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National Aeronautics and Space Administration

Scientific and Technical Information Branch

Summary

An investigation was conducted to determine the effect of relative humidity in air on the fretting wear behavior of several pure metals: iron, aluminum, copper, silver, chromium, titanium, and nickel. The fretting wear experiments were carried out under various humidity conditions. After each experiment the wear volume was measured and the fretted surfaces of some specimens were observed with a scanning electron microscope. Each pure metal examined had a maximum fretting wear volume at a specific humidity. The relative humidity RH_{max} at which maximum wear volume occurred for each metal did not depend on mechanical test conditions such as contact load, fretting amplitude, and frequency in the ranges studied. The fretting wear weight loss at RH_{max} for each metal decreased with increasing heat of oxygen adsorption on the metal, indicating that adhesive wear dominated at RH_{max}.

Introduction

Oxygen and water vapor in the environment significantly affect the fretting wear of materials but do not always cause an increase in fretting wear rate. Although many studies have been reported on the effect of environment on fretting behavior, it seems that the effect of water vapor (the humidity effect) is very complicated and not yet fully understood.

It is well known that the fretting damage to automobile bearings during shipment is more severe in the winter (with low humidity) than in the summer. Experimental results by Feng and Uhlig (ref. 1) indicate that the fretting wear of a mild steel in air decreases monotonically with increasing humidity from dry air conditions. On the other hand, Godfrey (ref. 2) and Soda and Aoki (ref. 3) show another tendency of fretting wear with humidity: the fretting wear of steel increases as the humidity is increased from dry air and maximum fretting wear occurs at a certain value of relative humidity. Further increases in humidity, however, result in a decrease in fretting wear. Bill (ref. 4) observed a similar trend for wear as a function of relative humidity in the fretting of pure iron and titanium. The reason, however, for a maximum fretting wear at a certain relative humidity level is not fully understood.

In the present study, fretting wear experiments were conducted to examine the effect of humidity in air on the fretting wear of the pure metals iron, aluminum, copper, silver, chromium, titanium, and nickel. Each of the pure metals examined also showed a maximum in fretting wear at a specific humidity. Thus contact load, amplitude of fretting motion, and frequency were varied for iron and copper in order to determine whether the relative humidity at which maximum fretting wear occurs for each pure metal depends on these mechanical factors. These results, together with the scanning electron microscope observations of the effect of humidity in air on the fretting wear of pure metals, are discussed.

Materials and Specimens

The materials used in this investigation were the pure metals iron, aluminum, copper, silver, chromium, titanium, and nickel. The purity of these metals was greater than 99.9 percent. Fretting specimens consisted of an upper, stationary, 4.76-mm-radius, hemispherical tip in contact with a lower flat tip. In all fretting wear experiments both specimens were of the same metal.

Apparatus and Procedure

Fretting wear experiments were conducted by using the fretting apparatus illustrated in figure 1. An electromagnetically driven vibrator with the frequency controlled by a variable oscillator provided an oscillatory fretting motion to a lower flat specimen in contact with the upper hemispherical specimen. Peak-to-peak amplitude of fretting motion was monitored with a capacitance proximity probe. The contact load was applied to the specimens by placing precision weights on a pan hung from the load arm.

Dry air was produced by flowing air through an absorption drier and then into the test chamber. Its absolute humidity was kept in the range 10 to 100 ppm. Various levels of relative humidity were obtained by mixing dry air with water-vapor-saturated air. A humidity sensor based on the capacitance change in a polymer thin-film capacitor was used to monitor the relative humidity of the air near the specimens in the test chamber. The accuracy of the humidity indicator was ±2

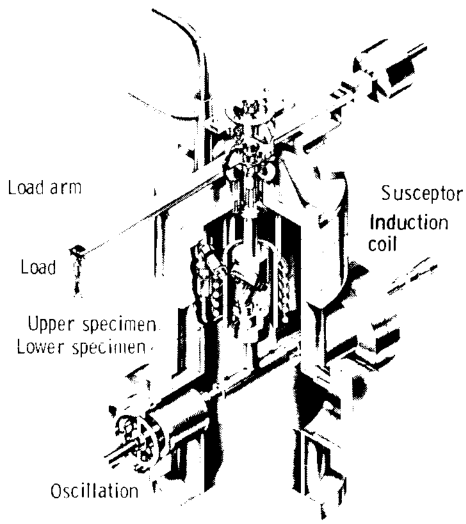


Figure 1.—Fretting apparatus.

percent in the range 0 to 80 percent relative humidity. The temperature in the test chamber was 23° C ±1 deg C.

