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AN INVESTIGATION OF MATERIALS FOR CAGES FOR AIRCRAFT GAS-TURBINE ROLLING-CONTACT BEARINGS

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FOREWORD

This report was prepared by the Engineering Mechanics Division of Battelle Memorial Institute under USAF Contract No. AF 33(616) 2100. The contract was initiated under Project No. 3066, "Gas Turbine Technology", Task No. 73599, "Investigation of Materials for Cages for Aircraft Gas Turbine Rolling Contact Bearings", formerly EO R506-204, "An Investigation of Materials for Cages for Aircraft Gas Turbine Rolling Contact Bearings", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt. R. D. Masteller acting as project engineer.

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ABSTRACT

An investigation has been carried out to develop new materials for cages for rolling-contact bearings used in jet aircraft. Two machines have been constructed to evaluate prospective materials. These are the rubbing-button-test machine and the cage-material testing machine. The rubbing-button machine is designed to screen the various materials in the simplest way possible, evaluating their resistance to galling and to seizure under thin-film lubrication at high rubbing velocities. The cage-material testing machine was designed to further evaluate promising materials from the screening tests under conditions simulating actual turbine-bearing operation. Material comparisons are based on the performance of silicon-iron bronze in these machines. At present, this cage material is used more widely than any other material for turbine bearings.

Two promising materials have been developed in the course of this research. These are chromized steel and boron nitride cermet. These materials have exhibited good corrosion resistance to hot MIL-L-7808 products used in the lubrication of turbine bearings.

An initial series of runs using the cage-testing machine with silicon-iron bronze specimens has proved the machine to be a valuable tool for simulating cage-pocket wear by the rolling elements. Comparison of cage specimens from this machine with cages from a bearing operated in a high-speed turbine showed marked similarity in the wear patterns. The loads on the cage pockets were measured with a strain-sensing device.

The cage-material testing machine may be modified to test whole bearings or race segments rubbing against the cage-locating lands of a bearing race.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. Whitmore
Technical Director
Materials Laboratory
Directorate of Research

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AN INVESTIGATION OF MATERIALS FOR CAGES FOR AIRCRAFT GAS-TURBINE ROLLING-CONTACT BEARINGS

INTRODUCTION

Advanced aircraft turbine design has been limited by the performance of the main rotor bearings currently in use. One important factor in these bearing shortcomings is the failure of the cage materials to withstand the higher temperatures and speeds required in future turbines.

The designs of bearings have been more or less conventional, but the characteristics that impose bearing distress in gas-turbine operation are the high rotative speeds, the high operating temperatures, and the inherent poor lubrication of the sliding surfaces. The proportions of the cage-locating surfaces, equivalent to narrow sleeve bearings, do not lend themselves to the development of ideal hydrodynamic lubrication. Also, the cage-pocket surfaces, which locate the rolling elements, are subjected to impact loads when slight bearing misalignments are present. This is because the rolling elements are attempting to travel at varying rotational speeds but must travel at a translatory speed equal to the average cage speed. These combined bearing characteristics cause surface failures, galling, scoring, and melting, and may cause accelerated wear, cage breakage, and general malfunctioning of the bearings.

The cage material currently in use, silicon-iron bronze, is prone to galling and seizure under boundary-lubrication conditions and deteriorates rapidly when galling is initiated. Silver plating the cages, which is general practice, has proved beneficial, but the silver plate eventually wears away, after which rapid wear of the base metal occurs.

An investigation has been undertaken to find cage materials superior to those in current use and satisfactory for use in bearings operating under the conditions forecast for future turbine designs. The materials must operate when mating with hardened-steel rolling elements at surface velocities up to 400 fps. A maximum operating temperature of 500 F has been imposed in this investigation, but future trends indicate that this temperature should be raised to 750 F and soak-back temperatures up to 1000 F are to be expected. The materials must also resist the hot synthetic lubricants (250-300 F) now in use and any new lubricants capable of withstanding higher temperatures than those presently in use. For instance, the use of copper in contact with the hot lubricant used today, MIL-L-7808, has been questioned because of the loosely adhering decomposition products that are formed on the copper.

The proposed materials should resist wear and galling under two types of wearing condition found in actual operation:

(1) Balls and rollers wearing the cage pockets, and

(2) Wear of the cage surfaces rubbing on the cage-locating bands.

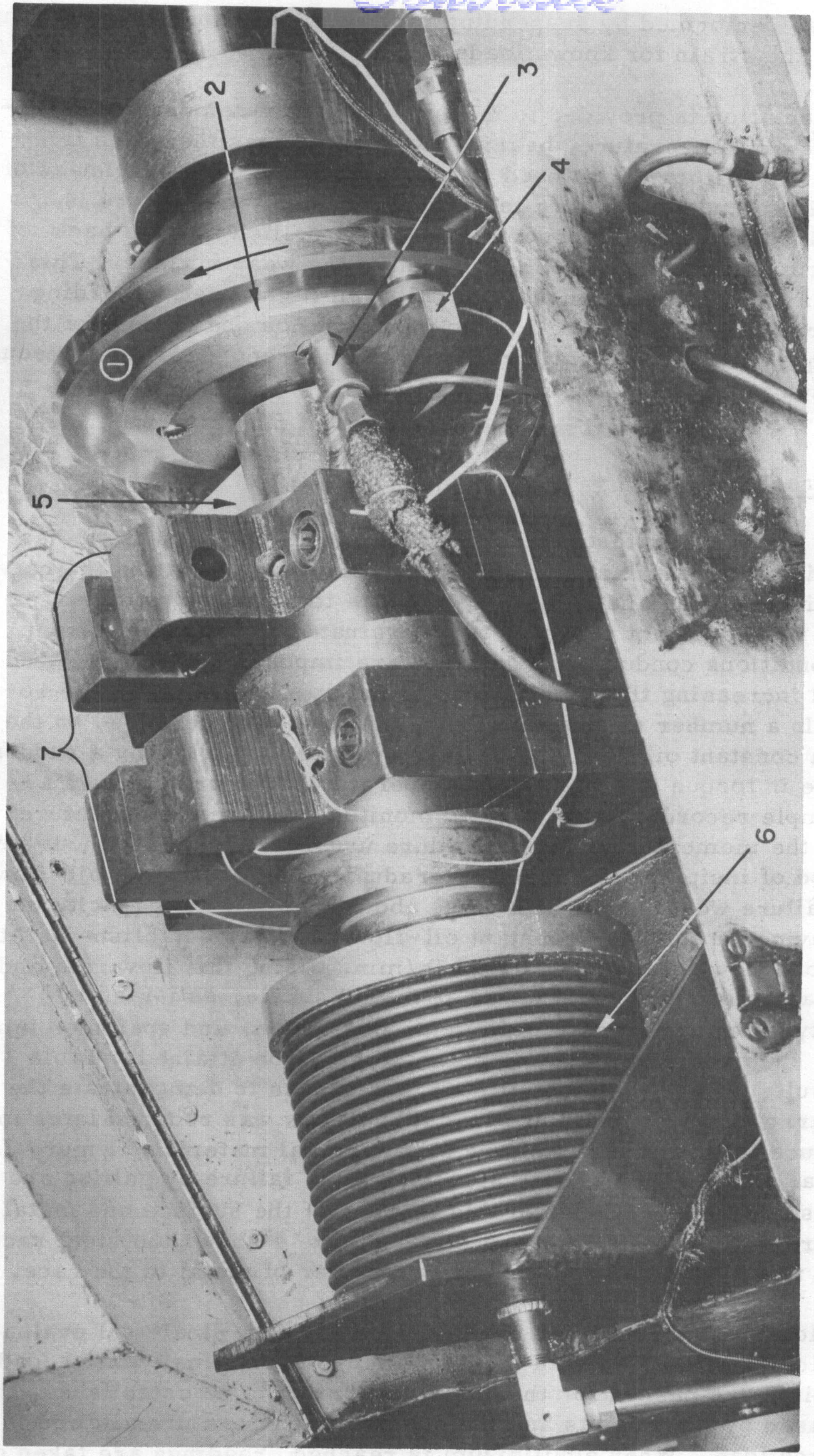
EXPERIMENTAL PROCEDURES AND RESULTS

Two machines were designed for evaluating cage materials. They are the rubbing-button machine and the cage-material testing machine. The former was an existing sleeve-bearing testing machine, modified to test the wear and galling characteristics of cage materials in sliding contact with ball and race materials under conditions of thin-film lubrication. Since observations of failed bearings and theoretical considerations of the relative speeds of bearing components indicate that the wearing surfaces of the cages experience mainly rubbing friction under poor lubrication conditions, the use of the rubbing-button machine was considered satisfactory for screening tests. This machine was used to evaluate prospective materials while the cage-testing machine, designed to simulate turbine-bearing operating conditions, was being built.

Preliminary Cage-Material Investigations - Rubbing-Button Tests

Description of Apparatus

A photograph of the modified sleeve-bearing machine is shown in Figure 1. A flat bearing race of SAE 52100 steel is mounted on a shaft and rotated at 10,000 rpm. The cage-material specimen, in the form of a 1/2-inch-diameter button, is mounted on the stationary shaft and torque-arm system. An air bellows, expanding against one end of the torque-transmitting shaft, is used to load the specimen against the rotating race. The load is transmitted to the specimen through a hardened steel ball to insure specimen self-alignment. Rubbing velocities up to 280 fps are attained with this machine. Lubrication is provided by the metering nozzle, which discharges a steady stream of oil, the oil stream impinging on the race at a point about 300 degrees of rotation from the cage specimen. During operation, this oil stream hits the race at its inner diameter and is carried to the outer edge by centrifugal forces, leaving a thin film of lubricant on the race surface at the point of contact with the cage specimen. The frictional force between the specimen and the race is measured by the lever arm, which transfers its thrust to a cantilever strain-gage transducer. This system is calibrated to read directly in pounds of frictional force.



1. Race
2. Oil impingement
3. Oil-metering nozzle
4. Specimen holder and specimen
5. Torque-measuring arm
6. Bellows thrust-loading device
7. Ball-bushing linear-motion shaft guide

FIGURE 1. MODIFIED SLEEVE-BEARING TESTING MACHINE

Calibration was performed by suspending dead weights from the lever arm and recording the strain for known loads.

Instrumentation is provided to measure specimen temperature, oil-flow rate, bulk oil temperature, bearing load on the specimen, and frictional force. A profilometer is used to measure the surface roughness of the cage specimen and race before testing. Specimen temperature is measured by inserting a thermocouple into a hole drilled into the back of the cage-specimen button to within 1/16 inch of the wear surface. This temperature is recorded continuously on a Brown High Speed Recording Potentiometer. The temperature is also monitored on one channel of the frictional torque-measuring strain recorder, being recorded simultaneously with the friction force.

