NASA TECHNICAL NOTE

NASA TN D-7756

NASA TN D-7756

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SOME METAL-GRAPHITE AND METAL-CERAMIC COMPOSITES FOR USE AS HIGH-ENERGY BRAKE LINING MATERIALS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1974

1. Report No.
NASA TN D-7756

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
SOME METAL-GRAPHITE AND METAL-CERAMIC COMPOSITES FOR USE AS HIGH-ENERGY BRAKE LINING MATERIALS

5. Report Date
August 1974

6. Performing Organization Code

7. Author(s)
Robert C. Bill

8. Performing Organization Report No.
E-7845

10. Work Unit No.
501-24

9. Performing Organization Name and Address
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Note

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
Four families of materials were studied as candidates for development as potential new aircraft brake lining materials. These families were (1) copper-graphite composites; (2) nickel-graphite composites; (3) copper - rare-earth-oxide (gadolinium oxide (Gd_2O_3) or lanthanum oxide (La_2O_3)) composites and copper - rare-earth-oxide (La_2O_3) - rare-earth-fluoride (lanthanum fluoride (LaF_3)) composites; (4) nickel - rare-earth-oxide composites and nickel - rare-earth-oxide - rare-earth-fluoride composites. For comparison purposes, a currently used metal-ceramic composite was also studied. Results showed that the nickel-Gd_2O_3 and nickel - La_2O_3-LaF_3 composites were comparable or superior in friction and wear performance to the currently used composite and therefore deserve to be considered for further development.

17. Key Words (Suggested by Author(s))
Brakes; High energy; Cermet; Nickel-graphite; Nickel - rare-earth-oxide; Copper-graphite; Copper - rare-earth-oxide; Hot-pressed composites

18. Distribution Statement
Unclassified - unlimited
Category 17

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	22	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

SOME METAL-GRAPHITE AND METAL-CERAMIC COMPOSITES FOR USE AS HIGH-ENERGY BRAKE LINING MATERIALS

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SUMMARY

A caliper-brake evaluation was used to study four families of candidate materials for potential applicability as aircraft brake linings. Also, a currently used metal-ceramic composite was studied as a basis for comparison. The four families of candidate materials were (1) copper-graphite composites; (2) nickel-graphite composites; (3) copper - rare-earth-oxide (gadolinium oxide (Gd_2O_3) or lanthanum oxide (La_2O_3)) composites and copper - rare-earth-oxide (La_2O_3) - rare-earth-fluoride (lanthanum fluoride (LaF_3)) composites; and (4) nickel - rare-earth-oxide composites and nickel - rare-earth-oxide - rare-earth-fluoride composites. Friction characteristics, wear rates, and photographic evidence were used to assess the performance of each of the materials studied. The nickel - rare-earth-oxide and nickel - rare-earth-oxide - rare-earth-fluoride composites performed well compared to the currently used metal-ceramic. These two families of materials ought to be considered for further development.

INTRODUCTION

The friction lining material in an aircraft brake assembly must convert the kinetic energy of the rolling aircraft into heat and conduct it to a heat sink without being destroyed itself. Typical brake applications require that the sliding interface convert about 15 000 to 20 000 foot-pounds per square inch (3200 to 4200 $N\text{-}m/cm^2$) of kinetic energy to heat in about 30 seconds (ref. 1). Thus, the materials composing the brake lining must have a high thermal conductivity and volume specific heat (product of density and specific heat) (ref. 2), and they must possess good friction and wear properties at high temperature. Ideally, a good lining material should have the qualities of low wear, uniform friction without fading or squealing, and the ability to maintain mechanical integrity through many brake applications.

Currently used brake materials are essentially sintered metal (usually copper) structures with various solid-lubricant additives, such as graphite, and other additives to control metal transfer, such as mullite (refs. 3 and 4). Copper is subject to softening at sliding interface temperatures that can easily exceed 870° C (1600° F), this softening being a primary cause of brake fading. Also, the sliding characteristics of graphite, after it is exposed to the many different environments experienced in aircraft operation, are unpredictable. Another undesirable brake phenomenon encountered in the currently used metal-ceramic composites is squeal, or friction induced vibration, usually occurring during low-speed applications. The vibrations can be destructive to the aircraft landing gear components and can be very annoying to the passengers.

The purpose of this report is to investigate the high-speed friction and wear behavior of some alternative metal-binder - solid-lubricant systems that might be used as brake lining materials. Results from a currently used commercial metal-ceramic composite (a copper-base graphite-mullite system) serve as a reference, or basis for comparison, against which to judge the performance of the experimental materials. The experimental material systems include copper-graphite, copper with rare-earth oxides and rare-earth fluorides, nickel-graphite, and nickel with rare-earth oxides and rare-earth fluorides. The solid lubrication potential of rare-earth oxides and fluorides at high temperatures was described in reference 5. The experimental copper-graphite system, similar to the currently used composite, provided a second basis for comparison with the other systems. This second basis is important, because the processing and material quality were on the same level as those of the other experimental materials.

The applied loads (70 to 80 N/cm^2) and sliding speeds (about 30 m/sec) used in this study were comparable to those encountered in hard landing operations. Hence, the frictional heat generated per unit experimental brake lining material area was of the same order as that in an actual aircraft brake application. The performance of the materials was judged on the basis of a wear parameter (see the appendix) defined by the lining material wear volume divided by the frictional energy flux (frictional energy per unit lining area). In addition, microscopic examinations were used to gain some insight pertaining to the wear mechanisms operating.

