NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1009

INVESTIGATION OF FRETTING BY MICROSCOPIC OBSERVATION

By DOUGLAS GODFREY



1951

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft/sec^2

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

REPORT 1009

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By DOUGLAS GODFREY

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

National Advisory Committee for Aeronautics

Headquarters, 1724 F Street NW., Washington 25, D. C.

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REPORT 1009

INVESTIGATION OF FRETTING BY MICROSCOPIC OBSERVATION[1]

By Douglas Godfrey

SUMMARY

An experimental investigation, using microscopic observation and color motion photomicrographs of the action, was conducted to determine the cause of fretting. Glass and other noncorrosive materials, as well as metals, were used as specimens. A very simple apparatus vibrated convex surfaces in contact with stationary flat surfaces at frequencies of 120 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

The observations and analysis led to the conclusions that fretting was initiated by the loosening, due to inherent adhesive forces, of finely divided and apparently virgin material, and that its initiation is independent of vibratory motion or high sliding speeds. The fretting of platinum, glass, quartz, ruby, and mica relegated the role of oxidation as a cause to that of a secondary factor. Fretting occurred to clean nonmetals and metals readily, and glass microscope slides and steel balls provided an excellent method for visual studies.

INTRODUCTION

Fretting, defined as surface failure that may occur when closely fitting metal surfaces experience slight relative motion, damages many machine parts subject to vibration. The phenomenon of fretting (also known as fretting corrosion and friction oxidation) is principally characterized by surface stain, pitting, and the generation of oxides, as described in detail in references 1 and 2. The determination of the cause of fretting has been the object of several research programs. The research reported in reference 2 supports Tomlinson's theory of molecular attrition (reference 3) that proposes that the cause of fretting is a physical action, or specifically that the disintegration of the metal surface is due to "molecular plucking." More recently, chemical action has been reported to be of primary importance (reference 4). Other investigators (for example, references 5 and 6) have advanced electrolytic, abrasion, welding, fatigue, and "vibrational decay" theories to explain the action that produces fretting. These theories are incompatible or divergent and more experimental evidence is needed before any one of them may be generally accepted.

The failure of certain aircraft parts due to fretting has produced a new incentive toward solving the problem of the prevention of the phenomenon. Antifriction bearings subject to rotational oscillation and side-thrust vibration experience the greatest amount of fretting, and such parts as connecting rods, knuckle pins, splined shafts, and clamped and bolted flanges suffer deleterious effects (reference 1).

The research reported herein was conducted at the NACA Lewis laboratory during 1949 to observe and to analyze the action of fretting in its initial stages in order to determine its cause. Inasmuch as the limits of mechanical variables such as load, frequency, and amplitude have been established (reference 2), this investigation was limited to microscopic observation, debris analysis, and surface analysis of fretting areas. The nonmetallic and noncorrosive materials, glass, quartz, ruby, and mica, and the metal platinum were used as specimens because their fretting would indicate whether the primary action was physical or chemical; in addition, the nonmetallic materials eliminated the possibility of ordinary welding, simplified the debris analysis, and in some cases permitted microscopic observation or color motion photomicrographs of the action (reference 7). The color motion photomicrographs describe fretting more effectively than words or black-and-white photomicrographs.

Fretting was induced by a very simple apparatus, which vibrated a convex (usually spherical) surface in contact with a flat surface at frequencies of 120 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

[1] Supersedes NACA TN 2039, "Investigation of Fretting Corrosion by Microscopic Observation" by Douglas Godfrey, 1950.

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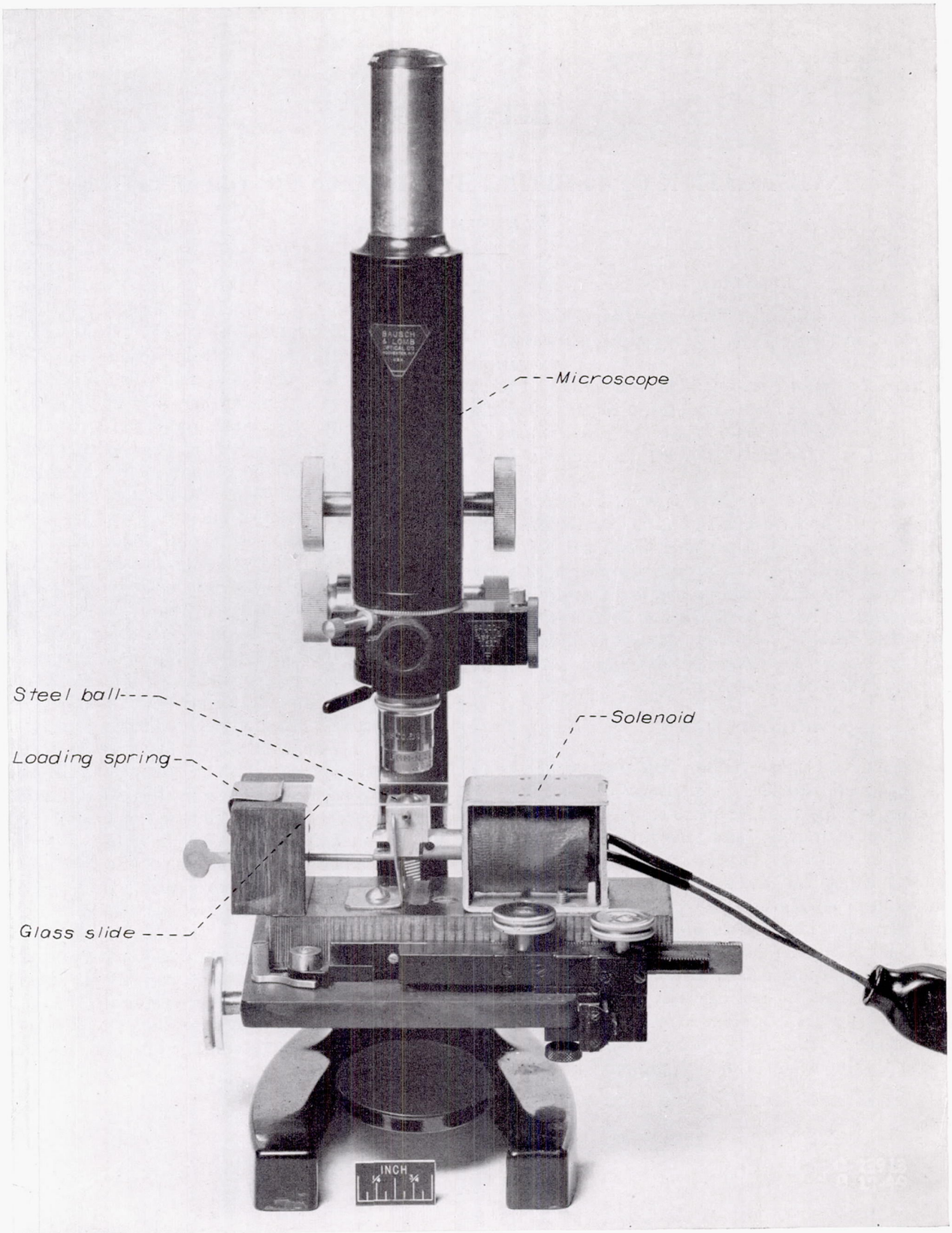


FIGURE 1.—Fretting apparatus.