Test Procedure

Several preliminary tests were made using silicon-iron bronze as the cage specimen to determine the best procedure for evaluating the cage materials. Since galling and seizure resistance to hardened-steel races and balls was the important property to be evaluated in prospective cage materials, conditions conducive to galling were imposed by reducing the oil supply and increasing the bearing load of the specimen against the rotating race. In a number of separate runs, the load was increased on the specimen at a constant oil flow until failure occurred, marked by a sudden large increase in torque and specimen temperature. Figure 2 shows a section of sample recorder chart used to monitor specimen temperature and torque at the moment of failure. Failure usually occurred without any warning period of incipient seizure. By gradually decreasing the oil-flow rate so that failure would occur at a value about one-half the capacity of the loading device, a standard constant oil-flow rate was established. At present, the oil-flow rate used is 0.020 lb/min. Using this flow rate and an oil temperature of 250 F, measured at the jet nozzle, satisfactory reproducibility in failure loads, coefficients of friction, and specimen temperatures for specimens of the same material could be attained. Table 1 shows the results of four tests on silicon-iron bronze to demonstrate the reasonably narrow scatter of failure loads. Oil flow was reduced later in order to produce failure in a promising experimental material. Figure 3 shows a typical silicon-iron bronze specimen after failure by galling and seizure in this apparatus. Considerable melting of the surface and metal transfer occurs during the failure process. Figure 4 shows the steel race against which this button ran and the heavy transfer of metal to the race.

The following procedure has been adopted for cage-material evaluation. The machine is started with the specimen under a small initial load. After ample time has passed for thermal equilibrium to be established, the load is increased by increments and the specimen temperature allowed to level off at each load. When equilibrium is reached, readings are taken of

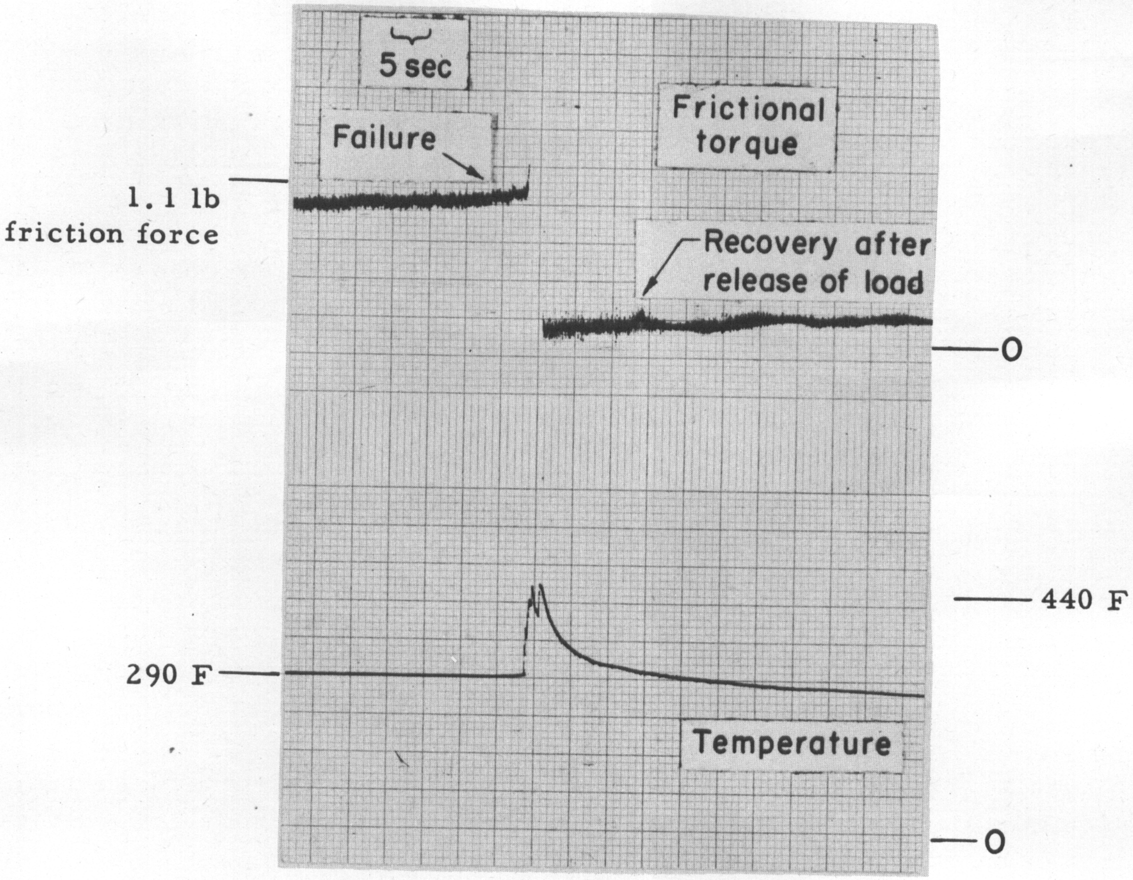


FIGURE 2. SAMPLE RECORDER CHART SHOWING TEMPERATURE AND FRICTIONAL TORQUE AT FAILURE CONDITIONS

Rubbing-button test
Cage specimen - leaded bronze
Race material - SAE 52100 steel hardened

TABLE 1. RESULTS OF RUBBING-BUTTON TESTS USING SILICON-IRON BRONZE TO DEMONSTRATE REPRODUCIBILITY OF THE TEST

Material	Failure Load, psi	Coefficient of Friction	Specimen Temperature Before Failure, F	Remarks
Silicon-iron bronze	1530	0.009	320	Galled badly; melted; gross metal transfer to steel race
	1110	0.009	310	
	1610	0.008	320	
	1610	0.006	335	

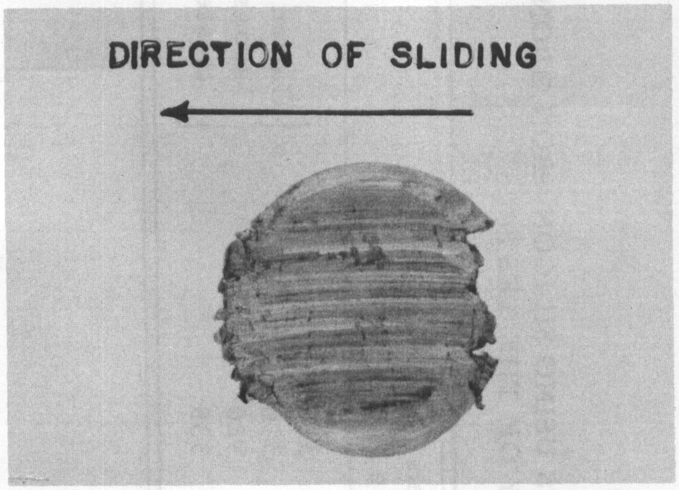


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FIGURE 3. SILICON-IRON BRONZE CAGE SPECIMEN AFTER FAILURE

Seizure load = 1610 psi; oil flow = 0.032 lb/min.
Specimen originally a 1/2-inch-diameter disk.

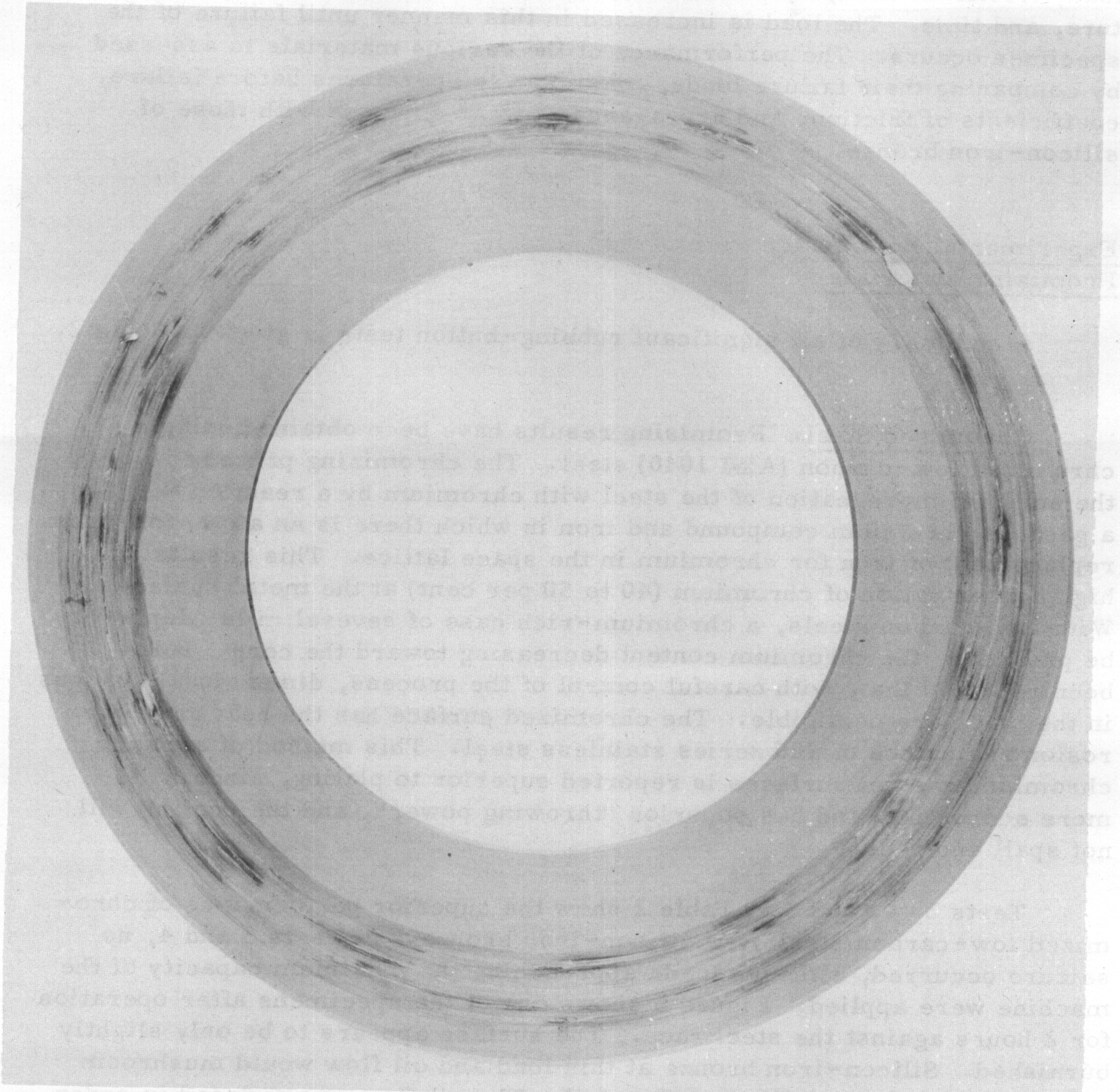

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FIGURE 4. SAE 52100 STEEL RACE AFTER FAILURE OF SILICON-IRON BRONZE CAGE SPECIMEN

Note heavy smearing of cage material on race.

load, frictional drag, specimen temperature, oil pressure, oil temperature, and time. The load is increased in this manner until failure of the specimen occurs. The performance of the various materials is assessed by comparing their failure loads, maximum temperatures before failure, coefficients of friction, and appearance of wear surfaces with those of silicon-iron bronze.

