. Relative humidity varied between 30 and 90%, while the ambient air temperature was 60 to 65°F at all times.

All test data accumulated since the last interim report appear in the Appendix of this report.

3.1.2 Copper on Gun Steel

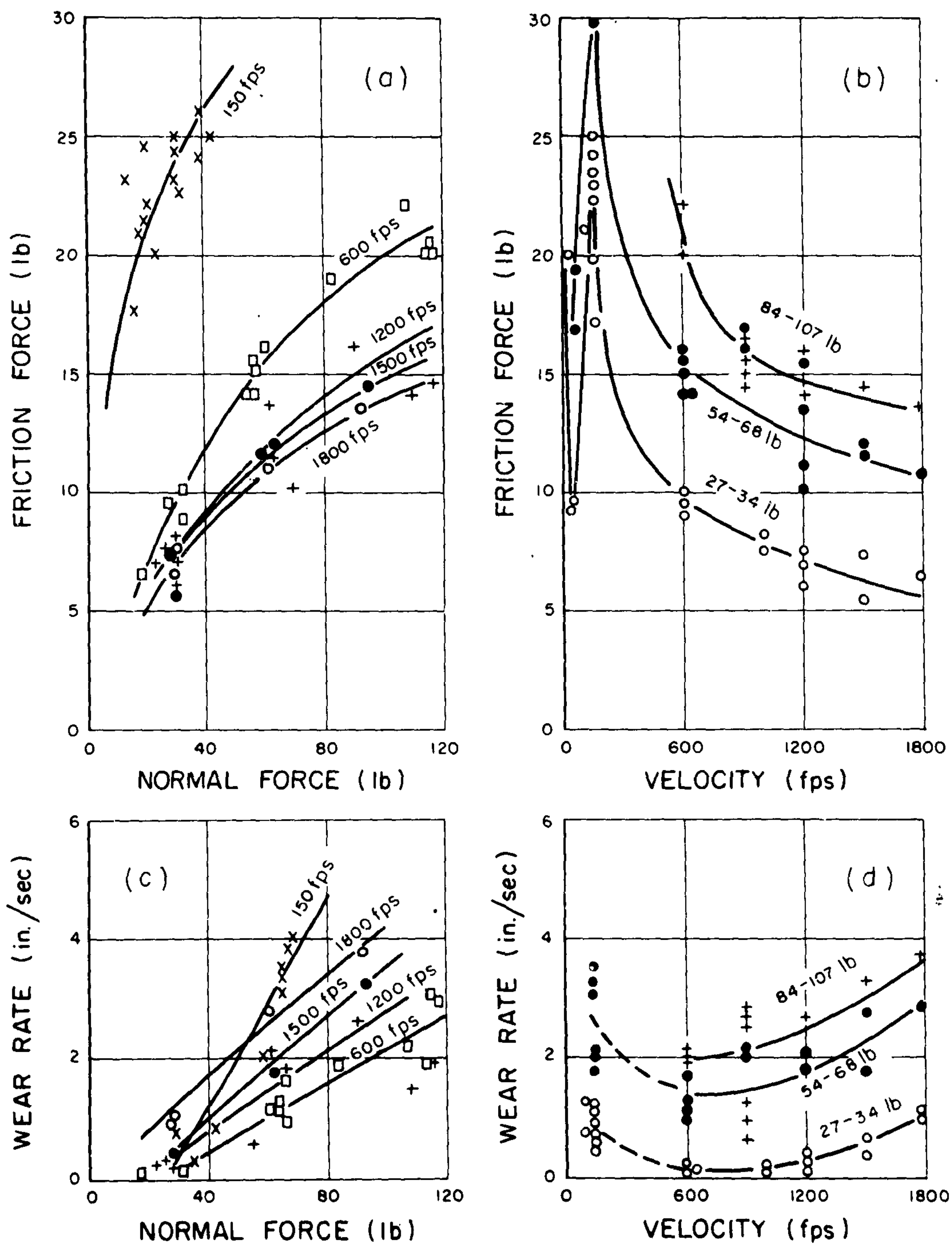
Previous reports presented the results of copper prods run against the gun steel disk[2,3,4,5]. Friction and wear data in the high speed range, 1200 to 1800 fps have been sparse. Recent test work has been devoted to this speed range. All of the data on copper accumulated to date has been summarized in graphical form in Figure 3-1. The variations in frictional force and wear rate were plotted against the major independent variables - load and velocity. As indicated in Subsection 3.2 of this report, the wear rate is independent of time. Hence, the wear rate (in./sec) rather than just the amount of wear (in.) was chosen as a dependent variable to allow the use of all of the data regardless of the test duration. Frictional force increases with increasing load, but at less than a constant rate. This indicates a decreasing coefficient of friction with increasing normal load. Abnormally high frictional forces are encountered in the region of 150 fps. In this speed range, oscillations are encountered which probably account for the high frictional forces. Above the speeds which produce oscillations, the frictional force decreases with increasing velocity. The wear rate appears to have a linear relationship with normal load. Above 600 fps, the wear rate increases with speed. The wear rates at velocities below 600 fps are abnormally high with respect to those above 600 fps. These high wear rates are encountered in the speed range where oscillations occur.