MATERIALS

Three procedures were used to prepare the composite materials studied in this investigation. The hot pressing (uniaxial) and the hot isostatic compression techniques were both used to consolidate mixtures of metal (nickel (Ni) or copper (Cu)) and ceramic powders (graphite, gadolinium oxide (Gd_2O_3), or lanthanum oxide (La_2O_3), or La_2O_3 and lanthanum fluoride (LaF_3)). Initially specimens were prepared by hot isostatic compression, but as difficulties were encountered in consistently sealing the isostatic compression cans, the uniaxial hot pressing technique was later adopted. Samples of nickel - 30-percent-graphite composites were obtained by using both techniques, and little difference was observed in their friction and wear behavior. In addition to the two powder consolidation methods, flame spraying was used to obtain a few specimens. The material combinations, methods of preparation, and preparation parameters are summarized in table I.

The copper and nickel powders were of 99.5 percent purity and had a nominal particle size of 100 mesh. The rare-earth oxides and fluorides were of 99.9 percent purity and had a particle size known to be smaller than that of the metal powders (but not known exactly because a size analysis was not available). The graphite powder used was of approximately 99.9 percent purity and had a particle size of approximately 20 micrometers.

The rotating disks were commercially produced aircraft brake rotors, composed of 17-22 A(S) steel (iron, 0.3 percent carbon, 1.3 percent chromium, 0.5 percent molybdenum, and 0.25 percent vanadium).

APPARATUS

The apparatus, shown in figure 1 consisted of a 35.6-centimeter- (14-in.-) diameter brake disk driven by a 40-horsepower electric motor. The lining material specimens were loaded, caliper fashion, against the disk by a pair of hydraulic cylinders. Both specimens were fully loaded against the disk within 0.1 to 0.5 second of one another. The grip assembly contained a ball-in-socket mounting to provide for specimen alinement with respect to the disk. The support holding the specimens and hydraulic cylinders was secured to the stationary framework by a pair of flexible plate assemblies, which allowed for the transmission of the friction force to a strain-gage ring, mounted on the framework. The rotational speed and normal force between the specimen and the disk (hydraulic pressure) were also measured.

The materials formed by hot pressing or hot isostatic compression were in the form of 1.27-centimeter- (1/2-in.-) diameter disks, about 0.64 centimeter (1/4 in.) thick, and were mounted in the grip assemblies in sets of four, two on each side of the disk. The flame-sprayed composites and the currently used metal-ceramic composite were in the form of 2.54-centimeter- (1-in.-) diameter disks, 0.32 centimeter (1/8 in.) thick, and were used in pairs, one on each side of the disk.

When the total performance of brake lining materials is assessed, the only substitute for actual vehicle tests is full-scale dynamometer testing. Such testing is impractical for screening research evaluation, however, as the specimen size and experimental costs are prohibitive. The caliper type of machine, such as the apparatus used in this study, is widely employed in screening and quality control work. Its chief drawback, which makes the extrapolation of caliper data to full-size situations uncertain, is the contact geometry (refs. 6 and 7). When the contact geometry is discontinuous, which is the case if the ratio of the stationary pad area to the total swept area is small, lining (pad) temperatures tend to stay lower than when a continuous contact situation exists on both the sliding and the stationary surfaces, as is the case in a full-size aircraft brake assembly. This difference between caliper geometry screening studies and full-scale simulation should be kept in mind when evaluating friction lining test results.

PROCEDURE

The experimental composite pads were surface finished on 600 grit wet polishing paper, cleaned, dried in a hot air blast, and stored in a desiccator prior to testing. In this condition, the surface areas occupied by both the metallic and ceramic phases were in proportion to the volume composition. The rotating disks were surface ground to a 0.4-micrometer (16-μin.) rms finish.

Immediately before being tested, the composite pads were weighed. They were then fastened into the specimen holders, thermocouples were implanted in the back of the holders (or the pads themselves in the case of the 2.54-centimeter- (1-in.) diameter specimens), and the specimens were loaded against the stationary disk surface. The ball-in-socket joints were tightened, and the pads were unloaded. The composite specimens were alined with respect to the disk surface, and the disk was cleaned with trichloroethylene.

Two types of brake evaluations were conducted in this investigation. The first was an inertial test designated a simulated stop, in which the motor rotor and disk were set into rotation so that the disk surface velocity at the contact radius was 31 meters per second (100 ft/sec). The power to the motor was then switched off, and the composite pads were loaded against the disk and braked it to a stop. The standard contact load varied slightly from 72 to 82 newtons per square centimeter, depending on the specimen configuration used, which was in turn dictated by the number of specimens of a given material available. Moment of inertia calculations of the rotating system showed that the rotational kinetic energy, when the brake was applied, was about 35 300 newton-meters (26 000 ft-lb). Thus, for the specimen dimensions used in this investigation, the kinetic energy conversion per unit pad area during a simulated stop was similar to that experienced by a typical full-size brake during a landing. This type of test was generally applied to a set of composite pad specimens three times in succession. The pads were then removed from the apparatus and weighed to determine the amount of wear that occurred.

The second type of evaluation was designated a constant-speed test. The motor and disk were brought up to a prescribed speed, and the pads were loaded against the disk with the speed held constant. This was performed in succession at three speed levels: 31, 26, and 20 meters per second (100, 83, and 67 ft/sec). The constant-speed tests were much more severe than the simulated stops, and measured weight losses were usually proportionally higher.

In addition to specimen weight loss measurements, micrographs of the composite pad sliding surfaces were made, and evidence of metal transfer to the disk, transfer film formation, or disk scoring was noted. A fresh 17-22 A(S) disk was used for each composite pad material.

RESULTS AND DISCUSSION

The coefficient of friction and the weight loss data for each material are presented in table II and figure 2. Note that the weight loss data are presented in two forms in table II. A simple weight loss measurement and a specific wear rate parameter are presented. The specific wear rate is obtained by dividing the measured weight loss by the density and by the total braking energy dissipated per unit contact area. This calculation actually gives wear volume per unit energy dissipated per unit area. The derivation of the specific wear rate parameter is presented in the appendix. The specific wear rate is felt to be a more valid basis for comparison than weight loss measurements, as it includes a measure of the braking performance of the materials.

