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FRICTION AND WEAR OF HOT-PRESSED BEARING MATERIALS CONTAINING MOLYBDENUM DISULFIDE

By Robert L. Johnson, Max A. Swikert
and Edmond E. Bisson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

An experimental investigation was conducted to determine the feasibility of bearing lubrication by a process involving the transfer of molybdenum disulfide from within the structure of a composite bearing material to the interface between the contacting surfaces. The investigation was also conducted to establish the proportionate amount of lubricant necessary in such a bearing material. A study was made of bearing materials composed of various amounts of molybdenum disulfide (up to 35 percent), silver, and 5-percent copper.

The experiments were performed with a kinetic-friction apparatus employing a rotating steel disk and a bearing-specimen assembly suspended and restrained by metal springs. The bearing specimen had a hemispherical contacting surface. Experimental runs were made over a range of sliding velocities between 75 and 8000 feet per minute with loads of 269, 519, and 1017 grams. Specimen surfaces were studied with standard metallurgical and physical techniques and equipment.

The materials investigated were lubricated by a transfer of solid lubricant (molybdenum disulfide) from within the structure of the rider to the interface between rider and slider. This transfer resulted in the formation of an effective lubricating film. The best composition studied in this investigation, from considerations of both friction and wear, contained 10-percent molybdenum disulfide. This composition showed the lowest rate of wear and relatively low friction (approaching the lowest obtained); the friction for this material was relatively unaffected by sliding velocity. Surface welding occurred with specimens containing less than 5-percent molybdenum disulfide.

INTRODUCTION

Some of the conditions under which aircraft-propulsion systems must operate can result in extreme boundary lubrication between the contacting surfaces; at these conditions, some metal-to-metal contact would result. As an example, Gurney in reference 1 states that the temperatures attained in rolling-contact bearings after shutdown can result in vaporization of the lubricant, which permits metal-to-metal contact on subsequent starting of the engine. Bearing materials containing a solid lubricant prepared by powder-metallurgy techniques might be suitable for reducing friction and preventing welding under conditions of metal-to-metal contact. These materials would consist of a relatively hard matrix in which small particles of a soft phase are dispersed. A material such as molybdenum disulfide MoS_2 might adequately serve as the soft phase. According to reference 2, MoS_2 is an effective solid-film lubricant under extreme conditions of sliding velocity and surface load. Analysis of the lubricating action of MoS_2, presented in reference 2, indicates that within the ranges of thermal and chemical stability of the material (reference 3) it should be an effective lubricant. Although prepared surface oxides are considered beneficial in MoS_2 lubrication of steel surfaces, research using MoS_2 as an additive in fluid lubricants (reference 4) shows that the prepared oxides are unnecessary for effective lubrication in all cases.

Experiments were conducted at the NACA Lewis laboratory to determine the mechanism of action and the friction and wear properties in dry sliding of hot-pressed bearing materials containing MoS_2. A secondary purpose was the determination of the optimum concentration of MoS_2 from considerations of both friction and wear. The principal constituent of the materials investigated was silver Ag with a small amount of copper Cu. This matrix was selected because of its known desirable bearing characteristics and because it could be formed by powder-metallurgy techniques.

The apparatus used for these experiments consisted of an elastically restrained rider having a hemispherical contacting surface sliding on a rotating steel disk. The friction and wear characteristics of the bearing materials were studied with loads from 269 to 1017 grams (0.58 to 2.19 lb) at sliding velocities up to 8000 feet per minute. Specimens were prepared of various concentrations of MoS_2 (from 1 to 35 percent), Ag, and 5-percent Cu.

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APPARATUS AND PROCEDURE

Friction and wear specimens. - The specimens used in these experiments consisted of a rotating steel disk, comprising the slider, and a cylindrical-shaped rider 3/8 inch in diameter with a hemispherical-shaped contacting surface (3/16-in. radius) on one end. The hemispherical surface of the rider was produced by shaping with a special cutter. The wear surface was reshaped after each friction run to remove the wear spot and the surface was then lightly polished with 0000 emery paper. The riders consisted of specimens with various concentrations of MoS_2 (from 1 to 35 percent), Ag, and 5-percent Cu.

In the contact of the spherical surface with the flat surface, the equivalent initial Hertz surface stress for the 269-gram (0.58 lb) load is approximately 61,000 pounds per square inch if elastic deformation of both specimens and a modulus of elasticity for the rider nearly equivalent to that for Ag are assumed. This value is an approximation as some plastic deformation probably occurs because of lack of homogeneity of the powder-metallurgy specimens. Also, the modulus of elasticity for these specimens is probably unequal to that for Ag in all combinations of MoS_2 and Ag.