Experimental Results – Promising Materials

A summary of all significant rubbing-button tests is given in Table 2.

Chromized Steel. Promising results have been obtained using a chromized low-carbon (AISI 1040) steel. The chromizing process involves the surface impregnation of the steel with chromium by a reaction between a gaseous chromium compound and iron in which there is an atom-for-atom replacement of iron for chromium in the space lattice. This results in a high concentration of chromium (40 to 50 per cent) at the metal surface. With low-carbon steels, a chromium-rich case of several mils' depth may be produced, the chromium content decreasing toward the core. It has been reported that, with careful control of the process, dimensional changes in the piece are negligible. The chromized surface has the heat and corrosion resistance of 400 series stainless steel. This method of applying chromium to steel surfaces is reported superior to plating, since it is more economical and has superior "throwing power", and the coating will not spall and peel.

Tests 3, 4, and 5 in Table 2 show the superior performance of chromized low-carbon steel over silicon-iron bronze. In Tests 3 and 4, no seizure occurred, although loads approaching the maximum capacity of the machine were applied. Figure 5 shows one of the specimens after operation for 2 hours against the steel race. The surface appears to be only slightly burnished. Silicon-iron bronze at this load and oil flow would mushroom and gall severely (see Figures 3 and 4). The oil flow was reduced in order to produce failure and, at a flow rate of 0.020 lb/min, seizure occurred at 1290 psi. Subsequent tests of silicon-iron bronze at this oil flow resulted in failure at an average load of 500 psi.

High-carbon steel was chromized and evaluated also. Chromizing high-carbon steel results in a relatively thin (0.0005-inch) case of very hard chromium carbide which is reported to be very galling and abrasion resistant. Some dimensional changes may be expected when chromizing high-carbon steel because compounds (CrC) are formed within the metal structure during the process. This material proved inferior to the "soft" chromized steel in the first screening test recorded - Test 6. Its failure load was 615 psi, within the expected scatter region of failure for silicon-iron bronze at an oil-flow rate of 0.020 lb/min. The coefficient of

TABLE 2. RESULTS OF TESTS ON CAGE SPECIMENS AT 280 FPS[a]

Test	Material	Maximum Load, psi	Coefficient of Friction[b]	Maximum Specimen Temperature, F	Lubricant Flow Rate, lb/min	Remarks
1	Silicon-iron bronze (Average results for 8 separate tests)	500	0.01	280	0.02	Galled badly; melted
2	Silicon-iron bronze (Higher lubricant-flow rate)	1290	0.006	317	0.024	Galled badly; melted
3	Chromized low-carbon steel	1978	0.008	304	0.040	No failure after 2 hours on test; chromized surface burnished; no wear
4	Chromized low-carbon steel	2235	0.008	304	0.025	No failure after 2 hours on test; chromized surface burnished; no wear
5	Chromized low-carbon steel	1290	0.008	260	0.020	Seizure; chromized case worn through to untreated steel
6	Chromized high-carbon steel	615	0.005	260	0.020	Specimen seized, but very little smearing noted on wear surface
7	50 BN-50 Cu, hot pressed	1450	0.01	345	0.032	Specimen fractured; slight galling noted
8	50 BN-50 Cu, hot pressed; Parawax used in mixing (Average of 3 tests)	500	-	300	0.022	No seizure; severe wear; friction erratic
9	50 Cr-Ni-50 BN, hot pressed	750	-	265	0.020	Seizure; some metal transfer to race; friction appeared low

TABLE 2. (Continued)

Test	Material	Maximum Load, psi	Coefficient of Friction(b)	Maximum Specimen Temperature, F	Lubricant Flow Rate, lb/min	Remarks
10	50 Cu-Cr-50 BN, hot pressed and precipitation hardened	410	0.019	310	0.020	Surface of specimen broken up; evidences of local galling and seizure; low wear rate
11	Cu-Cr, precipitation hardened	850	0.03	330	0.032	Galled badly; melted
12	Porcelain-enameled Steel A	600	0.04	250	0.032	Enamel wore through and spalled
13	Procelain-enameled Steel B	425	-	-	0.032	Enamel completely stripped from mild-steel base material
14	Electroless-nickel hard plate on steel	600	0.001	255	0.020	Nickel plate worn through to base metal
15	Al_2O_3 hard coating on aluminum	270	0.02	250	0.022	Hard coat worn through after 1 minute of testing
16	Porous ferrous alloy, impregnated with MIL-L-7808	150	-	-	0.022	Specimen failed as initial load was being applied
17	70 Cu-30 BN, hot pressed	550	0.013	320	0.020	Wore badly; friction erratic; some galling and seizure; metal transfer to race
18	Al_2O_3-Cr cermet	1400	0.005	260	0.020	Torque and temperature rose sharply at failure; but seizure was only superficial

TABLE 2. (Continued)

Test	Material	Maximum Load, psi	Coefficient of Friction[b]	Maximum Specimen Temperature, F	Lubricant Flow Rate, lb/min	Remarks
19	Leaded bronze	340	0.015	252	0.020	Some smearing and scoring on button surface; surface smooth and shiny

(a) Lubricant is Penola 15 (MIL-L-7808), supplied at 250 F, measured at the jet. The surface finish of the lapped specimens is 4 to 7 microinches.

(b) Coefficient of friction computed for applied load of 340 psi.

friction and operating temperature of hard chromized steel were low, however. Failure occurred in the usual manner, with rapidly rising friction and specimen temperature, but examination of the button and race after the test revealed a minimum of surface flow and scoring.

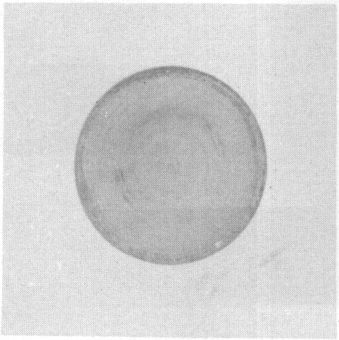

FIGURE 5. CHROMIZED SAE 1040 STEEL (ANNEALED) AFTER 2-HOUR RUN

Rubbing-button test
Maximum load = 2150 psi
Oil flow = 0.038 lb/min
No failure occurred under these conditions.

Metal-Boron Nitride Cermets. An effective method for reducing galling tendencies under conditions of inadequate lubrication is to impart self-lubricating properties to the sliding surfaces. This has been accomplished successfully in the past by impregnating plastic laminates or porous metals with graphite or molybdenum disulfide. However, because of the high temperatures inherent in gas-turbine bearings and the corrosiveness of synthetic lubricants used, these practices did not appear applicable to the cage-material problem. Boron nitride was suggested as a possible solid lubricant, because it possesses lubricating qualities similar to those of graphite, is very inert, and will resist much higher temperatures than any of the other known solid lubricants. In fact, this material is stable enough to permit it to be hot pressed with metals at temperatures exceeding 2000 F. By using a metal as a binder, therefore, this material can become an integral part of a cermet with self-lubricating properties. Cage-specimen samples were made by hot pressing 50 per cent by volume of boron nitride and 50 per cent by volume of copper at 1800 F under a pressure of 3500 psi. Copper was used as a binder so that fair thermal conductivity might be built into the material, reducing the tendency toward a build-up of surface heat on the specimen under sliding friction. The first such specimens showed promise, failing at a load of 1450 psi with an oil flow of 0.032 lb/min (silicon-iron bronze fails at about 1500 psi under these conditions). Failure occurred when the specimen fractured. This was caused by high local stresses imposed by the loading mechanism used. The two pieces of the specimen, shown in Figure 6, show little surface damage. Figure 7 shows the race against which this specimen ran, showing much less metal

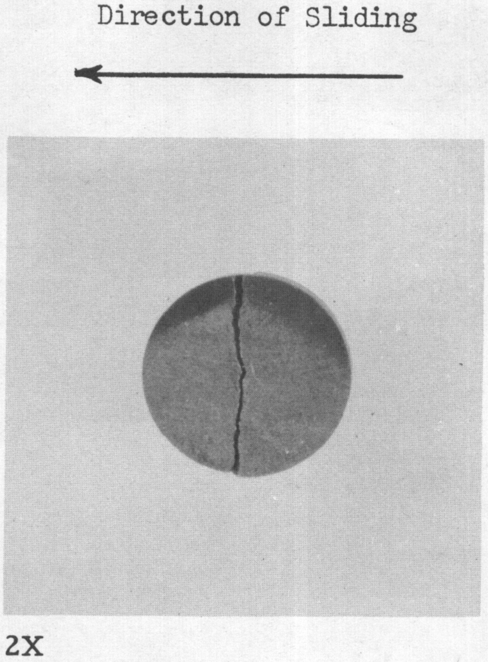

FIGURE 6. 50-50 COPPER-BORON NITRIDE HOT-PRESSED CAGE SPECIMEN AFTER FAILURE AT 1450 PSI

Rubbing-button test; oil flow = 0.032 lb/min. Brittle fracture was caused by high local loading stresses on specimen. Note absence of melting and surface distortion.