Currently Used Metal-Ceramic Composite (Reference Material)

The results in table II show that the average friction coefficient of the metal-ceramic composite was about 0.38 in the constant-speed tests and about 0.5 in the simulated-stop tests. These values were somewhat higher than those measured on the other materials. However, the specific wear rate (0.72 in constant-speed tests) was mediocre compared to those for the other materials.

A constant-speed friction trace and a simulated-stop trace are shown in figures 3(a) and (b), respectively. The significant features are the smooth steady-state friction force observed in both cases and some evidence of grabbing, or high unsteady friction, observed at the end of the simulated stop. Grabbing, a very undesirable feature, often occurs at the end of a landing roll and results in squealing and severe vibration.

Another problem commonly encountered in brake lining materials is fading, or the reduction in friction after severe brake operation during which very high lining temperatures are developed. In an attempt to observe fading in the metal-ceramic composite, the specimens were loaded against the disk running at a constant 31 meters per second (100 ft/sec) for 30 seconds. Bulk pad temperatures of 540° C (1000° F) were measured on the backing of the pads, but as may be seen in figure 3(c), no evidence of fading was observed.

Wear of the metal-ceramic composite seemed to progress largely by the mechanism of surface spall pit formation and growth, as may be seen in figure 4. The number and size of the spall pits increase with the number of sliding exposures and are not obviously related to the features initially present on the surface before sliding. Most likely the spall pits are a result of surface thermal effects. Locally unsteady contact and severe subsurface temperature gradients result in subsurface thermal stresses that cause cracking and spalling. This mechanism is described in detail in reference 2.

Copper-Graphite and Nickel-Graphite Systems

Three copper-graphite formulations were examined: copper - 50-percent-graphite, copper - 30-percent-graphite, and copper - 15-percent-graphite. As a class, the copper-graphite composites showed a specific wear rate (0.07 to 0.6) as low as or lower than that of any other category of materials examined, and from the standpoint of specific wear rate they generally performed better than the currently used metal-ceramic composite.

Of the copper-graphite composites, the copper - 50-percent-graphite composite showed the highest friction (0.3 to 0.34), with the 15- and 30-percent-graphite materials both having a coefficient of friction of 0.24 in simulated-stop tests. This observation is difficult to understand solely on the basis of graphite working as a solid lubricant. Perhaps it may be explained by considering that the graphite was able to lubricate effectively, even in the case of the 15-percent-graphite composite, by producing an easily shearable graphite transfer film and preventing gross metal transfer. Since the hardness of the nickel-graphite composites derives from the bonding between the nickel particles, one would expect the nickel - 50-percent-graphite composite to be softer than the nickel - 30-percent-graphite composite, as is shown to be the case in table I. The comparative softness of the nickel - 50-percent-graphite composite resulted in a large real area of contact between the pad and the disk. The shear strength of the contact areas is determined by the properties of the graphite transfer film, which should be about the same in the case of the nickel - 50-percent-graphite and nickel - 30-percent-graphite composites. Thus, the frictional force for the nickel - 50-percent-graphite composite ought to be higher than that for the nickel - 30-percent-graphite composite by virtue of the larger actual contact area associated with the former. This situation is described by Bowden and Tabor in reference 8.

The copper-graphite composites showed some evidence of fading toward the end of the simulated-stop experiments, as indicated in figure 5. The friction remained fairly uniform during the constant-speed experiments, with a slight increase observed with time of application at a given speed.

The surface cracking and pitting of the copper-graphite materials was similar to that observed in the current metal-ceramic composite. In addition, a surface smearing was observed, with the areas of actual contact being covered by a graphite film.

The results from the nickel - 50-percent-graphite composites show a friction coefficient of 0.17 in the 82-newton-per-square-centimeter (120-psi) application, with corresponding specific wear rates of 0.045×10^{-6} and 0.07×10^{-6} in the constant-speed and simulated-stop tests, respectively. These particular wear rates are even lower than those associated with the copper-graphite composites and are the lowest of those for all the materials examined. When the normal load was increased to 155 newtons per square centimeter (220 psi), however, the coefficient of friction rose to 0.28, and the specific wear rate increased dramatically to 1.1×10^{-6}, which indicated a change in the friction and wear mechanism. Evidence of nickel transfer to the disk was observed after the 155-newton-per-square-centimeter (220-psi) application, and significant differences emerged in the nature of the friction, as shown in figures 6(a) and (b), for the 85- and 155-newton-per-square-centimeter applications, respectively. Grabbing or seizure occurred near the end of the 155-newton-per-square-centimeter (220-psi) application.

Whereas the friction curve for the nickel - 50-percent-graphite composite was rather smooth during the 82-newton-per-square-centimeter (120-psi) application (fig. 6(a)), the nickel - 30-percent-graphite composite showed a higher, much rougher friction curve, as may be seen in figure 6(c). Furthermore, the specific wear rate parameter of the nickel - 30-percent-graphite composite was very high (3.2 to 8.6) compared to that of the nickel - 50-percent-graphite composite under the 82-newton-per-square-centimeter (120-psi) load condition.

Copper-Base and Nickel-Base Rare-Earth Oxide and Fluoride Composites

The coefficients of friction of the hot isostatically compressed copper-gadolinium oxide and copper - lanthanum oxide - lanthanum fluoride composites were 0.32 and 0.35, respectively, comparable with that for the currently used metal-ceramic composite. However, the specific wear rates of the experimental materials were higher. The primary wear mechanisms appeared to be copper transfer to the disk, which resulted in severe specimen plowing and crumbling due to the large transferred copper particles. This is a case in which the ceramic constituents, intended to act as lubricants, did not form a film efficiently enough to prevent excessive wear. Similar behavior was observed in the case of the flame-sprayed copper - rare-earth-oxide and copper - rare-earth-fluoride composites, which indicated that the composition and not the material processing technique was dominating the friction and wear process.