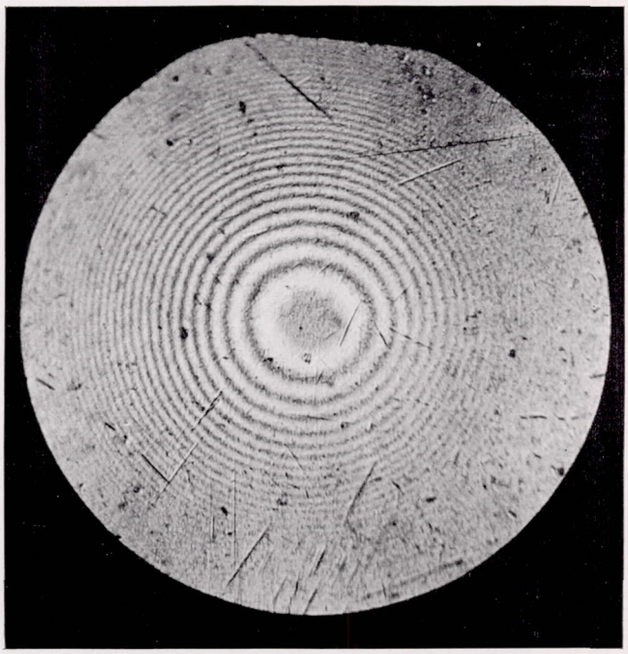


FIGURE 2.—Photomicrograph with vertical illumination and red filter of chrome-alloy steel ball through glass slide showing interference bands surrounding ontact area. × 100.

APPARATUS, MATERIALS, AND PROCEDURE

A photograph of the apparatus is shown in figure 1. The vibrating action of 120 cycles per second with an amplitude of 0.001 inch was induced by a solenoid. The specimen with the convex surface was firmly attached to the plunger of the solenoid, which was horizontal. The specimen with the flat surface was held stationary at one end and loaded vertically by a flat spring. The spring caused the flat surface to exert a load of approximately 0.2 pound on the convex surface.

The apparatus could be attached to the mechanical stage of a microscope, which permitted microscopic observation of the contact area with vertical or oblique illumination. With transparent flat specimens, the contact area could readily be located because it was surrounded by concentric interference bands (fig. 2). Amplitude was measured by noting the distance between the extreme positions of a scratch mark on the vibrating surface. The experiments conducted at 120 cycles per second were divided into three groups: (1) the preliminary metal against metal, (2) the metal against nonmetal, and (3) the nonmetal against nonmetal. No general material survey was made and the number of metals used was limited.

In the metal-against-metal group, mild steel, chrome steel, stainless steel, copper, and aluminum were vibrated against mild steel essentially to ascertain whether the apparatus would induce fretting with satisfactory reproducibility. In the metal-against-nonmetal group, the five metals plus platinum were each vibrated against glass microscope slides, mica, and Lucite and extensive observations were made with ½-inch-diameter chrome-alloy steel (SAE 52100) balls and the glass slides. Glass was used as one of the surfaces because it is rigid, noncorrosive, and transparent. These properties were desirable to permit observation of the action as well as to simplify debris analysis. The statement is made in reference 2 that glass not only produces fretting on steel but is itself attacked; the ability of glass to pick up metal during sliding is demonstrated in reference 8. In the third group, glass, quartz, ruby, mica, and Lucite were vibrated against one another. All the materials were shaped into convex or flat pieces as required and finished to a surface roughness of 1 to 3 root mean square by fine grinding and polishing.

A group of experiments that are considered to be ½-cycle experiments were conducted with an adapter on the apparatus, which provided for sliding the glass microscope slide over the surface of the stationary ball at a speed of approximately 0.002 inch per second or less. The motion was caused by hand-turning a fine screw to which the glass was attached. The direction was reversed each 0.001 inch, and the frequency was considered 1 cycle per second or less. A slow-motion vibration was thus simulated and the action that occurs in ½ cycle was observed.

All specimens were thoroughly cleaned immediately before being mounted in the apparatus. The metal cleaning consisted in degreasing in an organic solvent followed by scrubbing with surgical cotton in a paste of levigated alumina, a thorough rinse in tap water, a rinse in 95-percent alcohol, and drying in air. Particular effort was made to wash off all adhering alumina. The glass, ruby, quartz, and mica specimens were cleaned in fresh sodium dichromate—sulfuric acid cleaning solution followed by rinse in tap water and distilled water and oven drying. The Lucite was wiped clean with lens tissue.

