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A FUNDAMENTAL INVESTIGATION OF FRETTING CORROSION

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SUMMARY

This report summarizes all phases of an investigation of fretting corrosion which has been conducted over a period of several years. The presentation of the information is made in three parts. Part I describes a test machine for measuring fretting damage under controlled experimental conditions. Part II presents data for mild steel fretted against itself. Consideration is given to the effects of humidity, temperature, test duration, atmosphere, relative slip, pressure, and frequency. Part III suggests a mechanism for the fretting process.

INTRODUCTION

Fretting corrosion is a type of metal damage occurring at the interface of two contacting surfaces subject to relative slip. The damage to steel is evident by debris formed at the interface, usually red in color, accompanied by pitting of the metal. Damage of this kind is a source of uncertainty in the operation of all machinery subject to vibration, since it quickly destroys close tolerances, it increases the susceptibility to fatigue, and the debris may clog moving parts. Hence the practical importance of avoiding fretting corrosion increases as mechanical designs call for closer tolerances, higher loads, and higher operating speeds. Examples of fretting damage are often found in variable-pitch propellers, aircraft landing wheels, railroad tie plates, roller shafts in textile machinery, pins in gear trains, suspension springs, connecting rods, electrical contacts, and jewel bearings.

A study to reduce damage has been made by using lubricants (refs. 1 to 3), including molybdenum disulfide (ref. 4), by change in design so as to avoid slip, or by selection of materials (refs. 3 and 5), but the underlying mechanism is still not known, and present methods for mitigating damage are not always adequate.

Previous investigations have been concerned largely with the qualitative aspects of fretting corrosion. In general, the amount of damage has been estimated visually (refs. 1 to 3 and 5 to 7), depending in general upon the area of pitting or volume of corrosion product accumulating during the test. These tests have supplied useful information, although they have not made possible an estimation of the relative importance of experimental variables on the extent of damage. A limited amount of work has been reported in which weight loss of slipping metal rolls in the Amsler wear machine (refs. 8 to 10) or of oscillating specimens (ref. 11), or the determination of the volume of damaged metal (ref 3), was a measure of fretting. It is quantitative information of this kind that is so much needed at this stage in order to formulate a reasonable mechanism of the damage. A better understanding of the subject is bound to suggest improved mitigative measures.

In the present work, the extent of damage was measured by the weight loss of test specimens operating under defined conditions of test and with adequate control of the major variables. Weight loss becomes a less precise measure of damage after corrosion assumes the shape of deep pits on the faying surfaces, since the depth and shape of the pits enter into an evaluation of their possible source as fatigue nuclei. In general, however, the tests were not concerned with this later phase of damage, important though it is. The plan of attack was to study initial stages of damage first, since it is obvious that if the first phases of fretting corrosion are well-understood and can be eliminated the later phases of damage will never occur.

This work was conducted by the Departments of Metallurgy and Mechanical Engineering of the Massachusetts Institute of Technology under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. Not all of the authors have been involved in all phases of the investigation. The equipment design and operating procedures are attributed to H. H. Uhlig, W. D. Tierney, and A. McClellan. The study of mild steel fretted against itself is the work of I. Ming Feng and H. H. Uhlig, and H. H. Uhlig prepared the discussion of the mechanism of fretting corrosion.

I. TEST EQUIPMENT FOR EVALUATING FRETTING CORROSION

Test Specimen

The present machine was designed and constructed to produce fretting damage by oscillatory motion of two pairs of test specimens held in place by two moving and two stationary chucks (figs. 1 to 4). The standard test specimen, 1 inch in diameter and 1 inch long (fig. 5), was chosen after early tests showed it best met requirements of low elastic loss. One end is counterbored $7/8$ inch in diameter by $1/16$ inch deep, with the resulting

annular face providing the test surface (area equals 0.184 square inch at a mean radius of 0.438 inch). This test surface is dressed on a surface grinder and then carefully polished by hand on No. 1 emery paper. The opposite end of the specimen is cut away to form a centered square tang $5/16$ inch long by which it is held in the chuck. During the test two such specimens are pressed together under a measured load with the annular surfaces in contact. One is fixed in position and the other is subject to vibratory motion sufficient to cause slip. A jig is used to aline them concentrically with each other and with respect to the shaft of the moving chucks to within ± 0.0005 inch. Specimen load can be applied to a maximum pressure of 27,000 psi, frequency of motion can be varied between 56 and 3,000 cpm, and relative slip can be adjusted between 0 and 0.008 inch.

Specimen Chucks and Rocker Arm

Opposing pairs of setscrews in the clearance slot of each chuck act against thin shims of hardened tool steel, thereby clamping the specimen tang perpendicularly to the axis of the specimen. This achieves a stiff grip on the specimens and eliminates fretting or setscrew damage to the tangs. The shoulder of each specimen is seated against sheet nylon cemented to the chuck to avoid fretting at this area. Relative motion between chucks and specimens cannot be detected, and observed fretting is satisfactorily restricted to the test surface.

The two moving chucks are shrunk on milled sections $1\frac{1}{2}$ inches square by $3/4$ inch long at opposite ends of a 3-inch-square shaft. These have a $2\frac{1}{4}$ -inch outside diameter, are 2 inches long, and have a $1\frac{1}{2}$ -inch-square bore to fit the shaft. This shrink fit avoids lost motion and minimizes fretting in this area of the test apparatus. Each of the two stationary chucks, of $2\frac{1}{4}$ -inch outside diameter and 1 inch long, is bolted and pinned to the center of spring steel diaphragms of 5-inch outside diameter by $1/32$ inch thick and is pinned to stands (called end bells). By this arrangement a method of support is achieved which is very stiff radial to the test surface (torsion) but very pliable normal to the surface (bending). Consequently, the diaphragm will permit a normal load to be applied through the fixed specimens, pressing them against the moving specimens, while the fixed specimens are constrained against torsional motion. Also, the diaphragms bend sufficiently to relieve any slight angular misalignment between the mating pairs of specimens.

The square rocker-arm shaft which carries the moving chuck is pinned and bolted to eight leaf springs $2\frac{1}{2}$ inches wide, 0.100 inch thick, and

4 inches long. These leaf springs, in the form of two coaxial crosses, are bolted and pinned at their extremities to a square cage. Thus, the leaf springs constitute a bearing which allows small torsional oscillations of the shaft but which is extremely stiff with respect to any lateral motion.

At the center of the shaft, between the two leaf-spring crosses, an I-beam of aluminum is shrunk on the shaft and is the member through which motion is applied to the shaft. The rocker arm is $1\frac{1}{2}$ inches wide, 4 inches high, with $\frac{3}{8}$ -inch-thick web and flange, and is 15 inches long. The rocker arm passes through clearance holes in the spring cage to a cam drive at one end and a spring return at the other.

Eccentric and Drive Shaft

The cam drive consists of a hardened housing around a needle bearing which encases an eccentric section of the shaft. As the drive shaft rotates, its eccentric section transmits a sinusoidal motion to the rocker arm through the needle bearing. At the opposite end of the rocker arm, a coil spring keeps the arm in contact with the cam.

The eccentric is constructed of two parts. One part, a $1\frac{1}{4}$ -inch outside-diameter, 2-inch-long section of the $1\frac{1}{8}$ -inch outside-diameter drive shaft, is 0.040 inch eccentric (0.080-inch total indicator reading) to the shaft. Enclosing the eccentric portion of the driving shaft is a $1\frac{3}{4}$ -inch outside-diameter, $1\frac{1}{4}$ -inch inside-diameter, and 4-inch-long sleeve with the outside diameter 0.040 inch eccentric to the inside diameter. Eight setscrews (four in each end) clamp this eccentric sleeve to the $1\frac{1}{8}$ -inch shaft at any desired adjustment. By rotating the sleeve relative to the shaft before applying the setscrews, any eccentricity from 0.000 inch to 0.080 inch (or 0.160-inch total indicator reading) is available. In terms of relative motion between the fixed and moving specimens, the 0.160-inch total indicator reading corresponds to 0.0222 radian or about 0.0111 inch of arc at the specimen outside diameter.

The drive shaft carries V-belt pulleys which allow speeds of 540, 820, 1,300, and 2,000 rpm. Other speeds can be readily obtained by inserting other pulleys. The driving motor, a 230-volt, three-phase, 1-horsepower motor, mounted on rubber, operates at 1,800 rpm.

Vibration of the machine was reduced to a minimum so as to confine observed fretting corrosion to pure radial motion of the specimens. Extraneous relative motion of the specimens during the test was checked by a microscope comparator and the maximum found to be in the order of 0.0004 inch.

Pneumatic Load

The normal load between the fixed and moving specimens is applied by pneumatic pistons actuated by high-pressure nitrogen. The nitrogen pressure is measured precisely by a floating piston gage and roughly by Bourdon gages mounted in the gas-line system. Attached to the piston rods are hardened spherical ends which bear on hardened plates pinned to the back of the end-bell diaphragms in order to transmit the load through the fixed chuck to the test surface. Loads up to 5,000 pounds are attainable. In terms of normal stress at the test surface of the present specimens, this is equivalent to 27,000 psi.

Measurement of Slip

Slip is reported as the difference in motion of the moving with respect to the fixed specimen. It is measured by two different methods. The first makes use of a 40-power microscope comparator mounted on a micrometer-screw carriage graduated to 0.0001 inch. This is focused on lines scribed with a diamond across the interface of the two specimens parallel to their axes. Stroboscopic light illuminates the specimens at a frequency slightly different from the frequency of test; hence, the lines appear to move slowly back and forth making possible a measure of their extreme positions. The measurement is made for both moving and stationary specimens and the difference taken as the observed relative slip. Reproducibility was in the order of ± 0.0003 inch.

A method¹ having inherently better reproducibility (± 0.00005 inch) makes use of two strain gages mounted above and below a pointed flat spring steel strip which presses onto the surface of the moving specimen at right angles to its axis. The assembly for the strain gages is rigidly clamped to the fixed specimen, so that observed motion is a direct measure of relative slip.

¹Devised by I. Ming Feng of the M. I. T. Department of Mechanical Engineering.

Provision for Changing Environment

A split stainless-steel rectangular cell, $3\frac{1}{4}$ by $1\frac{1}{4}$ by $1\frac{1}{2}$ inches, fits over the two mating samples for fretting-corrosion tests in environments other than laboratory air. Neoprene gaskets tighten down on the two specimens preventing leakage of gases, yet do not interfere with vibratory motion of the specimens. A glass window bolted and cemented to the top of the chamber allows measurement of slip when the stroboscopic technique is used as described above.

A cell of similar construction is used when slip is measured using strain-gage techniques, but it is of larger dimensions so as to contain the strain-gage assembly.

Test Procedure

The samples to be tested are degreased by immersion in boiling distilled benzene, dried, and weighed. They are then mounted in the chucks and aligned with a jig. They are seated firmly against each other and against the chuck faces by applying a small nitrogen pressure to the end pistons. They are next clamped firmly in position and the full specified test pressure is applied. The machine is started and allowed to run the specified number of cycles, after which it shuts off automatically by means of a counterswitch. When the test is completed, the samples are degreased in hot benzene and immersed for 30 seconds in sulfuric acid (5 percent by weight) heated to 50° C (120° F) and containing 0.1 percent by weight of quinolinethiodide, a pickling inhibitor. The specimens are then scrubbed with a stiff bristle brush in running water, rinsed in hot acetone followed by hot distilled benzene, and weighed.

The loss of weight for clean specimens occurring through pickling was 0.3 milligram per specimen, a value which was subtracted from the observed weight loss in order to correct for the loss of metal.

II. FRETTING CORROSION² OF MILD STEEL IN AIR AND IN NITROGEN

Introduction

Using the test equipment and procedure described previously, measurements of fretting corrosion were made using SAE 1018 cold-finished steel, the certified mill analysis for which is as follows:

Carbon, percent	0.15
Manganese, percent	0.75
Phosphorus, percent	0.008
Sulfur, percent	0.027

A check analysis of the carbon content gave 0.16 percent.

²One of the authors, I. Ming Feng, is of the opinion that fretting damage or simply fretting would be a better name than fretting corrosion.

The effect of various surface preparations (turning, grinding, No. 1 emery paper polish, No. 0000 emery paper polish, and annealing plus No. 1 emery paper polish) was investigated, but no large differences were found. Hence, abrasion by hand with No. 1 emery paper without annealing was chosen as the standard procedure for all tests.

The physical appearance of a fretted 1018 steel specimen with corrosion products removed by pickling is shown in figure 6. Usually, in tests of sufficient duration, pitting occurred over most of the test area except for the rims at the extreme outer and inner diameters of the annular test surface. Even on the annealed specimens the inner and outer rims showed residual bright metal, proving that the cold-worked inner and outer surfaces were not the cause. Perhaps the stress was less here than elsewhere, or the edges were actually rounded in surface preparation. The visual damage appeared as shallow pits, with the deepest pits in the 67,800-cycle tests with a 5,300-psi load and 0.003-inch slip averaging about 0.007 inch.

Numerous data were obtained in the early stages of the investigation before it was realized that atmospheric humidity is one of the important variables requiring control. The literature had not disclosed a large effect of humidity, possibly because the effect was not expected and because previously reported experiments were predominantly qualitative. The effect was first indicated in this work by the disconcerting fact that weight-loss values obtained in winter were greater than similar values obtained in summer by a factor far exceeding the experimental error. The discrepancy was opposite to that expected of normal atmospheric corrosion where attack is always more pronounced during periods of high humidity (summer). This made the cause less obvious, but the effect was eventually traced to differences in relative humidity varying from extremes of 5 percent in winter to 100 percent in summer. Preliminary measurements at this time also showed that quantitative effects of temperature variation, particularly in the room-temperature range, are much larger than might have been anticipated. These facts made necessary a repetition of all earlier measurements with humidity precisely controlled and either the temperature of the specimens controlled or the weight-loss values corrected to room-temperature conditions.

The recorded weight losses herewith reported are the average of two mating specimens, except where temperature control of the specimens required that a thermocouple be attached to the stationary specimen, in which case only the moving specimen was weighed. In view of the large effect of humidity, tests were usually conducted in moving dry air, previously passed over anhydrous calcium sulfate contained in 1-inch-diameter tubes about 9 feet long. The relative humidity of air dried in this way measured 0 percent, as indicated by a hygrometer at the exit end of the chamber surrounding the test specimens. Nitrogen, when used, was purified by being passed through a liquid-air trap, then through 3 feet of copper

turnings maintained at about 400° C, and finally through another liquid-air trap. Metal connections were used from purifier to cell in order to minimize contamination by oxygen and moisture such as would otherwise have occurred by diffusion through walls of rubber tubing.

Effect of Duration of Test

With the variables of the test fixed, such as pressure, relative slip, and frequency of oscillation, weight losses of mild-steel specimens were determined for various times of test in both dry air and in purified nitrogen. The temperature recorded is the average achieved by the specimens (33° C) during the test as determined by thermocouple readings of similar specimens near the interface in parallel tests. The data are reported in figure 7. The rate of metal loss was rapid at first; but, after about 150,000 cycles of test, corresponding to a period of "run-in," the specimens reached a steady-state condition. Weight losses thereafter were linear with time, or the rate of metal loss was constant. Tests were carried out to a maximum of 1,250,000 cycles requiring about 39 hours.