In the nickel - rare-earth-oxide system, the nickel - 30-percent gadolinium oxide composite appeared to be more successful than the nickel - 30-percent lanthanum oxide composite, the specific wear rate parameters in constant-speed experiments being about 0.2 and 1.0, respectively. Note that the specific wear rate parameter of 0.9 observed in a nickel - gadolinium oxide composite occurred during an experiment in which the load was varied up to 105 newtons per square centimeter (142 psi), higher than the 82-newton-per-square-centimeter (120-psi) contact pressure normally used. Little evidence of nickel transfer to the disk was observed with either of these composites. The friction was smooth in both cases, with a slight trend of increasing friction with increasing time of application at constant speed, as may be seen in figure 7. The surfaces of the specimens showed evidence of film formation and the generation of wear by surface cracking or spalling mechanisms (fig. 8).

A nickel - 15-percent lanthanum oxide - 15-percent lanthanum fluoride composite was tested to verify whether the lanthanum fluoride addition improved lubrication of the nickel composite system, as was suggested in reference 4. The data showed that the specific wear rate parameter was approximately one-half that of the nickel - 30-percent lanthanum oxide composite, with the friction not significantly changed. In the simulated-stop experiments though, this material consistently showed grabbing or seizure behavior as the sliding speed approached zero, as may be seen in figure 9.

Increasing the concentration of lanthanum oxide and lanthanum fluoride to 25 percent each resulted in a marginal, if any, reduction in the specific wear rate parameter and a reduction in friction coefficient to 0.2 in the constant-speed experiments. Also, the tendency to grab or seize toward the end of a simulated stop was still present in the nickel - 25-percent lanthanum oxide - 25-percent lanthanum fluoride composites. Observe the similarity in behavior (in table II) of the hot-pressed and flame-sprayed composites of this composition.

Metallographic sections were made of hot-pressed nickel - 25-percent lanthanum oxide - 25-percent lanthanum fluoride pads after they were subjected to three constant-speed exposures. Examination of the sections revealed the presence of a continuous film about 10 micrometers thick on the sliding surface, as shown in figure 10. Also, the ceramic particles are broken up by the severe deformation of the composite to a depth of about 100 micrometers below the sliding surface. The surface film was probably responsible for preventing metal transfer and accelerated wear.

CONCLUSIONS

Based on the results of constant-speed and simulated-stop experiments on some metal-graphite and metal-ceramic composites for use as high-energy brake lining materials, the following conclusions may be drawn:

1. Nickel - gadolinium oxide composites and nickel - lanthanum oxide - lanthanum fluoride composites showed promising friction and wear properties, for example, lower

specific wear parameter than that of the current commercial composite. They are, therefore, considered to be worthy of further development.

2. On the other hand, copper - gadolinium oxide composites and copper - lanthanum oxide - lanthanum fluoride composites showed very high specific wear rate parameters and seemed prone to crumbling during the braking experiments.

3. The effectiveness of graphite additions to nickel were significantly different for 30- and 50-percent-graphite concentrations. The specific wear rate parameter of the 30-percent-graphite composite was two orders of magnitude higher than that of the 50-percent-graphite composite when tested at an 82-newton-per-square-centimeter load level. Increasing the load applied to the 50-percent-graphite composite to 155 newtons per square centimeter (to compensate for low friction), however, increased the specific wear rate parameter by about an order of magnitude.

4. The copper-graphite composites, similar to the currently used commercial reference material showed specific wear rate parameters generally lower than those of the reference material. Because of their temperature limitation, however, copper-based composites are not considered to be good candidates for future brake lining materials.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 1, 1974,
501-24.

APPENDIX - DERIVATION OF SPECIFIC WEAR RATE PARAMETER

The specific wear rate parameter is an expression comparing the volume of wear suffered by a lining material to the frictional energy generated per unit lining area. Wear volume is considered, rather than wear rate, since the criterion for actual brake lining rejection is based on wear volume. The frictional energy generated per unit experimental lining area is considered, rather than simply the frictional energy generated, because taking the area into account gives an indication of the temperature rise near the sliding surface and temperature gradients in the lining. These thermal effects determine the mechanical property degradation of the lining material and the wear mechanisms that operate.

The wear volume is found from the measured weight loss by

$$V = \frac{\Delta W}{\rho}$$

where V is the wear volume, ΔW is the measured weight loss, and ρ is the lining material density. The frictional energy generated is given by

$$E = \int_0^{t^*} \mu(t) F V \, dt$$

where E is the frictional energy generated, t^* is the time of brake application, $\mu(t)$ is the time-varying coefficient of friction, F is the normal load, and V is the sliding velocity. In general, it is possible to simplify this expression as follows:

$$E = \bar{\mu} F V t^*$$

where $\bar{\mu}$ is an average or effective friction coefficient. (This equation is true only for the constant-speed experiments where V does not vary with t. For simulated-stop experiments, $\bar{\mu} F V t^*$ is simply replaced by the rotational kinetic energy of the motor rotor and disk assemblies.) The area of concern A is simply the total apparent brake lining material surface area for an experiment. The specific wear rate parameter is then given by

$$\Omega' = \frac{\Delta V}{E/A} = \frac{\Delta W/\rho}{\overline{\mu}FVt^{*}/A} = \frac{\Delta W}{\rho\overline{\mu}PVt^{*}}$$

where P is the normal lining pressure. It turns out that Ω' is of the order of 10^{-6} cubic centimeter per newton-meter per square centimeter; for convenience in the text Ω' is replaced by Ω, where $\Omega = 10^{6}\Omega'$.