3.1.3 Shell Steel on Gun Steel

Previous reports presented the results of twenty-six tests of shell steel prods run against the gun steel disk[3,4,5]. Twenty-six additional tests were made to extend the range of the previous data. The variations in frictional force and wear rate were plotted against the

GRAPHICAL SUMMATION OF TESTS

(ETP Copper vs. Gun Steel)



REPORT F-2448 FIGURE 3-1

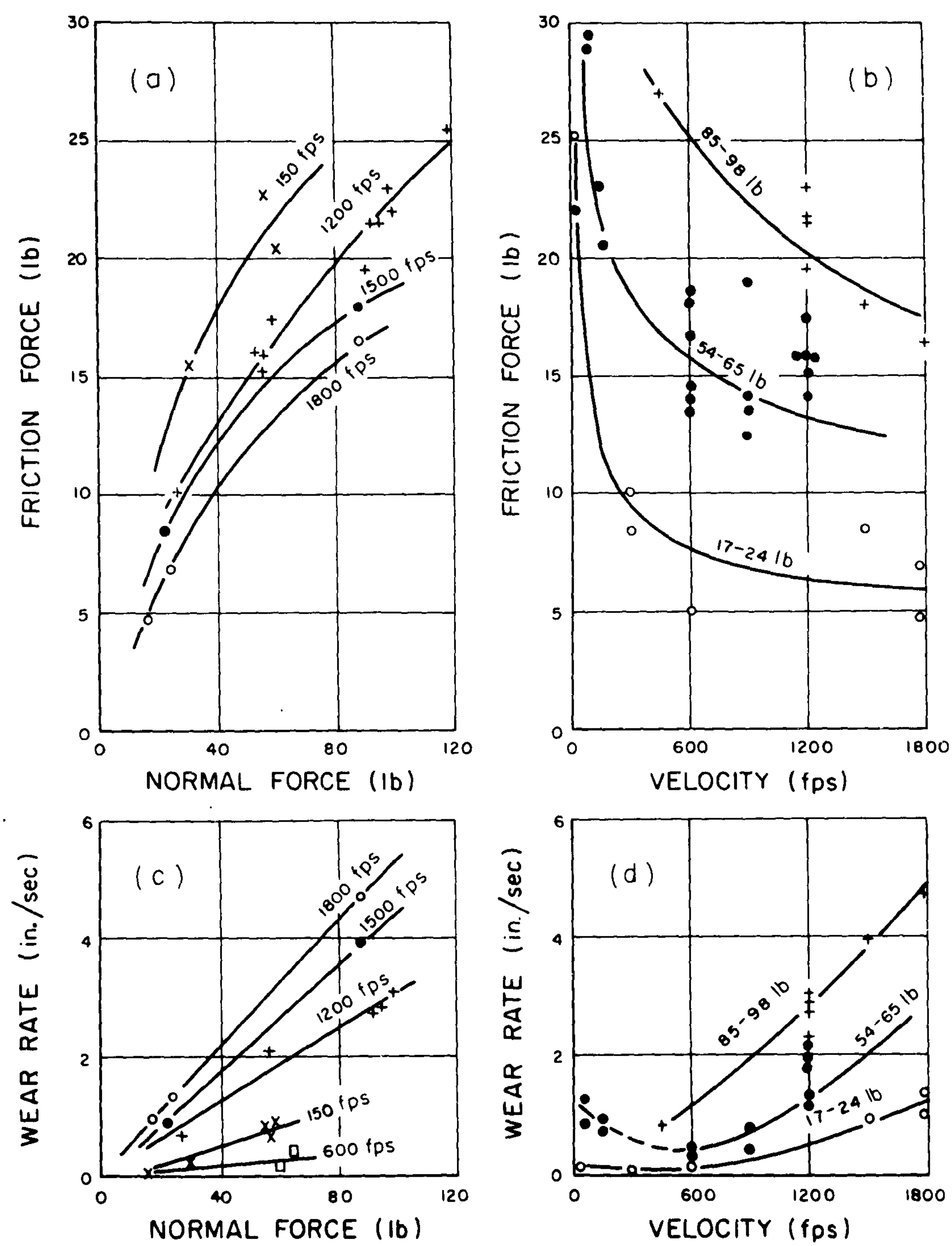
major independent variables - load and velocity - as shown in Figure 3-2. Although the data are somewhat scattered, some general tendencies may be observed. Over the range of normal loads tested, frictional force increases with increasing load, but at less than a constant rate. This would indicate a decreasing coefficient of friction with increasing normal load, as occurred with copper on steel. In general, there is some tendency for frictional force to decrease with increased speed, especially at the higher loads. The wear rate seems to have a linear relationship with normal force. Figure 3-2(d) indicates that the wear rate decreases with speed up to approximately 600 fps. Thereafter, the wear rate increases with velocity. However, it should be remembered that oscillations are encountered in the low speed range which may be adversely affecting the wear rate.

A thin martensitic layer was observed at the friction surface of the prod. The boundary between the "altered" layer and the unchanged material provides evidence of the depth of heat penetration. The layer is thought to have been heated past the transformation temperature (723°C) and rapidly cooled, the latter being a self-quenching phenomenon. Additional tests were made to extend the range of the previous data. As with previous tests, the prods were sectioned, polished and etched, and their "altered" layers examined by means of a measuring microscope.