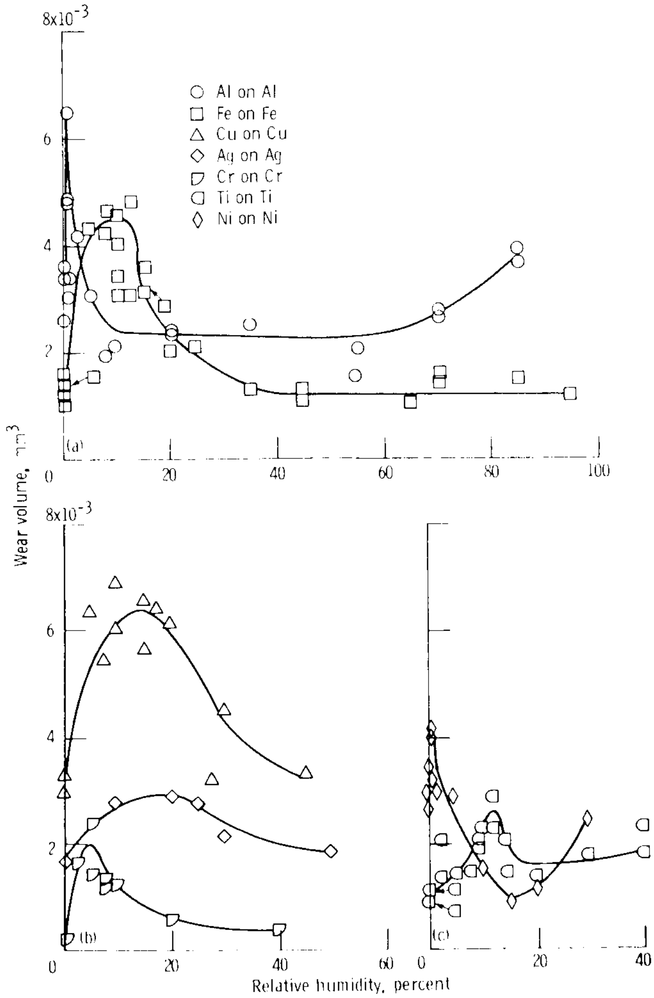
Before each wear test, the flat specimens were polished with emery papers and finally with 0.05-μm alumina polishing compound and then rinsed in pure ethanol. The hemispherical tips were ground to a 0.1-μm finish, scrubbed with 0.05-μm alumina, and then rinsed in ethanol.

After the specimens were assembled into the grips, the test chamber was purged with air of the desired relative humidity for about 1 hr. With the vibrator turned on for 1 min, sufficient weight was put into the pan to allow the specimens to just come into contact. Additional weight was added to apply the required load to the contacting surfaces, and the fretting wear experiment was then commenced. In the usual fretting wear tests the normal contact load was 2.94 N (300 g), the peak-to-peak amplitude of fretting motion was 80 μm, the frequency was 60 Hz, and the number of fretting cycles was 5.04×10^5. However, these factors were varied when their effects on fretting wear were studied.

After each fretting wear experiment the loose wear debris on the surface of the flat specimen was rinsed off with pure ethanol. The maximum and minimum diameters of the wear scar on the flat specimen were measured by using an optical microscope. The mean radius r of the wear scar was calculated from both the diameters. The total wear volume V of the upper and lower specimens was estimated by using the following equation:

$$V = \frac{\pi}{3}\left[2R^3 - (2R^2 + r^2)\sqrt{R^2 - r^2}\right]$$

where R is the radius of the upper (hemispherical) specimen.



(a) Iron and aluminum.
(b) Copper, silver, and chromium.
(c) Titanium and nickel.

Figure 2.—Fretting wear volume as a function of relative humidity. Contact load, 2.94 N; fretting amplitude, 80 μm; frequency, 60 Hz; number of fretting cycles, 5.04×10^5.

Specimens were ultrasonically cleaned in pure ethanol before viewing with a scanning electron microscope (SEM) in order to remove as much of the debris still adhering to the wear scar surface as possible.

Results and Discussion

Wear Volume Under Varied Humidity

The fretting wear volume for iron as a function of relative humidity (fig. 2(a)) indicates the same tendency with increasing humidity as obtained in reference 4, despite different fretting conditions but the use of the same apparatus. The fretting wear volume of iron increased as the relative humidity was increased from dry air. Maximum fretting wear occurred at 10 percent relative humidity (RH_{max}). The fretting wear volume gradually decreased from 10 percent to 40 percent relative humidity and then remained relatively constant between 40 and 95 percent.

The maximum fretting wear for aluminum (fig. 2(a)) occurred at less than 2 percent relative humidity. This value of RH_{max} is extremely small when compared with the RH_{max} of 10 percent for iron. Aluminum manifested the same fretting wear tendency with increasing relative humidity as was observed for iron to a relative humidity of 60 percent.

Since the primary purpose of this investigation was to study the reason for the occurrence of maximum fretting wear with a change of humidity, fretting wear experiments at low relative humidity levels were conducted for pure metals other than iron and aluminum. In tests at RH levels less than 50 percent (fig. 2(b)), maximum fretting wear for copper, silver, and chromium occurred at RH_{max} of 15, 20, and 5 percent, respectively.

Maximum fretting wear of titanium and nickel (fig. 2(c)) occurred at RH_{max} of 12 and less than 2 percent, respectively. Bill (ref. 4) observed a distinct minimum fretting wear at an RH_{max} of 15 percent in the fretting of nickel. He did not, however, conduct fretting wear experiments at relative humidity levels lower than 10 percent other than those in dry air. Thus in the present experiments fretting wear was studied in the range from dry air to 10 percent relative humidity.