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TABLE I. - MATERIALS TESTED

Material composition, vol. %	Preparation process	Conditions			Density, g/cm^3	Rockwell H hardness
		Pressure, N/cm^2	Temperature, ^oC	Time, hr		
Metal-ceramic[a]	Cold pressing and sintering	------	----	-	4.6	60
Cu-50graphite	Hot pressing	6 900	930	1	4.4	-50
Cu-30graphite	↓	↓	930	↓	4.9	69
Cu-15graphite	↓	↓	930	↓	5.0	5
Ni-50graphite	↓	↓	1150	↓	4.1	40
Ni-30graphite	↓	↓	1150	↓	4.5	85
Ni-30graphite	Hot isostatic compression	13 800	1260	2	4.5	40
Cu-30Gd_2O_3	↓	↓	980	↓	8.0	---
Cu-25La_2O_3-25LaF_3	↓	↓	980	↓	6.7	---
Ni-30Gd_2O_3	↓	↓	1260	↓	8.0	107
Ni-30La_2O_3	↓	↓	1260	↓	6.8	90
Ni-15La_2O_3-15LaF_3	↓	↓	1260	↓	6.7	85
Ni-25La_2O_3-25LaF_3	Hot pressing	6 900	1150	1	6.8	113
Ni-25La_2O_3-25LaF_3	Flame spraying	------	----	-	6.5	---

[a] Reference material.

TABLE II. - MATERIAL PERFORMANCE

Material composition, vol. %	Test type	Normal load, N	Normal stress, N/cm^2	Average friction coefficient, $\bar{\mu}$	Weight loss, g	Energy absorbed, N-m	Specific wear rate, Ω, $cm^3/(N\text{-}m/cm^2)$
Metal-ceramic[a]	Constant-speed	400	76	0.38	0.075	120×10^3	0.72×10^{-6}
	Simulated-stop	400	76	.50	.042	60	.56
Cu-50graphite[b]	Constant-speed	220	82	0.30	0.015	32×10^3	0.14×10^{-6}
Cu-30graphite[b]	Simulated-stop	220	82	.34	.014	30	.13
		220	82	.24	.025	10	.6
Cu-15graphite[b]	Constant-speed	220	82	0.28	0.008	30×10^3	0.07×10^{-6}
	Simulated-stop	220	82	.24	.016	30	.14
Ni-50graphite[b]	Constant-speed	220	82	0.17	0.002	14×10^3	0.07×10^{-6}
	Simulated-stop	220	82	.17	.004	30	.045
	Constant-speed	400	155	.28	.14	39	1.1
Ni-30graphite[b]	Constant-speed	220	82	0.21	0.55	18×10^3	8.6×10^{-6}
	Simulated-stop	220	82	.22	.13	12	3.2
Ni-30graphite[c]	Constant-speed	220	82	0.23	0.26	21×10^3	3.6×10^{-6}
Cu-$30Gd_2O_3$	Constant-speed	270	72	.32	.06	20	[d]1.4
Cu-$25La_2O_3$-$25LaF_3$	Simulated-stop	220	82	.35	.5	30	[d]13
Ni-$30Gd_2O_3$	Constant-speed	220	82	0.29	0.02	19×10^3	0.22×10^{-6}
		180 to 270	69 to 105	.22	.3	52	.9
Ni-$30La_2O_3$	Constant-speed	270	72	0.28	0.13	16×10^3	1.5×10^{-6}
		270	72	.30	.07	17	.8
Ni-$15La_2O_3$-$15LaF_3$	Constant-speed	220	82	0.26	0.04	21×10^3	0.4×10^{-6}
	Simulated-stop	220	82	.28	.07	30	.5
Ni-$25La_2O_3$-$25LaF_3$[b]	Constant-speed	220	82	0.20	0.04	26×10^3	0.25×10^{-6}
Ni-$25La_2O_3$-$25LaF_3$[e]	Constant-speed	400	76	0.19	0.031	53×10^3	0.43×10^{-6}
		270 to 460	51 to 87	.19	.025	55	.34
Ni-$25La_2O_3$-$25LaF_3$[e]	Simulated-stop	400	76	0.45	0.045	30×10^3	[f]0.72×10^{-6}

[a] Reference material.

[b] Preparation, hot pressing.

[c] Preparation, hot isostatic compression.

[d] Specimen crumbling.

[e] Preparation, flame spraying.

[f] Grabbing at end of test.