In nitrogen weight losses were much less, although not zero. At 200,000 cycles, for example, the weight loss was one-sixth that in air, and this fraction became less as the test was continued. The run-in period for nitrogen required about 30,000 cycles as compared with 150,000 cycles in air. The decrease of fretting damage in an inert atmosphere such as nitrogen or helium, or in vacuum, has been previously reported by several investigators (refs. 1, 6, 8, 10, 12, and 13).

Effect of Humidity

Humidity was controlled by passing air through distilled water using submerged sintered glass disks in order to produce a fine dispersion of gas bubbles. The flasks were submerged in a water thermostat maintained at a prescribed temperature to within 0.1° C. Humidity was recorded using a hygrometer manufactured by Serdex, Inc., located inside a gastight chamber at the exit system of the cell surrounding the test specimens. The hygrometer was checked at several humidities against a sling psychrometer. Although the entire range of relative humidity was possible, 100-percent relative-humidity air was not used because rusting of the test specimens and subsequent error in weight-loss determinations occurred. Air of 90-percent relative humidity did not cause such rusting during the time of the test and, hence, this was the maximum extent to which air was humidified.

Data given in figure 8 are for two times of test - one at 67,800 cycles which brought the test short of the run-in period, and the other at

457,800 cycles which was beyond run-in, where the weight losses of the specimens became linear with number of cycles. A temperature of 33°C was the average value of the specimens near the interface throughout the test period. The values of relative humidity were based on room temperature equal to 27°C . The percent effect of increased humidity on weight loss was appreciable and was about the same for both periods of test. At 100-percent relative humidity and 457,800 cycles, fretting corrosion as measured by extrapolated weight loss was only 55 percent the weight loss at 0-percent relative humidity and was correspondingly 65 percent at 67,800 cycles.

Fretting damage of mild steel in nitrogen, essentially saturated with water vapor, was found to be approximately the same as that in dry nitrogen (table I). This fact indicates that moisture in the air perhaps either decreases the abrasive properties of iron-oxide debris at the interface or alters the rate with which iron combines with oxygen (in the opposite direction to its effect in normal corrosion processes). In the absence of oxygen or oxides moisture is apparently not important.

In this connection it was of interest to determine what effect, if any, is exercised by iron-oxide particles on fretting damage in nitrogen. Two specimens were run in dry air for about 600,000 cycles, thereby becoming covered uniformly with compacted iron oxide on the contacting surfaces. One of the specimens was then replaced by a clean specimen and the weight loss of the latter determined after 30,000 cycles and also after 203,400 cycles. The results are listed in table I. For comparison, the weight losses of a clean specimen run with a clean specimen are also included. The results show no certain effect of oxide, whether the specimens were run in air or in nitrogen.

Nature of Corrosion Products

Previous investigators have reported ferric oxide $\alpha\text{Fe}_2\text{O}_3$ as the major component of the final debris when iron or mild steel is fretted (refs. 7 and 14 to 16). Roll and Pulewka (ref. 17), using the Hanffstengel wear machine, claimed that Fe_3O_4 may also be present depending on the load and velocity of the test. Fink and Hofmann (ref. 15), using the Amsler wear machine, also found Fe_3O_4 in some tests. The latter authors together with Thum and Wunderlich (ref. 14) and Dies (ref. 11) reported the presence of small amounts of metallic-iron powder along with iron oxide. Dies reported 24 percent ferrous oxide FeO , as determined by chemical analysis for debris of soft iron fretted against hardened chromium steel, the remainder of the debris being 68.6 percent Fe_2O_3 and 2.5 percent Fe . Traces of metallic nitrides were reported by Cornelius and Bollenrath (ref. 16) and by Dies (ref. 11).

In the present tests on mild steel, the major constituent of the dark red debris, as determined by X-ray,³ was found to be $\alpha\text{Fe}_2\text{O}_3$. This was true for specimens run at room temperature and at -140°C and 157°C . A small amount of metallic iron, less than perhaps 5 percent by weight, accompanied the oxide obtained from specimens run at 5,300 psi, 540 cpm, and 0.0036-inch slip. How much iron, if any, was present under other test conditions was not determined. The black powdered debris of specimens run in pure nitrogen proved to be entirely metallic iron.

Effect of Temperature

The effect of temperature was studied by heating or cooling the stationary specimen rather than the ambient air. For temperatures between -125°C and 100°C one turn of 3/16-inch-diameter copper tubing was soldered to the specimen through which liquid nitrogen was pumped (for temperatures below -50°C), or alcohol plus solid CO_2 (for temperatures below room temperature and above -50°C), or hot water (for temperatures below 100°C) was circulated. For temperatures above 100°C a resistance wire heating coil was wound around the specimen. The most difficult measurements were the long-time runs at low temperatures requiring large volumes of liquid nitrogen and constant manual adjustment.

Since heating or cooling one specimen of a pair produced a temperature gradient, the temperature near the interface was estimated for each condition of test. This was done in preliminary test runs maintaining conditions exactly as in regular runs. Thermocouples were soldered to each specimen near to and equidistant from the interface, and the test machine was then started. Generally, a thermocouple attached to the moving specimen gave a higher or lower reading than the stationary-specimen thermocouple, depending on whether the stationary specimen was heated or cooled. The average was taken of the two temperature readings when steady-state temperature and fretting conditions were reached.

During actual runs for which weight losses were recorded, a thermocouple was attached to the stationary specimen only, the reading of which combined with data from preliminary runs gave the specimen temperature. The weight loss was then determined for the moving specimen alone. One other precaution taken because of the temperature limitations of rubber was to omit the gasket between the cell and the specimen for runs above 80°C or below 0°C . The cell for these measurements was reconstructed so that it fitted tightly without gaskets around the stationary specimen but allowed a small annular space around the moving specimen, thereby permitting free relative motion of the two but, nevertheless, preventing the influx of air to the chamber in which dry air was maintained.

³Carried out by P. Rautala of the M.I.T. Department of Metallurgy.

Data are recorded in figure 9 for two periods of test, again corresponding to periods before and after run-in. The weight losses were greater the lower the temperature. Before the run-in period, weight losses at 50° C were only about 50 percent or one-half those at 0° C, and after the run-in, about 65 percent. As temperatures fell below 0° C, fretting corrosion increased for long periods of test but apparently remained relatively fixed for shorter periods. Above 50° C, and to a maximum of 150° C, the temperature coefficient of corrosion was relatively small. These data, of course, are all for unlubricated surfaces in dry air. The data may or may not correspond to observations on lubricated surfaces, where properties of the lubricant also enter as factors, although qualitative effects of temperature should probably be the same. For example, Almen (ref. 1) found in the case of lubricated automotive bearings that fretting corrosion when it occurred was more severe in winter than in summer, which agrees with the present conclusions based on figure 9.

Effect of Slip

Relative slip of the specimens was varied from 0.0004 to 0.0091 inch, employing a pressure of 5,300 psi, a frequency of 540 cpm, and a total test period of 67,800 cycles. The values of relative slip were corrected for slight elastic loss between the fixed points of the transducer used to measure relative displacement. This amounted to 0.0003 inch.

Whereas temperature corrections were not necessary for previous runs because the specimens were near room temperature or the temperature was controlled, corrections became of increasing importance to runs where load, slip, and frequency were increased. Temperature rise was appreciable for specimens oscillating at high frequencies or high values of slip or load, and the corresponding corrections made necessary by the higher temperatures were not small. Ideally, a temperature-correction curve should be constructed for each condition of test. This would require considerable time, however, in view of the major effort compelled by the two temperature curves of figure 9 for a single set of conditions. Hence, the compromise situation was to use the data of figure 9 and assume that the effect of temperature for any condition of test was the same percentage based on weight loss. For example, the weight loss of a specimen fretted for 67,800 cycles at 5,300 psi, 540 cpm, and 0.0036-inch slip is 7.8 milligrams at 25° C and 4.7 milligrams at 50° C. Correspondingly, if the temperature during a run achieved by a specimen fretted at a specified slip, load, and frequency happened to be 50° C, its weight loss was corrected by multiplying the observed value by 7.8/4.7. This order of correction is justified only in the absence of a better correction and was used in the expectation that it marks an improvement over no correction at all. However, recognizing the inherent limitations of the assumptions that are made, the data recorded in the various figures include weight-loss values not temperature-corrected, as well as those corrected as

described. It should also be mentioned that some scatter in the corrected results for similar test conditions comes about through variations in room temperature.

Preliminary tests were run to determine the relationship of slip to the average temperature rise of the specimens. A maximum temperature rise of 22° C for 0.0091-inch slip corresponded to a maximum correction in the order of 8 milligrams. Data are presented in figure 10 showing that weight loss is a linear function of slip. This is true for all temperature-corrected values of weight loss, as well as for uncorrected values corresponding to the higher values of slip. The greater the amplitude of oscillatory motion, therefore, the greater the fretting corrosion. Furthermore, it appears from the extrapolated data that corrosion no longer occurs for zero slip.

Effect of Pressure

As pressure on the test specimens is increased without change of other factors, relative slip gradually decreases. Weight losses correspondingly increase at first, reach a maximum, and then decrease as more and more motion induced by the cam is taken up in elastic losses both in the machine and in the specimens. When the applied pressure is so high that the relative slip of the specimens is reduced to zero, fretting corrosion also becomes nil.

It is of greater fundamental interest to know how fretting damage varies with applied pressure under conditions where the relative slip is maintained constant. This was determined in a series of tests by adjusting the cam after each change of pressure, so that slip was maintained at 0.0036 ± 0.0002 inch after appropriate corrections were made for elastic losses in the specimens between the fixed points of the transducer. Figure 11 shows that weight loss increases with pressure up to the maximum pressure applied of 5,300 psi.

Effect of Frequency

By means of a strain-gage transducer, the relative slip between two mating specimens was found to be independent of frequency. This was checked at 5,300 psi and 0.0036-inch slip.

The maximum temperature rise reached by the test specimens increased appreciably with frequency, necessitating trial runs as described previously in order to establish temperature corrections. The highest value of temperature at 3,000 cpm and 0.0036-inch slip, for example, was found to be 61° C. The corresponding correction required adding 3.6 milligrams, or 11.2 percent of the observed weight loss. The temperatures attained

were still higher at 1,300 cpm and 0.0091-inch slip (77° C) and the corresponding corrections greater. Great reliance, of course, cannot be placed on corrections of this order. At lower frequencies or lower values of slip the corrections were less as the data of figure 12 show.

Temperature corrections tend to diminish the observed frequency effect of fretting corrosion, but the effect nevertheless remains sizable. Weight losses are definitely lower the higher the frequency for a given number of test cycles. It is also apparent that the greater the slip, the greater is the frequency effect; and, for a very small value of applied slip (0.0004 inch), any applied frequency effect is within the experimental error. In nitrogen the frequency effect also disappears (fig. 13), even though a cam displacement of 0.08 inch was employed which produces a slip of 0.0036 inch in air but variable slip in nitrogen. The data were not temperature-corrected.

III. MECHANISM OF FRETTING CORROSION

A satisfactory theory of fretting corrosion should account for several facts among which are the following:

- (1) Fretting damage is reduced in vacuum or inert atmosphere.
- (2) Debris formed by fretting of iron is largely of the composition Fe_2O_3 .
- (3) Greater damage occurs at low frequencies for a given number of cycles than at high frequencies (fig. 12).
- (4) Metal loss increases with load and relative slip (figs. 10 and 11).
- (5) Greater damage occurs below room temperature than above room temperature (fig. 9).
- (6) Damage is greater in dry air than in moist air (fig. 8).

The fact that fretting corrosion involves a chemical process can hardly be doubted in view of the fact that a chemical reaction product is formed. The process of fretting, therefore, is truly one of corrosion, a term defined as the chemical or electrochemical reaction of a metal with its environment (ref. 18). This terminology is perhaps reasonably clear, but there is still ample room for discussion as to whether the observed chemical process accompanies or follows consumption of metal in fretting damage.

There are good reasons for believing, based on work of other investigators and on data presented in part II, that both situations occur in practice. The frequency effect of damage, for example, is plausibly explained as evidence of chemical reaction accompanying the fretting process, which proceeds as a function of time rather than of distance traveled during the oscillatory motion of the specimens. Accordingly, at high frequencies where the time of fretting is short for a given number of oscillations, the over-all weight loss is less. On the other hand, evidence of mechanical wear comes from the observed presence of iron particles in the debris. Also, photomicrographs (e.g., fig. 14) of a fretted specimen surface show unmistakable disturbance or cold-working of the surface, and, in some cases, there are areas where metal appears to have seized and separated. Adhesion and shearing of such areas are logical sources of metallic debris (refs. 19 and 20). The fact that so little metallic debris appears is evidence not of minor mechanical wear, but rather of conversion of metallic debris to oxide subsequent to removal of metal from the specimen surface.

It should be pointed out that typical pitting of fretted surfaces is not a result of electrochemical action such as occurs in aqueous media through operation of galvanic cells. The pits, instead, result from localized stress concentration at these areas through accumulation of oxide. Ferric oxide Fe_2O_3 formed by fretting action has a density of 5.12 compared with the density for iron of 7.86. This means that the oxide has greater volume than the iron from which it forms by a factor of 2.2. Therefore, the metal surface areas initially in contact and first fretted remain or become highly stress loaded because the oxide of greater bulk than the metal tends to separate the two surfaces. Consequently, fretting corrosion is accentuated locally, in accord with the data of figure 11, and the tendency is toward pitting attack rather than uniform surface wear. Fretting action thereafter between two moving surfaces is transmitted largely by compacted oxides retained in the pits. The forced separation of metal areas surrounding pits was observed in many of the present test specimens, particularly before the run-in period. At these areas, marked by the persistence of unattacked bright metal, original scratch lines formed during surface preparation of the specimen are still clearly seen under the microscope.

Theory of Fretting Corrosion

Facts assembled from the literature and from the present test program suggest the following model for the mechanism of fretting corrosion. Assume a surface with n circular asperities or contact "points" per unit area of metal (or oxide) with average diameter c and an average distance s apart. In the fretting process these asperities move over a plane metal surface at a linear velocity v , each asperity, in turn, plowing out a path and exposing clean metal, the area of which depends

on the width of the asperity and length of travel. Behind each asperity on the track of clean metal gas from the atmosphere will rapidly adsorb, or perhaps a thin layer of metal oxide will form. The next asperity will wipe off gas or oxide film as it traverses the path of the first asperity, and so on for all asperities. (See fig. 15.)

The average time during which either gas adsorbs or oxide forms is t . Then

$$t = s/v \quad (1)$$

The corresponding amount of oxide W removed by one asperity plowing out a path l long and c wide is dependent on the total oxidation of a clean iron surface of area cl in time t .