Effect of Mechanical Factors on Maximum Fretting Wear

To study the effect of frequency on the fretting wear of iron (fig. 3), frequencies of 10, 60, and 80 Hz were used for the fretting motion. As a smaller number of fretting cycles was used in the experiments at 10 Hz than in those at 60 and 80 Hz, wear rate (wear volume per unit cycle) was calculated to examine the frequency effect. The maximum fretting wear rate at each frequency occurred near 10 percent relative humidity. The fretting wear rate was greatest at the lowest frequency (as also shown in refs. 1, 5, and 6).

To determine the effect of fretting amplitude on the fretting wear of iron (fig. 4), fretting amplitudes of 80 and 120 μm were used. Although the fretting wear volume was higher at the higher fretting amplitude, maximum fretting wear occurred at about 10 percent relative humidity at both fretting amplitudes.

Contact loads of 1.47, 2.94, and 4.41 N (150, 300, and 450 g) were used to study the effect of contact load on the fretting wear of iron (fig. 5(a)). Wear volume increased with increasing contact load, but the RH_{max} for iron was 10 percent regardless of contact load. The fretting wear of copper was studied at contact loads of 0.98 and 2.49 N (100 and 300 g) (fig. 5(b)). The RH_{max} for copper was 15 percent regardless of contact load.

The effect of mechanical factors on RH_{max} was not studied for pure metals other than iron and copper. However, figures 3 to 5 suggest that the RH_{max} for other pure metals would not depend on such mechanical factors as contact load, fretting amplitude, or frequency. This is borne out by the different RH_{max} values for pure metals when mechanical factors were not considered (fig. 2).

Wear Curves

Sequential wear experiments were conducted by subjecting a pair of specimens to fretting exposures of 3.6×10^3, 10^4, 4×10^4, 10^5, 2.16×10^5, and 5.04×10^5 cycles in dry air and at 10 and 70 percent relative humidity. After each exposure the specimens were

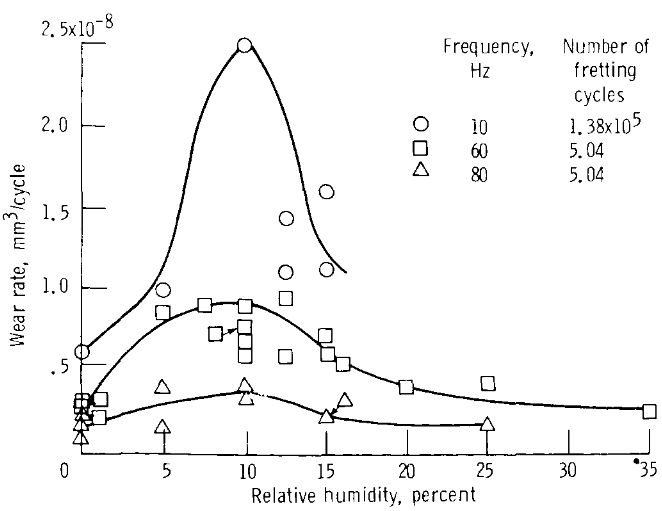


Figure 3.—Fretting wear rate of iron as a function of relative humidity, frequency, and number of fretting cycles. Contact load, 2.94 N; fretting amplitude, 80 μm.

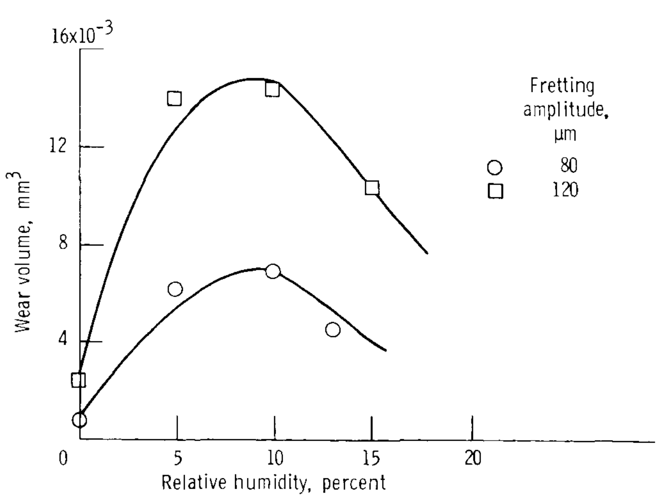
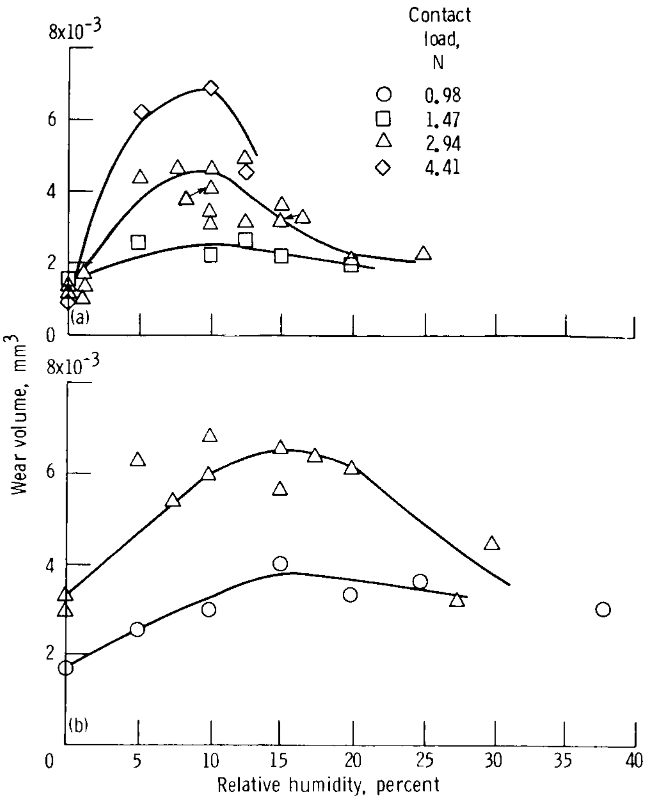