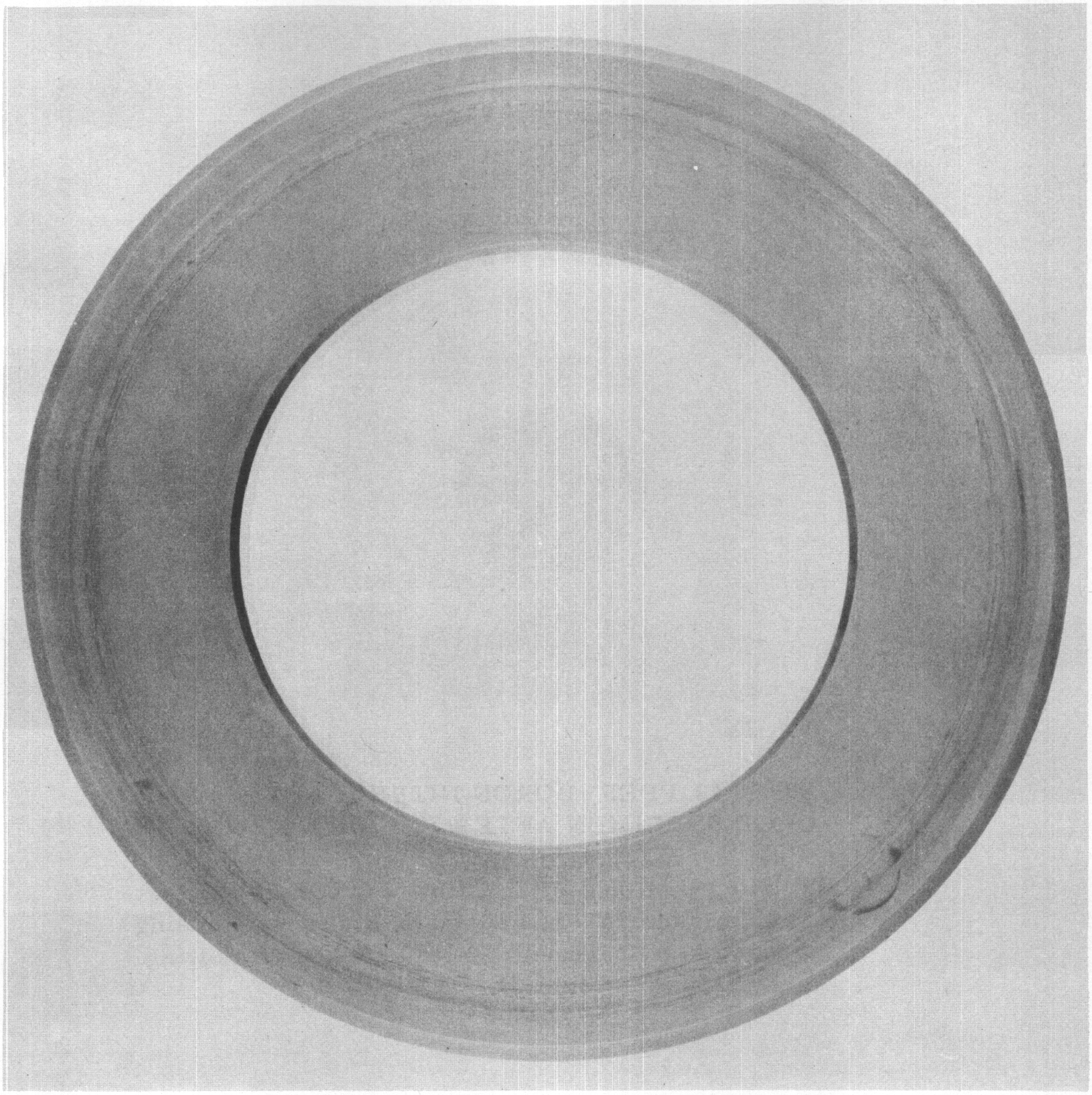

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FIGURE 7. SAE 52100 STEEL RACE AFTER FAILURE OF COPPER-BORON NITRIDE CAGE SPECIMEN

The metal pickup is considerably less than when silicon-iron bronze is used.

transfer than silicon-iron bronze. Improvement in the specimen-loading mechanism resulted in a more uniform load distribution on the specimens, but premature shear failures, resulting from laminations in the Cu-BN cermets were experienced. Laminations were assumed to be caused by incomplete mixing of the metal and boron nitride powders. Parawax was added to the next batch to insure proper mixing, but these specimens tended to wear badly, as shown in Test 8 in Table 2. Metallographic examination of these specimens revealed that the addition of Parawax had inhibited coalescence of the metal particles, weakening the metal matrix and presumably causing the material to crumble away under high surface stresses. A precipitation-hardening, high-thermal-conductivity, copper-chromium alloy was hot pressed with boron nitride and heat treated in an attempt to strengthen the cermet and retain the thermal-conductivity properties of the metal. Test 10 in Table 2 shows that the copper-chromium-boron nitride cermet operated at a high coefficient of friction and high temperature, and failed at a relatively low load. The wear rate was low, but the surface indicated localized galling and seizure across the wearing surface. A subsequent test, using a copper-chromium alloy, precipitation hardened, revealed this metal to be prone to galling. It operated at high frictional drag and high surface temperature.

More success has been achieved with a chromium-nickel-boron nitride cermet. This material, as shown in Test 9, behaved better than silicon-iron bronze and is presumed to have a low coefficient of friction, as evidenced by its low operating temperature. The friction forces could not be measured in this test owing to failure of the strain-sensing mechanism.

Evaluation of higher percentage copper-boron nitride cermets (70 Cu-30BN) indicated that the percentage of boron nitride was too low to be effective as an antigalling agent (see Test 17).

Metal-Aluminum Oxide Cermets. A commercial cermet, containing Al_2O_3 and chromium also showed promise. The results of an evaluation of this material are given in Table 2, Test 18. The specimen operated at a low coefficient of friction and failed at a relatively high load with a minimum of surface damage. Its failure load of 1400 psi was the highest failure load recorded for any material tested at the 0.020-lb/min oil flow. This material is reported as resistant to deformation at high temperatures (1800-2500 F) and resistant to oxidation. It has a tensile strength of 17,500 psi at 1800 F, with virtually no elongation or reduction of area.

Coatings. Porcelain-enameled steel, recorded in Tests 12 and 13, behaved poorly, the enamel spalling at relatively low loads. Apparently, the rubbing speeds are too high for the relatively weak porous structure of the porcelain enamel.

Electroless-Nickel Plate on Steel. This material, used in Test 14, failed at about the same load as expected for silicon-iron bronze. The coating wore through to the base metal, but it operated at a very low coefficient of friction. The deposit is a nickel phosphate (91 per cent nickel) coating on a metal surface without the use of electric current. The resultant coating is harder (400 to 450 Knoop) than electroplated nickel and is well bonded. Use of the process for cage material is doubtful, however, in the light of the results of this screening test.

Aluminum Oxide Hard Coating on Aluminum. This material, used in Test 15, proved to be unsatisfactory as a wear-resistant material at the high rubbing velocity imposed. The coating is an anodized aluminum surface about 2 mils thick. The anodizing process is modified so that a hard, thick film of Al_2O_3 is chemically bonded to the aluminum. The coating is file hard and similar to nitrided steel in properties. It is reported to be highly abrasion resistant*.

Conventional Bearing Materials. A special leaded bearing bronze having self-lubricating properties was evaluated. As may be seen in Test 19, this material failed at lower load than did silicon-iron bronze. Its coefficient of friction was about the same as that of silicon-iron bronze, and there was less smearing and melting of the surface during failure.

Porous Ferrous Bearing Material. This material was vacuum impregnated with MIL-L-7808 and evaluated in the screening apparatus, Test 16. It proved unsatisfactory, since it seized during the application of the initial load.

Discussion of Rubbing-Button-Test Results

Two materials stand out clearly as promising in these screening tests. They are chromized steel and boron nitride cermet. The wear and galling resistance of the chromized mild steel was exceptional in that the

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* Gillig, F. G., "Study of Hard Coating For Aluminum Alloys", WADC-TR 53-151, May and October, 1953.

"soft" chromized surface has not been used in the past for wear-resistant surfaces, although chromized high-carbon steels have been recommended for wear resistance. It is known that a hardness of about 25 to 50 Rockwell C may be attained on chromized low-carbon steels and, as a rule, the hardness of the extreme outer surface may be higher than that of the main coating. This has been attributed to the presence of sigma phase.* The presence of this extremely hard phase in the surrounding relatively soft supporting matrix may be a reason for the anomalous performance of the "hard" and "soft" chromized coatings. The hardness of the chromized surface increases with increasing carbon content and, conversely, the depth of penetration of chromium decreases with carbon content. Therefore, the high-carbon steel that has been chromized has a thin layer (0.0005 inch) of a high proportion of carbides with a hardness of over Rockwell C 70. Under this layer, there may be a decarburized zone of low yield strength if certain techniques are not followed in the chromizing process. If this decarburized zone is present, the load-carrying capacity of the hard, thin surface layer will be reduced appreciably. It is possible that the chromized high-carbon-steel specimen evaluated in the rubbing-button test failed because the hard surface layer was crushed through into a soft, decarburized zone.

Chromized low-carbon steel has certain advantages over the chromized high-carbon steels. Since there is little formation of carbides in the chromizing of low-carbon steel, the chromium enrichment of the metal surface is accomplished by the exchange of similarly sized atoms, with no resulting change in the space-lattice parameters. Theoretically, therefore, it should be possible to chromize mild-steel cages, in the finished condition with negligible dimensional changes. In chromizing high-carbon steels, however, a high percentage of carbides is formed, causing "growth" of metal parts. It is possible to chromize to a much greater depth in the low-carbon steels, making possible a longer wearing case of 2 to 3 mils' thickness. The maximum thickness of the high-carbon-steel chromized case is about 0.5 mil.

Boron nitride cermets appear to improve the galling resistance of cage specimens. At least 50 per cent (by volume) of boron nitride is necessary, and care must be taken to insure complete mixing of the powders before hot pressing. Full coalescence of the metal powders during hot pressing is also important. The use of copper as a binder material was considered advantageous because of the inherent low thermal conductivity of a cermet of this type; however, it appears from test results that better results are attained with the eutectic mixture of nickel and chromium as a binder. Fewer difficulties were encountered in producing a consistent product when using the nickel-chromium binder. This material is also advantageous in that it exhibits good high-temperature oxidation resistance,

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* Samuel, R. L., "The Protection of Metallic Surfaces by Chromium Diffusion", Metal Treatment and Drop Forging, (December, 1951), p 544.

whereas the copper tends to form nonadherent oxides in the temperature range of turbine-bearing operation. The advantage of using boron nitride as the solid-lubricant component was demonstrated in the hot pressing of the chromium-nickel alloy, which required a sintering temperature of 2100 F, well within the temperature limits for boron nitride.

Problems concerning the fabrication of cages from this material and the strength of these cages have not yet been determined, but constitute an important area of future investigation.

