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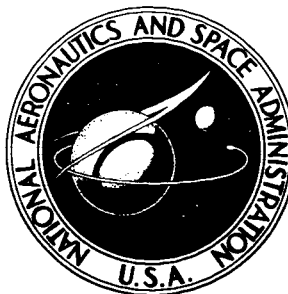
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NASA TN D-3958

N67-24474
(ACCESSION NUMBER) (THRU)

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(PAGES) (CODE)

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(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

FACILITY FORM 602

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1967

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SUMMARY

Friction and wear tests were conducted with some impregnated mechanical carbons to determine their performance at high temperatures. Loaded hemispherically tipped carbon riders were in sliding contact with rotating chromium-plated disks in air or in nitrogen. A surface speed of 10 000 feet per minute (50.8 m/sec), a load of 1000 grams, and temperatures to 1400° F (760° C) were used.

Results indicate that impregnated mechanical carbons can function satisfactorily in air to 1200° F (649° C). Performance of the materials was generally better in nitrogen than in air at 1200° F (649° C). Oxidation plays an important role in friction and wear behavior at high temperatures.

INTRODUCTION

Mechanical carbons are molded self-lubricating solid materials used for mechanical components with surfaces in sliding contact (e.g., bearings and seals). The use of mechanical carbons for seals is especially important in aerospace applications. Varied combinations of carbon constituents and additives, as well as careful selection of mating materials, can be employed to make mechanical carbons useful in many environments, such as cryogenic liquids and gases (refs. 1 and 2), high-temperature air (ref. 3), and conventionally lubricated systems (ref. 4).

Turbine engines for advanced aircraft require substantial improvement in seal materials to enable operation at high temperatures (to 1200° F or 649° C), at high surface speeds (to 1000 ft/sec or 305 m/sec), and for extended periods of time (greater than 3000 hours). The life of a contact seal is most commonly limited by wear of the carbon nosepiece. New seal designs frequently use externally supplied hydrostatic or internally generated hydrodynamic pressures to separate the surfaces in relative motion with thin films. The leakage rate of a seal depends on the thickness of the interface film (ref. 5, p. 27), thus, thin films are essential. Some contact between the moving surfaces is

almost impossible to avoid when very close clearances are used. Therefore, wear and other effects of rubbing contact are important to fluid-film seals as well as to contact seals.

Wear rates of mechanical carbons are accelerated by increases in ambient temperature, sliding velocity, or load. Increased sliding velocity and load both increase frictional heating and, therefore, surface temperature. Wear rate varies linearly with load (refs. 6 and 7). Pressure balancing of seals is important if minimum contact forces are to be achieved.

Advanced turbine engines may require shaft seals to seal nitrogen or air as well as the lubricant; compressor, interstage, and end seals may also seal high-pressure, high-temperature air. The use of mechanical carbons in high-temperature air introduces corrosive wear (oxidation) as a wear mechanism of primary importance. Experiments in liquid oxygen showed that highly graphitic mechanical carbons have low wear and friction in a highly reactive oxidizing environment (ref. 2). Also, impregnation of oxidation-inhibiting additives in the carbon bodies reduced corrosive wear in liquid oxygen. Graphite begins to oxidize in air at 842° F (450° C), while for amorphous carbon oxidation begins at 662° F (350° C) (ref. 8). When seals must run in ambient air at 1200° F (649° C) and with added frictional heating, it is clear that oxidative wear must be expected for even completely graphitic carbons. The effectiveness of impregnants in limiting oxidative wear is not well defined and needs to be studied. A nitrogen environment would eliminate oxidative wear, but adhesive wear might become more of a problem. Adsorbates are important to the film-forming and self-lubricating functions of bodies containing carbon (refs. 9 to 12). The presence of most lubricants reduces the wear of mechanical carbons unless degrading chemical reactions occur.

This investigation was conducted to determine experimentally the wear and friction of potentially useful mechanical carbons in air or in nitrogen at high temperatures. A study was made with hemispherically tipped carbon specimens sliding under load against the chromium-plated flat surface of a rotating disk. Data were obtained at disk temperatures to 1400° F (760° C) with a surface speed of 10 000 feet per minute (50.8 m/sec) in atmospheres of air or dry nitrogen. The mechanical carbons studied were materials with varied carbon-type compositions and additives. These carbons were supplied by Morganite, Inc.; Pure Carbon Co., Inc.; United States Graphite Co., and National Carbon Co.

MATERIALS

A list of the mechanical carbons used with certain of their mechanical properties (where available) is presented in table I. The types of impregnant used were phenolic

TABLE I. - TYPICAL PROPERTIES OF CARBON-BASE MATERIALS

[Data from Manufacturers.]

Material designation	Carbon type	Impregnant	Transverse strength, lb/sq in.	Hardness schleroscope	Density, g/cu cm	Transverse elastic modulus, lb/sq in.
A-C	Carbon	None	9600	76	1.85	--------
B-Gr	Recrystallized high-density graphite	None	5500	65	1.95	2.40×10^6
C-G	Graphite	None	6000	60	1.6	.93
A-CG-c	Carbon graphite	Carbonized resin	8900	84	----	----
A-G-1c	Graphite	Carbonized resin, metal phosphate	8000	70	----	----
B-CG-1	Carbon graphite	Metal phosphate	6700	95	1.77	3.40
D-G-1	Graphite	Metal phosphate	----	--	----	----
D-G-1d		Metal phosphate (double impregnated)	----	--	----	----
C-G-1		Metal phosphate	6500	65	1.65	1.00
C-G-1d		Metal phosphate (double impregnated)	----	--	----	----
A-G-3		Borax	5500	60	----	----
A-G-2		Borosilicate glass	5500	60	----	----

resins, metal phosphates, borosilicate glass, and borax. Impregnation of mechanical carbons normally has the following effects:

(1) Reduction of the porosity of the carbon skeleton and, therefore, the surface area on which oxidation can occur

(2) Increase of transverse rupture strength

(3) Increase of hardness

Hard chromium-plated mating surfaces were used because high hardness and oxidation resistance are desirable. The plated material was a high-temperature nickel alloy. Previous work indicated that similarly impregnated carbons had much lower wear than a tool steel and a stainless steel when sliding against chromium plate at elevated temperatures. Although very thin oxide films have beneficial effects, thick layers have an adverse influence on wear and friction (ref. 6).