The empirical relation for the initial stages of oxidation of a metal is given by:

$$W = clk \log_e \left(\frac{t}{\tau} + 1 \right) \quad (2)$$

where τ and k are constants. This logarithmic oxidation-rate equation was first suggested by Tammann and Köster (ref. 21) as applying to oxidation of iron at low temperatures (252°C to 385°C), as well as to oxidation of various other metals. The logarithmic equation has since been confirmed by other investigators for iron and other metals (refs. 22 to 27), again for relatively low temperatures. Another relation holds when the oxide films that form are comparatively thick, but this is not the present situation.

The logarithmic equation was reported by Armbruster and Austin as applying to oxidation of iron at room temperatures (ref. 28) but after initial adsorption of oxygen on the surface too rapid to measure. Instead of oxidation, their data alternatively may represent the rate of chemisorption of oxygen on iron, where the first layer of molecules rapidly adsorbed is held by Van der Waals forces (physical adsorption), followed by less rapid conversion to dissociated atoms which become chemically bonded to the surface (chemisorption). The first layer of gas, in turn, as it becomes chemisorbed encourages adsorption of additional gas less tightly bound. On this basis, mechanical energy of abrasion supplies the necessary activation energy to convert immediately the adsorbed gas film to stoichiometric chemical compound of which oxide is one example. Conversion to oxide at room temperature is much slower in the absence of such an activation energy. This model for the metal surface is not essential to the present discussion but is made here in order to include what seems to be a plausible detail of fretting action to be considered again later in an interpretation of the facts.

The final equation derived below for the rate of fretting corrosion is the same whether one assumes gas adsorption followed by formation of oxide through mechanical action, or rapid oxide formation wiped off directly by abrasion. Perhaps, in the general case, both situations apply.

Substituting equation (1) into equation (2):

$$W = c l k \log_e \left(\frac{s}{vT} + 1 \right) \quad (3)$$

In the presently described fretting tests, the motion of one annular ring specimen slipping with respect to a similar specimen is sinusoidal. Since $2l$ is the total length of travel in any one cycle, the linear displacement x from the midpoint of travel at time t is given by:

$$x = \frac{l}{2} \cos \theta \quad (4)$$

and

$$\frac{dx}{dt} = v = - \frac{l}{2} \sin \theta \frac{d\theta}{dt} \quad (5)$$

If f represents constant linear frequency, this is related to constant angular velocity by the expression:

$$\frac{d\theta}{dt} = 2\pi f \quad (6)$$

Therefore, the average velocity is given by:

$$\bar{v} = - \frac{\pi l f \int_{\theta}^{\pi} \sin \theta \, d\theta}{\pi} = 2lf \quad (7)$$

Hence, for n contacts or asperities per unit area of interface, the weight loss designated by W_{corros} per single cycle caused solely by oxidation, in accord with equation (3), is:

$$W_{\text{corros}} = 2n\ell ck \log_e \left(\frac{s}{2\ell f\tau} + 1 \right) \quad (8)$$

To this must be added mechanical loss of metal because each asperity, on the average, digs below the oxide layer (or adsorbed gas layer) and dissipates metal in an amount proportional to the area of contact of the asperities and length of travel. The area of asperity is important now rather than width, because of the "tearing out" or welding action occurring during mechanical wear in contrast with the scraping off of chemical products from the surface. A shearing off of asperities without welding also leads to wear dependent on the total area of contact. For n circular asperities, the weight loss per cycle is given by:

$$W_{\text{mech}} = 2k'n \left(\frac{c}{2} \right)^2 \pi \ell \quad (9)$$

But $n\pi \left(\frac{c}{2} \right)^2$, the total area of contact, is known to be equal to the load L divided by the yield pressure p_m (ref. 19, p. 20).

Hence,

$$W_{\text{mech}} = 2k' \frac{L}{p_m} = k_2 L \quad (10)$$

where k_2 is a constant equal to $2k'/p_m$. The total wear or metal loss per cycle is the sum of the oxidation, or corrosion term, and the mechanical term:

$$W_{\text{total}} = W_{\text{corros}} + W_{\text{mech}} \quad (11)$$

Returning to equation (8), the logarithmic term can be expanded according to the relation

$$\log_e (x + 1) = x - \frac{x^2}{2} + \frac{x^3}{3} - \dots$$

where x is equal to $s/2lf\tau$. When the latter expression is much smaller than unity, the square and higher terms can be omitted. This condition applies particularly to high load (small values of s), high frequency f , and large values of slip l . The constant τ for oxidation of iron or adsorption of oxygen on iron has not been determined empirically with great precision, nor has its theoretical significance as yet been made clear. The value equals 0.06 second for all of Tammann's data on iron (ref. 21) and is variable, but is in the order of 3 seconds for Winterbottom's data (ref. 27) and variable, and in the order of 60 seconds for some of Armbruster and Austin's data (ref. 28).

In the present experiments f is approximately 10 cps and l is about 0.01 centimeter. The average distance between asperities at 5,000 psi after the run-in period approaches perhaps 10^{-2} to 10^{-6} centimeter. The quantity $s/2lf\tau$, therefore, is approximated by

$$\frac{10^{-4}}{2 \times 0.01 \times 10 \times 0.06} = 0.008$$

Therefore, whenever experimental conditions are such that higher terms of the logarithmic expansion can be neglected:

$$W_{\text{corros}} = \frac{2nlcks}{2lf\tau} = \frac{ncks}{f\tau} \quad (12)$$

This expression, it will be noted, is equivalent to assuming, from the very start, a linear rate of oxidation or of gas adsorption on clean iron where k/τ is the reaction rate constant. The linear rate reasonably approximates the actual state of affairs considering the short times of adsorption or oxidation which are being dealt with here.

From the fact that the number of asperities along one edge of unit area is equal to \sqrt{n} , it follows that $s + c$ is approximated by $1/\sqrt{n}$.

Also, recalling that $n\pi\left(\frac{c}{2}\right)^2 = L/p_m$,

$$W_{\text{corros}} = \frac{k_0 L^{1/2}}{f} - \frac{k_1 L}{f} \quad (13)$$

where

$$k_0 = \frac{2}{\sqrt{p_m \pi}} \frac{k}{\tau}$$

and

$$k_1 = \frac{4}{p_m \pi} \frac{k}{\tau}$$

Combining equations (10), (11), and (13), one has the final expression for fretting as measured by weight loss corresponding to a total of C cycles:

$$W_{\text{total}} = \left(k_0 L^{1/2} - k_1 L \right) \frac{C}{f} + k_2 L C \quad (14)$$

Note that this final equation is made up of three terms, the first two terms representing chemical reaction or corrosion and the third term representing mechanical wear. According to this relation, the total weight loss is:

(1) Linear with total number of cycles. This is in accord with the observations, the linear steady state being reached after a run-in period (fig. 7).

(2) Parabolic with applied load L . This trend is also indicated by the data (fig. 11).

(3) Hyperbolic with frequency f . Figure 12 confirms this prediction except for small values of slip. The lack of frequency effect for small applied slip is explained later.

The first two terms of equation (14) show that the corrosion factor of fretting damage:

(1) Is predominant at low frequencies but is overshadowed by mechanical wear at high frequencies.

(2) Is a function of total time of test regardless of frequency, since C/f is equivalent to total time.

(3) Becomes zero when $\pi\left(\frac{c}{2}\right)^2$, the actual area of contact, approaches the maximum area of the interface (or $s = 0$ and $l/\sqrt{n} = c$). This occurs at a load L equal to $\pi p_m/4$.

(4) Is independent of total slip l , whereas the mechanical term increases linearly with slip. As l approaches zero, the term $2nlck \log_e \left(\frac{s}{2lf\tau} + 1 \right)$ approaches zero and, therefore, W_{total} also approaches zero. Zero fretting damage in the absence of slip has been established by previous investigators and also by the present data.

The above conclusions are in essential agreement with the experimental results.

Chemical and Mechanical Contribution to Fretting Damage

Equation (14) in combination with the data of part II makes possible a correlation of all the reported data and an evaluation of how much fretting damage can be attributed to corrosion or chemical reaction and how much to mechanical wear. This necessitates evaluation of the constants k_0 , k_1 , and k_2 . An examination of weight loss plotted against pressure (fig. 11) shows that the following equation adequately describes the empirical curve:

$$W = 0.038L^{1/2} + 0.0009L \quad (15)$$

Since the data of figure 11 are for 67,800 cycles, a frequency of 540/60 cps, and a slip of 0.0036 inch, equation (14) becomes:

$$W = 7,540k_0L^{1/2} + \left(244k_2 - 7,540k_1\right)L \quad (16)$$

Therefore, comparing equation (15) with equation (16):

$$k_0 = \frac{0.038}{7,540} = 5.05 \times 10^{-6}$$

The constant k_1 can be evaluated from k_0 employing the relation:

$$k_1 = \frac{2}{\sqrt{p_m \pi}} k_0$$

where p_m , the yield pressure, is approximated by 3 times the elastic limit (ref. 19, pp. 19 and 30) or for mild steel equals 100 kg/mm² or 140,000 psi.

Substituting this value into the above equation,

$$k_1 = 1.51 \times 10^{-8}$$

Finally, k_2 can be evaluated knowing k_0 and k_1 and is equal to 4.16×10^{-6} . This gives as the final expression for fretting weight loss:

$$W = \left[(5.05 \times 10^{-6}) L^{1/2} - (1.51 \times 10^{-8}) L \right] \frac{C}{f} + (4.16 \times 10^{-6}) l L C \quad (17)$$

where W is in milligrams per specimen (0.184-square-inch (1.19-square-centimeter) surface); L is in pounds per square inch; f , in cycles per second; C , in cycles; and l , in inches.

How well this equation describes the weight-loss data for tests with variation of load (pressure), slip, and frequency can be judged by referring to table II. Agreement, by and large, is good.

At 56/60 cps and 0.0036-inch slip, the deviation of the calculated from the observed value can be explained on the basis that the approximate expansion of the logarithmic term in equation (3) no longer holds. The rate of oxide formation is not so great, in other words, as is calculated from the linear rate constant obtained from higher frequency data. It seems that deviations from the linear oxidation rate appear below 238 cpm, as shown by figure 16, where the weight losses plotted with reciprocal frequency are otherwise in accord with the predictions of equation (14). By increasing the slip 2.5 times from 0.0036 to 0.0091 inch, thereby decreasing the value of the term $s/2lf\tau$ within the logarithm, agreement between the calculated and observed weight loss at 56/60 cps is better (34.4 compared with 32.7 milligrams).

Whenever increased specimen surface temperatures are generated through use of high frequencies or large values of slip or both, correspondence between theory and observation is obscured by the uncertain correction for the temperature effect. It is significant, nevertheless, that the calculated values, by and large, fall between the corrected and uncorrected observed values. When the test conditions are such that surface temperatures are high, the calculated values seem to agree better with the uncorrected values, suggesting that the approximate temperature corrections that were used are much too large in these instances.

A frequency effect of weight loss is calculated by equation (17) to exist for 0.0004-inch slip; however, figure 12 shows that essentially no frequency effect is found for this value of slip. The mechanical-wear term is calculated to be 0.6 milligram and the chemical-wear term, 2.2 milligrams. The observed weight-loss value of 1.1 milligrams, therefore, is in between these two values and suggests that a high-frequency oscillation may have been superimposed on the applied frequency. If this extraneous frequency were constant regardless of applied frequency, the sought frequency effect would be masked. This fact suggests that vibration of the test machine, which despite all efforts was not entirely eliminated, interfered with the weight-loss values for this low value of slip. Vibration tests confirmed that extraneous motion may actually reach a maximum of 0.0004 inch. The data of the lowest curve of figure 12, therefore, are not inconsistent with the theory but apply instead to small values of slip for an unspecified range of high frequencies.

The percentage of fretting damage attributable to corrosion and that part represented by mechanical wear, calculated using equation (17), are included in table II. It will be noted that the chemical factor of fretting damage predominates for small values of load, slip, and frequency but is only a small percentage of the total effect at high frequencies.

These calculations bear out Fink's statement (in a discussion of ref. 9) that mechanical wear predominates over chemical wear as slip increases and that the high rate of wear in nitrogen reported by Rosenberg and Jordan (ref. 9), contrary to his findings, is explained in part by the larger slip employed by them.

In view of the fact that the mechanical factor at 540/60 cps, 5,300 psi, and 0.0036-inch slip is relatively large (71 percent), a significant question can be raised concerning the much smaller percentage of metallic iron actually found in debris for specimens fretted under these particular test conditions. The obvious answer is that iron particles worn off the moving surfaces are later oxidized by secondary fretting action of one particle rubbing against another or against the metal surface. Action of this kind reduces the amount of metallic iron in the debris and produces more of the same composition oxide as forms in the primary process. It seems less likely that iron particles

dislodged from the metal surface should be oxidized spontaneously upon contact with air as is suggested by Tomlinson (ref. 2). For one thing, the particles are probably much larger than the atomic dimensions he suggested, since the mechanism of wear appears to emphasize fracture of macroscopic asperities, rather than the tangential plucking out of atomic-size metal fragments. Dies (ref. 11), for example, reported that the size of fretting-debris particles is about 1 micron (10^{-4} centimeter or about 10,000 atom diameters). Furthermore, fretting debris consisting entirely of metallic-iron powder obtained from test specimens run in nitrogen displayed no observable tendency to oxidize spontaneously upon exposure to air. In view of the reduced tendency of iron to oxidize at subzero temperatures, the fact that fretting action at these same low temperatures still produces predominantly an oxide debris (see the section "Nature of Corrosion Products" in part II and ref. 29) is further evidence that spontaneous oxidation is not likely. Godfrey (ref. 7) reported a change in color of iron debris from black in the center of fretting action to red at the outer rim, which he explained as spontaneous oxidation of black iron particles to red Fe_2O_3 . If the change of color is truly one of continuous oxidation and not due to change in particle size, hydration, or ratio of Fe to O in the oxide, any one of which may influence color, the observed effect can be explained by secondary fretting action as discussed above.

The weight losses of test specimens run in nitrogen are no longer frequency-dependent (fig. 13). The theory successfully predicts this situation because the chemical factor of fretting no longer exists, and all weight losses are accounted for by the mechanical term alone. It is noted from equation (14) that the mechanical contribution to wear does not include a frequency factor.

Explanation is required for the fact that weight losses in nitrogen are observed to be lower than corresponding calculated values of the mechanical contribution to fretting corrosion. For example, the calculated mechanical term for specimens in air at 5,300 psi, 540/60 cps, 0.0036-inch slip, and 67,800 cycles is 5.4 milligrams, whereas the corresponding weight loss in nitrogen is 1.4 milligrams. This difference is explained by favorable conditions for metal transfer from one metal surface to another when test specimens are run in an inert atmosphere. In air, metal transfer occurs infrequently or not at all, because the final, if not the initial, debris is predominantly oxide rather than metal. Such metal particles as are formed become rapidly covered with oxygen or oxide, reducing the probability of their subsequent rewelding or fusing to one of the metallic surfaces. Weight-loss measurements of specimens, of course, do not include amounts of metal transferred; therefore, in nitrogen weight losses are invariably lower than the calculated mechanical term in air, where dislodged metal particles may be lost permanently to either specimen surface.