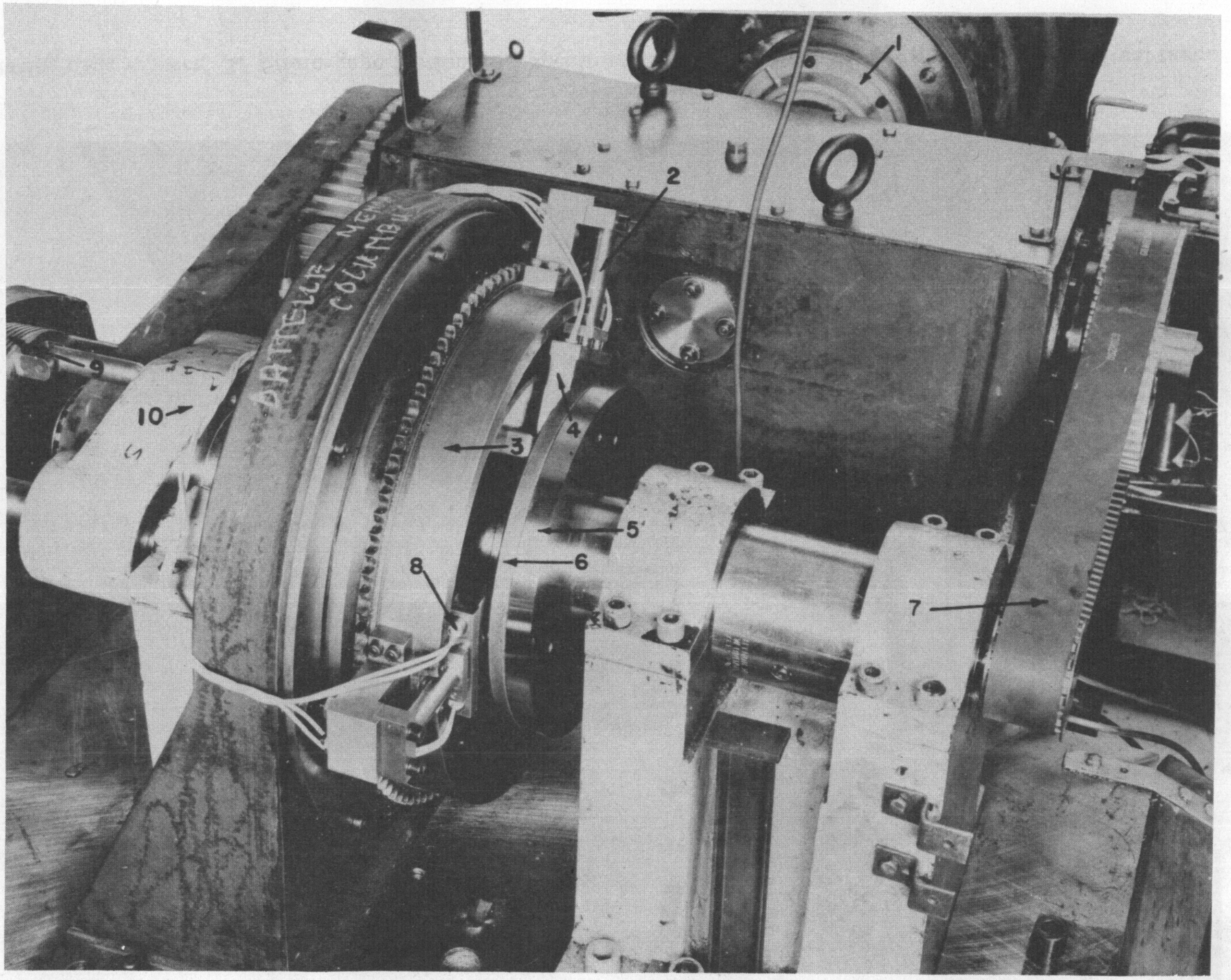
The initial success of the Al_2O_3-chromium cermet indicates that further study of the use of the cermet class of materials for bearing cages is of interest.

Cage-Material Testing Machine — Simulated Turbine-Bearing Operating Conditions

Description of Apparatus

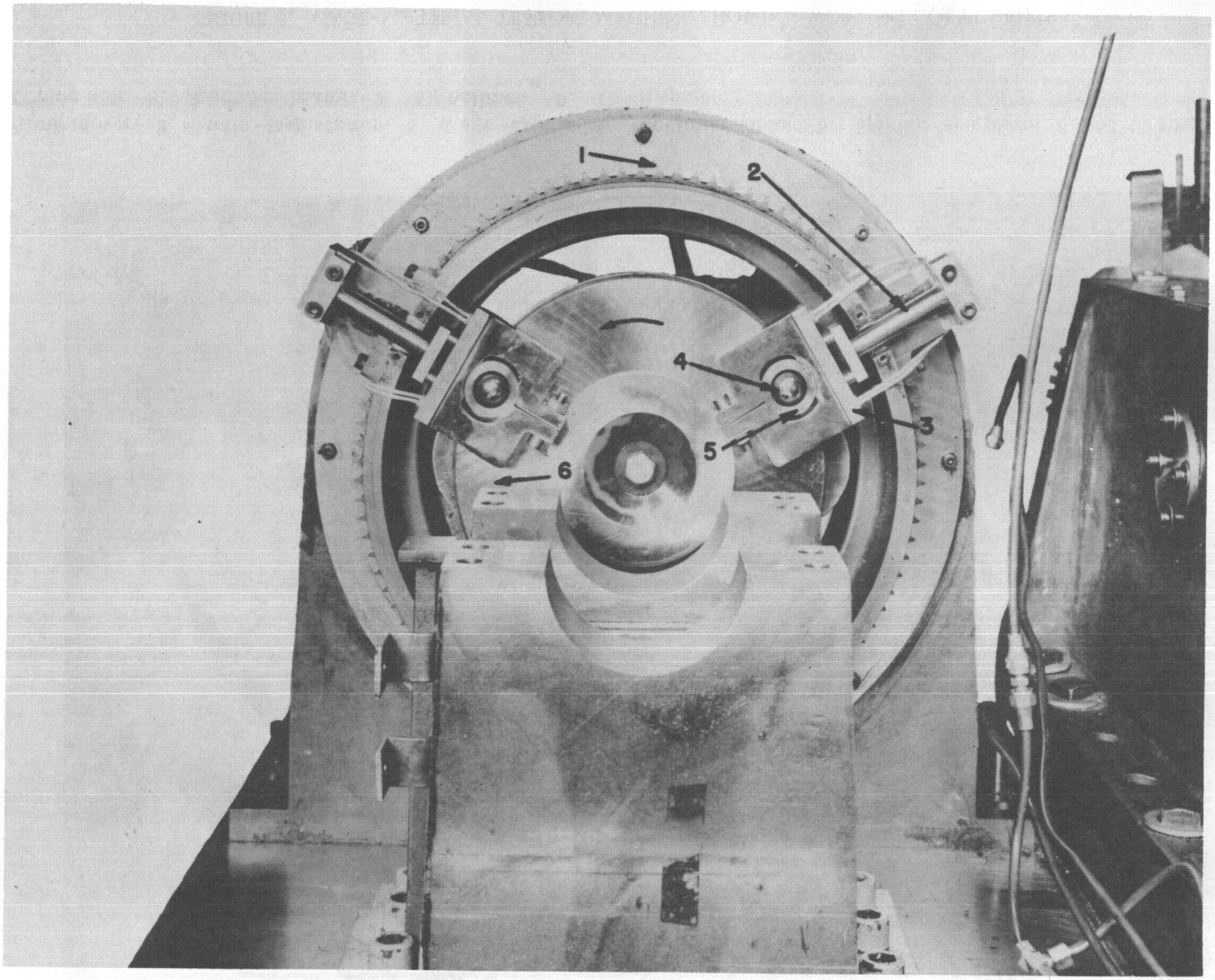
A machine has been designed and built to evaluate promising cage materials under simulated turbine-bearing operating conditions. Materials showing promise in the screening tests are investigated in this machine under the two basic conditions of cage wear: (1) hardened balls wearing the cage pockets, and (2) wear of cage surfaces rubbing on the cage-locating lands.

Figures 8 and 9 are photographs showing the working principles of the machine when set up for evaluating cage-pocket wear. (The machine can be used for testing the wear of cage surfaces rubbing on cage-locating lands and, with simple modification, for testing complete bearings.) Figure 8 shows the machine with the oil-collector covers removed, showing the specimen holders in position. Two counterrotating high-speed spindles are mounted face to face, so that three steel balls may be held between them. SAE 52100 hardened-steel races, lapped flat, are mounted on the spindle face plates and constitute the races against which the balls bear. The thrust spindle on the left is mounted on ball bushings, so that it may move axially. A thrust load is applied to the balls through this thrust spindle by means of an air bellows pushing on the spindle housing. The specimen holders, containing cylindrical cage specimens, are held between the two steel disks by the cage support, which is free to rotate concentric with the spindle axis. The spindles are driven by positive-drive "timing belts". An electric motor is used as a prime mover and is coupled to a right-angle-drive gear box through a flexible controlled-torque coupling. The gear box supplies equal rotative speeds to the two timing-belt pulleys at a 1-to-1 ratio with the prime mover. The prime mover may be operated at either 1800 or 3600 rpm. Figure 9 shows a head-on view of the face plate of one spindle, the foreground spindle having



1. Prime mover; 2. Strain-gage section; 3. Cage support; 4. Specimen holder; 5. Spindle face plate; 6. 52100 steel race; 7. Timing belt; 8. Specimen heater; 9. Air bellows; 10. Thrust spindle.

FIGURE 8. CAGE-MATERIAL TESTING MACHINE SHOWING WORKING COMPONENTS



1. Rotating cage support; 2. Strain-gage section; 3. Specimen holder; 4. Steel ball; 5. Specimen; 6. Steel race.

FIGURE 9. END VIEW OF CAGE-MATERIAL MACHINE, SPINDLE REMOVED

been removed. The three steel balls are positioned 120 degrees from each other by the cylindrical cage specimens mounted in the specimen holders. The counterrotating races, against which the balls bear, spin the balls at about 400 fps within the cage specimen "pockets". Oil is supplied to each cage specimen by a jet positioned so that the oil stream impinges on the rotating ball.

A detail sketch of the cage-material-testing-machine specimen holder is shown in Figure 10. Cylindrical cage specimens are mounted in a copper heat block and clamped in place by a compression screw. A thermocouple is inserted in the holder and into the side of the specimen, where a hole had been drilled previously. This point was selected for temperature measurement because the highest velocity surface of the ball contacts the cage pocket in that area. The holder is rigidly attached to the cage support by bolt-type fastenings on the end of the cylindrical strain-sensing element. Strain gages are mounted on the strain-sensing element in such a way that both bending in a plane normal to the race axis and twisting about the axis of the strain-sensing cylinder can be measured simultaneously. The strain-gage configuration and the two circuits, one sensitive to bending only, the other sensitive to twisting only, are shown in Figure 10. The strain gages are protected from the heat of the specimens by attaching the strain element to the heat block by four stainless steel pins, which act as heat barriers. The strain gages are effectively protected from hot-oil spray by wrapping them, after they are affixed to the strain-sensing element, with uncured Teflon tape and sealing the tape seams with a hot iron. Heat is supplied to the specimens by two 120-watt cartridge heaters pressed into the copper heat block.

The bearing-test components are as follows:

Bearing Races - Two flat steel disks, SAE 52100, hardened and stabilized, 10-inch OD, 4-inch ID, 9/16 inch thick. These disks are lapped with 400 Alundum to a microinch surface roughness of 4 to 7 rms profilometer. Hardness is 58-61 R_C.

Bearing Balls - Three steel balls, SAE 52100, hardened and stabilized, 15/16-inch diameter, within 20 microinches of sameness of diameter and sphericity. Hardness is 58-61 R_C. Surface roughness is 0.5-1 microinch rms.