Figure 4.—Fretting wear volume of iron as a function of relative humidity and fretting amplitude. Contact load, 4.41 N; frequency, 60 Hz; number of fretting cycles, 5.04×10^5.



(a) Iron.
(b) Copper.

Figure 5.—Fretting wear volume as a function of relative humidity and contact load. Fretting amplitude, 80 μm; frequency, 60 Hz; number of fretting cycles, 5.04×10^5.

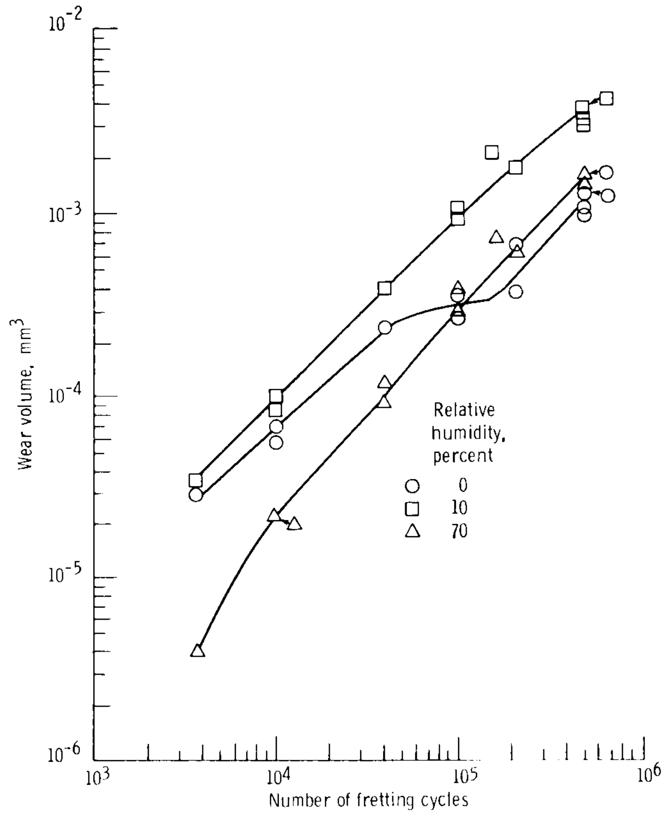


Figure 6.—Fretting wear volume of iron as a function of number of fretting cycles and relative humidity. Contact load, 2.94 N; fretting amplitude, 80 μm; frequency, 60 Hz.

rotated to bring virgin surface into contact. From these experiments wear curves were obtained (fig. 6). On a logarithm-logarithm scale the wear volume at 10 and 70 percent relative humidity increased almost linearly with the number of fretting cycles. In contrast, the wear volume in dry air shows a step-wise change with fretting cycles.

The fretting process was divided into three stages for convenience: (I) the initial stage ($n = 0$ to 10^4 cycles), (II) the intermediate stage ($n = 10^4$ to 10^5 cycles), and (III) the steady-wear stage ($n \cong 2 \times 10^5$ to 5×10^5 cycles). From figure 6, the wear rate (wear volume per unit cycle) at each stage was obtained, as indicated in figure 7. The wear rates for all stages (W_{I}, W_{II}, and W_{III}) were higher at 10 percent relative humidity than at the other humidity levels, indicating the occurrence of maximum fretting wear with a change in humidity level. In dry air, W_{II} and W_{III} were smaller than W_{I}, indicating a change of wear surface condition in the early stages of fretting.