Aluminum and stainless steels are especially damaged by fretting action, not only because hard oxide debris particles form having the compositions Al_2O_3 and Cr_2O_3 but also because the metals themselves may inherently oxidize or adsorb oxygen particularly rapidly upon exposure to air. This suggests that the chemical factor of fretting damage may be more important for these metals than for metals having less affinity for oxygen. By the same reasoning, damage to noble metals must be largely or entirely mechanical.

Effect of Temperature and Humidity

The data presented in figure 9 show that fretting corrosion is greater at low than at high temperatures. Oxidation of metals in air, on the other hand, almost always increases with temperature. One can assume, therefore, that (1) the mechanical factor is much greater at low temperatures, overshadowing the chemical term, or (2) the reaction rate constant k/τ is greater at low temperatures despite a decreased oxidation tendency. If the latter is correct, k/τ may refer to the rate of adsorption of gases on the metal surface rather than to the oxidation rate, implying that the rate of adsorption of gases at low temperatures may be greater than that at high temperatures.

In order to distinguish between these possibilities, further experimental data are needed. For example, data obtained at several temperatures for a variety of frequencies, slips, and loads would help evaluate the temperature coefficient of the mechanical factor as distinct from the chemical factor.⁴

Increased damage at low temperatures makes less likely any assumption that fretting occurs solely by oxidation of metal by reason of high local temperatures induced by friction. This assumption was also denied by Fink (ref. 29) who ran steel specimens in the Amsler wear machine in the presence of liquid air, observing, nevertheless, rapid formation of an oxide debris. In addition, were this assumption correct, it would seem that fretting debris for steel should be mostly of mill-scale composition comparable with the high-temperature iron oxide Fe_3O_4 . None

⁴One can assume with Fink and Hofmann (ref. 30) that "lockerstellen," or chemically active surface sites, which are produced by mechanical disturbance of the surface and which oxidize as rapidly as they are formed, increase in number as the temperature is lowered. Certainly, the rate of recovery of disarranged or cold-worked metal is suppressed at low temperatures, in agreement with this premise. But were this the entire mechanism, one would expect that for a given number of cycles the number of active sites produced would always be the same. In other words, a frequency effect would not be expected, contrary to what is found.

of this oxide, however, was found in the present tests. Further evidence along the same lines comes from less observed fretting damage at high frequencies under conditions where the highest interface temperatures are expected and found.

Because fretting corrosion is less in high-humidity air than in dry air, the view is supported that moisture (1) decreases abrasive wear of the oxide debris or (2) decreases the rate of adsorption or of chemical reaction of oxygen with iron. Experiments in which humidified pure nitrogen was substituted for dry nitrogen showed no accelerating effect of moisture on weight loss (table I). Hence, water itself presumably will not react with iron in the absence of oxygen, even though mechanical activation energy is supplied. This fact lends support to the possibility where water is considered of perhaps hydrating the debris and thereby reducing abrasive wear. On the other hand, adsorbed water can also be considered to form a film of lubricant between the contacting surfaces, which is either a hydrodynamic or a boundary film, over which asperities can move without mechanically activating the reaction between adsorbed oxygen and metal. The first assumption ascribes most of the effect to the mechanical factor of fretting damage, whereas the second possibility leans on the chemical factor. Again, more data are needed to differentiate clearly one factor from the other.

Calculation of Reaction Rate Constant for Iron

The coefficients k_0 and k_1 of equation (14) contain the reaction rate constant k/τ for oxidation of iron, or for adsorption of oxygen on iron, whichever predominates in the fretting process. The reaction rate constant can be obtained from the value k_0 in equation (14) or from the slope of the curve of weight loss against reciprocal frequency in fig-

ure 16. In the first instance, it is equal to $\frac{(\pi p_m)^{1/2}}{2} k_0$ where $k_0 = 5.05 \times 10^{-6}$ (eq. (17)) and $p_m = 140,000$ psi. In the second instance, the rate constant is equal to $\frac{\text{Slope}}{\sqrt{\frac{4L}{\pi p_m}} - \frac{4L}{\pi p_m}}$ where Slope = 1.26×10^3 mg min⁻¹

$$\sqrt{\frac{4L}{\pi p_m}} - \frac{4L}{\pi p_m}$$

or 21.0 mg sec⁻¹ for 67,800 cycles referring to a specimen having an apparent contact area of 1.19 square centimeters. After converting the value for k_0 and the slope to unit area, k/τ is calculated equal to 1.4×10^{-3} mg cm⁻² sec⁻¹ in the first instance and 1.5×10^{-3} mg cm⁻² sec⁻¹ in the second instance. The two values are in satisfactory agreement with each other.

Precise data for the initial oxidation rate of a clean iron surface at room temperature have not been reported. Data for the rate extending over several days for hydrogen-reduced iron exposed to air at room temperature (20°C) have been presented in graphical form by Winterbottom (ref. 27) who employed an optical polarized-light method. Tammann and Köster (ref. 21) reported data for polished specimens exposed several minutes above 250°C , using interference colors as a measure of oxide thickness. The data of both Winterbottom and Tammann and Köster follow the equation:

$$X = k \log_e \frac{t}{\tau} + 1$$

where X is the thickness of the oxide film in angstrom units (10^{-8} centimeter) formed in t seconds. On the basis of Winterbottom's data, k has the approximate value 3.3 \AA , but τ varies with each of the three reported runs from 2.6 to 10.4 seconds. For his experiment 26, the data for which seem the most reliable of three runs, τ equals 2.6 seconds and, therefore, k/τ is equal to 1.3 \AA per second. Tammann, whose values of τ are the same for all temperatures, reported an extrapolated value of k/τ at 15°C equal to $27,120 \text{ \AA}$ per minute or 450 \AA per second for an equivalent air film. On the basis that Fe_3O_4 (index of refraction, 2.5 (ref. 27), and density, 5.18) is the film substance, as was assumed to be reasonable by Winterbottom, $k/\tau = 180 \text{ \AA}$ per second, or $6.7 \times 10^{-3} \text{ mg Fe cm}^{-2} \text{ sec}^{-1}$ for Tammann's data, and the corresponding value for Winterbottom's data is $0.05 \times 10^{-3} \text{ mg Fe cm}^{-2} \text{ sec}^{-1}$. These two values are not in agreement with each other, making it more difficult to evaluate k/τ obtained from fretting data in terms of what might be expected. Since fretting action on one of two surfaces subject to relative slip occurs on the average half the time (compacted oxide slips on only one specimen surface), the value of the reaction rate constant from present fretting measurements should be multiplied by a factor in the order of 2, making the value approximately 2.9×10^{-3} . This value is roughly 0.4 of the Tammann value and 58 times the Winterbottom value. The close agreement with Tammann's value extrapolated from above-room-temperature data suggests that a clean iron surface at room temperature oxidizes directly rather than first adsorbing gas which later reacts to oxide by mechanical activation. However, this conclusion is not certain, for one reason because of doubt introduced by the extrapolation and by some uncertainty concerning the absolute values of oxide thickness measured by the interference-color technique (ref. 31). If Winterbottom's value, which does not involve an extrapolation, is taken as correct, the lower value of k/τ compared with the fretting-data value supports the view that the mechanism of fretting actually involves gas adsorption rather than direct oxidation, since the former process is initially very rapid, as Langmuir (ref. 32) and Armbruster and Austin (ref. 28) reported. The premise is less likely that k/τ from the fretting data exceeds the observed film

growth rate because of the high surface temperatures of the fretted specimens. This at first appears to be a distinct possibility, even if the temperatures achieved are not sufficient to produce the high-temperature oxide Fe_3O_4 . But less observed fretting damage at high frequencies where interface temperatures are higher than those at low frequencies is a strong argument opposing this assumption. The gas-adsorption mechanism, on the other hand, is in accord with the observed frequency effect and is, furthermore, given weight by the fact that the calculated amount of oxygen removed from the surface corresponding to the chemical factor of equation (17) for each cycle of fretting action is less than a monolayer. The amount of iron oxidized through fretting at a load of 5,300 psi is calculated as $2.7 \times 10^{-5} \text{ mg cm}^{-2} \text{ cycle}^{-1}$ averaged over all the specimen surface, which corresponds to $1.2 \times 10^{-5} \text{ mg oxygen cm}^{-2} \text{ cycle}^{-1}$ (assuming Fe_2O_3 as the reaction product). A close-packed monolayer of chemisorbed oxygen atoms of covalent radius 0.7A, on the other hand, is equivalent to $16 \times 10^{-5} \text{ mg oxygen cm}^{-2}$.

It appears from these comparisons that the reaction rate constant for iron calculated from the fretting data is not an unreasonable value and, accordingly, the proposed model for fretting action is plausibly in line with the facts available so far. The proposed model and the present data do not provide support for Tomlinson's molecular attrition theory. Oxidation of metallic particles after they are dislodged from the metal, for example, would not give rise to a frequency effect as is observed. Alternatively, the described model is in better agreement with the view of Fink and Hofmann that oxide forms on the metal surface as a result of relative slip. But the data do not indicate that the formation of active chemical sites on the surface through mechanical disturbance of the metal is a major condition of the fretting process, as the latter authors propose. The facts support only the view that fretting action is one of continuously removing chemical reaction products from the metal surface, the amounts of which depend mainly on time and load, combined with a purely mechanical-wear factor resulting in metallic debris that forms in amounts depending largely on load, slip, and number of cycles. The metallic debris, in turn, may further oxidize by secondary fretting action.

Remedial Measures

The proposed mechanism of fretting corrosion suggests that remedial or control measures in order to be successful must depend on reduction of both the chemical- and the mechanical-wear factors. Excluding air from the metal interface, such as by use of special atmospheres, cements, or elastomer gaskets, will reduce the chemical factor of fretting damage. The mechanical factor of fretting will persist, however, its importance depending on the conditions under which slip occurs. But with rigid exclusion of air and other substances capable of reaction with the metal,

the mechanical wear of metal may also be reduced, as the present nitrogen data show. Any reduction of this kind occurs because of metal transfer in place of metal loss with the formation of metallic-debris particles, the transfer being accompanied by severe cold-working of the surface metal. The factors influencing metal transfer have not yet been evaluated, other than the influence of air itself.

The proposed mechanism of fretting also suggests that interposition of a substance at the interface that can bond itself to the metal surfaces with greater strength than it is bonded to itself would reduce fretting damage. Unless the substance is metallic and a good thermal conductor, such a substance must presumably have good high-temperature characteristics because of the high local temperatures generated by friction in a poor conductor. By the same token, the internal coefficient of friction for the substance should preferably be low so as to reduce generation of heat. Perhaps, molybdenum sulfide which has been shown to be beneficial (ref. 4), and is an effective high-temperature lubricant, approaches these requirements.

It has been suggested that one surface of the interface be made flexible through use of certain plastics or rubber. Fretting damage is minimized presumably by eliminating relative slip. Also, fretting debris may possibly be reduced by using a soft metal in combination with a hard metal. It would seem from the preceding discussion that one should, in this instance, apply a load approaching the yield pressure p_m of the soft metal, since the space between asperities where oxidation occurs is thereby minimized. Should the debris particles become embedded in the soft metal, they may, of course, continue to accelerate mechanical wear, but chemical wear will be reduced by the exclusion of air from a large fraction of the surface.

CONCLUDING REMARKS

A test machine has been designed and built to measure fretting damage quantitatively under controlled experimental conditions. Damage is measured by the weight loss of specimens subject to defined oscillatory slip. Load can be applied to a maximum of 27,000 psi, frequency is made variable between 56 and 3,000 cpm, and relative slip can be adjusted between 0 and 0.008 inch.

Data are reported for mild steel fretted against itself. The humidity of ambient air was found to be a sensitive variable requiring control, a fact first discovered through discrepancies of weight-loss data obtained in winter compared with those obtained in summer. Fretting corrosion of

mild steel was less in moist air than in dry air, the weight loss at 100-percent relative humidity being only 55 to 65 percent of the weight loss at 0-percent relative humidity. Because of this large difference, further tests were consistently carried out in dried air. At the same time, it was observed that fretting corrosion was appreciably greater below room temperature than above room temperature (up to 150° C). Weight losses of specimens fretted at 50° C were approximately 50 percent or one-half the losses at 0° C.

The rate of fretting corrosion in air was found to be constant with time after an initial run-in period during which the rate was temporarily higher. In moist or dry nitrogen, weight losses were much less, although not zero. The greater the relative slip, the greater the fretting damage, and in the complete absence of slip the data indicate that no weight loss occurs. Increased pressure or load was found to increase fretting damage. For low frequencies of oscillation and for the same number of cycles weight loss was greater than for high frequencies. The frequency effect increased with relative slip. In nitrogen, the frequency effect disappeared.

A review of the facts suggests that the mechanism of fretting corrosion includes a chemical factor and a mechanical factor, with observed damage in general resulting from the sum of both. An asperity rubbing on a metal surface is considered to produce a track of clean metal which immediately oxidizes or upon which gas rapidly adsorbs. The next asperity wipes off the oxide or initiates reaction of metal with adsorbed gas to form oxide, and so forth. This is the so-called chemical factor of fretting. In addition, asperities dig below the surface to cause a certain amount of wear by welding or shearing action in which metal particles are dislodged. This is the mechanical factor of fretting. Metallic debris produced by fretting is thought not to oxidize spontaneously, as Tomlinson proposed, but instead to convert partially to iron oxide by secondary fretting action of particles rubbing against themselves or adjacent surfaces. This accounts for the fact that Fe_2O_3 has been found by X-ray to be the major corrosion product and metallic iron is present, if at all, in only very small amounts.

The quantitative expression for fretting corrosion derived on the basis of the above model is:

$$W_{\text{total}} = (k_0 L^{1/2} - k_1 L) \frac{C}{f} + k_2 \ell LC$$

where W is the specimen weight loss, L is the load, C is the number of cycles, f is the frequency, ℓ is the slip, and k_0 , k_1 ,

and k_2 are constants. The first two terms represent the chemical factor of fretting corrosion and the third term is the mechanical factor. Accordingly, the equation predicts that fretting-corrosion weight loss is a hyperbolic function of frequency, is parabolic with load, and is linear with number of cycles or magnitude of slip. Furthermore, the terms concerned with a frequency effect disappear when the chemical factor is suppressed, as is observed when fretting tests are conducted in nitrogen. These conclusions are confirmed by the presently reported data. In addition, the calculated reaction rate constant for oxidation of a freshly formed iron surface obtained from fretting data is reasonable and falls between two independently observed values. In the present experiments, the chemical or corrosion factor falls within 6 to 78 percent of the total observed fretting damage depending on the conditions of test. Remedial measures are outlined in the light of the data and the proposed mechanism.

Massachusetts Institute of Technology,
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TABLE I.- EFFECT OF MOISTURE IN NITROGEN AND OXIDE AT THE INTERFACE ON FRETTING DAMAGE

[Pressure, 5,300 psi; slip, 0.0036 in. for air^a]

Atmosphere	Frequency, cpm	Total number of cycles	Weight loss of clean specimen run with clean specimen, mg	Weight loss of clean specimen run with oxide-coated specimen, mg
Dry N ₂	2,000	67,800	1.8	
Moist N ₂	2,000	67,800	1.6	
Dry N ₂	540	67,800	1.4	
Moist N ₂	540	67,800	2.0	
Dry N ₂	540	30,000	1.2	1.3
Dry air	540	30,000	4.7	4.9
Dry N ₂	540	203,400	1.9	1.0
Dry air	540	203,400	10.7	11.4

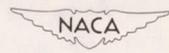
^aCam displacement was same for N₂ measurements, but slip varied with number of cycles.