Cage Specimens - Three cylindrical specimens of the material to be evaluated, 1-7/16-inch OD x 0.953-inch ID x 1/2 inch (0.015-inch clearance between ball and pocket).

In order to simulate severe wearing conditions in a turbine bearing that will result in scuffing of the balls against the cage-pocket surfaces,

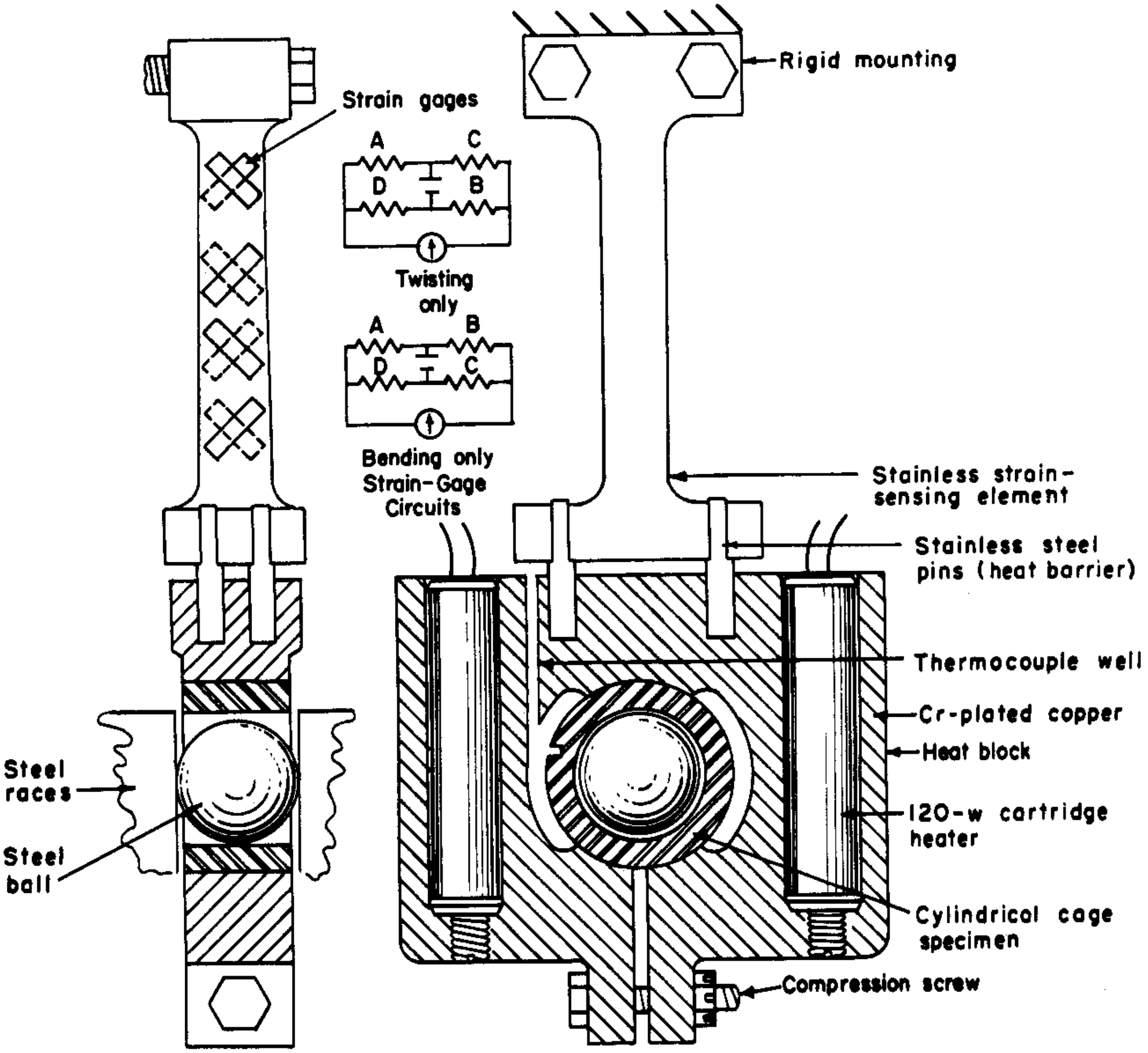


FIGURE 10. DETAIL SKETCH OF CAGE-SPECIMEN HOLDER AND STRAIN-GAGE CIRCUITS

methods were investigated to produce wear patterns similar to those found in bearings from actual turbine installations. Such a bearing cage is shown in Figure 11. It is known that most turbine bearings operate under conditions of misalignment owing to mechanical difficulties in producing true alignment and the warpage of housings from operating-temperature differentials. A theoretical analysis of the relative speeds of bearing components in an angular-contact bearing operating with misalignment* revealed that the balls would oscillate in the cage pockets. To simulate this type of ball loading on the cage pockets, the cage support was oscillated during a run so that the balls were loaded alternately against opposite surfaces of the cage pocket. Figure 12 shows the resulting wear patterns on the cage-specimen "pockets" for conditions of oscillation and no oscillation. It can be seen that these wear patterns are similar to those in the bearing-cage pockets and that oscillating the specimen holder extends the wear track to a greater portion of the pocket circumference. The wear of cage pockets in turbine bearings usually covers over 300 degrees of the surface. It was decided that the oscillating specimen holder should be incorporated in the standard test procedure.

Several preliminary tests have been run using silicon-iron bronze specimens, and the following conditions have been established for a standard test:

Speed - 410 fps (measured at the point of contact with the balls and the races)

Specimen temperature - 500 F

Normal load on balls - 1000 lb

Lubricant - Penola Turbo Oil 15 (MIL-L-7808 product)

Lubricant flow rate - 0.6 lb/min or 0.2 lb/min per specimen

Lubricant temperature - 350 F

Frequency of specimen oscillation - 180 cpm

Surface roughness of cage pocket - 10 to 20 microinches rms

Surface roughness of balls - 0.5 to 1.0 microinch rms

Surface roughness of flat races - 4 to 7 microinches rms

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* Jones, A. B., The Fafnir Bearing Company, "A Theoretical Investigation of the Performance of a Split-Inner-Race Ball Bearing Under Combined Load at High Speed", ASME-ASLE Lubrication Conference, Baltimore, Maryland (October 18-20, 1954).

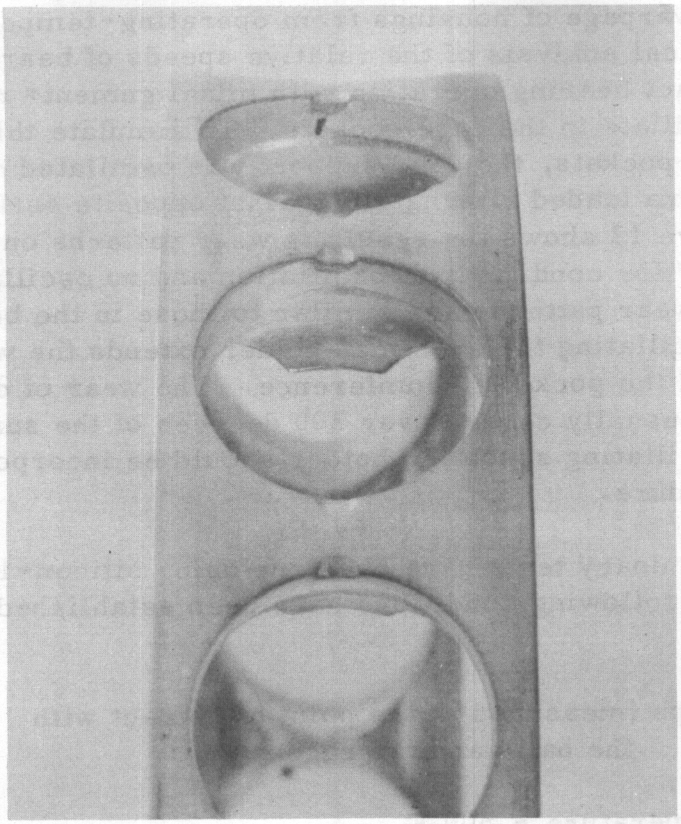
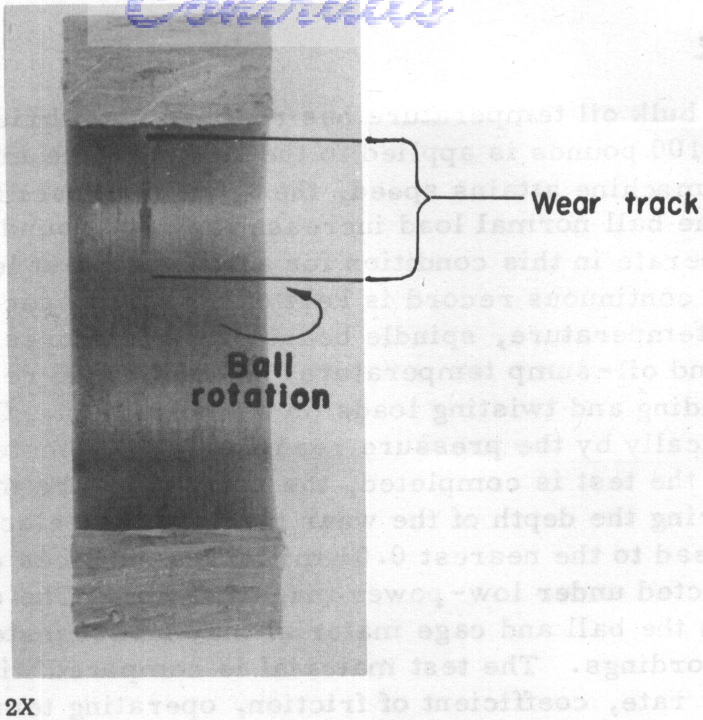


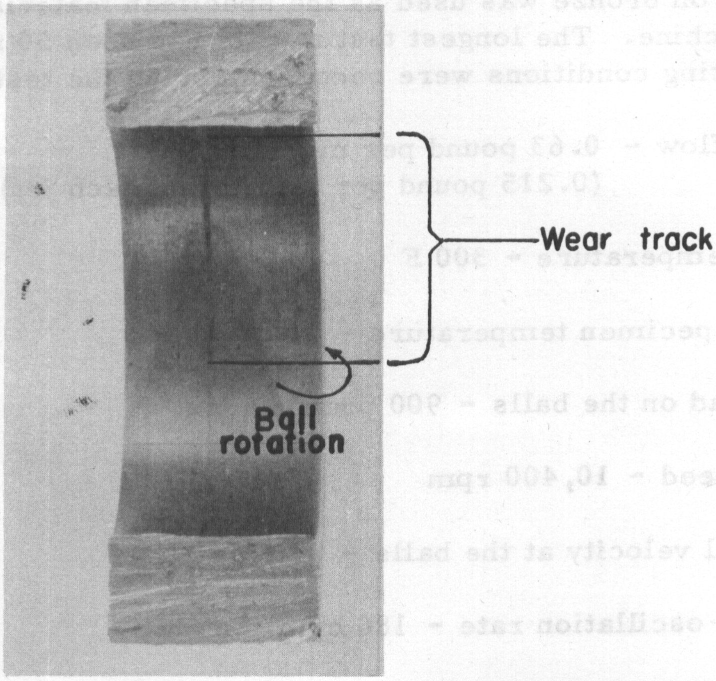
FIGURE 11. CAGE FROM ANGULAR-CONTACT TURBINE BEARING AFTER OPERATION WITH SLIGHT MISALIGNMENT, SHOWING WEAR TRACK MADE BY THE BALLS ON THE CAGE POCKETS



2X

a. First Test

No oscillation of specimen holders.