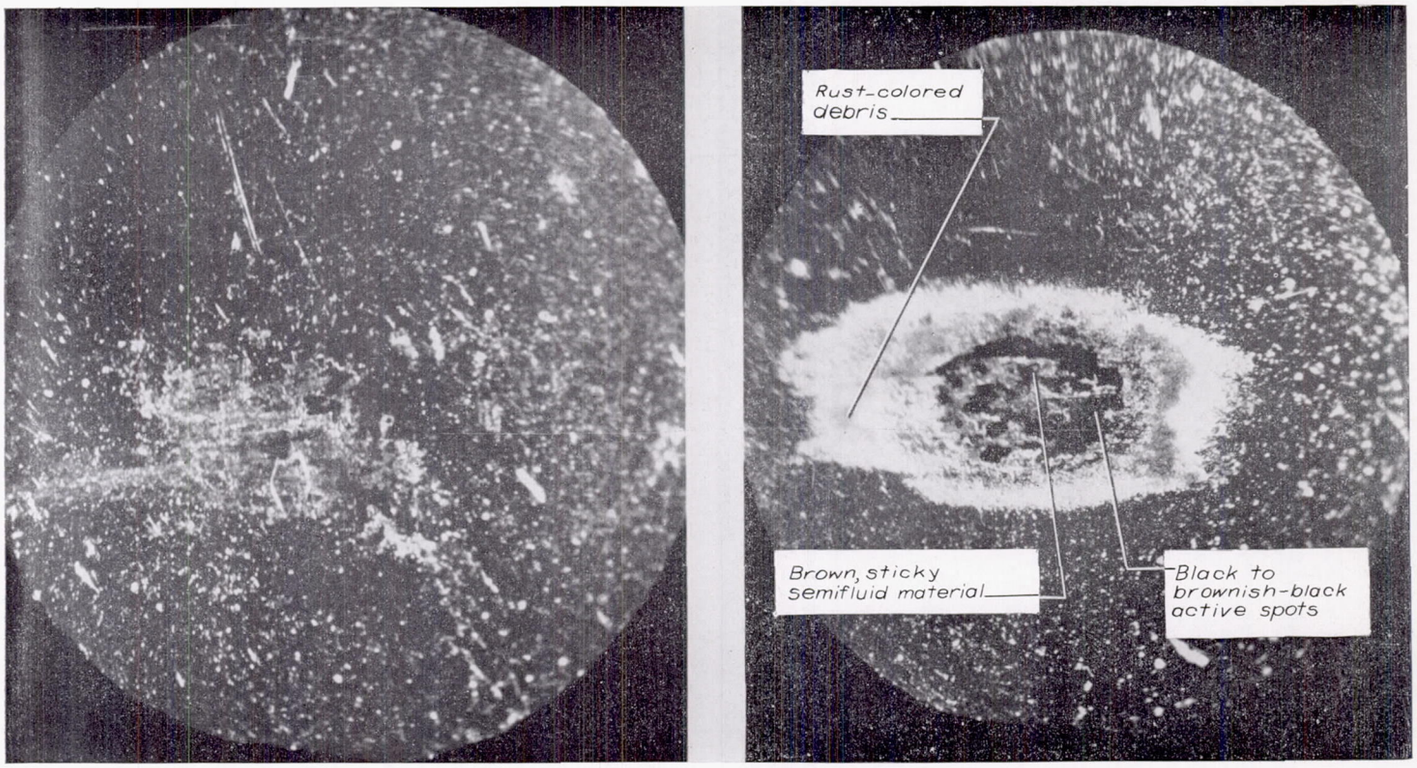
The number of cycles that any pair of specimens had experienced was determined by measuring the length of time current was supplied to the solenoid. In those cases in which the flat specimens were not transparent, the vibration was induced for periods of 1, 2, 4, 8, 16, 32, 60, 120, 180, 300, and 600 seconds cumulatively. After each period, the flat specimen was removed and the spots on the convex specimen and on the flat specimen were each microscopically examined. Photomicrographs were taken in some cases to aid in the description of the action. When transparent specimens were used, the complete action could be viewed or photographed with ease. The vibration could be stopped at any time, however, and the contact area viewed or photographed at rest.

RESULTS AND DISCUSSION

PRELIMINARY METAL AGAINST METAL

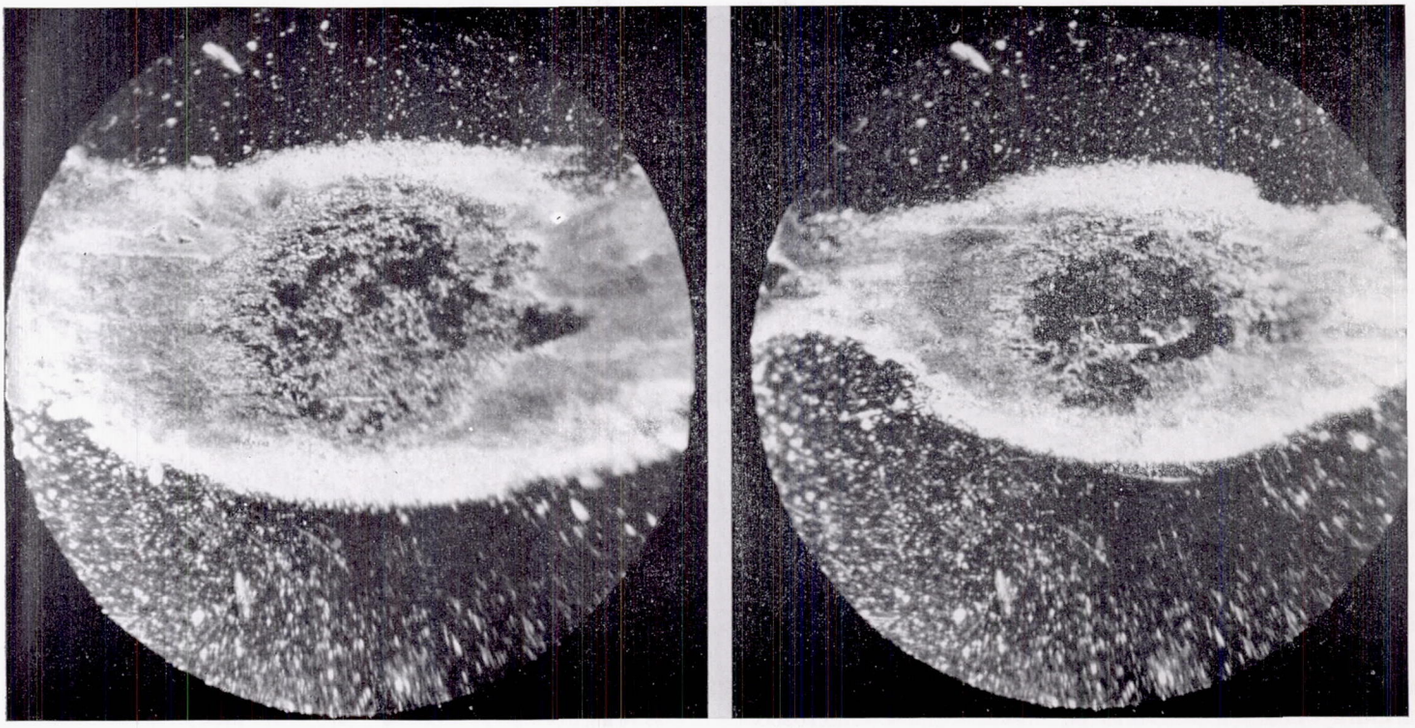
In the preliminary metal-against-metal experiments, each of the several pairs of specimens investigated exhibited fretting within approximately 300 seconds and produced the characteristic debris and wear area. The pattern of the spot on the flat surface was always similar to the pattern of the spot on the convex surface. These experiments revealed that load, amplitude, and frequency were such