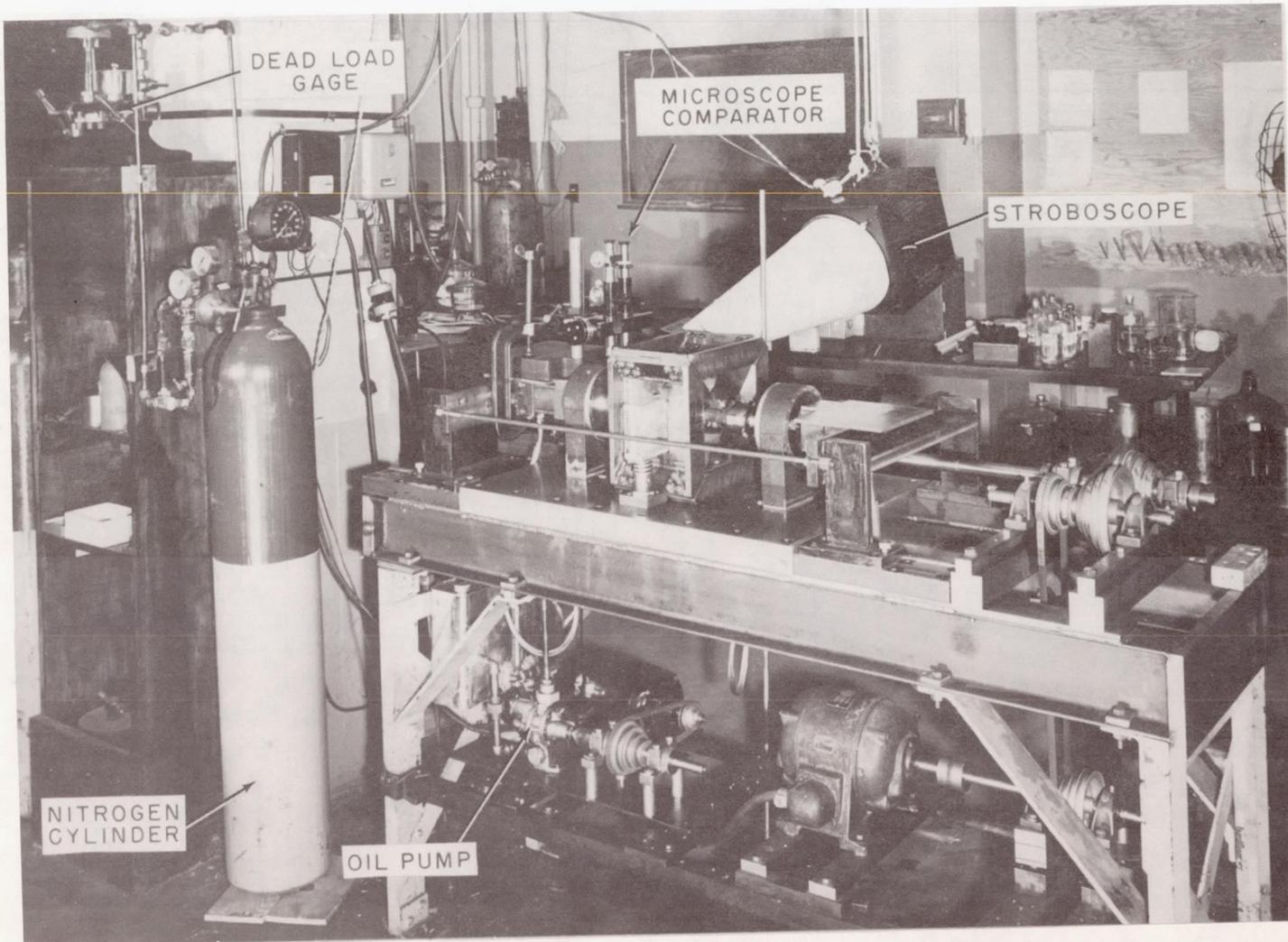


TABLE II.- EFFECT OF LOAD, SLIP, AND FREQUENCY ON FRETTING DAMAGE OF MILD STEEL

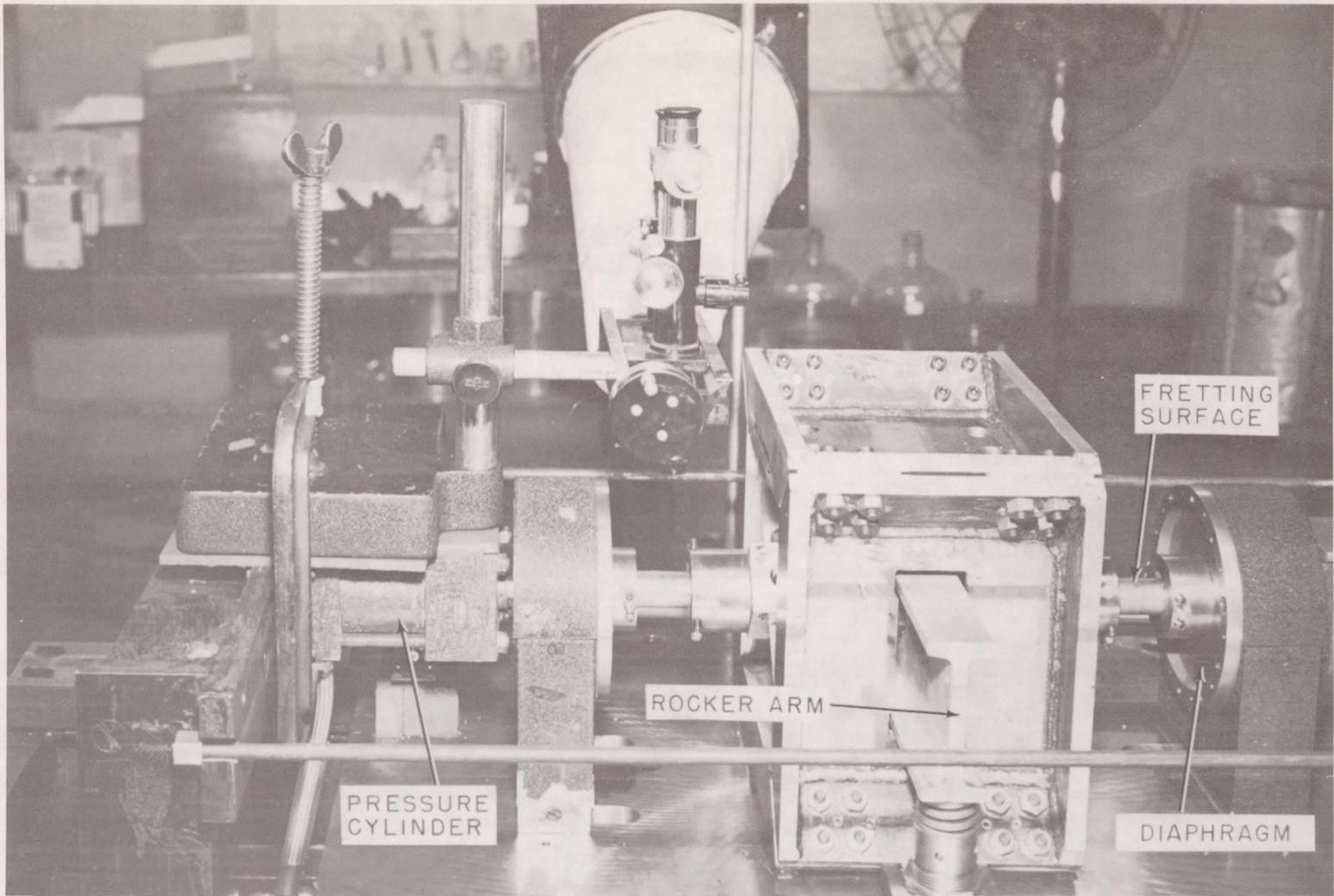
[Total test of 67,800 cycles]

Pressure (load), psi	Frequency, cps	Slip, in.	Specimen weight loss, mg						
			Observed		Calculated				
			Corrected	Uncorrected	Total	Chemical term	Mechanical term	Chemical wear, percent	Mechanical wear, percent
500	540/60	0.0036	1.3	1.0	1.3	0.79	0.51	61	39
1,000	540/60	.0036	2.2	1.8	2.1	1.1	1.0	52	48
2,000	540/60	.0036	3.8	3.4	3.5	1.5	2.0	43	57
5,000	540/60	.0036	7.5	6.6	7.2	2.1	5.1	29	71
5,300	56/60	.0036	11.3	10.3	26.2	20.8	5.4	48	52
5,300	238/60	.0036	9.8	9.1	10.3	4.9	5.4	29	71
5,300	540/60	.0036	7.9	6.8	7.6	2.2	5.4	21	79
5,300	840/60	.0036	5.7	4.9	6.8	1.4	5.4	14	86
5,300	1,300/60	.0036	5.0	4.0	6.3	.9	5.4	10	90
5,300	2,000/60	.0036	5.3	3.3	6.0	.58	5.4	7	93
5,300	3,000/60	.0036	6.6	3.2	5.8	.4	5.4		
5,300	56/60	.0091	32.7	30.0	34.4	20.8	13.6	61	39
5,300	540/60	.0091	23.0	14.8	15.8	2.2	13.6	14	86
5,300	1,300/60	.0091	24.2	9.7	14.5	.9	13.6	6	94
5,300	540/60	.0004	1.1	1.1	2.8	2.2	.6	78	22
5,300	540/60	.0036	7.9	6.8	7.6	2.2	5.4	29	71
5,300	540/60	.0067	15.1	11.3	12.2	2.2	10.0	18	82
5,300	540/60	.0091	23.0	14.7	15.8	2.2	13.6	14	86

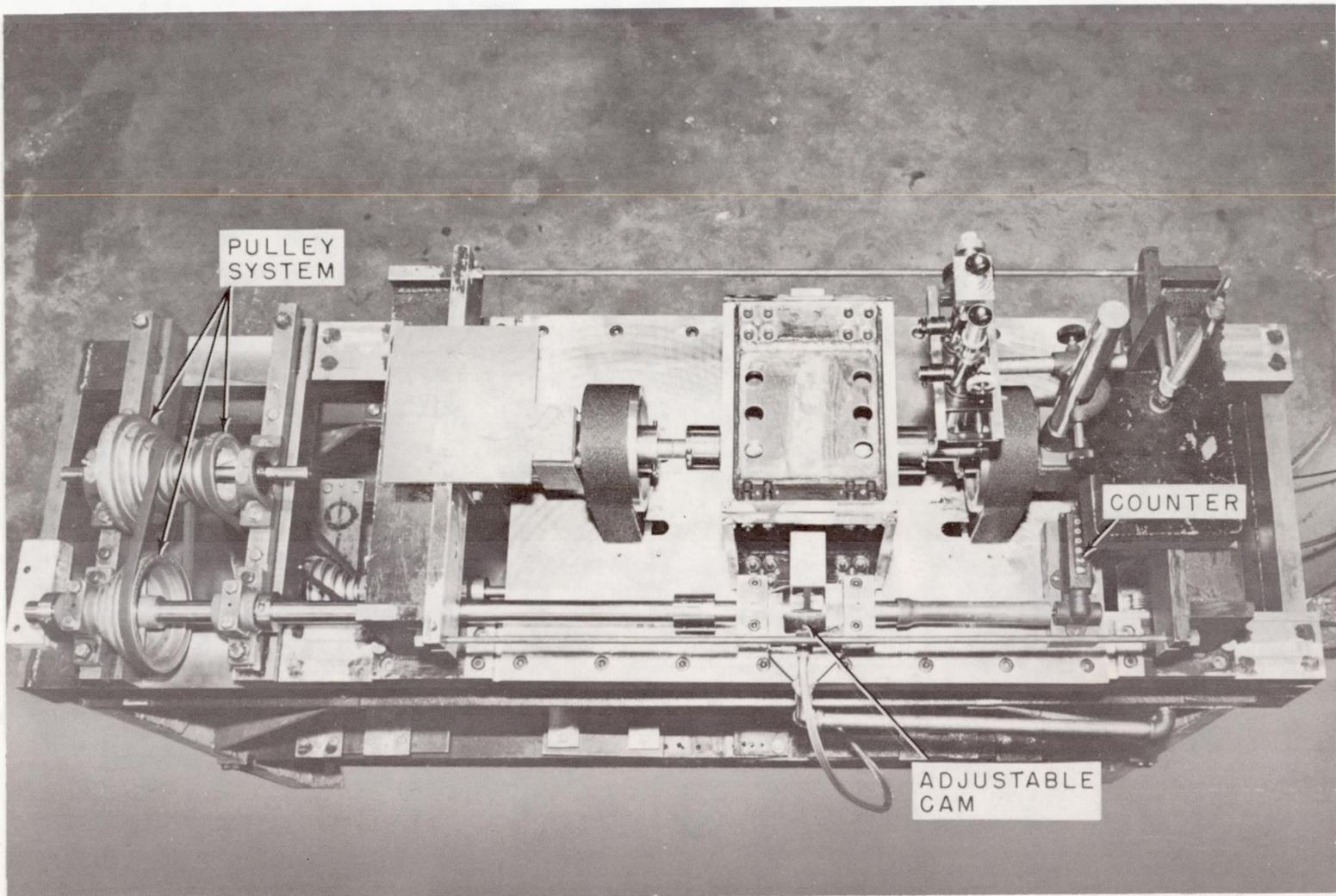




L-80262.1
Figure 1.- Side view of fretting apparatus.



L-80263
Figure 2.- Detailed view of specimens in place.



L-80264
Figure 3.- Top view of fretting apparatus.