APPARATUS AND PROCEDURE

The apparatus used in these tests is shown in figure 1. The basic elements are a

rotating disk specimen ($2\frac{1}{2}$-in. diam chrome-plated nickel-base alloy) and a hemispherically tipped mechanical carbon rider (3/8-in. diam) in sliding contact with the disk (see inset, fig. 1). The disk is rotated by a hydraulic motor operating through a gearbox speed increaser and a spindle-mounted shaft. The rider is loaded against the disk by a dead-weight system, the force of which is transmitted through a shaft vertically mounted in porous-metal gas bearings. The specimens are located in a test chamber, and the atmosphere is supplied by flow through the gas bearings of the rider shaft. Heating is by induction heating of a susceptor surrounding the disk.

The friction force was continuously measured by a dynamometer-ring strain gage attached to the rider shaft. Rotational speed was measured by a magnetic pickup connected to an event counter. Disk temperatures were obtained with a Chromel-Alumel thermocouple located approximately 0.030 inch (0.076 cm) above the wear track on the disk. This thermocouple temperature was related to the actual disk temperature by calibration with an infrared pyrometer.

The gases (air and nitrogen) used in this investigation were dried by passage through an adsorbant just before they were used to pressurize the gas bearings, from which they passed into the test chamber. The relative humidity of the gases was less than 1 percent. In the tests where oxygen concentration was varied, monitoring was done by an oxygen gage.

The disk specimens were finish-ground to 4 to 8 microinches and polished to remove machining marks. Before each use, the specimens were scrubbed with moist levigated alumina on a soft cloth, rinsed with water, rinsed with alcohol, and allowed to dry. The carbon riders were soaked in alcohol for a few minutes, allowed to dry and stored over a desiccant capable of absorbing alcohol as well as water.

The specimens were mounted in the test chamber, which was then closed and purged with the gas to be used. The disk was brought to a linear surface speed of 10 000 feet per minute (50.8 m/sec) and heated to the desired temperature. When a stable operating temperature was achieved, a 1000-gram load was applied to the rider, and the induction heating was adjusted to compensate for frictional heating. The maximum temperature variation during a run was $\pm 20^{\circ}$ F ($\pm 11^{\circ}$ C) with $\pm 10^{\circ}$ F ($\pm 6^{\circ}$ C) a typical variation.

The usual run time was 1 hour. At high temperatures, however, some carbons showed very high wear and/or bulk oxidation rates, and in these cases, the test duration was shortened to 1/2 hour or even 15 minutes. Wear volumes were calculated from the diameter of the scar on the hemispherical tip of the rider.

The coefficients of friction and the wear rates presented in this report are usually typical values. In some cases, erratic friction readings occurred during a run and are plotted as ranges. When the average wear rate for a material under a given set of conditions showed a relatively wide variation, a range of values is presented. In a few cases, performance was so poor that the tests were not repeated.

The mechanical carbons were first screened in air at 600°, 900°, and 1200° F (316°, 482°, and 649° C). The three best materials were then run at temperatures to 1400° F (760° C). All carbons were run in a nitrogen atmosphere at 1200° F (649° C). A few runs were also made at 1200° F (649° C) in an attempt to determine the critical oxygen concentration at which high friction and wear occurred.

RESULTS AND DISCUSSION

The carbon materials listed in table I were run in air against chromium-plated disks at three temperatures 600°, 900°, and 1200° F (316°, 482°, and 649° C). Friction coefficients and average wear rates are presented in figure 2. These values are typical for a given set of conditions. In some cases, however, the friction coefficient varied erratically during a run, or the wear rate showed a large variation for a given set of runs. In such cases, a range of values is indicated.

Two materials, A-CG-c and B-CG-1, had good friction and wear properties at all three initial temperatures, even though others were as good or better at 600° F (316° C) (fig. 2). A third, A-G-3, was good at 600° and 900° F (316° and 482° C). These three materials were run at additional temperatures to 1400° F (760° C) with the results shown in figure 3.

Photographs of the rider wear areas of the two best materials are presented in figure 4. The appearance of these surfaces indicates that "cropping" or spalling (ref. 6) accompanied increased wear rate.

Photographs of the rider wear areas of all materials run in air at 1200° F (649° C) are presented in figure 5. Because the runs were of different durations, the wear scar areas must not be compared for relative wear rates. These photographs indicate that spalling is common to all carbon materials that show high wear rates.. This spalling is probably associated with adhesion resulting from chemical bonding (refs. 6 and 9).

At high temperatures, carbon is a chemically active material (ref. 8, p. 417). Frictional heating can cause surface temperatures to approach the lower melting point of the contacting materials (ref. 13). For carbon-base compositions sliding on chromium, extremely high temperatures are likely at the contacting asperities. The probability of chemical reaction between the carbon rider and the mating surface (oxide film) must therefore be considered.