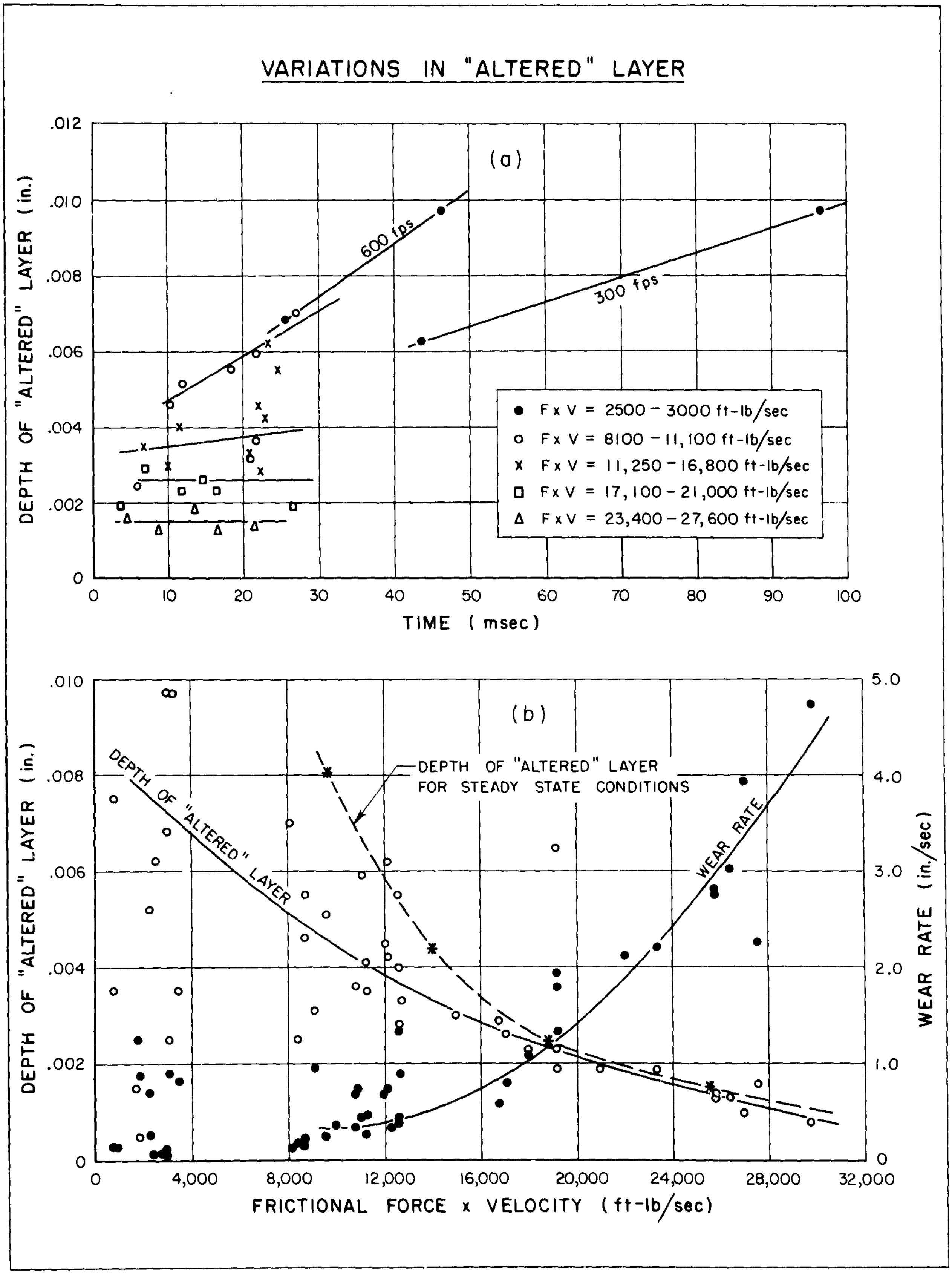
A series of tests at relatively high rates of heat generation (23,400 to 27,600 ft-lb/sec) was run at constant speed and load to substantiate the fact that the depth of "altered" layer remains essentially constant with time, following an initial temperature build-up into the prod. The results are plotted in Figure 3-3(a). Similar data for lower heat generation ranges have also been plotted in the same figure. The resulting curves indicate that frictional energies above approximately 15,000 ft-lb/sec produce a constant thickness of "altered" layer in a few milliseconds. Moreover, the curves also indicate that the depth of "altered" layer decreases as the rate of heat generation increases. This

GRAPHICAL SUMMATION OF TESTS

(Shell Steel vs. Gun Steel)



REPORT F-2448 FIGURE 3-2



REPORT F-2448 FIGURE 3-3

is borne out by Figure 3-3(b), which is a plot of depth of "altered" layer and wear rate vs. frictional energy. The solid curve of the depth of "altered" layer represents the experimental data without regard to the test duration. The dotted curve was plotted by obtaining approximate values of the depth of "altered" layer from Figure 3-3(a). Estimates were made for the data at low values of heat generation because it is conceivable that, allowing sufficient time for the test, temperature penetration would approach steady-state conditions.

The fact that the depth of "altered" layer decreases with increased heat generation might be explained from the steady-state equation of heat conduction:

$$b = \frac{kA\ (t_w - t_b)}{Q} ,$$

where:

- b = depth of penetration of temperature t_b.
- k = conductivity.
- A = area.
- Q = heat input rate.
- t_w = surface temperature.