Others have observed negative wear during the fretting of an aluminum alloy under dry air conditions (refs. 7 and 8). This was caused by the formation of an adhered layer of oxidized wear debris in the contact area. As indicated in figure 7, the wear rate in dry air decreased

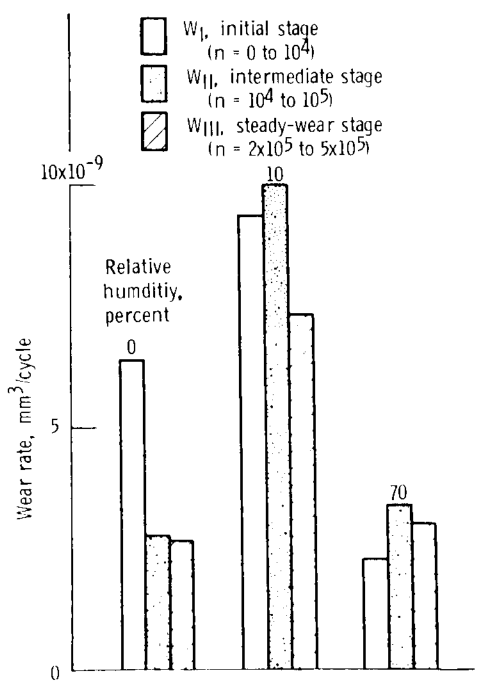
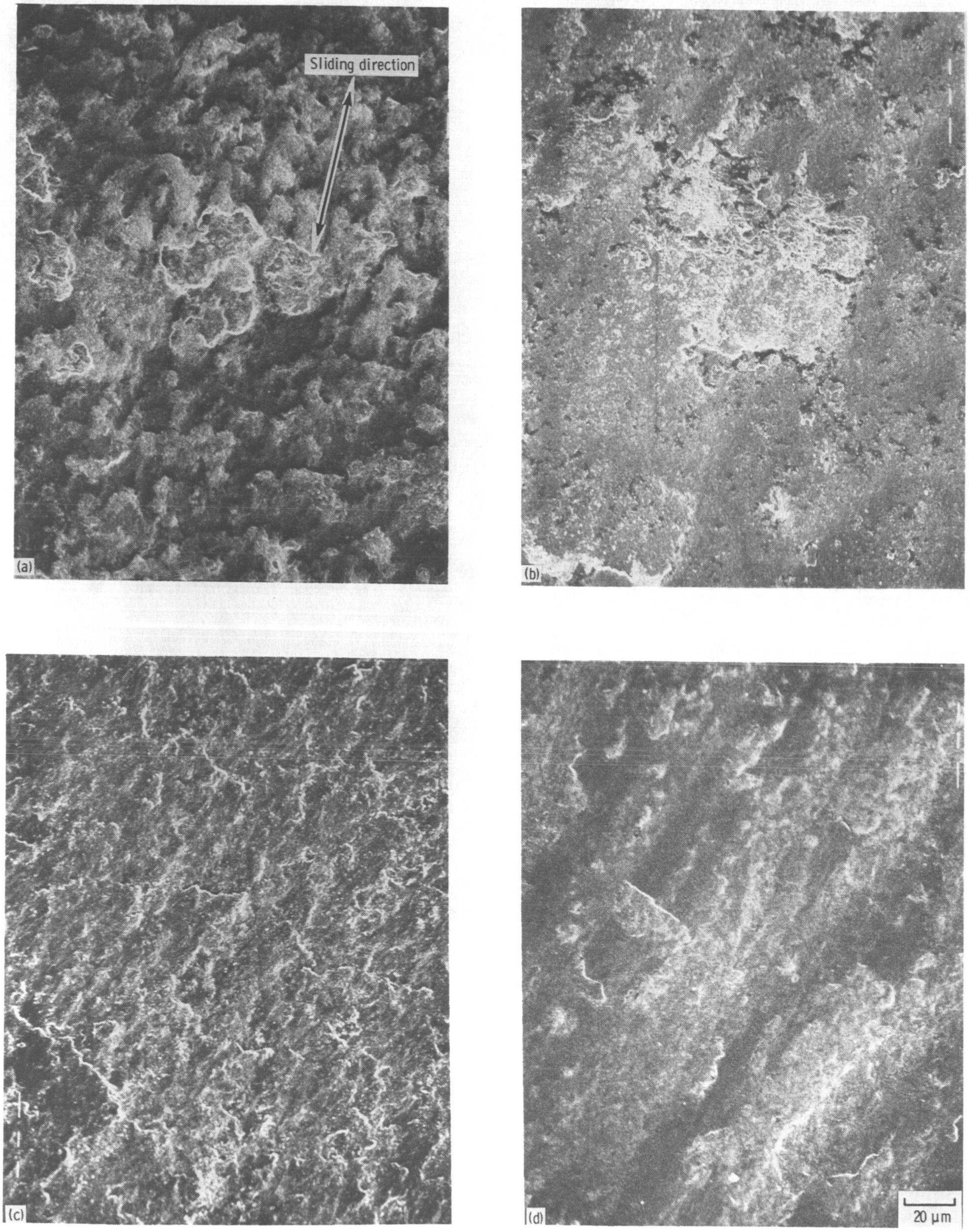
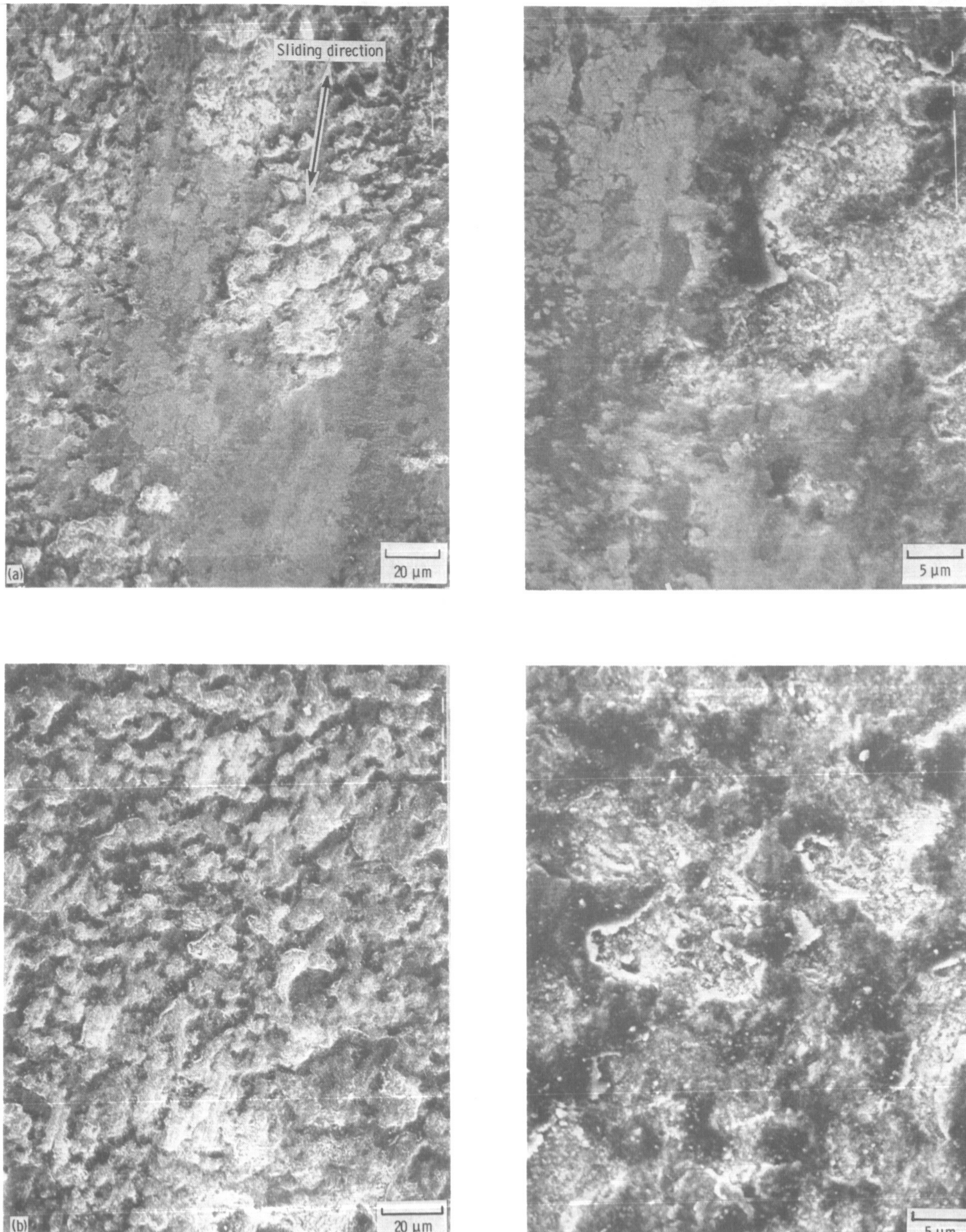