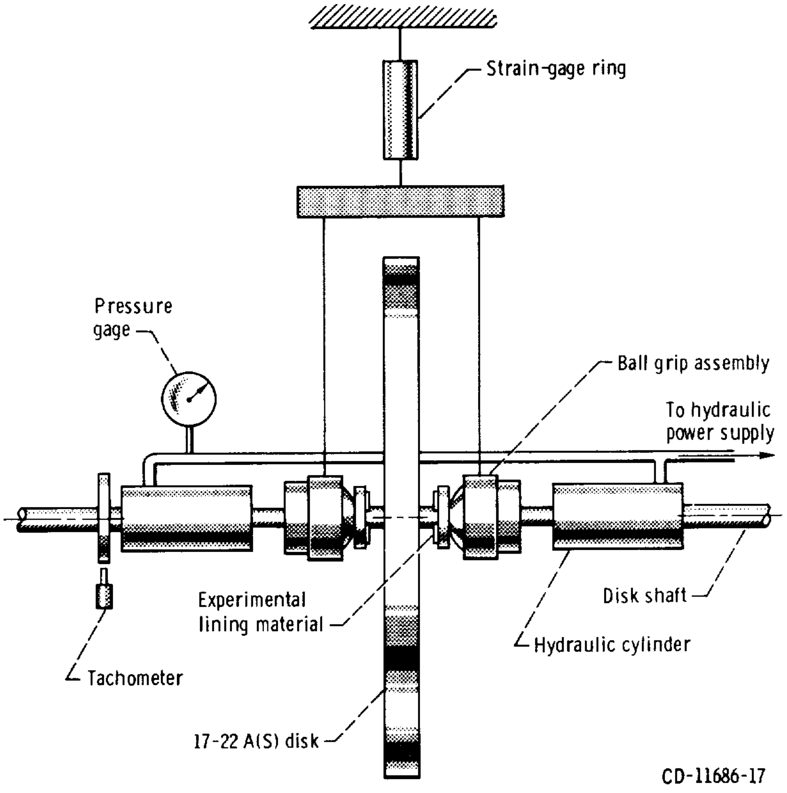


Figure 1. - Schematic of disk brake rig.

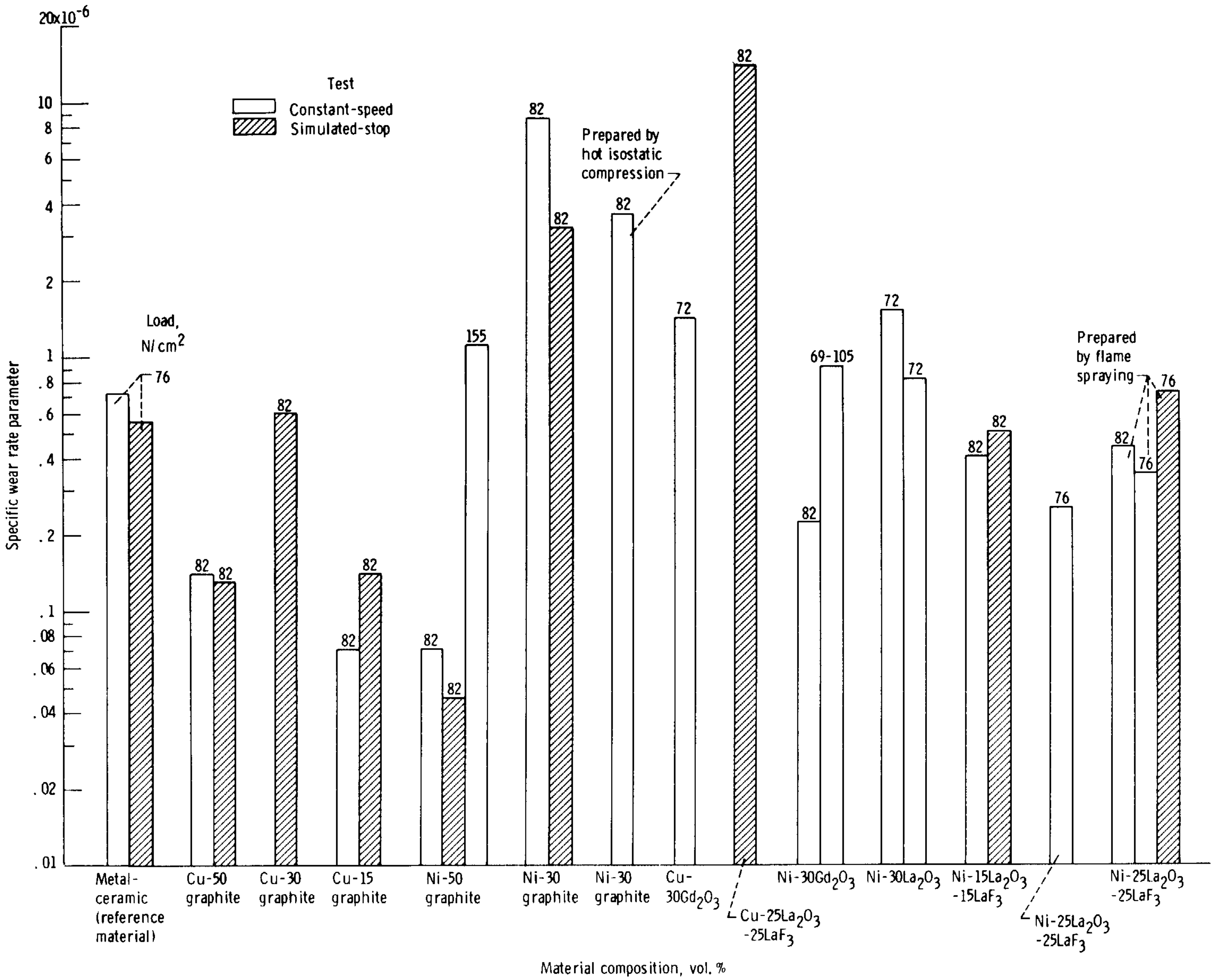
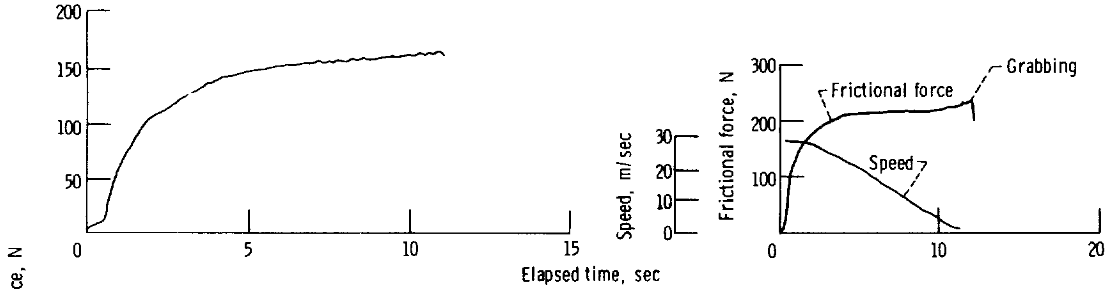


Figure 2. - Specific wear rate parameter for different experimental brake lining materials. All materials hot pressed unless otherwise noted.