If k, A, t_w, and t_b are assumed to be constant, t_w is assumed to be the melting temperature, and t_b the transformation temperature of steel, then:

$$b = \frac{K'}{Q} ,$$

where symbol K' is a new constant.

Under these conditions, the depth of "altered" layer is inversely proportional to the heat entering the prod. It should be noted that the amount of heat entering the prod is less than the total amount of heat generated. This fact can have an effect on the above relationship, especially at high speeds.

The wear rate (Fig. 3-3(b)) increases exponentially with increased heat generation. There is a wide scatter of the data in the low range of heat generation with some evidence of abnormally high wear rates. Here again, oscillations may be adversely affecting the wear rate.

Trabant[7] suggests that the "altered" layer may have a thermal conductivity quite different from that of the untransformed steel. As a matter of interest, a test was run under load and speed conditions that would produce an "altered" layer of approximately 0.006 inch in thickness (Test 1231). This worn prod with its martensitic friction surface was again tested under the same speed and load conditions (Test 1232). In the second test, the prod showed a wear rate of 40% less than the first test. Approximately 0.002 inch of wear occurred during the second test, and an "altered" layer depth of approximately 0.005 inch was measured when the prod was sectioned and examined. This would indicate that the boundary between martensite and untransformed steel formed in the first test probably was 0.007 inch from the original martensitic friction surface instead of 0.006 inch. In that case, the boundary would not have moved during the second test. While this is likely, it is impossible to tell from these results whether the above analysis is correct or not. However, a difference in thermal conductivity between the "altered" layer and the base steel does seem entirely possible.

3.2 Distributed Wear Measurements

In previous reports, a method was presented for measuring the distribution of copper in the wear track on the disk[3,4]. In general, the method showed that the wear, when neglecting the transient beginning and end portions of a test, was uniform and that the measurements were reasonably consistent in a number of tests. It was also ascertained that all of the material worn from the prod does not adhere to the disk. No additional measurements using the above mentioned method were made since those last reported.

The measurements of the loss in length of prod material after test also allows us to determine the distribution of wear if speed and load conditions are held constant and the time of test varied. Sufficient data have been accumulated to make such a determination for copper and shell steel prods. The curves in Figures 3-4 are a plot of wear vs. time for several conditions of constant speed and load of both copper and shell steel prods. These curves indicate that the wear throughout a test is uniform, or, in other words, the wear rate is constant.

3.3 Examination of Prods and Disk

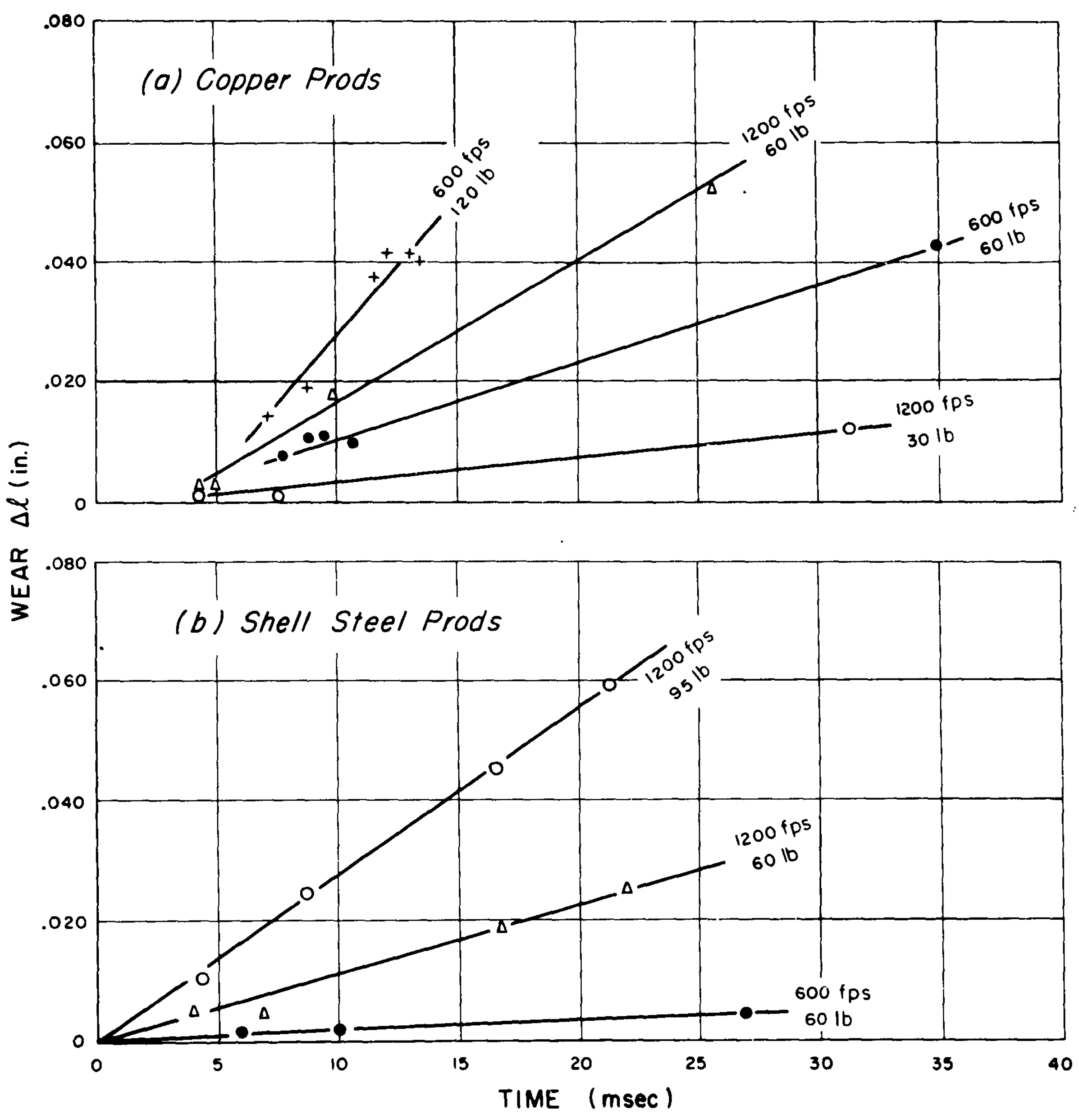
3.3.1 Metallographic Examination of Prods