Chemical reaction can remove carbon from the rider in two ways: First, it could be lost as carbon dioxide or metal carbonate. Second and possibly more important, bonding to the mating metal oxide can occur while atoms are still bonded to the bulk carbon since the surface will have free valences available because of abrasive and corrosive wear. A sufficiently strong carbon-to-oxide bond would "pluck" crystals

from the rider surface, which would contribute to the cropped appearance actually observed. An additional consequence of this plucking is increased friction. In general, higher friction occurs with increased wear rate (fig. 2).

From a consideration of individual test results, the following evaluations of the compositions run in air can be made:

The best material over the temperature range investigated (600° to 1400° F or 316° to 760° C) can be considered to be B-CG-1. Substantially increased wear was, however, noted at 1300° F (704° C). Only at 1400° F (760° C) was there a noticeable spalled appearance of the wear scar or loss due to oxidation of the bulk rider material. Friction coefficients usually attained stable values within seconds of startup.

Although friction coefficients and wear rates were lower for A-CG-c than for B-CG-1, this material showed signs of loss of effectiveness (fig. 4) at a lower temperature (i. e., spalling occurred at 1200° F (649° C)). Spalling is particularly damaging in seals because the resulting wear particles increase separation of the sealing faces and therefore leakage.

The A-G-3 composition loses effectiveness between 900° and 1100° F (482° and 593° C). The loss of effectiveness, as indicated by erratic friction, may have resulted from melting of the impregnant. At disk bulk temperatures of 1100° F (593° C) and above, there is increasing exudation of the impregnant around the wear scar. The rider, a smaller mass, with continual friction heating, would be at a higher bulk temperature than the disk and evidently reaches the impregnant melting point ($>1300^o$ F or $>704^o$ C).

The material A-G-2 performed well except for a relatively high wear rate, especially at 1200° F (649° C) and had good oxidation resistance with no evidence of spalling or bulk corrosion. Friction coefficients were low at 600°, 900°, and 1200° F (316°, 482°, and 649° C).

Although A-C was good at 600° F (316° C), it was poor at 900° and 1200° F (482° and 649° C). Not only were friction coefficients and wear rates high, but spalling, as well as bulk oxidation of the rider, occurred.

The unimpregnated base grade of C-G-1 and C-G-1d, that is, C-G, was tested only at 1200° F (649° C) for comparison. Oxidation resistance, friction coefficient, and wear rate were poor.

Although impregnation in C-G-1 and C-G-1d was beneficial in that they performed better than C-G, the improvement is believed to result from decreased porosity (less surface available for reaction). Friction coefficients were erratic, and spalling occurred at all three temperatures. Bulk oxidation was not pronounced at 600° and 900° F (316° and 482° C).

The poorest material tested appeared to be A-G-1c. Although friction coefficients and wear rates were comparable with those of other materials, oxidation resistance was

very poor. Even at 600° F (316° C), there was severe bulk oxidation extending into the wear scar. At 1200° F (649° C), there appeared to be actual crumbling of the specimen.

A high-density (i.e., low porosity) material, B-Gr, performed well considering that it was unimpregnated. Friction and wear were comparable to those of most of the impregnated materials.

Similar results were obtained with D-G-1 and D-G-1d. Friction coefficients and wear rates were high at 600° and 900° F (482° and 649° C). Some bulk oxidation of the riders occurred at these temperatures.

Although graphite is more oxidation resistant than nongraphitic carbon (ref. 8, p. 418), the two materials which performed best were carbon-graphite compositions.

Impregnation of carbon materials is a method of increasing oxidation resistance and also of obtaining low friction and wear. Care must be taken, however, as to the type and method of impregnation. For example, A-G-1c which had a combination of the individual impregnants of the two best materials (B-CG-1 and A-CG-c) had poor friction, wear, and oxidation resistance even at 600° F (316° C).

Depth of impregnation is considered important. Although not very noticeable in the photographs (figs. 5(g) to (j)), a comparison of each material over several temperatures indicates the impregnant is probably deficient in the center of the wear scar. Thus, as wear occurs, a surface deficient in impregnation is exposed, and the problems alleviated by the impregnant could be reintroduced.

The impregnants used in the carbon-graphite materials were of little or no benefit in fully graphitized materials. Several graphite-base compositions (C-G-1, C-G-1d, D-G-1, and D-G-1d) with the same type of impregnant as the best material (B-CG-1) had poor friction and wear properties at 900° and 1200° F (482° and 649° C).

The carbon-graphite materials have two advantages which may contribute to good performance. Greater hardness reduces the real contact area and, therefore, the friction coefficient (ref. 13). Lower porosity means that less total surface area is exposed to oxidation. The reduction in surface area available for oxidation can compensate for the lower oxidation rate of graphite. The result could be reduced oxidative wear.

All the materials listed in table I were also run in nitrogen at 1200° F (649° C) with the results presented in figure 6. Results from the runs in air at 1200° F are also plotted for comparison. The wear areas of the carbon riders are shown in figure 7.

All materials had lower wear rates in nitrogen than in air at 1200° F (649° C). Coefficients of friction were also generally lower in nitrogen. In addition, as shown in figure 7, spalling or cropping did not occur as it did in the air runs (fig. 5). Also, in general, a composition that showed a relatively high wear rate and friction coefficient in air showed relatively high values in nitrogen (fig. 6).

The material that had the best friction and wear properties in 1200° F (649° C)

nitrogen was A-G-3. However, as in air, there was some exudation of the impregnant, which could be a limiting factor in long term use of the material.

The best materials in air, B-CG-1 and A-CG-c, had friction and wear values in nitrogen that were comparable with the air values. However, friction values varied for different runs (A-CG-c) or were somewhat erratic (B-CG-1).