2X

b. Second Test

Specimen holders were oscillated. Note extension of wear track.

FIGURE 12. CAGE-MATERIAL SPECIMEN (SILICON-IRON BRONZE) FROM COUNTERROTATING-SPINDLE TESTS

Test Procedure

When the bulk oil temperature has reached equilibrium, an initial normal load of 100 pounds is applied to the balls and the machine is started. As soon as the machine attains speed, the specimen-oscillating device is turned on and the ball normal load increased to 1000 pounds. The machine is allowed to operate in this condition for a standard test length (tentatively 2 hours), and a continuous record is kept of the three specimen temperatures, bulk oil temperature, spindle bearing temperatures, gear-box oil temperature, and oil-sump temperature. A continuous recording is also made of the bending and twisting loads on one specimen. Oil-flow rate is checked periodically by the pressure readings of each metering orifice in the jets. After the test is completed, the specimens are measured for wear by measuring the depth of the wear track with an electrolimit gage, which may be read to the nearest 0.01 mil. The surfaces of the balls and races are inspected under low-power magnification. The coefficient of friction between the ball and cage material may be estimated from the torque and bending recordings. The test material is compared with silicon-iron bronze for wear rate, coefficient of friction, operating temperature, and general appearance of wearing surfaces.

Test Results

Silicon-iron bronze was used as the specimen material in the initial runs of this machine. The longest test to date has been 50 minutes. The following operating conditions were recorded during the test:

Total oil flow - 0.63 pound per minute
(0.215 pound per minute for each jet)

Bulk oil temperature - 300 F

Average specimen temperature - 280 F

Thrust load on the balls - 900 pounds

Spindle speed - 10,400 rpm

Peripheral velocity at the balls - 410 fps

Specimen-oscillation rate - 180 cpm.

The amplitude of the specimen oscillation was measured as 18.8 degrees, or about 1-1/2 inches at the center of the ball. During the test, the oil flow to one specimen was reduced considerably, and it was noted that the specimen's operating temperature rose continually until it reached a point 50 F above the bulk oil temperature. Oil flow to this specimen eventually was cut off completely. Although the temperature rose another 100 F before the machine was shut down, no adverse effects could be observed on the wearing surfaces of the specimen. The wear tracks on all three specimens were similar to that pictured in Figure 12 and were clearly visible over 300 degrees of the cage-pocket surface. The average depth of the wear track was fairly constant for all three specimens and was measured as 0.1 mil. The sphericity of the wear track was checked by calculating the length of the chord across a spherical segment 0.1 mil deep (see Figure 13). This was found to be 0.018 inch. The width of the wear tracks was measured and found to be about 0.02 inch. Assuming the wear track to have a perfect circular-segment cross section, the weight loss was calculated to be 0.00078 gram per specimen, the wear rate being 0.00094 gram per hour. The weight loss could not be measured accurately by comparing the weights of the specimens before and after a test run, because of oxide-film formation on the specimens during the test and metal transfer from the specimen holder to the specimen. The balls taken from these tests all had characteristic patterns of concentric scratches on them. A typical ball with these "bull's-eye" scratches is shown in Figure 14. These concentric scratches indicate that the axis of rotation of the balls remains constant throughout the test.

Bending and twisting of the specimen holder were measured simultaneously, using the strain-gage configuration shown in Figure 10. Bending of the bar is caused by the normal load between the ball and the cage-pocket surface when the ball is being driven by the cage specimen. Twisting of the bar is caused by friction forces between the spinning ball and the ball-contact area of the cage specimen. Before the test run, this strain-sensing device was calibrated by attaching weights to the specimen holder to simulate bending loads and torsional loads. Calibration was performed both before and after the test run, and little deviation was noted between the two calibrations.

The effect of interaction of the two strains was investigated during calibration of the strain-sensing element. Pure torsional and bending loads were applied to the cage specimen simultaneously. The torsional load was removed and the effect of its removal on the bending-strain recording observed. The torsional load was then reapplied and the bending load removed and its effect on the torsional-strain recording noted. When using load values assumed for actual operating conditions, the effect of interaction of combined loads was negligible. This was because the twisting strain, which is constant over the cylinder's length, was measured at the point of least bending strain and the twisting moment expected under operating conditions was too low to affect the bending strain noticeably. In fact, a twisting moment of 20 times that assumed for operating conditions was required in order to cause a 1 per cent change in the strain recorded as bending.

A sample recording of the strains measured during the 50-minute test run is shown in Figure 15. The maximum bending load at 1/2 cycle is 14 pounds (this results in a deflection of the cage specimen and holder of about

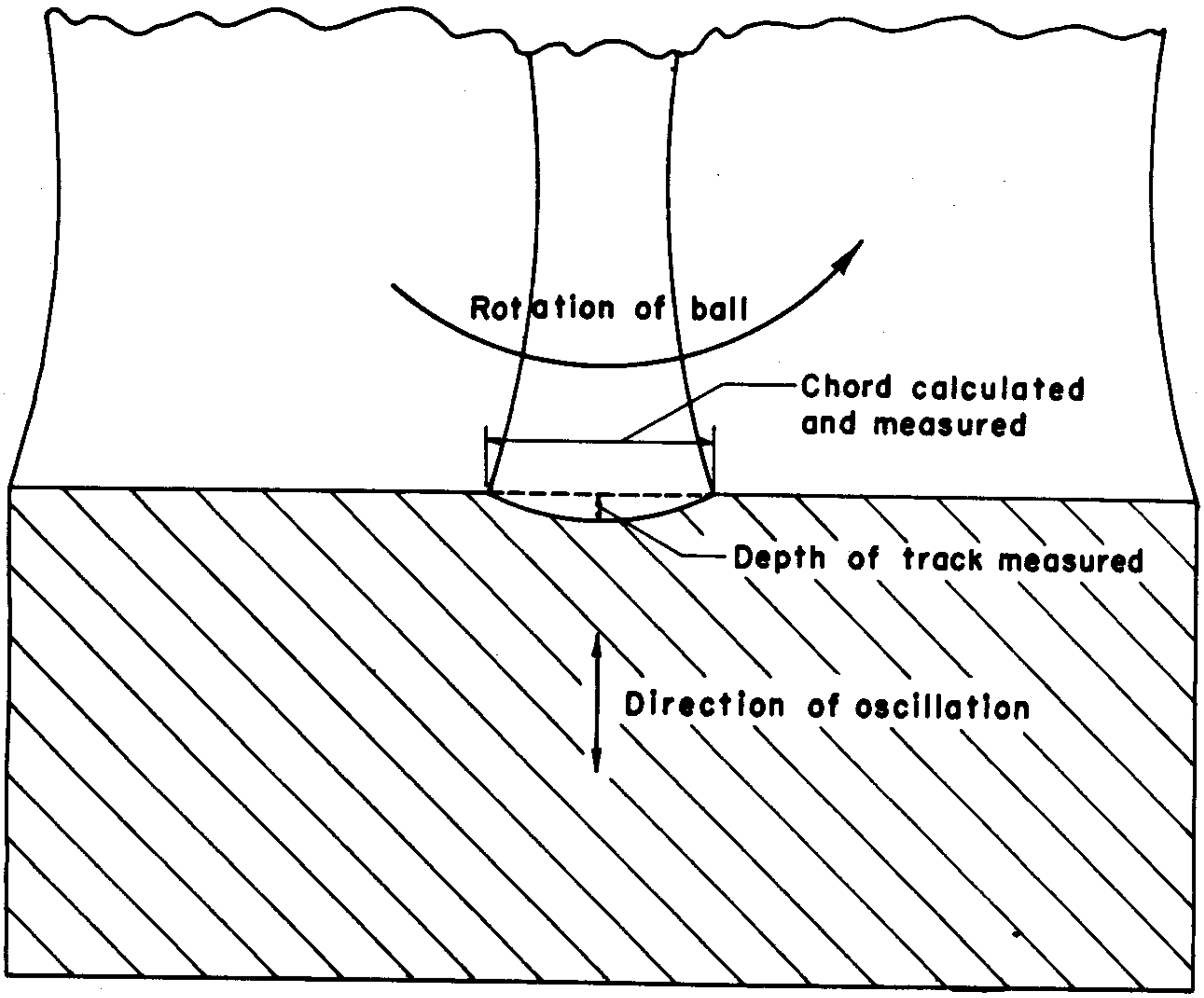


FIGURE 13. SECTION OF WEAR TRACK ON CAGE-SPECIMEN-POCKET SURFACE

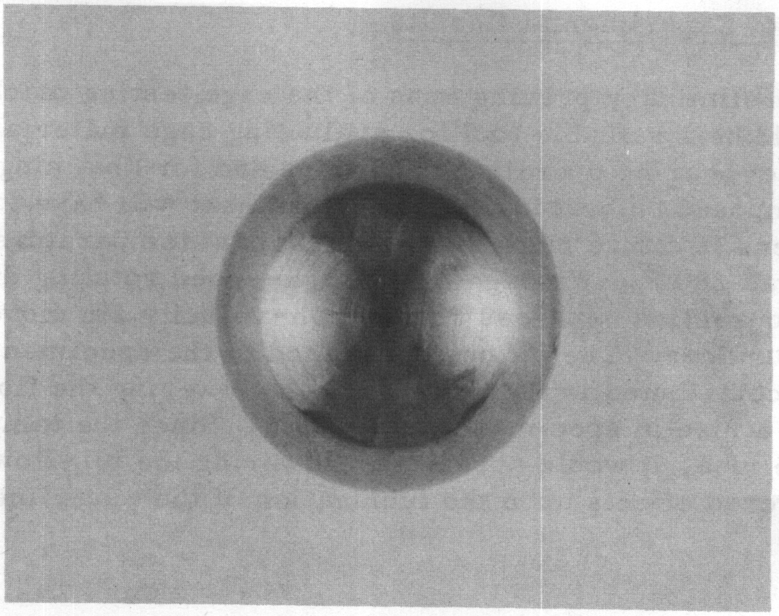


FIGURE 14. SAE 52100 STEEL BALL TAKEN FROM CAGE-MATERIAL TESTING MACHINE AFTER A 50-MINUTE RUN

Note concentricity of the scratches, forming a "bull's-eye" pattern.