A previous report presented the results of an investigation to find definite proof of melting at the friction interface[3]. Tested prods of various materials were sectioned, polished, etched and examined under a microscope. In general, the physical evidence remaining after a friction test indicates the presence of high temperatures, but is inconclusive as to whether melting actually took place. Recent work along these lines has been devoted to metallographic examination of tested shell steel prods to determine depth of penetration of the "altered" layer.

3.3.2 Light Microscope Examination of Disk

In conjunction with the metallographic examination of worn prods, several wear tracks were examined in great detail for indications of molten prod material. This work is described in a previous report[3]. For this work a large speed range was covered, the thought being that the lowest speed would be a non-melting condition and the highest speed most certainly a melting condition. No definite conclusions concerning molten prod material in the wear track could be made.

VARIATION OF WEAR WITH TIME



REPORT F-2448

FIGURE 3-4

3.3.3 Electron Microscope Examination of Replicas of Prods and Disk Wear Surfaces

Since the examination of wear surface on the disk using the light microscope did not produce conclusive evidence of any melting at the interface, the use of the electron microscope appeared to be the next logical step. The lack of sufficient depth of field with the light microscope was one of the major obstacles. The electron microscope seemed to offer a possible solution to this difficulty. It has a rather large depth of field. Also, if the need arises for high magnification, the electron microscope is the only adequate instrument available.

Details of the procedure of making replicas may be found in a previous report[5]. Replicas were made of worn and unworn prods as well as wear tracks on the disk. As many as 30 photographs of each replica were made because there were nearly that many different areas on the replica when it was scanned by an expert electron microscopist. Some little similarity between photographs of the same replica was found by further study of the photographs themselves. A selection of between 5 and 10 could be said to be representative of the larger group. Unfortunately, the comparison of photographs among the different replicas showed almost no similarity. Moreover, very few of these photographs indicated that melting had occurred, which essentially had been the main purpose for this study. The only thing approaching a conclusion is that the material formed at the overhanging lip of the prod had been melted previously. This applies to both copper and shell steel, and is based on the usual appearance of a molten surface that has frozen while in motion.

It is possible that molten prod material may either remain on the wear surface of the prod, be carried to the overhanging lip of the trailing edge of the prod, or be carried away by the disk. Of these possibilities, the material carried to the overhanging lip seems the most likely to form a smooth surface, since it has sufficient time, is present in reasonable bulk, and is not cooled quickly by the disk. Due to high rubbing speeds, molten material at other locations would be unlikely to have a typical molten appearance. These last few statements may explain why the electron microscope study of wear surfaces turned up such little evidence of melting.

3.4 Study of Friction Oscillations

Past reports have indicated that, over a portion of the speed range of the friction machine, oscillations occur in some tests[3,4,5]. The oscillations are present in the film records of frictional force, normal force and, to a lesser extent, temperature. When the oscillations are severe, they create some doubt as to whether the average levels of the force records are representative of the speed and load conditions surrounding any particular test. For that reason, attempts have been made either to eliminate the oscillations or, if that is impossible, to determine their true cause and their quantitative effect on friction test data. Previous efforts have shown frequencies of from 300 to 90,000 cps present in test records and in the wear track on the disk. More recent tests with shell steel prods have yielded oscillations at a frequency of 250,000 cps. Although it is not possible to resolve such a high frequency oscillation on the test record, the frequency was calculated by measuring the frequency of discrete wear deposits on the disk.

No additional work to explain or eliminate these friction oscillations has been undertaken since that last reported. Recent testing has been conducted, where possible, to avoid severe oscillations.

3.5 Improvements to Instrumentation

In previous tests, the time signal had been a pulse shaped and positioned so as to sweep completely across the film at the rate of 1, 3, 5, and 9 kc. While this was especially convenient for reading test films, it used a signal channel which might otherwise be showing the variation of an additional temperature or force signal. In order to release this signal channel for more useful information in the future, a glow modulator tube (1B59) was installed in the drum camera in such a position as to cause time marks to be photographed on the film at the rates mentioned above. An addition was made to the pulse generator circuit (timer) to drive the glow modulator tube directly. This modified time marker was used successfully on another project where a need existed for recording a fourth variable. Also during this same project, a crash program for the Air Force, the four-gun cathode ray tube of the four-channel oscilloscope failed. It was replaced with a new four-gun cathode ray tube of slightly greater sensitivity.