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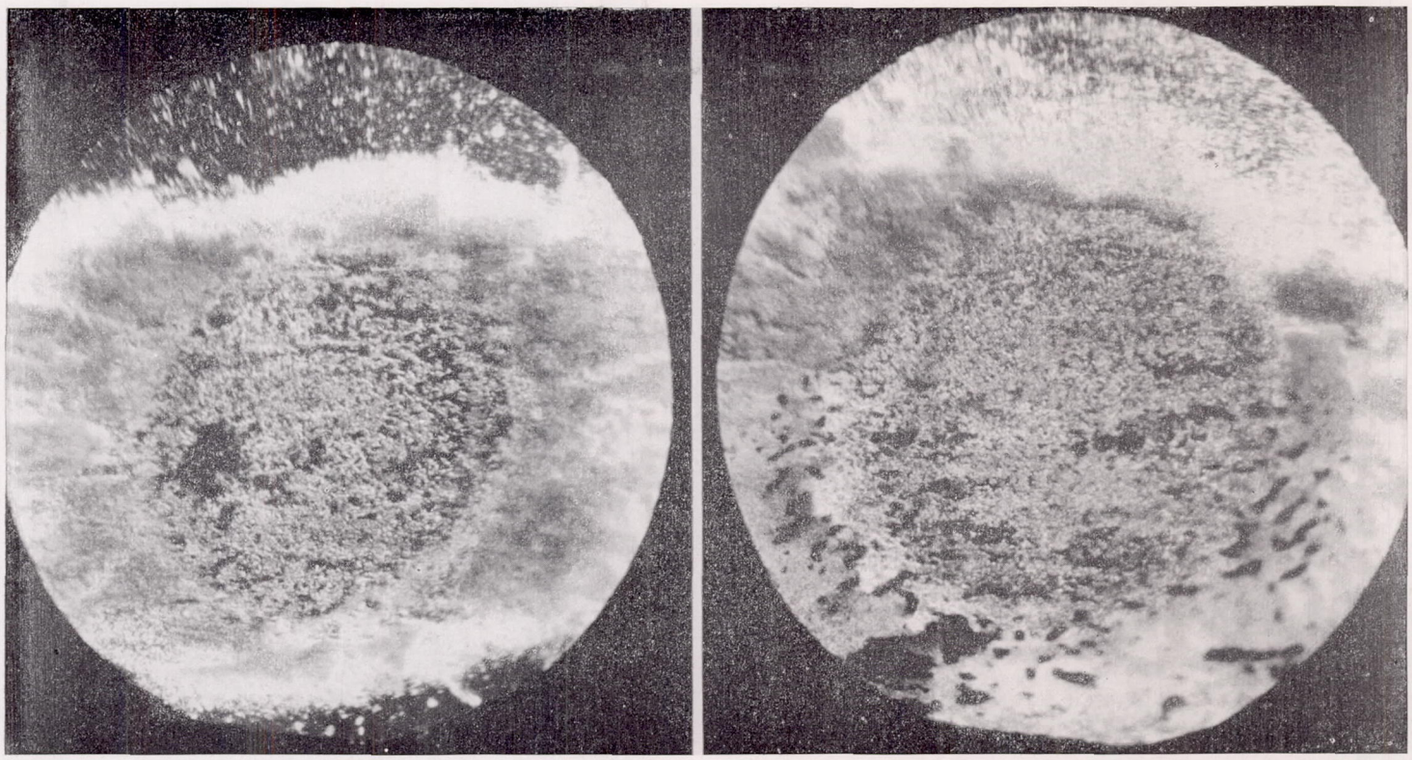
(a) Cycles, 30. (b) Cycles, 120.

FIGURE 3.—Photomicrographs showing progressive stages in fretting between glass microscope slide and chrome-alloy steel ball. × 120.



(c) Cycles, 240. (d) Cycles, 720.

FIGURE 3.—Continued. Photomicrographs showing progressive stages in fretting between glass microscope slide and chrome-alloy steel ball. × 120.



(e) Cycles, 1200. (f) Cycles, 3600.

FIGURE 3.—*Concluded. Photomicrographs showing progressive stages in fretting between glass microscope slide and chrome-alloy steel ball.* × 120.

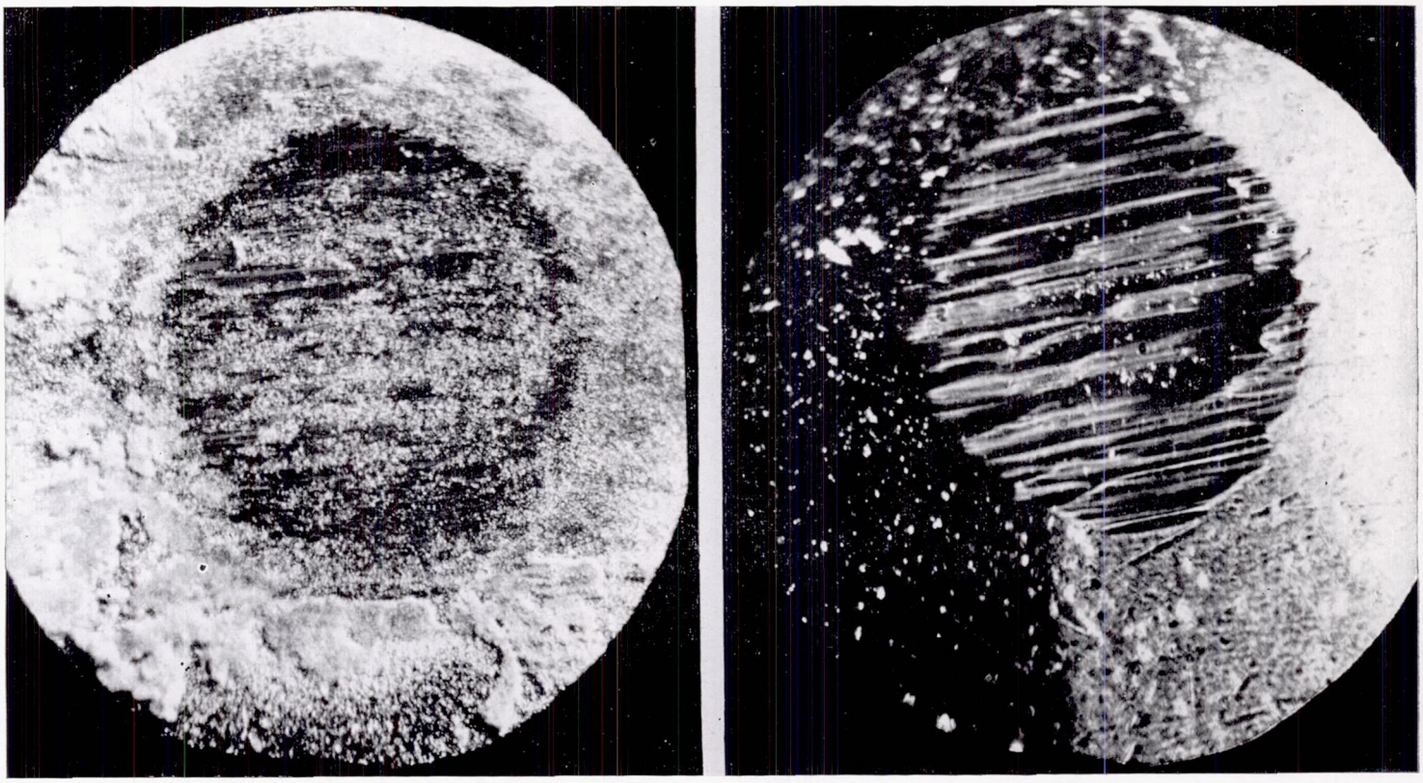
as to produce fretting quickly and that the amount of debris and the size of the wear spot could be reproduced for any given pair in the same number of cycles.