In nitrogen, A-G-2, with a great decrease in wear rate, and A-G-1c, with large decreases in friction coefficient and wear rate, are nearly as good as A-G-3.

Comparing C-G-1 and C-G-1d with the base grade, C-G, indicates that in nitrogen at 1200° F (649° C) the impregnant lowers the friction coefficient slightly but increases the wear rate.

Several runs were made at a sliding speed of 500 feet per minute (2.55 m/sec) and 1200° F (649° C) to determine the oxygen concentration at which detrimental effects became evident. Oxygen concentration was varied by admitting air to the nitrogen entering the test chamber. The material that was used as the rider sliding against the chromium plate, C-G-1, had shown a marked difference of friction and wear in air and in nitrogen. An oxygen concentration above 5 parts per million increased the friction coefficient from 0.15 (in nitrogen containing about 3 ppm oxygen) to 0.75. When the air supply was shut off, the friction coefficient returned to 0.15.

SUMMARY OF RESULTS

Experimental wear and friction studies of mechanical carbons for seals run dry in air and in nitrogen at high temperatures gave the following results:

1. At a temperature of 1200° F (649° C), mechanical carbons gave better performance in dry nitrogen than in dry air.

2. Two mechanical carbon compositions (B-CG-1 and A-CG-c) functioned well in air during sliding contact with chromium plate at temperatures to 1200° F (649° C).

3. A primary cause of wear for carbons in air at high temperatures appeared to be oxidation (corrosive wear). Failure at high temperature occurred at the high rate of wear associated with spalling or cropping of the sliding surface. Chemical bonding at the interface may increase adhesion and thus cause spalling and the observed high, erratic friction.

4. Additive agents or impregnants acted as oxidation inhibitors and effectively reduced wear for both graphite and carbon-graphite mechanical carbons at temperatures to 1200° F (649° C).

5. Increased graphite content in a carbon seal did not sufficiently improve oxidation resistance to provide low wear at the higher temperatures studied.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, January 27, 1967,
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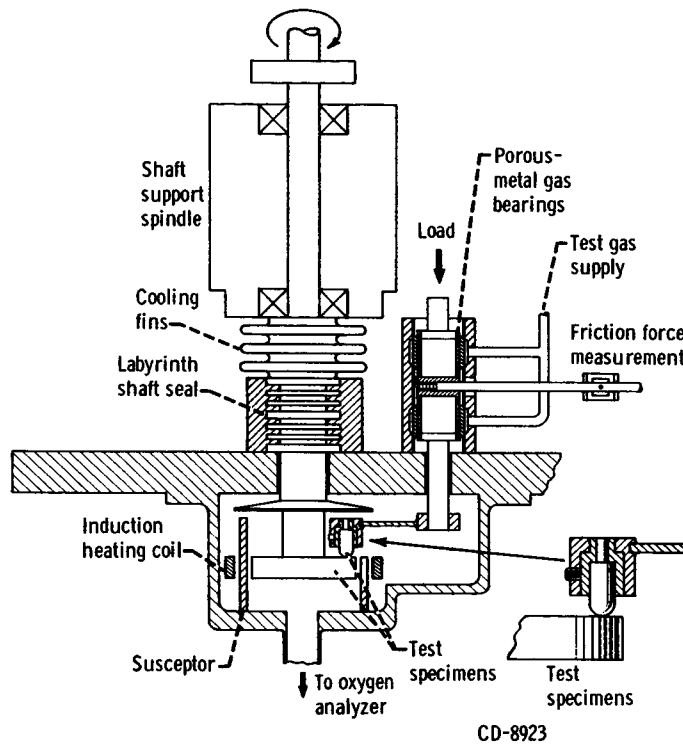13. Bowden, F. P.; and Tabor, D.: The Friction and Lubrication of Solids. Part I, Clarendon Press, Oxford, 1950.