In tests where measurements of the thermoelectric output of the prod-disk thermocouple were not made, the spare signal channel was used to obtain an accurate measurement of rpm of the disk during test. This was accomplished by introducing a signal, once per revolution, onto the test film. Over the usual speed range (1500 to 18,000 rpm), calculations of the disk speed by this method agreed within 1% of the speed indicated by the tachometer-generator. No evidence of the disk decelerating during test was detected using this method. The deceleration of the disk during test, if measurable, would offer an independent check of the frictional force occurring during tests. One possible method is to record numerous marks during each revolution rather than a once-per-revolution indication.

3.6 Thermocouple Calibrations

Past efforts at calibrating thermocouples made of copper vs. gun steel and shell steel vs. gun steel were satisfactory for a preliminary investigation[1,3]. However, the data from the tests of copper prods showed temperatures above the melting point of copper and, therefore, required an extension to the calibrated range. Furthermore, the difficulty of calibrating shell steel vs. gun steel in the room atmosphere indicated the need for repeating the calibration in a non-oxidizing atmosphere. Accordingly, several calibration runs were made in a vacuum furnace at an absolute pressure of less than 0.3 microns.

Pieces of the copper bar stock used for prods, the rim of the friction disk forging, and the 105mm shell also used for prods were swaged to form lead-in wires of these respective materials. The wires were connected to the larger pieces in the crucible of the vacuum furnace. A tungsten element surrounding the crucible provided the heat. Several runs were necessary because of the difficulties experienced when the copper melted and lost contact with the steel. In addition, the strange results from the first run of shell steel vs. disk steel prompted a repeat run. The results are presented in Figure 3-5.

The three recent calibration runs of copper vs. gun steel obviously are different from the average of previous runs. The reason for these differences is not apparent. However, a size effect may have some bearing on these variations. The previous runs were made by using 1/8-in. diameter rods butt-welded to form the copper-steel junction. Runs 1 and 2 were made with a disk steel wire inserted into a piece of copper. Run 3 was made with a copper wire inserted into a piece of disk steel. These differences in setup seem to match the differences in the results. However, the exact cause of the discrepancies is not known. It is interesting to note that the curves for Runs 1, 2, and 3 all change sign near the transformation temperature of steel. Despite these discrepancies, it is possible to conclude that an emf measured during a friction test indicates a temperature at least as high as the previous calibrations.

Figure 3-5(b) shows the strange behavior exhibited when the junction of a disk steel wire inserted into a piece of shell steel is heated in a vacuum. Very little can be offered in the way of explanation for this seeming hysteresis loop. The sharp drop in output upon cooling through the range from 1300° to 1100°F may be due to the change in crystal structure known to occur in steel. The dip, around 700°F, is more difficult to understand. It should be noted, of course, that a combination of two different steels is present and, therefore, a combination of effects could occur. Furthermore, the effects may lag behind the temperature of the standard thermocouple to some extent.