The introduction of a mineral oil film increased the time required to produce fretting but did not otherwise appreciably alter the results.

METAL AGAINST NONMETAL

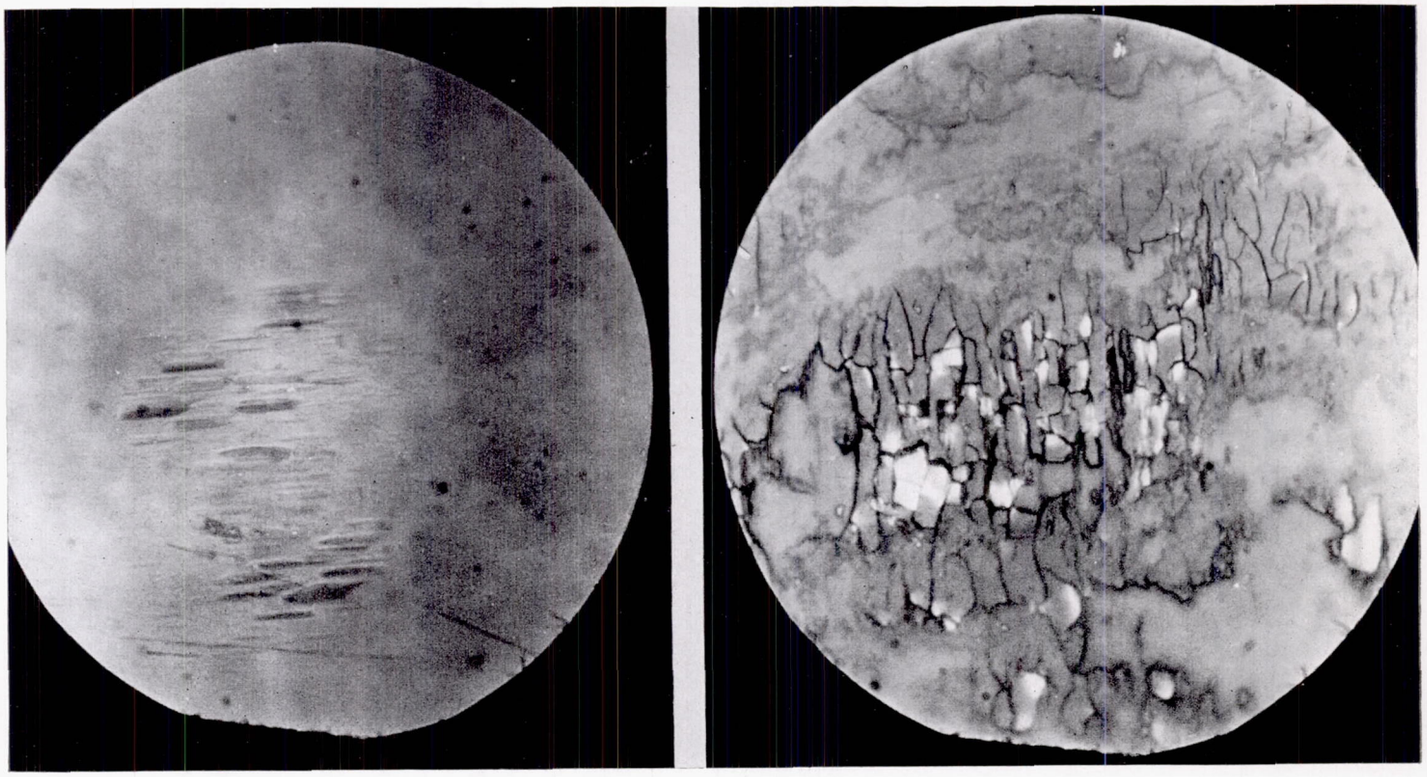
Photomicrographs of the contact area at various stages of the fretting caused by vibrating a chrome-alloy steel ball against a glass specimen are shown in figure 3. Within ¼ second (30 cycles), fretting was evident as a small black irregular spot on the ball, which steadily grew in size and became discontinuous (figs. 3 (a) and 3 (b)). A brown, sticky semifluid oxide was then generated within the contact area, spread over the glass, and adhered tenaciously to it. This oxide shares the contact area with the black material (figs. 3 (b) to 3 (f)). A rust-colored fine dry oxide was also formed that was extruded from the area in increasing quantities and accumulated just outside the rubbing area, as evident in figures 3 (b) to 3 (f). Active black spots shifted position as the phenomenon progressed because of disintegration of peaks bearing the load for the moment. Color motion photomicrographs of this action can be seen in the aforementioned film.