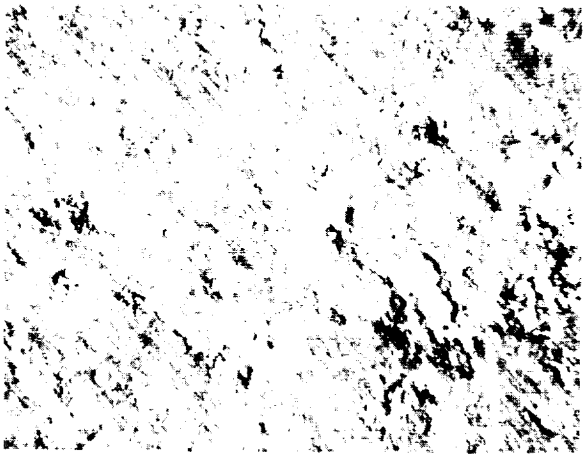


(a) Constant speed, 31 meters per second (100 ft/sec) for 10 seconds.

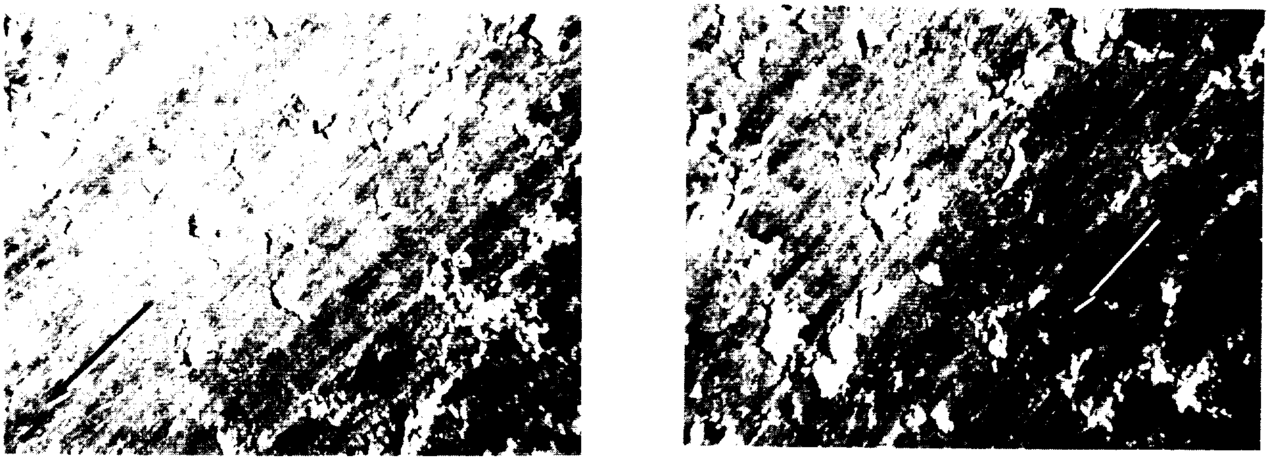
(b) Simulated stop from 31 meters per second (100 ft/sec).

(c) Constant speed, 31 meters per second (100 ft/sec) for 30 seconds. Bulk pad temperatures of 610° C (1100° F) were measured.

Figure 3. - Friction traces for currently used metal-ceramic composite. Normal load, 400 newtons (76 N/cm^2).



(a) Before sliding exposures.



(b) After one set of constant-speed sliding exposures.

(c) After two sets of constant-speed sliding exposures.

Figure 4. - Photomicrographs of surface of currently used metal-ceramic composite pad before and after successive constant-speed sliding exposures. Arrows indicate sliding direction. X30.

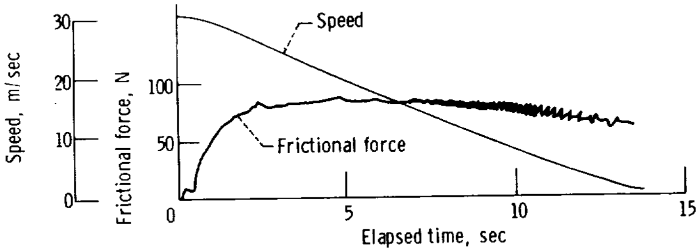
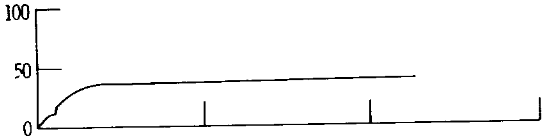
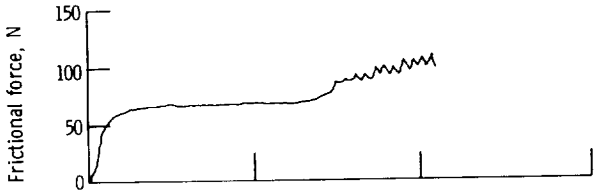


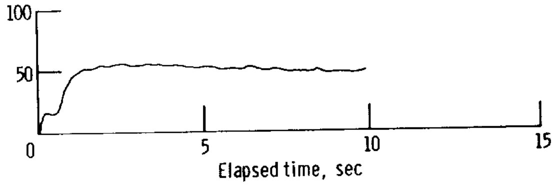
Figure 5. - Friction and sliding speed of copper - 50-percent-graphite composite as function of elapsed time of application. Normal load, 220 newtons (82 N/cm^2).



(a) Nickel - 50-percent-graphite composite; normal load, 220 newtons (82 N/cm^2).



(b) Nickel - 50-percent-graphite composite; normal load, 400 newtons (155 N/cm^2).