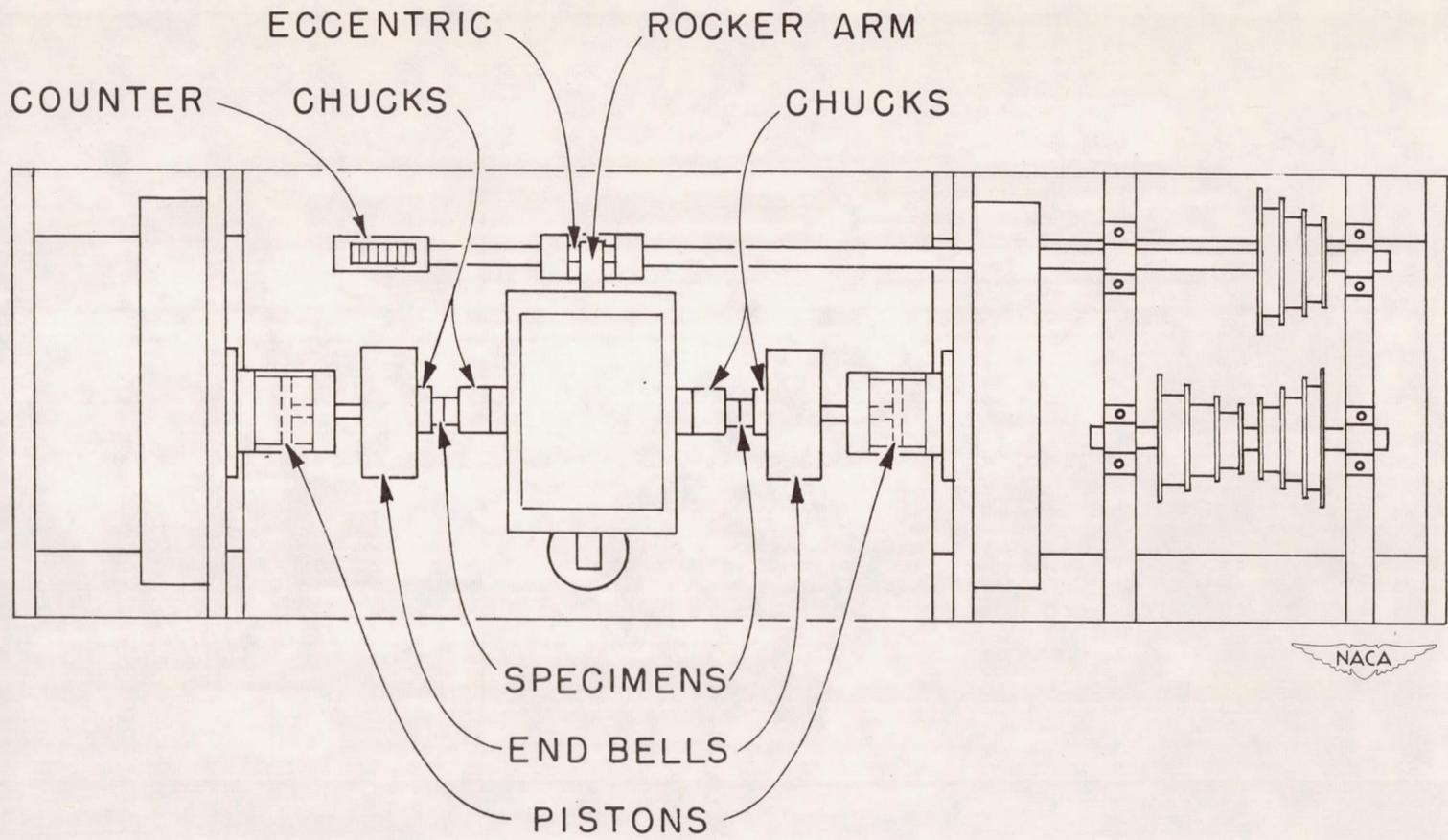


Figure 4.- Schematic plan of fretting apparatus.



Figure 5.- Test specimen. (1 inch in diameter and 1 inch long.)

L-30265

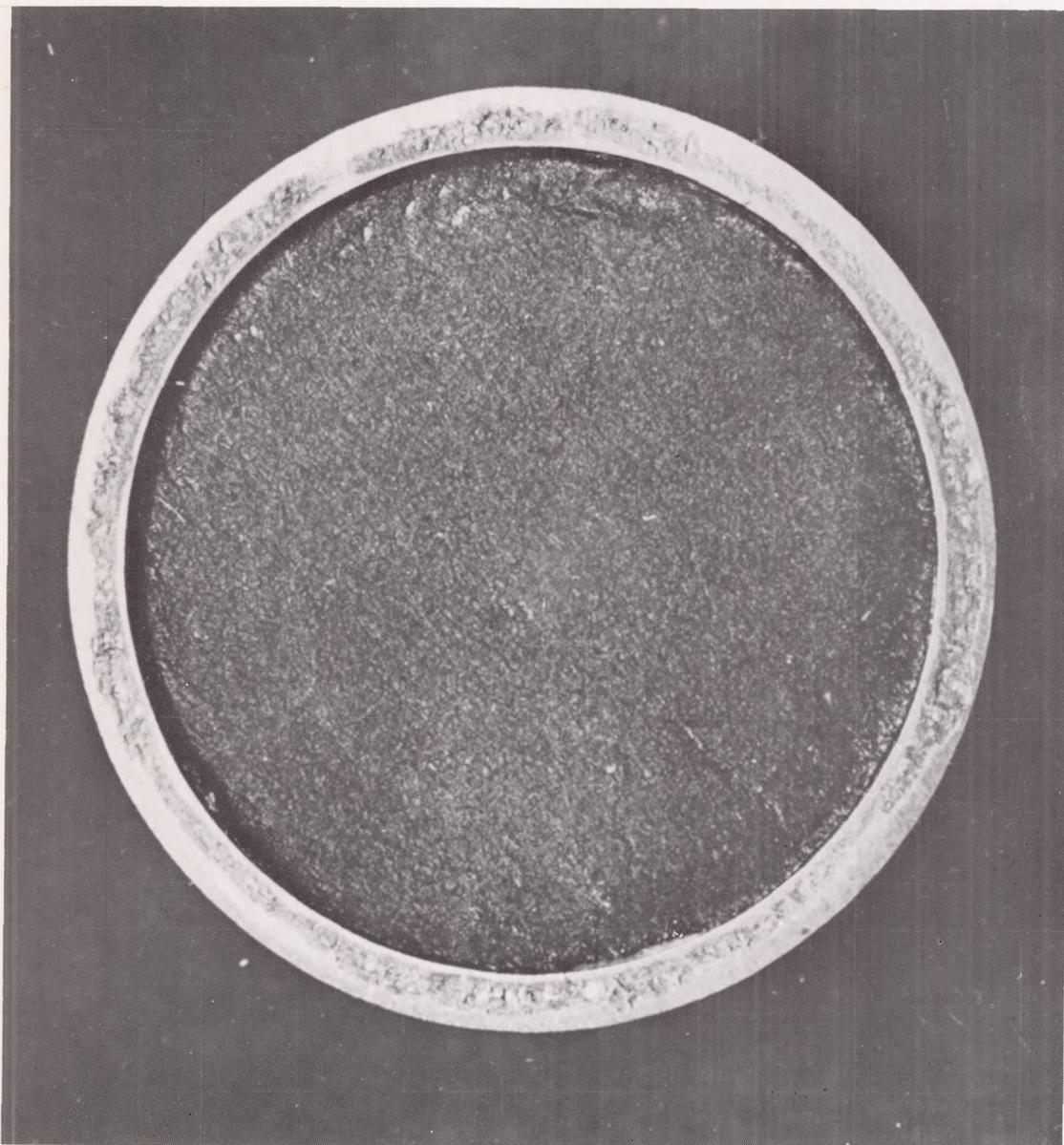
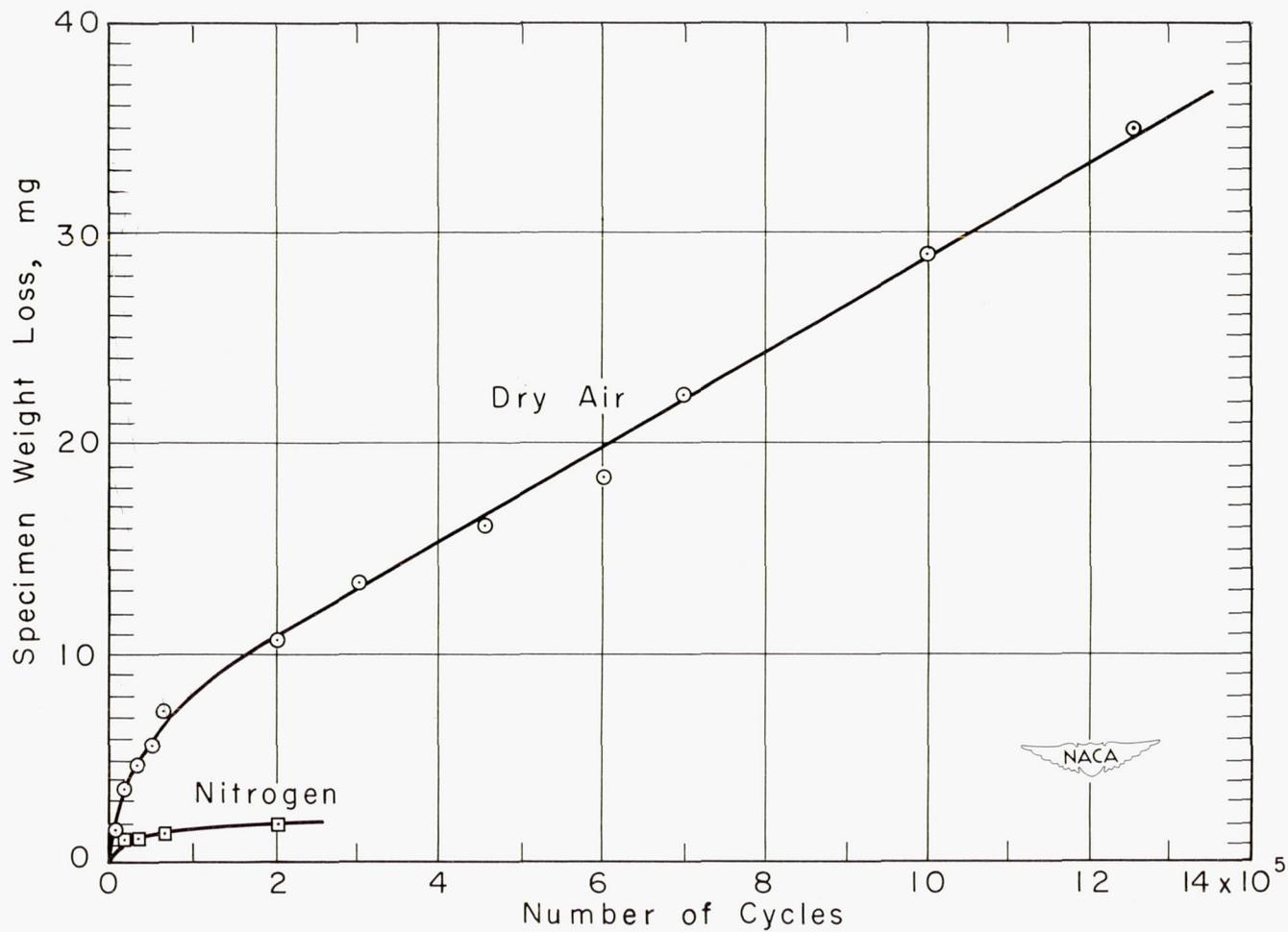
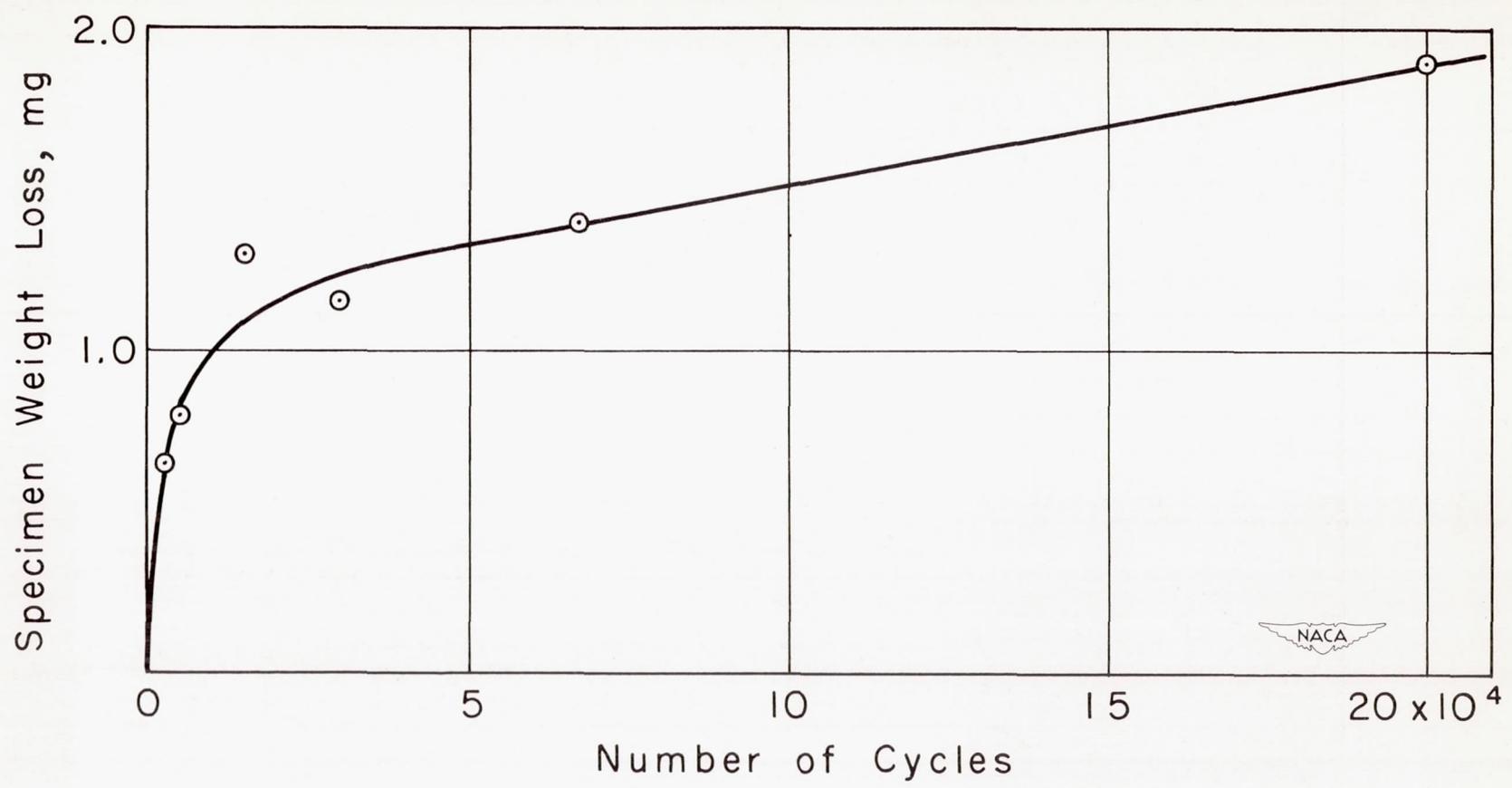


Figure 6.- Fretted surface of test specimen tested in air at load of 5,300 psi, 540 cpm, 0.003-inch slip, and 67,800 cycles. L-80266



(a) In dry air and in nitrogen.

Figure 7.- Effect of duration of test on fretting of mild steel in dry air and in nitrogen. Pressure, 5,300 psi; frequency, 540 cpm; slip, 0.0036 inch; average temperature, 33° C.



(b) In nitrogen. (Same data as in figure 7(a) but enlarged.)

Figure 7.- Concluded.