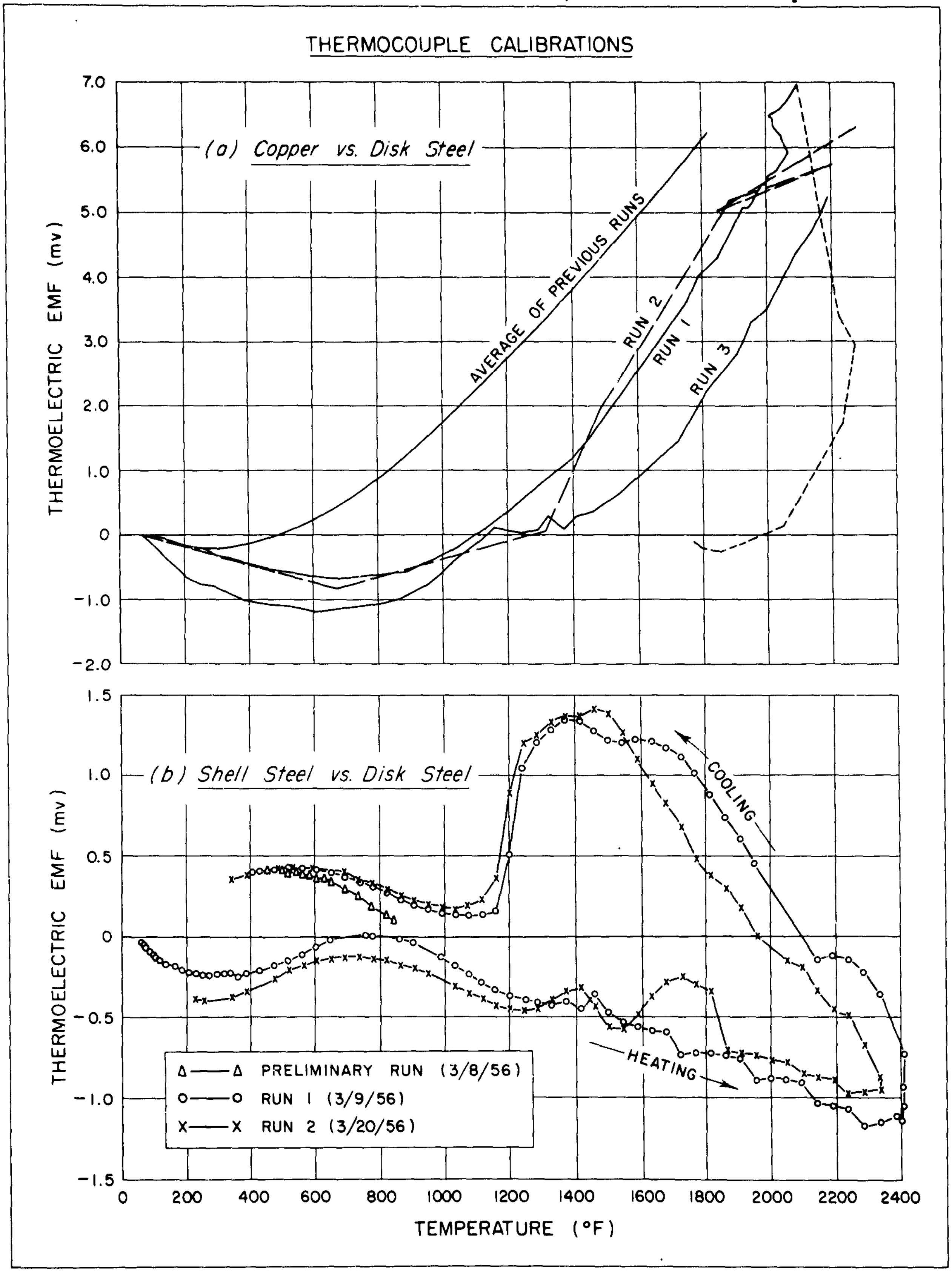

THERMOCOUPLE CALIBRATIONS
(a) Copper vs. Disk Steel
AVERAGE OF PREVIOUS RUNS
RUN 2
RUN 1
RUN 3
THERMOELECTRIC EMF (mv)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
-1.0
-2.0
(b) Shell Steel vs. Disk Steel
COOLING
HEATING
THERMOELECTRIC EMF (mv)
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
Δ——Δ PRELIMINARY RUN (3/8/56)
o——o RUN 1 (3/9/56)
x——x RUN 2 (3/20/56)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TEMPERATURE (°F)

FIGURE 3-5

The second run was made in order to determine whether a permanent change had been taking place during the first run. During the time between the first and second run, a period of 11 calendar days, there was no need to use the vacuum furnace for other work so that the setup remained untouched. The results of the second run were in very good agreement with those of the first run. This fact, unfortunately, does not make them any easier to understand. It is obvious that this combination of metals is not satisfactory as a thermocouple.

4. SUMMARY

The experimental data in this report and in previous reports evolving from this contract are applicable to practical problems where friction and wear data are needed under conditions similar to the test conditions. For problems outside of these conditions, careful extrapolation may extend the usefulness of the data. It is unfortunate that better correlation could not be found between theory and experiment, since that would permit an extrapolation of the experimental data with greater confidence. The theory, apparently, has not reached the stage of development to make good correlation possible.

The major conclusion evolving from the theoretical study is that consideration of merely the flow of heat away from the interface is not enough. In order to expect correlation with the experimental data, a more complete theoretical approach is necessary. It should include the fact of the formation of heat at the interface, and take wear into account at least to the extent of the heat lost in the wear debris. Further study along the lines of the hydrodynamics of a fluid film may prove rewarding if a molten layer is assumed to exist at the interface. Landau's theoretical work which includes melting and Rosenthal's work on welding are two sources of immediate interest in a continuation of this work[8,9].

Several conclusions are possible from the experimental work. Temperatures as high as the melting point of copper exist at the interface when copper is run on steel. The evidence of this fact is found in the output of the copper-steel thermocouple formed by the prod on the disk. Further substantiation is found in the melted appearance of the overhanging lip formed on the trailing edge of the prod during tests at speeds of between 100 and 300 fps. The overhanging lip shows that, in this speed range at least, the trailing edge of the prod must remain relatively cool. The appearance of the prod shows that the trailing side of the prod curves up but is not deformed sufficiently to remove the machining marks. Still another interesting feature of the prod with the overhanging lip is that a layer of prod material next to the interface appears to be recrystallized. The recrystallized layer, which occurred in copper and gilding metal, has a greater thickness at the trailing edge than it does at the leading edge.

When shell steel prods are run at speeds above 10 fps, an "altered" layer (martensite) is formed on the worn surface. The thickness of the layer decreases when the heat at the interface is increased by increasing either the frictional force or the velocity, or both. The wear rate also increases with an increase in heat at the interface. The latter fact probably has some bearing on the thickness of "altered" layer decreasing with increased generation of heat. The amount of wear may be progressing at a rate greater than the amount of heat being conducted into the prod.

In addition to the theoretical work outlined above, continuation of this work would benefit from an experimental program also. The use of other metals as prods may be worth while both in the measurement of interfacial temperature and in an attempt to induce a phase change similar to the martensitic transformation. Another approach would be a series of tests in which the usual frictional heat is supplemented by the heat caused by a high electrical current as it heats the friction interface. This technique was used in a recent Franklin Institute experimental program completed for the Air Force through the General Electric Company[10]. In a crash program to obtain a few data on the characteristics of many materials, no time was available to make a detailed study of the effect of supplementary heating. However, the technique appears to have particular advantages at low speeds, e.g., where the electrical heat could simulate the effect of a much higher load.