After approximately 40,000 cycles, the action stabilized to a steady-growth condition with continued generation of material in the black spots surrounded by brown semifluid oxide and the formation of fine powder-like oxide. The black color of the active areas indicated the presence of finely divided iron; this indication was further confirmed by subsequent change to dark brown and then to rust brown. If the vibration was stopped, the trapped black material could be seen to gradually turn brown. Finely divided iron, ferrous oxide FeO, and ferrosoferric oxide Fe_3O_4 are black, whereas ferric oxide Fe_2O_3 and its hydrated form $Fe_2O_3 \cdot H_2O$ are reddish. The fretting debris of steel was identified by electron diffraction as Fe_2O_3 and the color changes that occurred suggest the progressive oxidation of the iron. Fretting is apparently initiated by the loosening, due to inherent adhesive forces, of extremely finely divided and apparently virgin material that is extruded and reacts with oxygen simultaneously. Examination of the ball after the experiment revealed a flat oxide-encrusted spot (fig.4 (a)), which on subsequent cleaning was revealed to be an abraded flat spot (fig. 4 (b)). The sticky oxide on the glass was removed with difficulty but completely with acids, and a striated cracked area was revealed. The striations could not be brought into sharp focus with the microscope, indicating appreciable depth and irregularity (fig. 5 (a)). If the action was continued for longer periods, the glass fragmented locally (fig. 5 (b)) and was pitted.



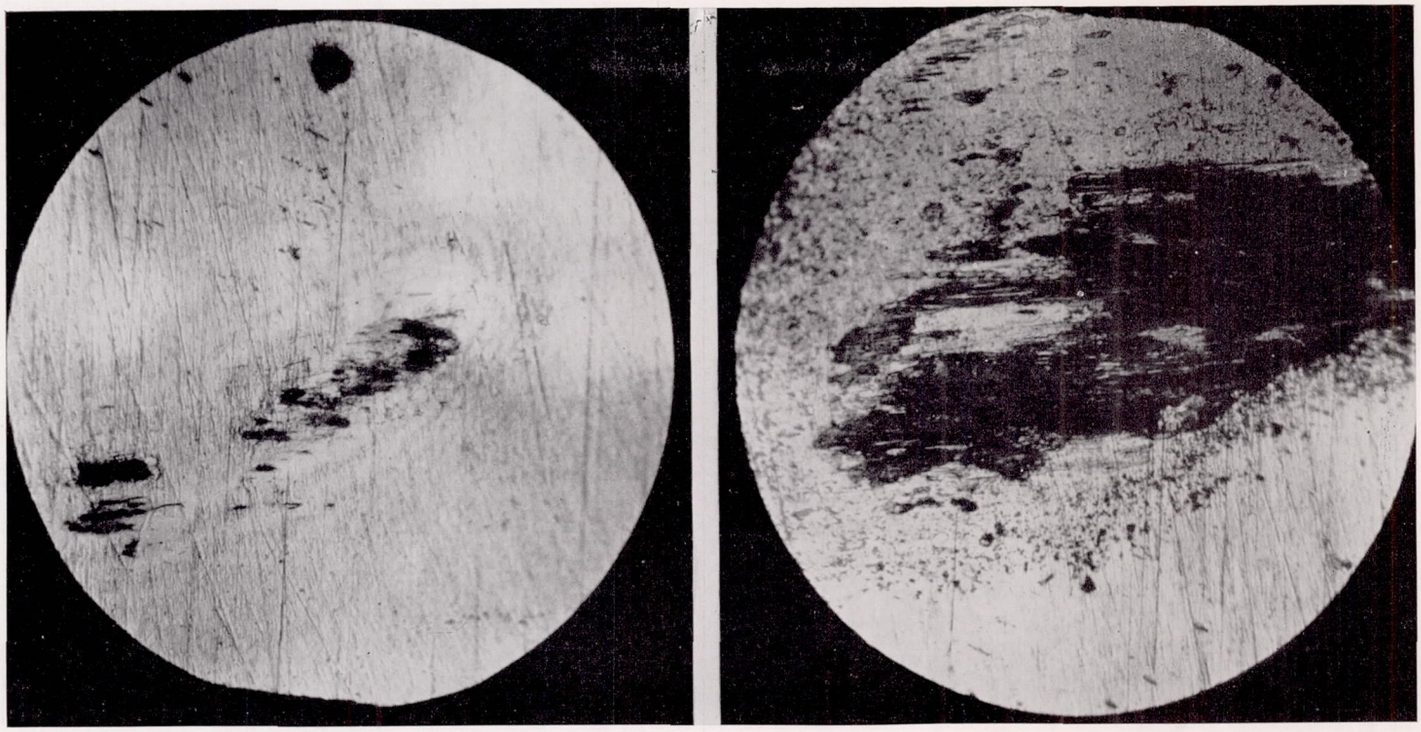
(a) Before cleaning. (b) After cleaning.

FIGURE 4.—Photomicrographs showing fretting area on chrome-alloy steel ball after 3600 cycles. × 120.



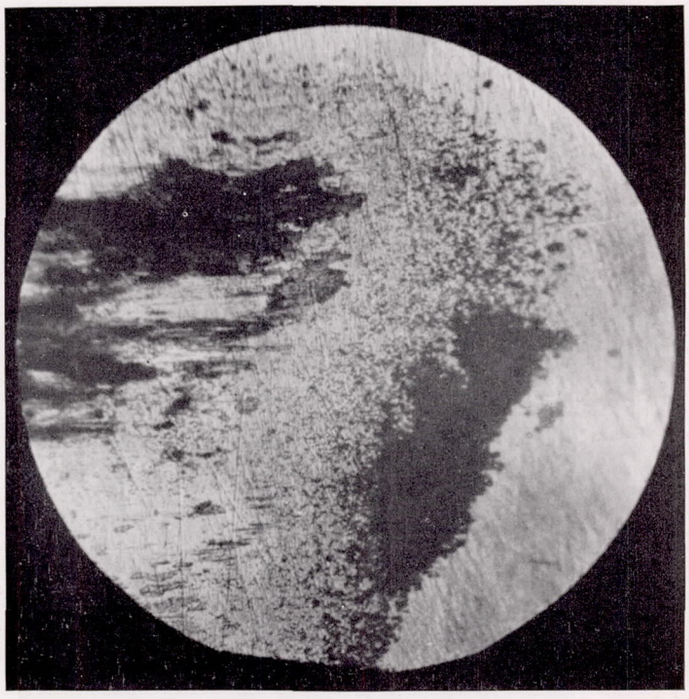
(a) Early stage, × 120. (b) Later stage, × 250.

FIGURE 5.—Photomicrographs of cleaned wear area on glass showing striations and cracking produced by vibration of contacting chrome-alloy steel ball.



(a) Early stage. (b) Advanced stage.