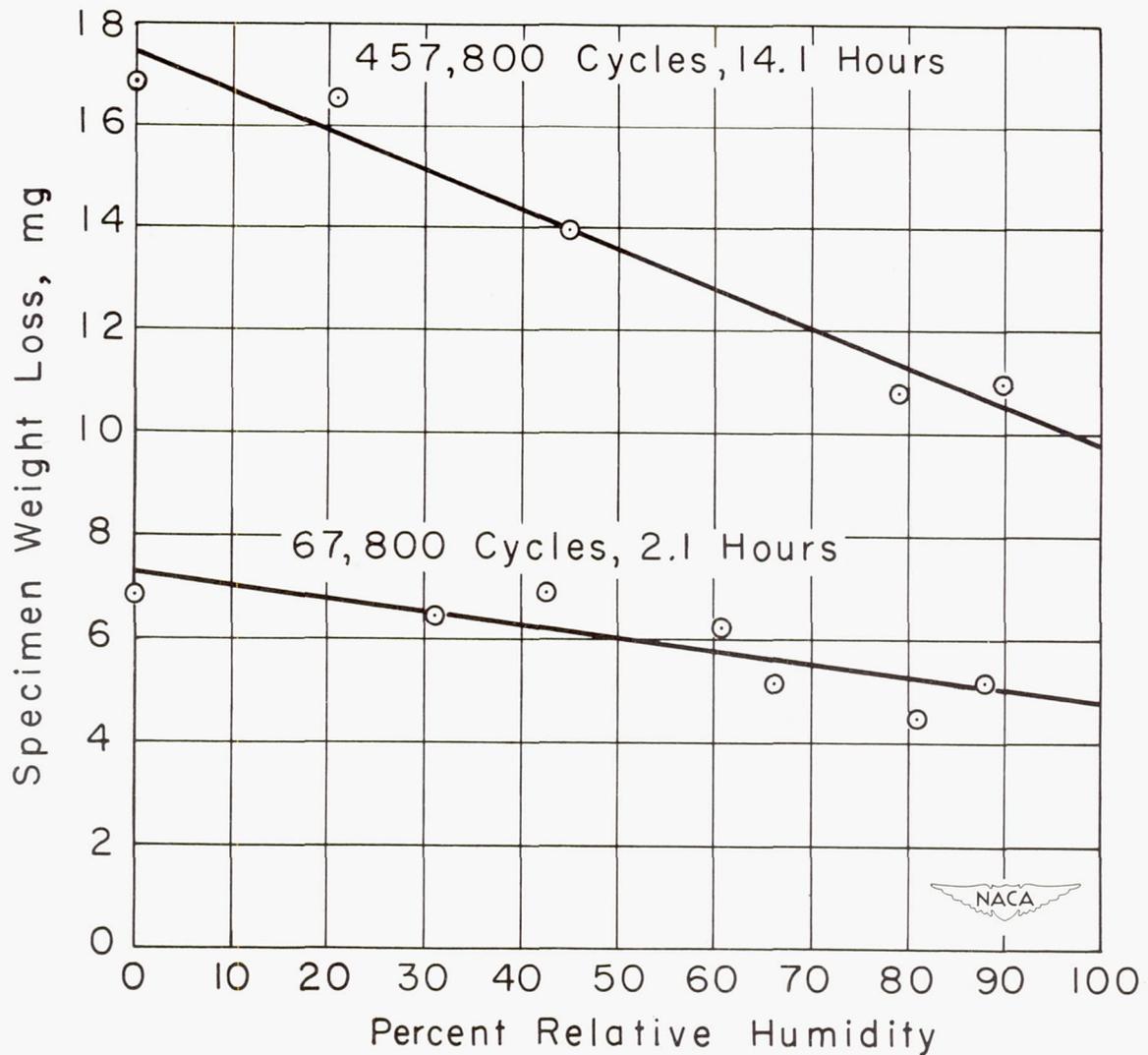


Figure 8.- Effect of humidity on fretting of mild steel for two test periods in air. Pressure, 5,300 psi; frequency, 540 cpm; slip, 0.0036 inch; average specimen temperature, 33° C; room temperature, 27° C.

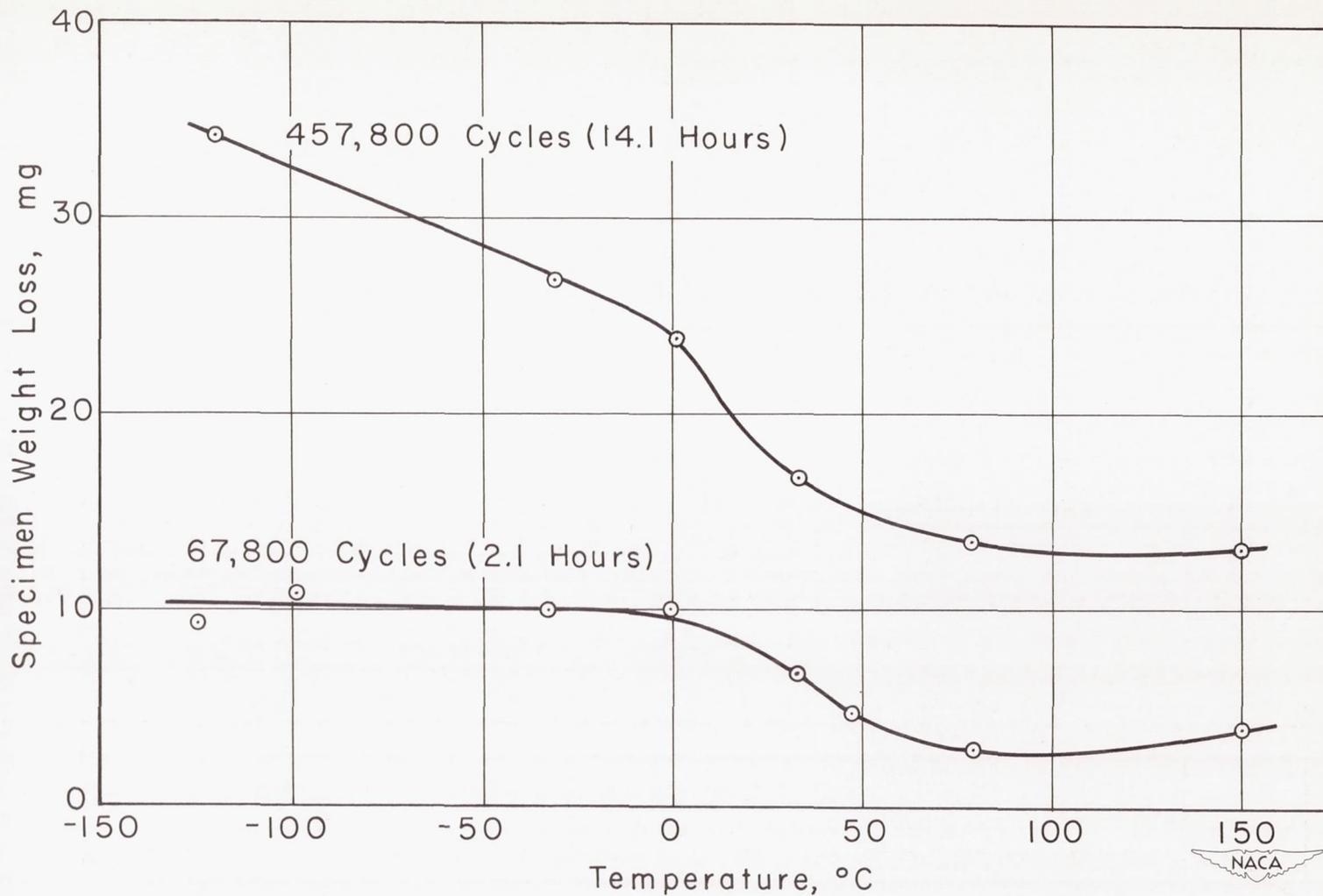


Figure 9.- Effect of temperature on fretting of mild steel for two test periods in dry air. Pressure, 5,300 psi; frequency, 540 cpm; slip, 0.0036 inch.

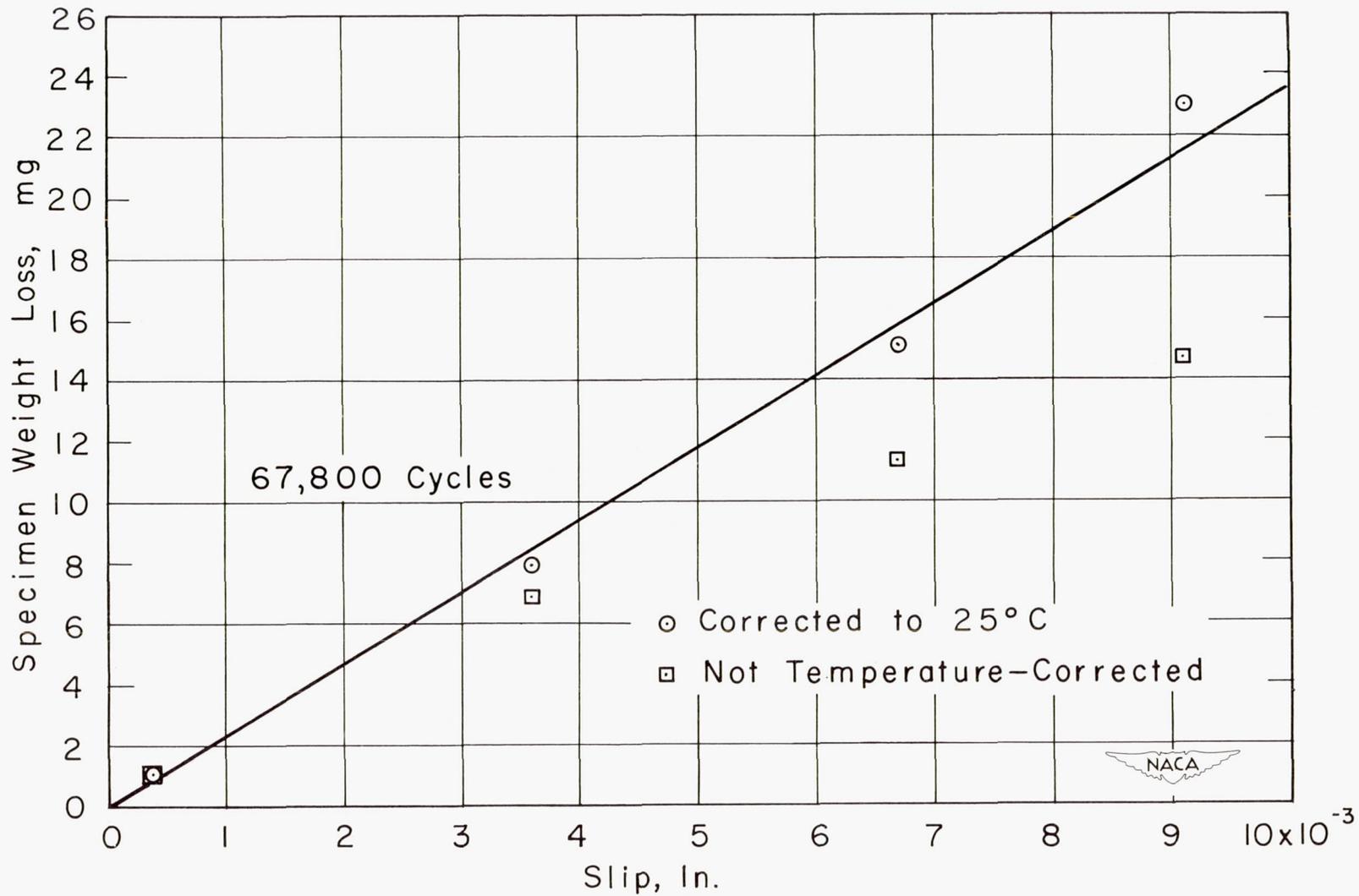


Figure 10.- Effect of relative slip on fretting of mild steel in dry air.
 Pressure, 5,300 psi; frequency, 540 cpm.

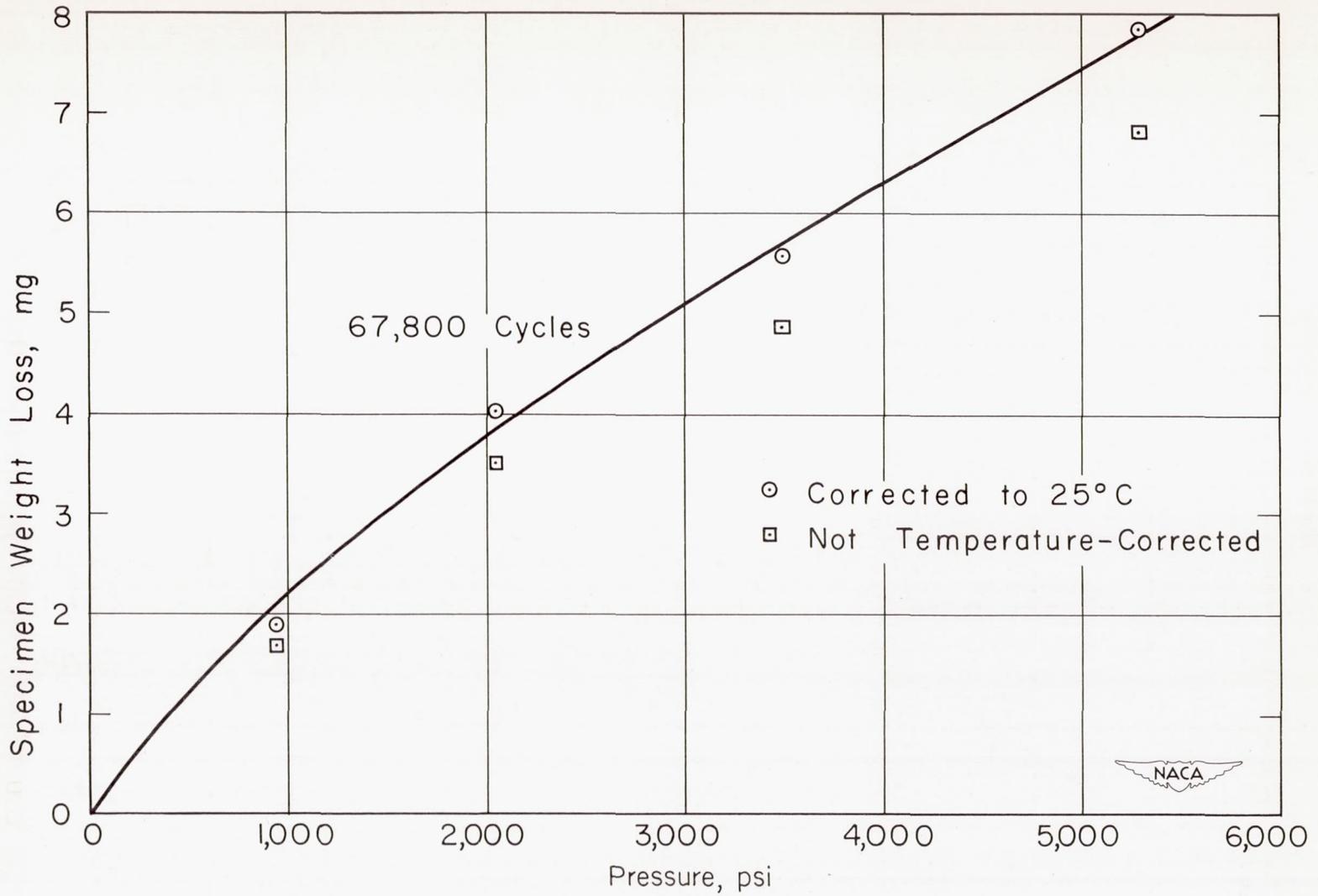


Figure 11.- Effect of pressure (load) on fretting of mild steel in dry air. Frequency, 540 cpm; slip, 0.0036 inch.