Other approaches are possible to a more complete explanation of the phenomena occurring at the friction interface. However, the suggestions offered above were presented because they stem directly from the work covered by this report.

William W Shugarts Jr
William W. Shugarts, Jr.
Project Engineer

Approved by:

Dudley D. Fuller Jr
Dudley D. Fuller, Chief
Friction and Lubrication

Frank S. Chaplin Jr
Frank S. Chaplin
Associate Director
Mechanical Engineering

Nicol H Smith
Nicol H. Smith, Director
Laboratories for Research
and Development

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A P P E N D I X

TEST DATA

TEST RESULTS[a]

Test No.	Prod Material	V Velocity (fps)	N Load (lb)	T Travel (in)	$\Delta \ell$ Wear (in)	ΔW Wear (mg)	F Frictional Force (lb)	μ Coeff. of Friction	t Time of Test (msec)	Room Temp. (°F)	Rel. Hum. (%)	"Altered" Layer Depth (in)
1233	Shell Steel	0	~34	0	N.R.[c]	N.R.[c]	46.0(max.)	~1.35	-	80	70	-
1234[b]		30	~20[d]	72	0.0202	11.6	~26[d]	~1.30[d]	191.6	84	63	0.0075
1239[b]		30	~20	33	0.0131	7.7	~26	~1.30	90.0	82	30	0.0035
1235[b]		300	~20	352	0.0045	3.1	~10	~0.50	96.7	81	60	0.0097
1238[b]		300	~18.5	160	0.0020	1.3	~8.5	~0.46	43.9	80	47	0.0062
1227		450	85.0	118	0.0159	10.0	27.0	0.32	21.7	82	60	0.0042
1214		600	65.0	158	0.0099	6.1	18.5	0.28	21.8	86	55	0.0059
1229		600	60.5	170	0.0088	4.9	16.7	0.28	23.6	80	70	-
1230[e]		600	28.5	92	0.0010	0.6	6.7	0.24	12.7	82	70	0.0056
1231		600	61.0	174	0.0081	4.8	18.0	0.30	24.1	85	60	-
1232[f]		600	62.5	78	0.0021	1.5	17.0	0.27	10.7	80	70	0.0047
1236		600	18.0	329	0.0029	1.9	5.0	0.28	45.4	82	65	0.0097
1237		600	17.5	187	0.0009	0.9	5.0	0.29	25.8	84	50	0.0068
1215		900	42.0	251	0.0109	6.7	12.5	0.30	23.0	84	60	0.0041
1216		1200	27.0	321	0.0150	9.3	10.0	0.37	22.1	84	70	0.0045
1212		1200	57.5	387	0.0551	34.2	17.5	0.30	26.8	81	58	0.0019
1221		1200	98.0	65	0.0102	6.6	23.0	0.24	4.5	82	55	0.0016
1222		1200	91.5	127	0.0242	14.5	21.5	0.24	8.8	82	55	0.0013
1225		1200	91.0	198	0.0301	18.7	19.5	0.21	13.6	83	45	0.0019
1223		1200	99.0	239	0.0454	28.9	22.0	0.22	16.5	80	60	0.0013
1224		1200	94.0	309	0.0591	36.6	21.5	0.23	21.3	82	50	0.0014
1213		1200	118.0	305	0.106+	99.6	25.5	0.22	21.2	84	50	-
1217		1500	22.0	389	0.0196	12.3	8.5	0.39	21.5	81	67	0.0033
1240		1500	88.0	315	0.0682	41.5	18.0	0.20	17.4	83	50	0.0010
1218		1800	17.0	458	0.0205	13.4	4.8	0.28	21.2	82	70	0.0031
1226[g]		1800	20.0	514	0.0166	10.6	6.0	0.30	23.8	81	55	0.0036
1228		1800	24.0	481	0.0302	19.4	7.0	0.29	22.2	82	60	0.0028
1241		1800	88.0	225	0.0494	31.1	16.5	0.19	10.4	79	75	0.0008

1219	Copper (C)	0	~34	0	N.R.[c]	N.R.[c]	20.0(max.)	~0.59	-	80	60
1242	↓	1200	28.5	453	0.0124	3.7	7.5	0.26	31.3	81	58
1243	↓	1200	61.0	370	0.0530	12.3	13.5	0.22	25.7	85	63
1246	↓	1200	90.0	134	0.0237	5.1	16.0	0.18	9.3	85	55
1244	↓	1500	28.0	422	0.0151	6.6	7.3	0.26	23.4	86	60
1245	↓	1500	59.5	394	0.0606	21.4	11.5	0.19	21.9	84	67
1247	↓	1500	94.0	172	0.0308	10.8	14.3	0.15	9.5	84	50
1220	↓	1800	30.0	312	0.0138	7.6	8.0	0.26	14.4	79	60
1248	↓	1800	29.0	431	0.0212	11.6	6.5	0.22	19.9	87	50
1249	↓	1800	60.5	275	0.0364	16.4	11.0	0.18	12.8	85	65
1250	↓	1800	92.5	175	0.0305	15.0	13.5	0.15	8.1	86	58

[a] All tests used Prod Arm V.

[b] Test highly oscillatory.

[c] N.R. - Not recorded.

[d] Values assumed same as for Test 1239.

[e] Used worn prod from Test 1229.

[f] Used worn prod from Test 1231.

[g] Contaminated test surface.

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