FIGURE 6.—Photomicrographs of convex platinum surface through glass slide showing wear and debris produced. × 120.



(c) Debris accumulation outside field of view of figure 6 (b).

FIGURE 6.—Concluded. Photomicrographs of convex platinum surface through glass slide showing wear and debris produced. × 110.

The introduction of a film of pure mineral oil between the surfaces increased the time for the first evidence of fretting action 50 times. This delay also provided a slow-motion study of the fretting process and showed that oxides were produced in the same manner in the presence of oil. Once the phenomena were well under way, the modifying effect of the oil was reduced.

Results obtained when other metals were vibrated against glass slides supported the explanation of fretting deduced from the steel-glass experiments. In one experiment, flame-cleaned platinum foil supported by a steel ball was vibrated in contact with clean glass. The generation of a black powder in the characteristic way was observed (fig. 6). This powder remained black and that which adhered to the glass could be completely removed only by a 4-hour treatment in aqua regia. Color, acid resistance, electron-diffraction patterns, and source indicated that the material was finely divided platinum (platinum black). Because platinum will not oxidize in air at any temperature, the theory that oxidation is a primary cause of fretting is not supported.

The action of a stainless-steel (SAE 30705) convex surface against the flat glass was similar to that of the chrome-alloy steel balls except that the number and the extent of the active black areas were greater. Copper produced a brownish-black material that also adhered tenaciously to the glass. At times, large particles of metallic copper could be seen to leave the contact area. During the third minute of vibration, the contact area assumed the greenish tint characteristic of copper oxide. Both these metals were pitted and abraded and the glass was striated.

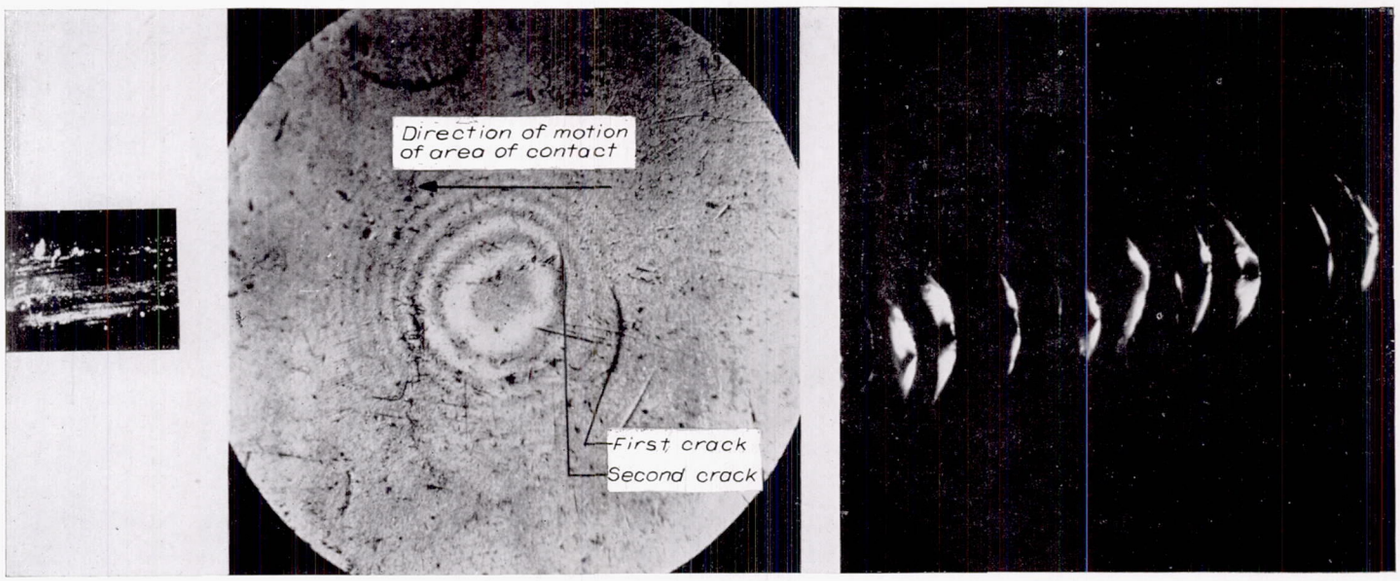
Under the conditions of the ½-cycle experiment, two types of action were observed. If the surface of the ball was previously roughened with 2/0 emery paper, the glass would polish the contact area on the ball and become smeared with the semifluid oxide, which would again tenaciously adhere to the glass. The amount of debris accumulated in three ½ cycles of vibration is shown in figure 7 (a).

An increase in frictional force was apparent when the oxide was present between the surfaces. This greater motivating force was required to continue relative sliding because a nonlubricating material was present between the surfaces and tenaciously adhered to each. The oxide itself was sheared and the two new faces thus formed became the sliding surfaces. If a ball with its original polished surface was used, much less oxide would be smeared, but the movement would cause the glass to grip the ball and as the relative sliding continued the glass would visibly and audibly crack. The cracking occurred at the trailing edge of the contact area. A photomicrograph of the glass in the process of forming a second crack is shown in figure 7 (b). The row of cracks produced in the glass during continued sliding is shown in figure 7 (c). The smearing of the metallic oxide onto the glass and the cracking of the glass are apparently due to a great amount of adhesion permitted by the extreme cleanliness of the specimens. The surface finish on the ball determines which phenomenon will occur. A rough surface supports the load on a number of peaks, the average particle of which is relatively exposed. Sliding of the smooth glass over these peaks results in disintegration of the peaks and subsequent oxidation of the removed metal. A smooth polished surface on the ball supports the load on a few broad undulations, the material of which is secure. Sliding of the smooth glass over these contact areas results in failure of the glass rather than the metal. This concept is in agreement with reference 8, which presents data to show that the amount of material transferred from base to rider increased with increase in surface roughness if the rider was harder than the base. With the steel ball considered as the rider and the steel harder than the glass, some incongruity may exist in this comparison in that the glass picked up material from the steel.

The glass appeared to plow into the aluminum, scoring it heavily. Large metallic pieces were mixed with a grayish-black powder. Some of the debris adhered tenaciously to the glass in the characteristic manner. The powder was insoluble in nitric acid but soluble in alkali, indicating that aluminum was still present. Mica and Lucite always wore away the metal surfaces and produced very great amounts of flocculent debris. Observation of the action of the metals was difficult because of the great dilution of the metal debris by the voluminous debris from the flat specimen. This experiment indicated that no property peculiar to glass was inducing the action.