Shaft support spindle

Cooling fins

Labyrinth shaft seal

Induction heating coil

Susceptor

Load

Porous-metal gas bearings

Test gas supply

Friction force measurement

To oxygen analyzer

Test specimens

Test specimens

CD-8923

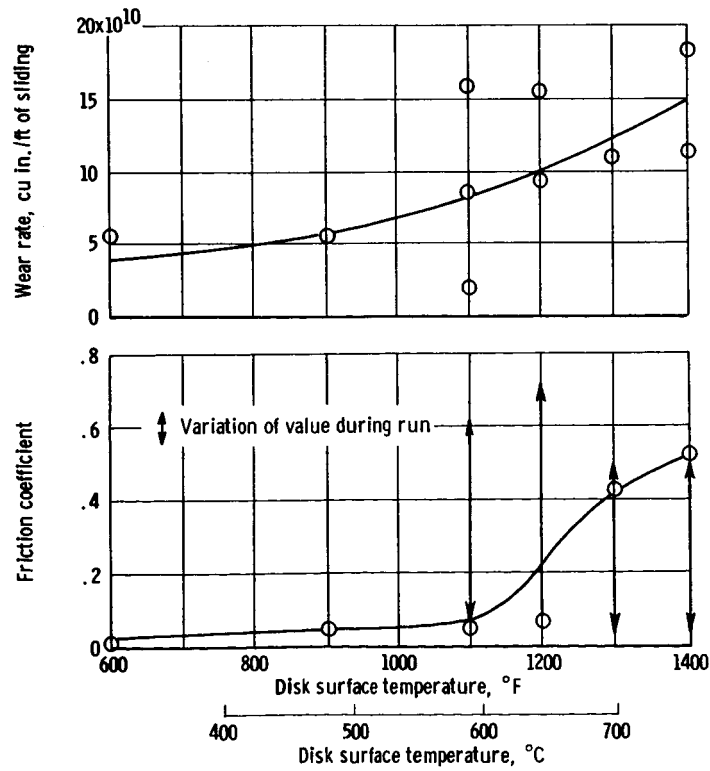Figure 1. – Friction and wear test apparatus.
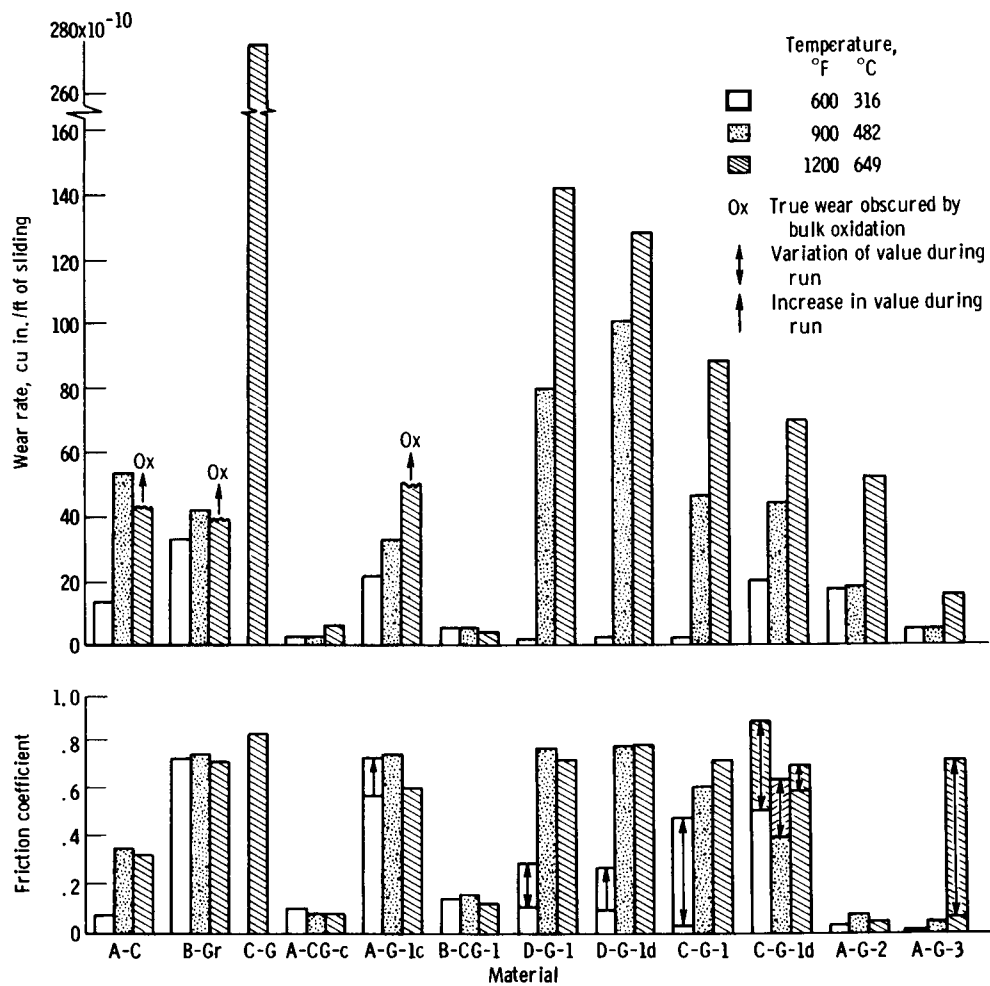
Figure 2. – Friction and wear of carbon-base materials sliding against chromium-plated nickel-base alloy in air at various temperatures. Load, 1000 grams; sliding velocity, 10 000 feet per minute (50.8 m/sec).
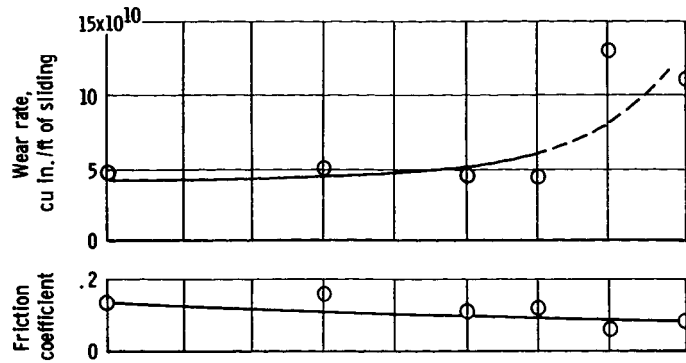
(a) Material, B-CG-1.
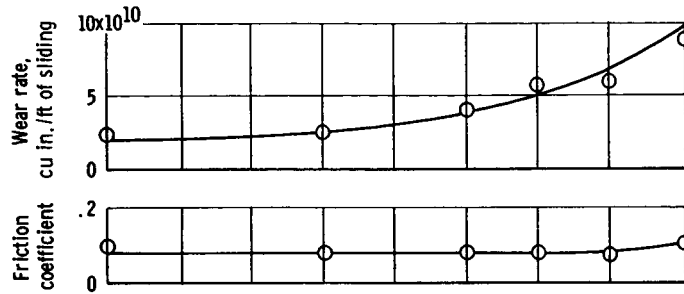
(b) Material, A-CG-c.

(c) Material, AG-1.