(c) Nickel - 30-percent-graphite composite; normal load, 220 newtons (82 N/cm^2).

Figure 6. - Constant-speed friction traces for nickel - 50-percent-graphite and nickel - 30-percent-graphite composites. Sliding speed, 31 meters per second (100 ft/sec).

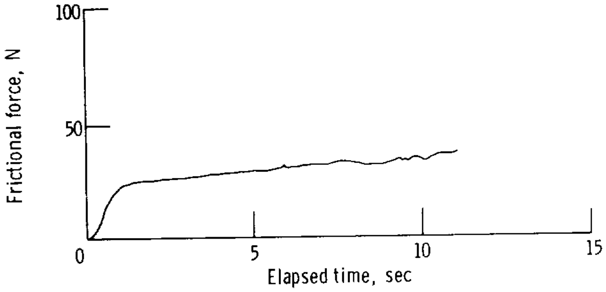
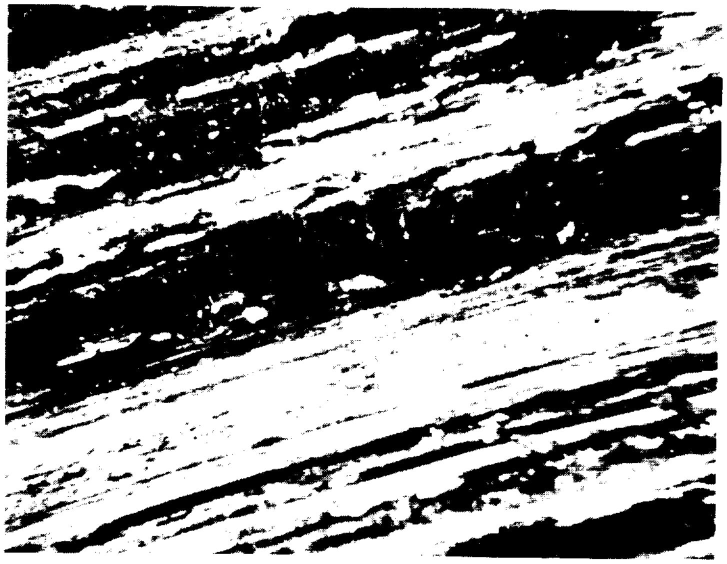


Figure 7. - Constant-speed friction trace for hot isostatically compressed nickel - 30-percent gadolinium oxide composite. Normal load, 220 newtons (82 N/cm^2); sliding speed, 100 feet per second (31 m/sec).



(a) Region showing cracking and incipient spalling.

(b) Region showing uniform film formation.

Figure 8. - Hot isotatically compressed nickel - 30 percent lanthanum oxide composite after successive constant-speed exposures. X30.

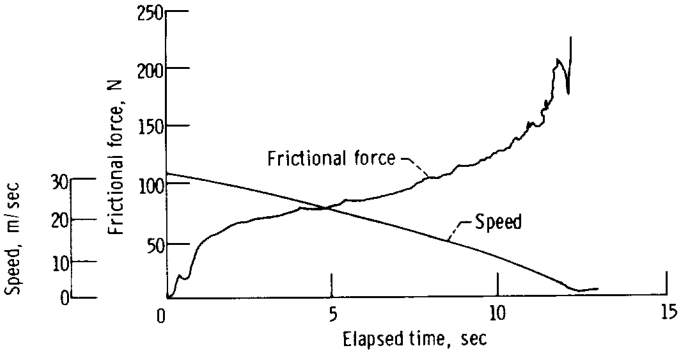


Figure 9. - Simulated-stop friction trace for hot isostatically compressed nickel - 15-percent lanthanum oxide - 15-percent lanthanum fluoride composite. Normal load, 220 newtons (82 N/cm²).

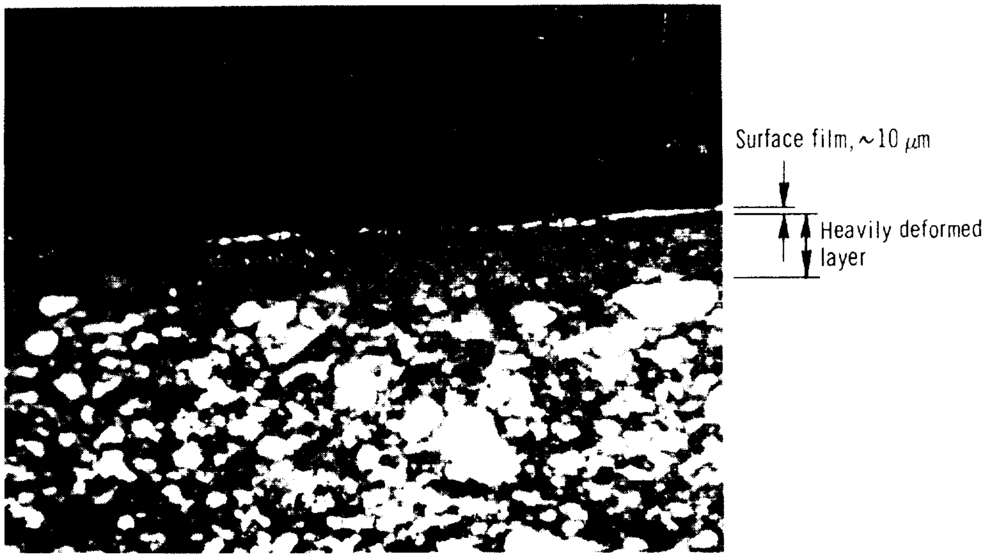


Figure 10. - Cross-sectional view of hot-pressed nickel - 25 percent lanthanum oxide - 25 percent lanthanum fluoride composite after three constant-speed exposures.

NASA-Langley, 1974 E-7843