NONMETALS AGAINST NONMETALS

The independence of fretting from chemical action was indicated in a group of experiments involving the nonmetallic, nonoxidizing materials with glass vibrated against quartz, ruby, or mica. By vibrating a ruby with a convex surface against a glass slide and observing the action under a microscope, surface disintegration could be seen to occur. The glass, after 2 to 3 seconds of rubbing, suddenly collapsed locally and distributed debris about the contact area, leaving a pit. This action shifted the bearing area to the edge of the pit and the disintegration was continued (fig. 8). An early stage of disintegration with two pits formed is shown in figure 8 (a), whereas the advanced stage of 20 or more pits is shown in figure 8 (b). The ruby was simply further polished, that is, the microscopic scratches were erased. Quartz against glass acted the same as ruby against glass. Mica



(a) View of glass slide showing amount of debris transferred from roughened steel. (b) View of ball through glass showing second crack being formed in glass on trailing edge of area of contact. (c) View of glass slide showing resultant row of cracks.

FIGURE 7.—Photomicrographs showing effects of ½ cycle vibration between glass and steel surface. × 120.



(a) Early stage. (b) Advanced stage. (c) Advanced stage after removal of debris.

FIGURE 8.—Photomicrographs showing results of fretting between ruby and glass. × 120.

against a glass ball and Lucite against a glass ball also behaved similarly. In all cases, the debris was produced, extruded, and accumulated in the same physical manner observed with metal debris, except that no change in color took place. Fretting occurred to mica in the least number of cycles, the number required being progressively greater for Lucite, glass, quartz, and ruby, which is also the order of increasing hardness of the materials. The tendency for fretting between the various nonmetals and glass and the amount of debris generated therefore appear to be inversely proportional to the hardness of the nonmetal.

CONCLUDING REMARKS

The observations made indicate that fretting can occur between two nonmetals. The susceptibility to fretting of nonoxidizing materials such as glass, quartz, ruby, mica, and platinum relegates the role of oxidation as a cause to that of a secondary factor and indicates that finely divided and apparently virgin material is first produced. In the metals, this production of virgin metal is suggested by the color changes through which the metal passed as it oxidized. The oxides are therefore considered a byproduct of the initial action. The spontaneity of the oxidation is probably due to the increased chemical activity of the particles. This increase is called mechanical activation in reference 9, which also states that the increase is more than that produced by cleanliness or reduced particle size. The oxide formation was induced at extremely low speeds and light loads where the dissipation of frictional heat is sufficiently rapid to minimize the occurrence of local hot spots. The possibility of fretting being caused by rubbing off a regenerative high-temperature-forming oxide film is therefore unlikely.

The conclusion is made in reference 2 that alternating slip is a necessary condition for fretting. The production of a smear on the glass surface in ½ cycle and the cracking of glass on smooth metal indicate that alternation of motion is unnecessary to initiate fretting, although alternation does give it its usual characteristics. This idea is supported by the observation that fretting starts with the sliding or slip. Lowering the frequency only decreases the rate at which fretting occurs. This relation indicates that the basic cause of fretting is independent of frequency.

The metal transfer caused by sliding one metal over another demonstrated in references 8 and 10 was attributed to adhesion. Similarly, in the experiments reported herein the action observed, namely, removal of material, cracking, and general surface destruction, was attributed to adhesion, which leads to the conclusion that fretting is a manifestation of the adhesion component of friction.

RESULTS AND CONCLUSIONS

An experimental investigation was conducted to determine the cause of fretting. Glass and other noncorrosive materials were vibrated in contact with one another and with metals and microscopic observation was made of the action. Convex surfaces were vibrated in contact with stationary flat surfaces at frequencies of 120 cycles or less than 1 cycle per second, an amplitude of 0.001 inch, and a load of 0.2 pound.

The following results and conclusions were indicated:

1. Fretting is initiated by the loosening, due to inherent adhesive forces, of extremely finely divided and apparently virgin material that is extruded from the contact area and reacts with oxygen simultaneously.

2. The fretting of platinum, glass, quartz, ruby, and mica relegated the role of oxidation as a cause to that of a secondary factor.

3. Fretting readily occurred between clean nonmetals and metals. Steel balls vibrating in contact with glass microscope slides provided an excellent method for observing fretting.

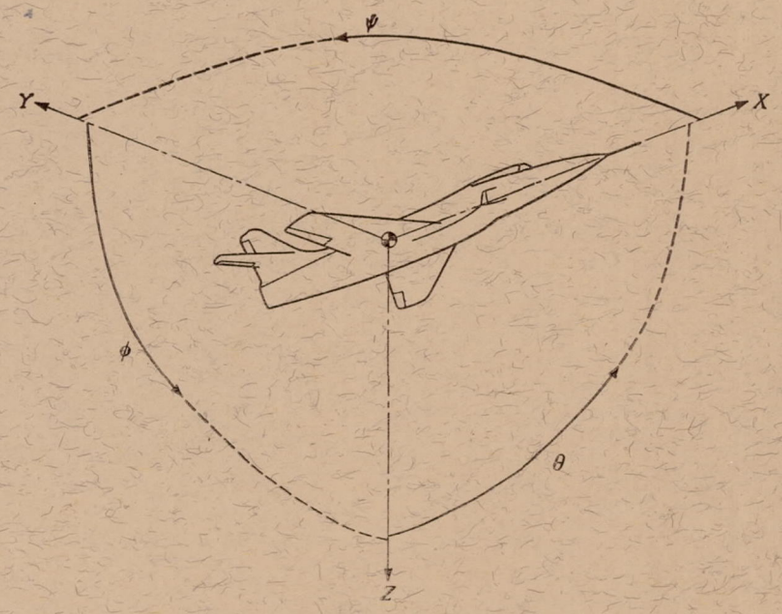
4. The initiating of fretting is independent of vibratory motion or high sliding speeds.

LEWIS FLIGHT PROPULSION LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
CLEVELAND, OHIO, *August 31, 1949.*

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Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D Diameter

p Geometric pitch

p/D Pitch ratio

V' Inflow velocity

V_s Slipstream velocity

T Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$

Q Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$

C_s Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$

η Efficiency

n Revolutions per second, rps

Φ Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec

1 metric horsepower=0.9863 hp

1 mph=0.4470 mps

1 mps=2.2369 mph

1 lb=0.4536 kg

1 kg=2.2046 lb

1 mi=1,609.35 m=5,280 ft

1 m=3.2808 ft