Figure 3. - Effect of temperature on friction and wear of carbon-base materials sliding on chrome plate. Load, 1000 grams; sliding velocity, 10 000 feet per minute (50.8 m/sec).
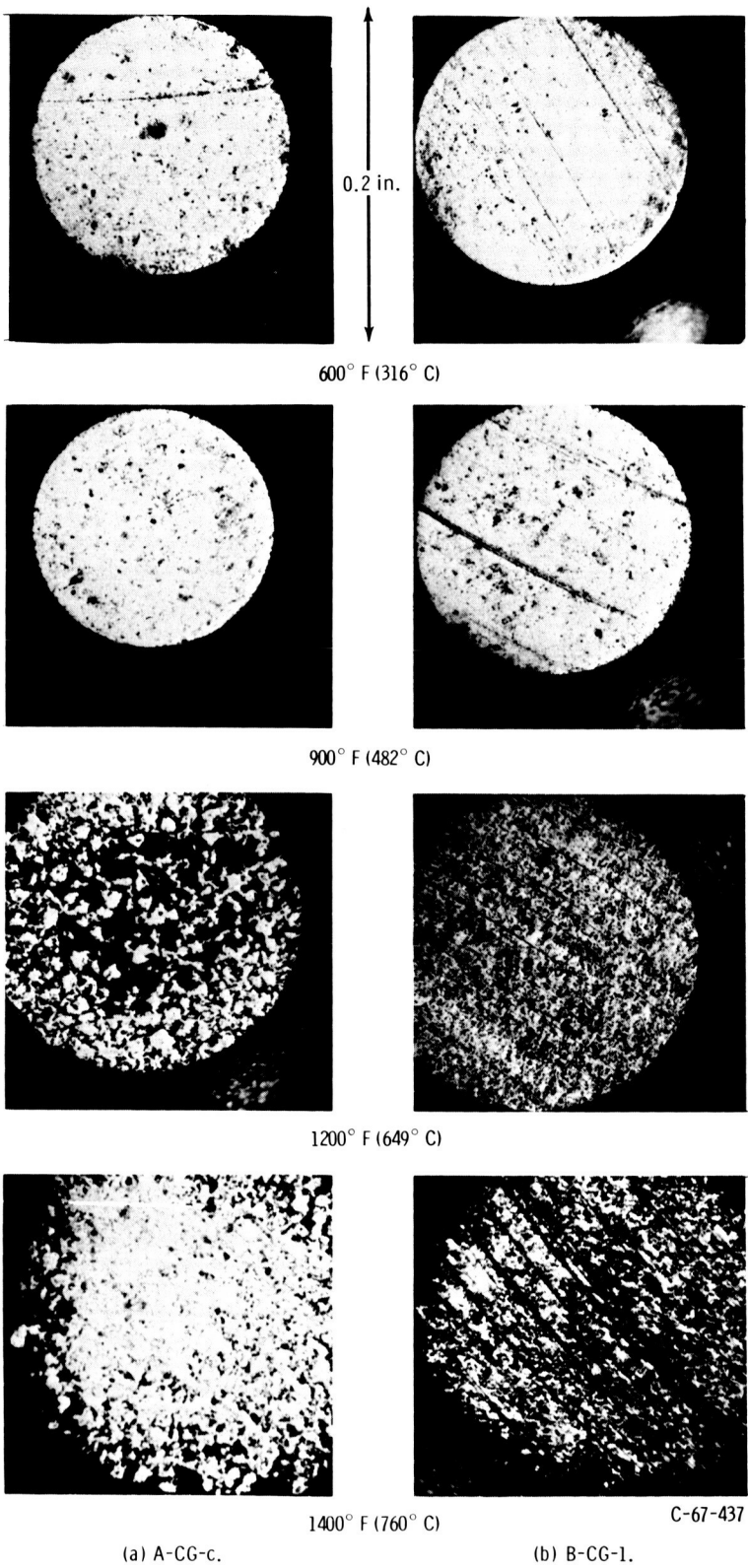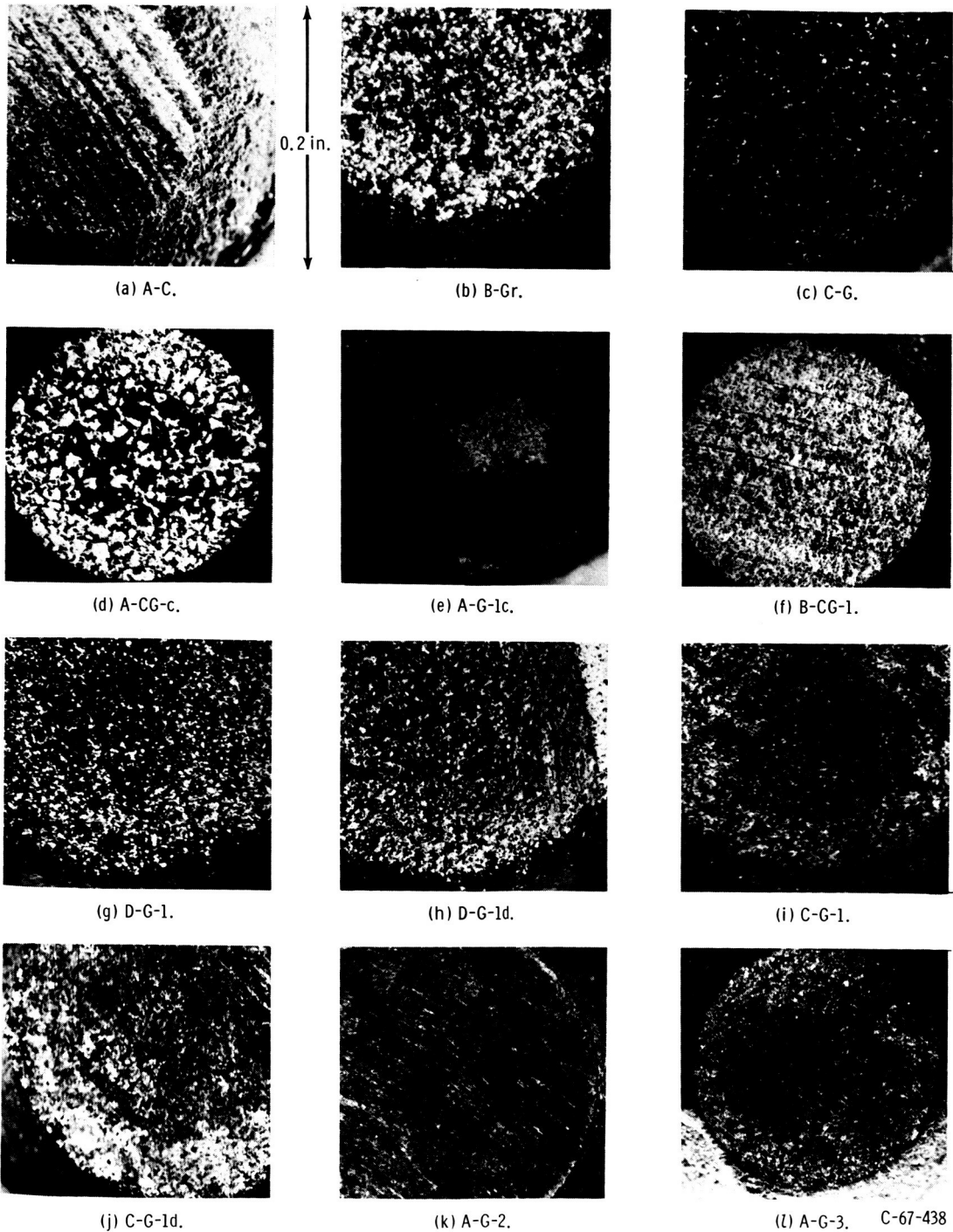
0.2 in.