Figure 7.—Fretting wear rate of iron at three stages under varied relative humidity.



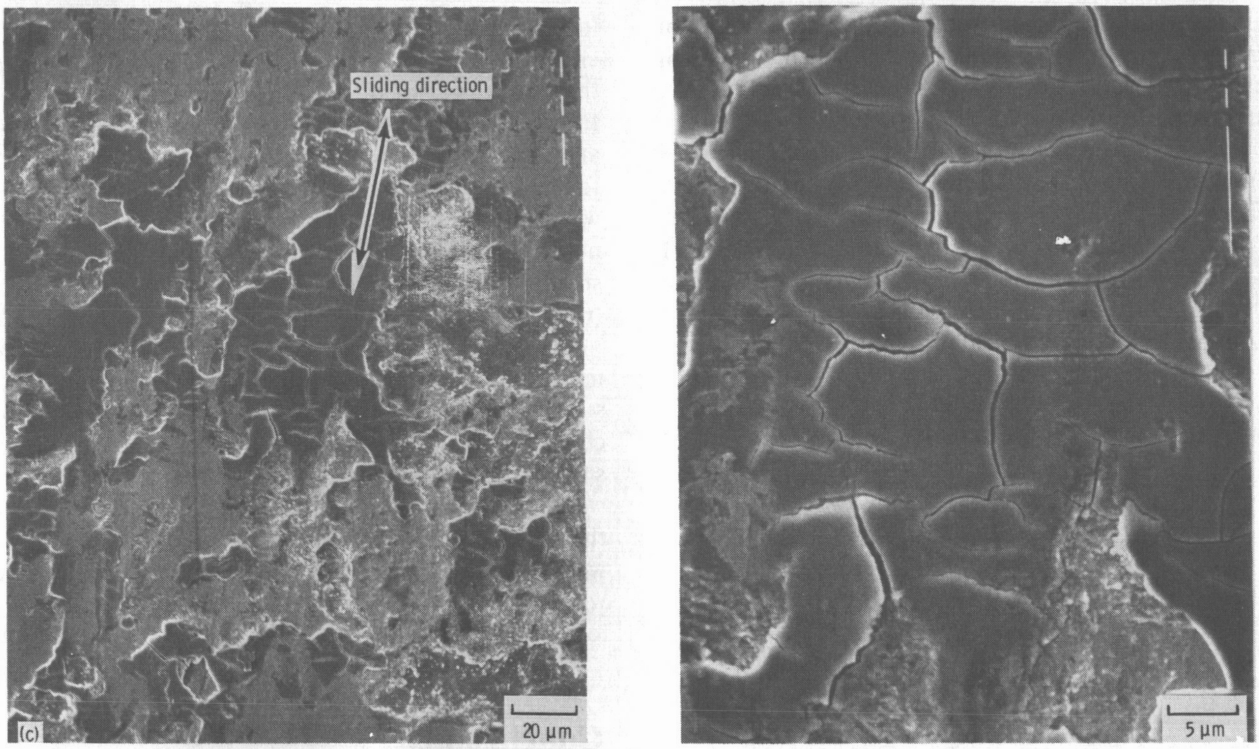
(a) In dry air, without ultrasonic cleaning.
(b) In dry air, after ultrasonic cleaning.
(c) At 10 percent relative humidity
(d) At 70 percent relative humidity

Figure 8.—Fretting wear surface of iron after 5.04×10^5 cycles. Contact load, 2.94 N; fretting amplitude, 80 μm; frequency, 60 Hz.



(a) In dry air.
(b) At 5 percent relative humidity

Figure 9.—Fretting wear surface of chromium after 5.04×10^5 cycles. Contact load, 2.94 N; fretting amplitude, 80 μm; frequency, 60 Hz. (Left photographs are overviews; right photographs show central region.)



(c) At 20 percent relative humidity

Figure 9.—Concluded.

after the first 10^4 fretting cycles (a step-wise change of the wear curve in fig. 6). After a fretting exposure of 5.04×10^5 cycles in dry air and rinsing in ethanol (fig. 8(a)) the wear surface was still covered with much wear debris. The wear debris retained in the contact area probably protected the metal surfaces from direct contact and thus decreased fretting wear.

Observation of Fretting Surface by SEM

The ultrasonically cleaned surface of iron after fretting wear at three humidity levels was then observed by SEM. The surface of iron after fretting in dry air (fig. (8(b)) was rather smooth and seemed to be covered with an oxide film. In spite of the ultrasonic cleaning much debris still adhered to the contact surface. The ultrasonically cleaned surface of iron after fretting at 10 percent relative humidity (fig. 8(c)) showed many cracks approximately perpendicular to the sliding direction. Thus considerable wear debris had probably formed from the repeated sliding motion. The ultrasonically cleaned worn surface of iron (fig. 8(d)) produced by fretting at a high humidity level (RH = 70 percent) was quite smooth (as found also in ref. 4) and covered with a stable oxide film.

The surface of chromium after fretting wear at three humidity levels was also observed by SEM. The dry-air-fretted contact surface of chromium (fig. 9(a)) was covered with an oxide film that was broken in places. The fretted contact surface of chromium at 5 percent relative humidity (fig. 9(b)) was roughened and pitted, mostly from the fracture of bulk metal. Thus severe wear, including adhesive wear, partly occurred at RH_{max}. The fretted contact surface of chromium at 20 percent relative humidity (fig. 9(c)) was flat and partly covered with a cracked oxide film. This reveals that fretting wear occurred in the mild wear regime with oxidation.

Fretting Wear Behavior at Low Humidity Levels

The fretting wear behavior of pure metals in the steady-wear stage varied with humidity (water vapor content) in the range of low humidity levels including RH_{max}. In dry air, wear debris retained in the contact area reduced the extent of metal-to-metal contact, as mentioned earlier, and the metal surface was heavily oxidized. Therefore the fretting wear volume was comparatively small.

With an increase in humidity from dry air to RH_{max} for each metal, water vapor easily adsorbed on the freshly sheared metal surfaces and disturbed the adsorption of oxygen to the surface. Thus the rate of oxygen adsorption, or oxidation, decreased (as found also in ref. 9). This suggests that the small amount of water vapor in the environment increased the extent of adhesion between contact surfaces under sliding conditions (as shown also in ref. 10).