2 mils), with a concurrent torque of 7 inch-pounds. The twisting loads recorded were higher than expected.

Discussion of Experimental Results

The preliminary proving runs of the cage-testing machine indicate that it should be a valuable tool for evaluating cage materials under simulated turbine-bearing operating conditions and for obtaining information on the loads imposed on bearing cages. More heat will have to be supplied to the specimens in future runs, since the highest temperature reached during operation was 280 F. Windage of the high-speed rotating disks caused considerable convection heat loss as the high-velocity air moved over the specimen surfaces. The oil being supplied to the specimen for lubrication apparently contributed to the cooling, since lowering the flow rate was attended by a rise in specimen temperature. Since the temperature leveled off after the rise, it would appear that lowering the oil-flow rate would have no adverse effects upon the lubrication of the experimental bearing components.

Corrosion Tests

Hot MIL-L-7808 products are known to attack some materials, notably copper, lead, silver, and the elastomers. Materials selected for screening as cage-material specimens were tested for corrosion resistance in hot MIL-L-7808. The results of these tests on materials that have been tested are given in Table 3. Each sample of cage material was placed in a separate container of fresh oil and placed in an electric furnace that had been heated to 347 F. The samples were allowed to remain in the furnace for 72 hours and then were removed and their change in weight measured. Lubricant neutralization number and viscosity were also measured after the test and compared with those of the fresh oil. A dummy sample of oil was placed in the 347 F furnace for 72 hours and its change in viscosity and neutralization number noted. The neutralization-number change for the dummy sample was from 0.14 to 4.4, which was higher than any of the changes noted for the oil samples with specimens in them. This indicates that refinements in the corrosion test are needed in order to assess more accurately the effects of various experimental cage materials on the lubricant. However, it can be seen from Table 3 that none of the more promising cage materials were affected much by the hot lubricant.

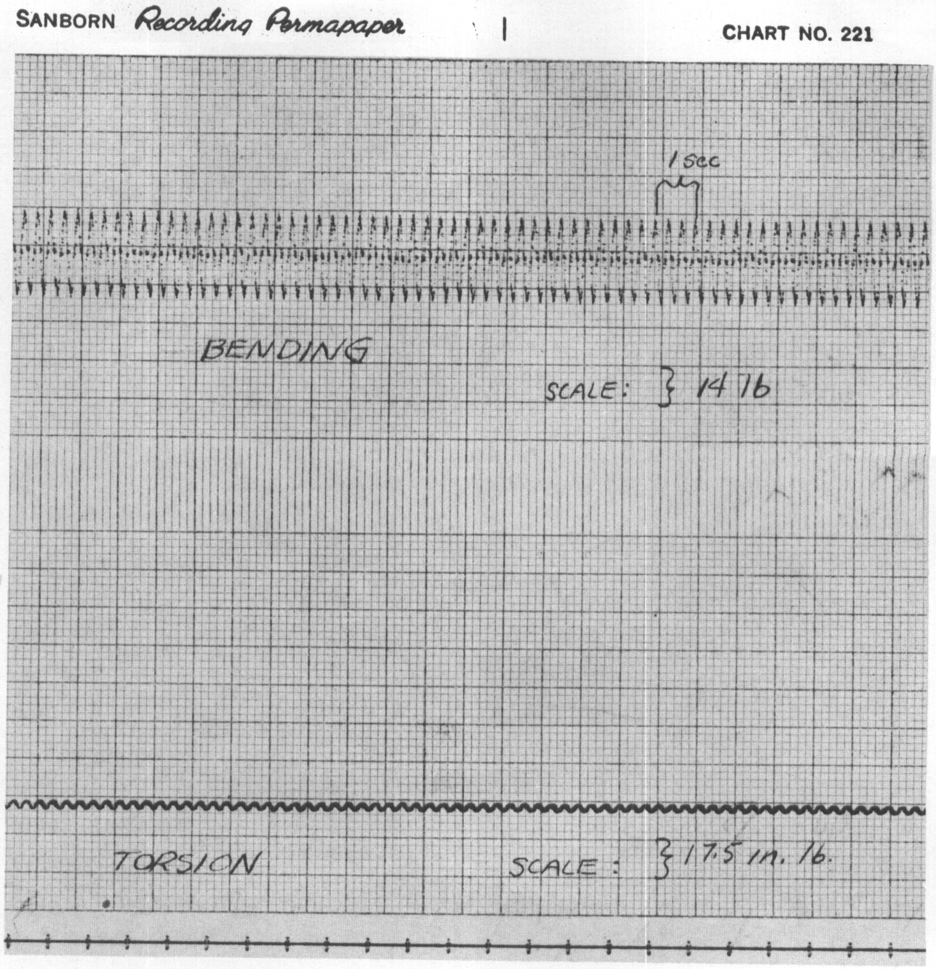


FIGURE 15. STRAIN RECORDING OF BENDING AND TORSION IN CAGE-SPECIMEN HOLDER

Speed, 10,400 rpm or 410 ft/sec; normal load on balls, 900 lb; holder oscillating 18 degrees at 180 cpm.

TABLE 3. PROPERTIES OF CAGE MATERIALS AND RESULTS OF CORROSION TESTS IN MIL-L-7808 LUBRICANT

Material	Composition	Hardness	Oxidation-Corrosion Test (72 Hours at 347 F)[(a)]			
			Weight Loss, mg/cm^2	Lubricant Neutralization Number	Lubricant Viscosity at 100 F, centistokes	Remarks
Silicon-iron bronze	2.5-4.0% Si 1.0-2.0% Fe 1.5-4.0% Zn 1.0% Mn 0.1% P Balance Cu	78 R_B	-0.02	3.1	14.59	Slight tarnishing
Silver-plated silicon-iron bronze (second test)		-	-0.06	2.3	14.44	No blistering observed
Battelle 50-50 alloy (second test)	-	14 R_E	+0.15	1.9	14.55	Dark film covering specimen
Battelle 70-30 alloy (second test)	-	34 R_E	+0.16	2.0	14.59	Dark film covering specimen
Chromized steel	0.002-in. case of high chromium content on mild steel	46 R_{30N}	+0.04	2.8	14.46	No change in appearance
Bronze screen - epoxy resin laminate		20-30 R_E	+0.7	2.3	14.44	No apparent change in appearance
Siliconized steel	0.001-in. case of high silicon content on mild steel	55 R_{30N}	+0.7	2.6	14.44	Thin, loose coating on specimen

TABLE 3. (Continued)

Material	Composition	Hardness	Oxidation-Corrosion Test (72 Hours at 347 F)[a] Weight Loss, mg/cm^2	Lubricant Neutralization Number	Lubricant Viscosity at 100 F, centistokes	Remarks
Electroless-nickel-plated steel	Hard nickel phosphate (70% Ni) coating plated on steel without electric current	400-450 Knoop	+0.04	-	-	Black tarnish
Graph M-N-S (Timken)	1.50 carbon 1.25% Mn 0.025% P 0.025% S 1.25% Si 1.75% Ni 0.50 Mo 0.50 Cr	63 R_C	00	-	-	No change in appearance

(a) As-received oil properties:
Viscosity = 13.96
Neutralization No. = 0.14
Dummy oil sample heated without corrosion specimen:
Viscosity = 14.46
Neutralization No. = 4.4

RECOMMENDED FUTURE WORK

More materials have been suggested for screening in the rubbing-button test. These include:

Copper-Nickel Silicide - an alloy of high thermal conductivity with a hardness of 80 R_B. This material has proved exceptionally wear resistant in other boundary-lubrication studies at Battelle.

Hy-Ten-Sil No. 1 - aluminum-manganese bearing bronze.

Timken Graph MNS - an oil- or air-hardening steel containing free graphite. This material is reported to possess high abrasion and seizure resistance.

Electrodeposited Chromium-Iron Alloy - a deposit reported to be harder than conventional hard chromium plate and to possess much better hot-hardness properties.

Porous Chromium Plate - a material possessing oil-retention properties for conditions of poor lubrication.

Beryllium-Copper-Boron Nitride - a cermet hot pressed and heat treated. A hardness of 40 R_C may be attained in heat-treated beryllium copper.

Nitrided Steel - an extremely hard surface treatment for steel.

Cermets should be investigated further, in consideration of the promising results in the screening tests. Recent investigations in the field of wear and galling under thin-film-lubrication conditions indicate that sintered chromium-nickel impregnated with silver, Inconel, nodular iron, and H Monel are worthy of being investigated. The two materials showing promise in the rubbing-button screening tests should be evaluated fully by comparing their performance under conditions of balls rubbing on cage pockets and of cage surfaces rubbing against the cage-locating lands in the cage-testing machine with that of silicon-iron bronze. Finally, these materials should be tested as full cages in a bearing operating under simulated aircraft turbine operating conditions. Interrupted-oil-flow studies, using the cage-load-measuring device to detect incipient seizure, would be valuable in comparing these materials for use in aircraft turbine-bearing cages.

The cage-material testing machine should be operated for a longer period of time, using silicon-iron bronze specimens. A probable standard test length would be 2 hours. The specimen temperature should be increased to at least 500 F by the addition of more heat to the specimen holders, decreasing the lubricant flow and insulation of the heated surfaces exposed to the high-velocity air flow. A maximum specimen temperature of 750 F is deemed necessary to meet increasing demands on the turbine bearings as higher temperature lubricants become available.

Radioactive-tracer techniques have been investigated for use in this investigation and have been found applicable to the problem. Wear rates can be measured continuously during a test as the concentration of radioactive wear debris increases in the lubricant. Silicon-iron bronze cage specimens have been irradiated successfully at Brookhaven National Laboratory, but time limitations precluded their use in this report period. The transfer of cage material by adhesion to the balls can be measured by using autoradiographs made by rolling the balls taken from the machine on sensitized photographic film. The possibility of transfer of material from the cage to the ball and then to the bearing race may be investigated by this method also.

Corrosion studies should be continued on experimental cage materials in hot MIL-L-7808 products and any new high-temperature lubricants that become available. The test methods used in determining MIL-L-7808 specifications should be strictly followed, so that the results can be compared with the present specifications and new specifications can be written.

The design of future aircraft turbine bearings should be aided substantially by data that can be obtained from the cage-material testing machine. Not only may cage materials be evaluated under simulated turbine-bearing operating conditions, but data on loads imposed by the balls on the cages may be obtained, full high-speed bearings may be tested, and the lubricating qualities of various experimental lubricants for aircraft gas turbines can be estimated.