600° F (316° C)

900° F (482° C)

1200° F (649° C)

1400° F (760° C)

C-67-437

(a) A-CG-c.

(b) B-CG-1.

Figure 4. - Wear areas of mechanical carbons run on chromium-plated disks in air at various temperatures. Load, 1000 grams; sliding velocity, 10 000 feet per minute (50. 8 m/sec); duration of run, 1 hour.

(a) A-C.

(b) B-Gr.

(c) C-G.

(d) A-CG-c.

(e) A-G-1c.

(f) B-CG-1.

(g) D-G-1.

(h) D-G-1d.

(i) C-G-1.

(j) C-G-1d.

(k) A-G-2.

(l) A-G-3.　　C-67-438

Figure 5. – Wear areas of mechanical carbons run on chromium-plated disks in air at 1200° F (649° C). Load, 1000 grams; sliding velocity, 10 000 feet per minute (50.8 m/sec).
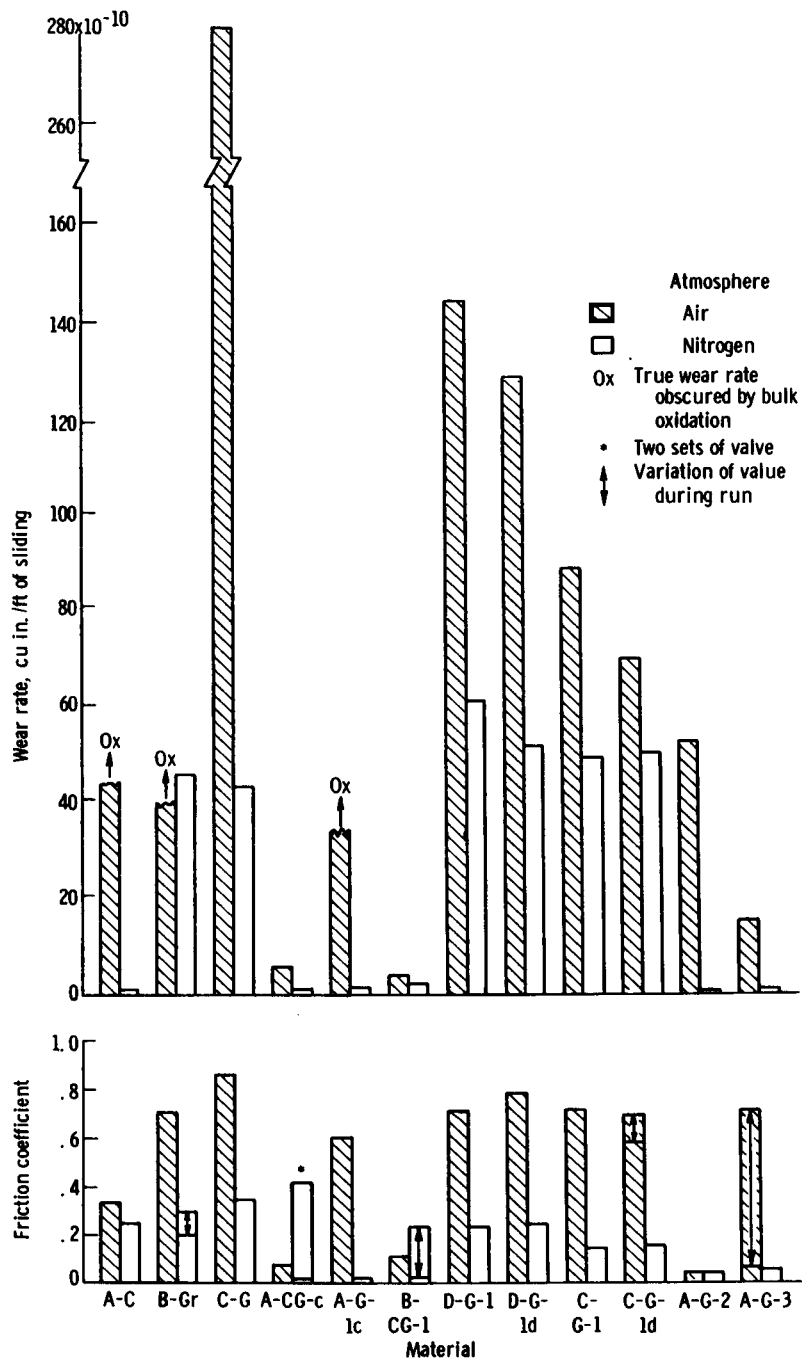