Decreasing fretting wear volume with increasing shear strength was generally observed (fig. 10) for all of the metals except silver, as is often seen in adhesive wear. (The data for shear strength are summarized in ref. 11 from the results of Bridgman (ref. 12).) The wear weight loss at RH_{max} was determined (fig. 11) for each metal as a function of the heat of oxygen adsorption on the metal Q (ref. 13). This parameter is related to the surface chemistry of metals. The weight loss decreased with increasing Q, except for silver. The metal with the least chemical activity had the greatest weight loss, revealing that adhesive wear predominated at RH_{max}. In the fretting wear of the metals with higher chemical activity, an oxide film, which reduced the adhesion, was easily formed. However, there was no correlation between the wear volume at RH_{max} and the ratio of oxide hardness to metal hardness, which may be a measure of the susceptibility of a metal to abrasive wear by its oxide (ref. 14).

The test chamber was an open system; water vapor was immediately supplied from the environment and consumed in adsorption. Thus even at low humidity levels considerable water vapor could adsorb on the contacting surfaces and form a water film. With the existence of a water film a stable oxide film could be easily produced on the contacting surfaces. It is considered that the fretting wear above RH_{max} for each metal is a state of mild wear with oxidation. Therefore the more active metals have a lower RH_{max} (fig. 2).

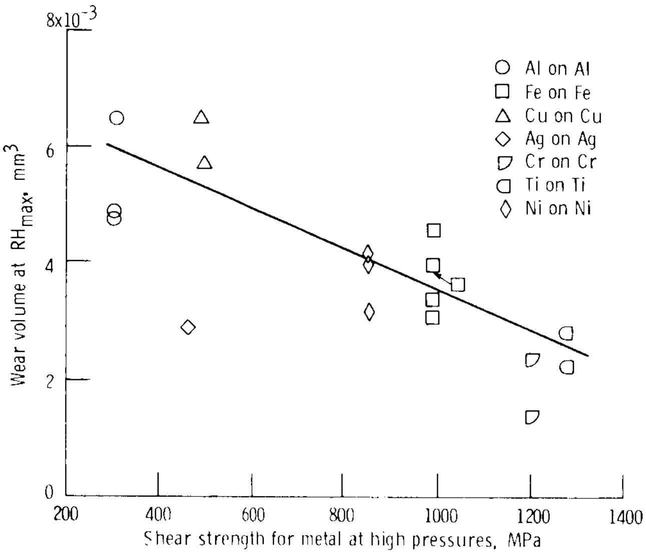


Figure 10.—Fretting wear volume at RH_{max} as a function of shear strength for pure metal at high pressures.

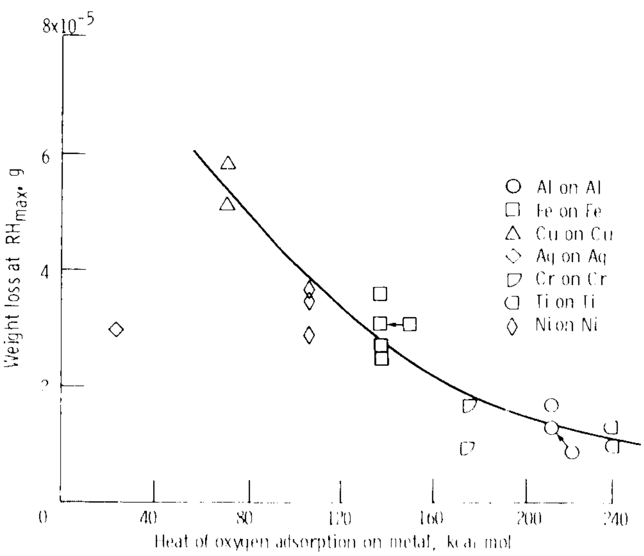


Figure 11.—Weight loss due to fretting wear at RH_{max} as a function of heat of oxygen adsorption on metal surface.

Conclusions

From fretting wear experiments conducted with several pure metals under varied humidity in air and from scanning electron microscope observations, the following conclusions were drawn:

1. Pure metals such as iron, aluminum, copper, silver, chromium, titanium, and nickel have their maximum fretting wear at a particular relative humidity level.
2. The relative humidity level of maximum wear RH_{max} does not depend on mechanical factors such as contact load, fretting amplitude, and frequency in the ranges studied.
3. The wear weight loss of pure metals at RH_{max} is strongly related to the heat of oxygen adsorption on the metal, indicating that adhesive wear predominates at RH_{max} for each metal.

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio, September 18, 1984

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15. Supplementary Notes

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16. Abstract

Fretting wear experiments with several pure metals were conducted in air at various relative humidity levels. The materials used were iron, aluminum, copper, silver, chromium, titanium, and nickel. Each pure metal had a maximum fretting wear volume at a specific humidity level RH_{max} that was not dependent on mechanical factors such as contact load, fretting amplitude, and frequency in the ranges studied. The weight loss due to fretting wear at RH_{max} for each pure metal decreased with increasing heat of oxygen adsorption on the metal, indicating that adhesive wear dominated at RH_{max}.

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