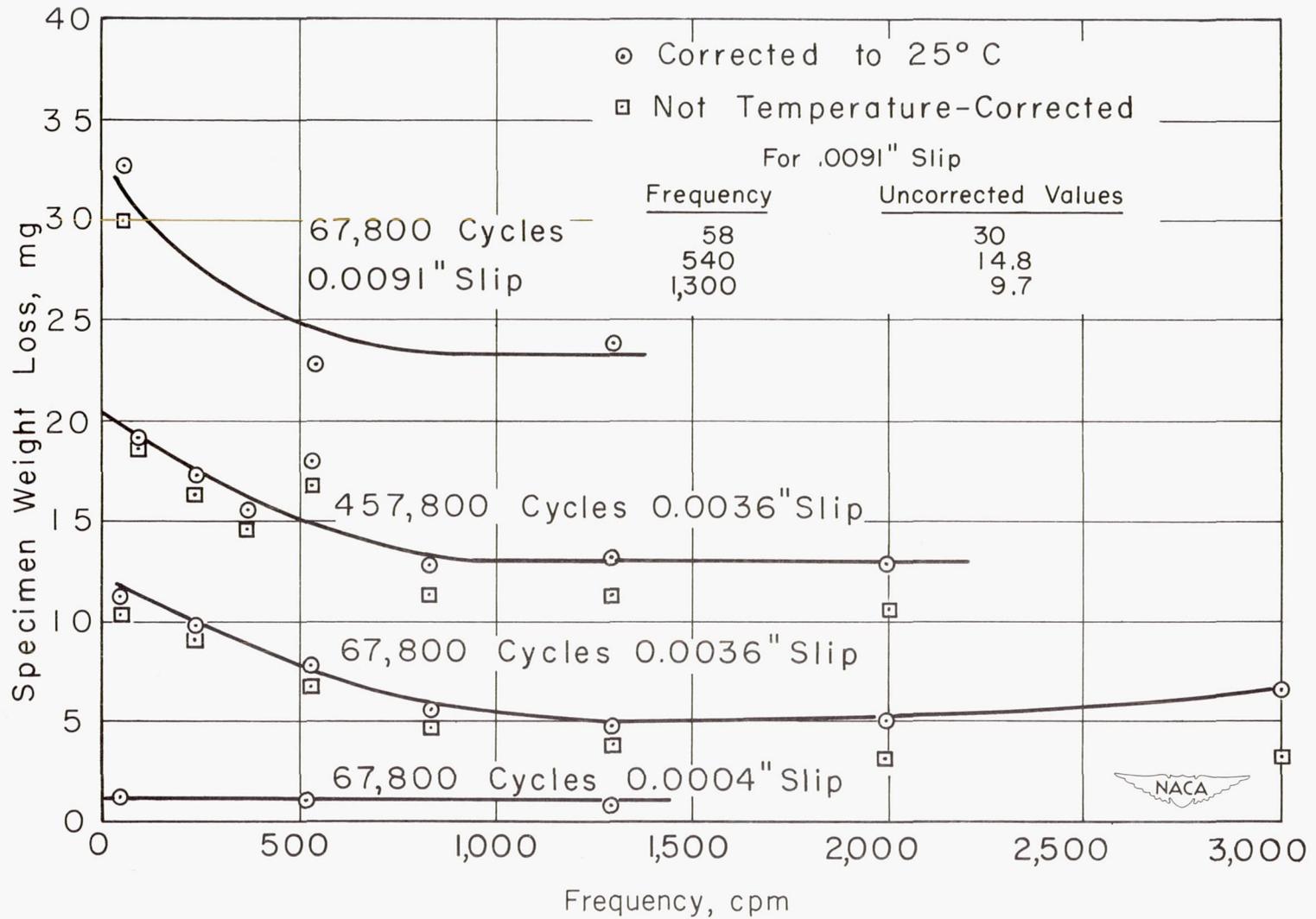


Figure 12.- Effect of frequency on fretting of mild steel in dry air.
 Pressure, 5,300 psi.

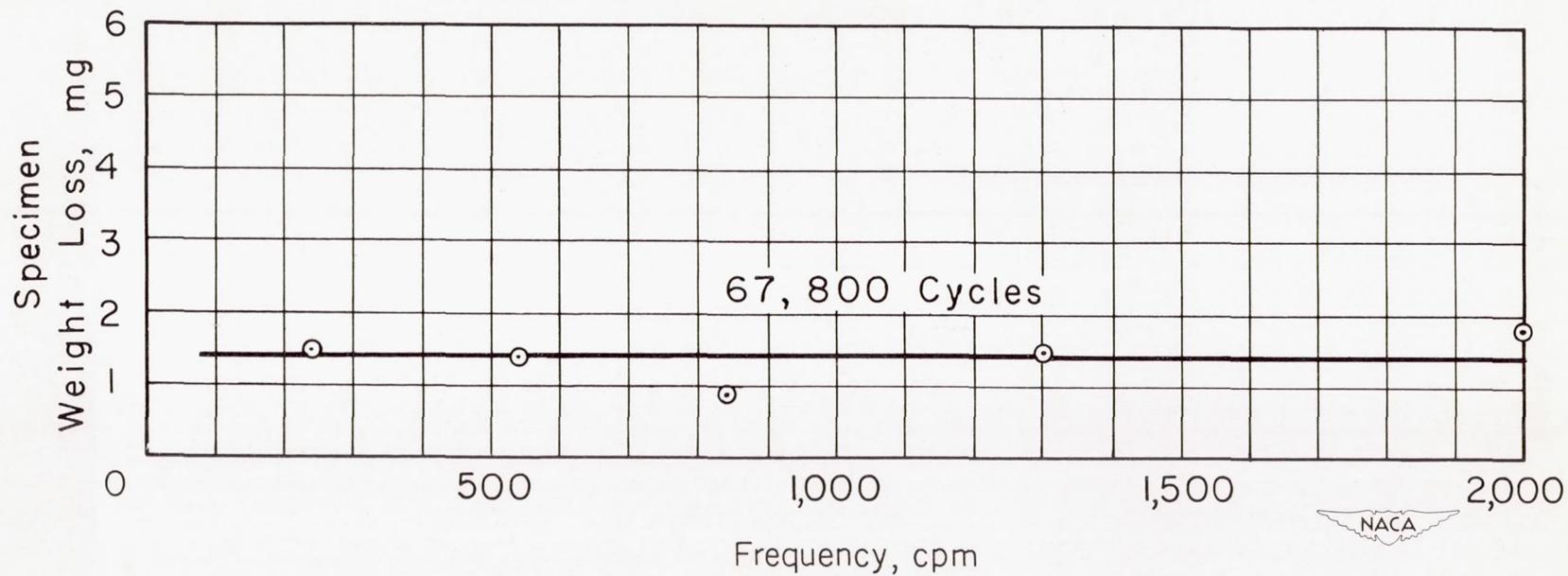


Figure 13.- Effect of frequency on fretting of mild steel in nitrogen.
Pressure, 5,300 psi; slip adjusted to 0.0036 inch but was actually variable.

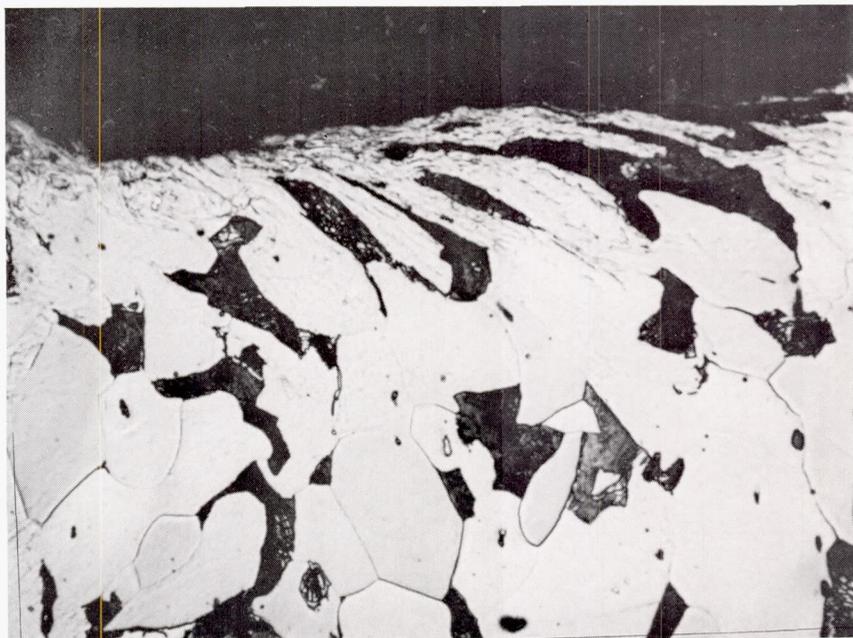


Figure 14.- Photomicrograph of mild steel surface fretted in air, X500. Pressure, 5,300 psi; frequency, 1,320 cpm; 0.0036-inch slip; 318,000 cycles.

L-80267

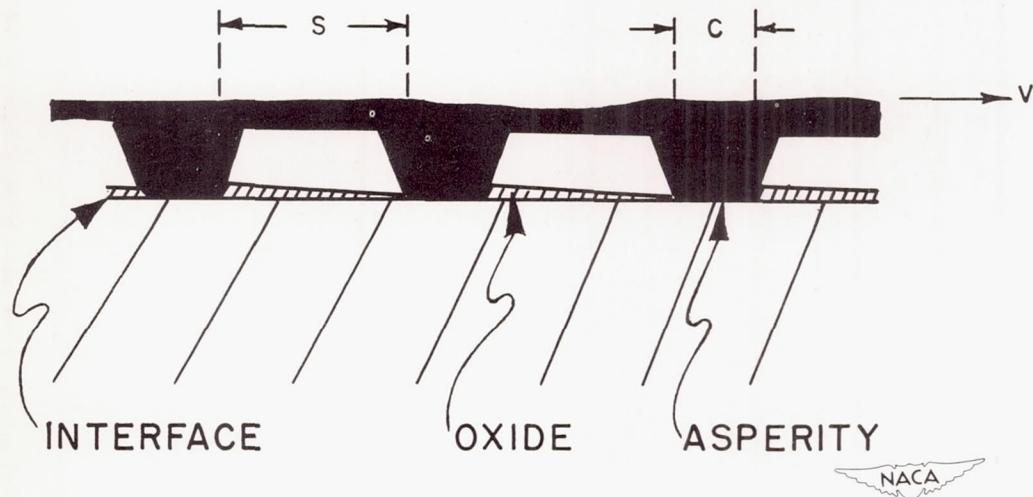


Figure 15.- Idealized model of fretting at a metallic surface. Asperities of upper surface move over plane undersurface.

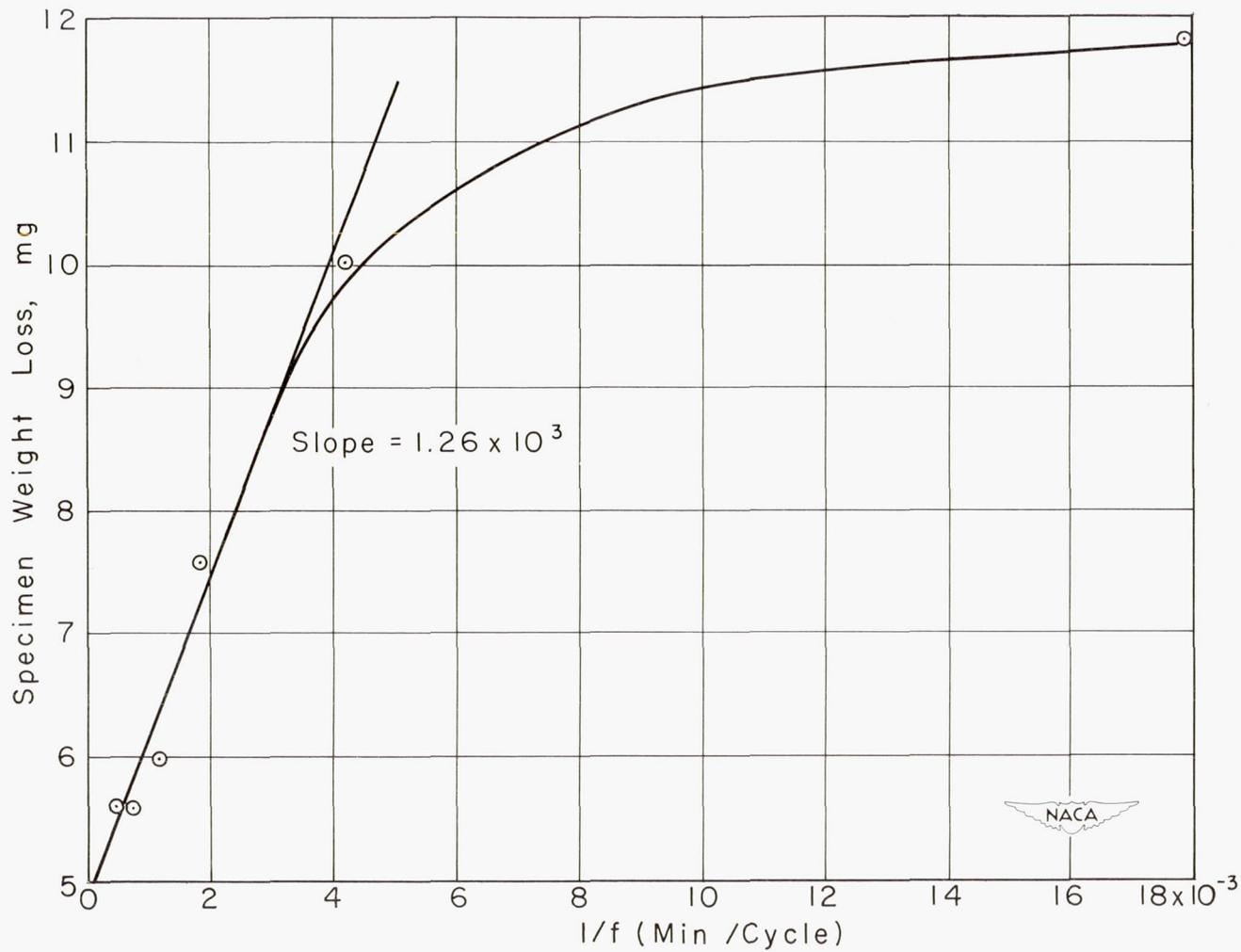


Figure 16.- Dependence of specimen weight loss on reciprocal frequency.
 Pressure, 5,300 psi; slip, 0.0036 inch; 67,800 cycles.