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Figure 6. - Friction and wear of carbon-base materials sliding against chromium plate in air and in nitrogen at 1200° F (649° C). Load, 1000 grams; sliding velocity, 10 000 feet per minute (50.8 m/sec).
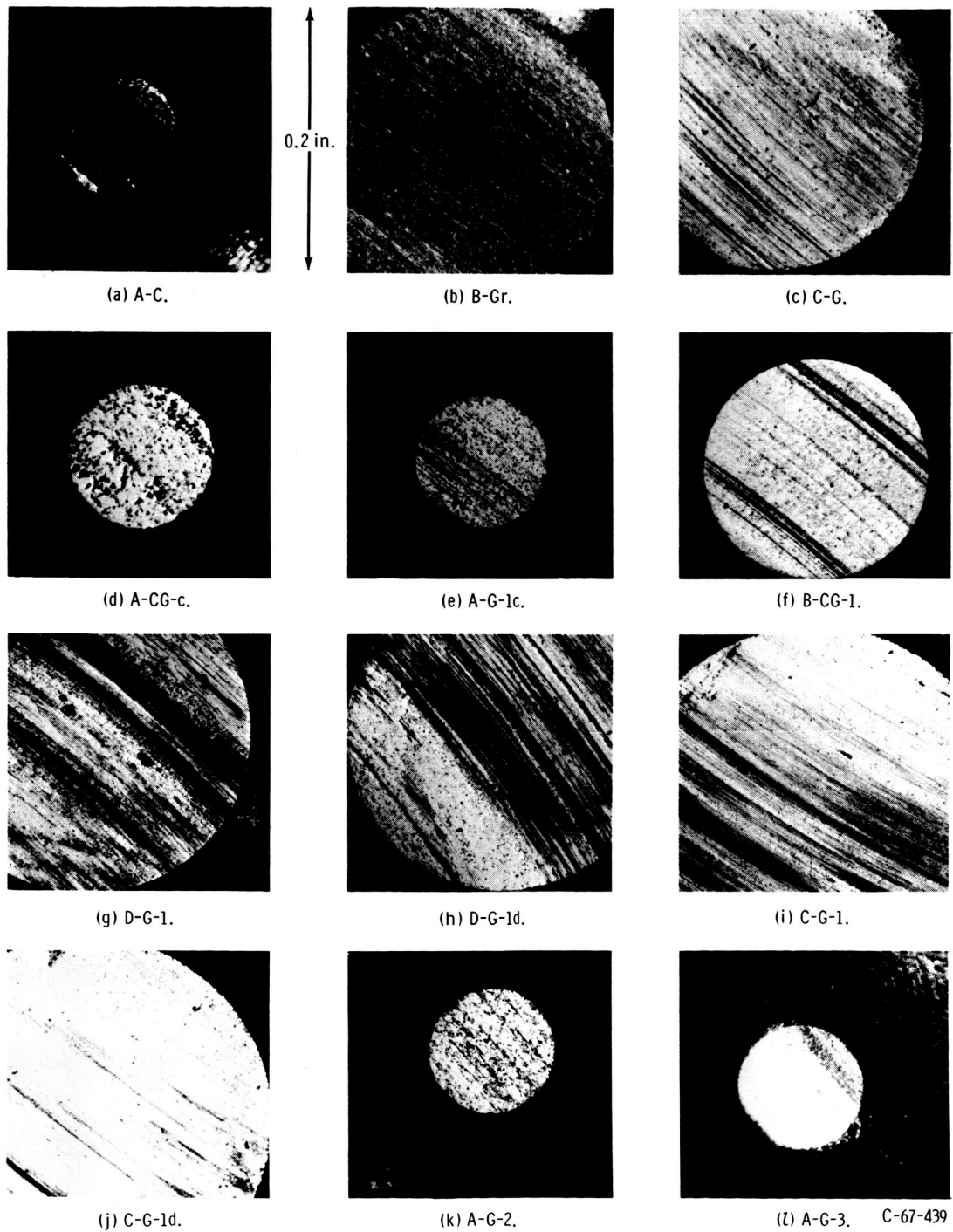
(a) A-C. (b) B-Gr. (c) C-G.

(d) A-CG-c. (e) A-G-1c. (f) B-CG-1.

(g) D-G-1. (h) D-G-1d. (i) C-G-1.

(j) C-G-1d. (k) A-G-2. (l) A-G-3.   C-67-439

Figure 7. - Wear areas of mechanical carbons run on chromium-plated disks in nitrogen at 1200° F (649° C). Load, 1000 grams; sliding velocity, 10 000 feet per minute (50.8 m/sec).

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