Specimen preparation. - The bearing specimens used were formed by hot-pressing powdered constituents. The apparatus used to form the specimens consisted of an induction heating unit, a hydraulic press, and a carbon die. The carbon die was made from a 3-inch-diameter rod approximately 5 inches long with a 3/8-inch-diameter hole bored along its axis. The die was heated to a temperature of 1400° F within a few minutes by the induction unit; subsequently, the powdered mixture in the die was compressed within 10 to 15 seconds by a 3/8-inch-diameter carbon rod contacting the anvil of the hydraulic press. The maximum pressing force was 900 pounds, producing a maximum unit loading of approximately 8100 pounds per square inch. After pressing, the specimens were allowed to cool in the dies to a temperature below 140° F, which required several hours. The disks of the friction apparatus, made of SAE 1020 steel, were finished and cleaned as described in reference 5. After cleaning, the disk surface was free of adsorbed grease film as indicated by the ability of water to wet the surface. A thin (15 to 25 A) film of ferroso-ferric oxide Fe_3O_4, however, remained on the surface as stated in reference 5.

The materials used in the riders could not be satisfactorily mixed in a conventional ball mill; consequently, it was necessary to mix

them by hand with a spatula. The MoS_2 adhered to the operating parts of the ball mill to such an extent that it was impossible to obtain specimens having known concentrations of MoS_2. 1220

Friction apparatus. - The friction apparatus used for these experiments is the same as that described in reference 5 except that it was modified to accommodate the cylindrical-shaped rider specimen. A diagrammatic sketch of the apparatus showing the elastically restrained rider-holder assembly and the rotating disk that are the primary parts is presented in figure 1. The disk is rotated by a hydraulic-motor assembly that provides accurate speed control over a range of sliding velocities from 50 to 18,000 feet per minute. Loading is accomplished by placing weights on the rider holder. Friction force is measured by four temperature-compensated strain gages mounted on a copper-beryllium dynamometer ring and connected to an observation-type potentiometer converted to use as a friction-force indicator.

The apparatus includes an electrically driven radial-feed mechanism calibrated to indicate radial position of the rider. The radial feed is used to position the specimen and, when desired, to cause the specimen to traverse a spiral path on the rotating disk. The friction-force readings are recorded by a motion picture camera (64 frames/sec) timed to operate for 3 seconds, covering each separate friction run. The specimen disk is mounted on a flywheel assembled with its shaft supported and located by a mounting block containing bearing assemblies for accurate location.

Method of conducting experiments. - Friction runs were made with loads of 269, 519, and 1017 grams (0.58, 1.14, and 2.19 lb) at sliding velocities from 75 to 8000 feet per minute using riders containing various percentages of MoS_2 with a Ag and Cu base. Separate wear runs were made with a load of 519 grams at a sliding velocity of 5000 feet per minute for periods of 1 hour.

In conducting the friction runs, the disk is rotated at a predetermined speed and, by means of a cam arrangement, the loaded rider is lowered onto the disk as the radial feed is started. As the rider traverses the disk along a spiral track, friction force is indicated by the potentiometer and recorded by the camera; disk rotative speed is determined with an electric revolution counter and a synchronized timer. The run is terminated after 3 seconds by lifting the rider from the moving disk surface. Mean sliding velocity for the experiment is computed from the recorded disk rotative speed and the mean diameter of the rider path. The change in diameter of the rider path on the disk resulting from the radial travel

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of the rider causes a maximum deviation in sliding velocity of approximately 3 percent from the mean value.

Time lag in the mechanical drive that determines the response rate of the potentiometer used for indicating friction force was more than one-half of the total duration of a single run (3 sec) in cases where high friction values were obtained. In order to minimize this difficulty and thereby obtain the longest possible period of time at stabilized friction values, it was normal procedure to preload the force-measuring system to approximately the expected friction-force value.

The wear runs were made by allowing the rider to slide over the same track on the disk. The duration of the wear runs was determined with a conventional stop watch.

The limits of experimental error in the friction values presented were not constant in all the experiments because of inconsistencies in the rider specimens. In all but isolated cases, the reproducibility in coefficient of friction was within ± 0.05 of the values given and in general was less. By definition, the coefficient of friction is the ratio of the friction force to the applied normal load. This scatter of data, although relatively great, may possibly be explained by non-homogeneity of rider specimens, which resulted in high friction when wearing through the hard matrix and low friction whenever an inclusion of the solid lubricant MoS_2 was reached. The limits of reproducibility in the wear-spot diameter measurements was within ± 20 percent and the error in weight-loss measurements was greater; in consequence, the most emphasis was placed on the wear-spot diameter measurements.

Wear of the rider was determined from measurements of wear-spot diameter made with a calibrated microscope and by weight loss obtained with an analytical balance. Hardness measurements of the matrix of each specimen were made with a Bierbaum Microcharacter (scratch hardness tester).

RESULTS AND DISCUSSION

Sliding velocity. - In order to evaluate the friction data obtained with the hot-pressed bearing specimens, the data of reference 5 relative to the effect of sliding velocity on the coefficient of kinetic friction for dry steel surfaces are presented in figure 2. These data include loads from 269 to 1017 grams (0.58 to 2.19 lb); for the steel-on-steel surfaces, friction coefficient was independent of load (that is, Amonton's law was verified). Comparative data presented in reference 6 indicate that with common bearing materials, including steel sliding on bronze, cadmium-nickel, or babbitt, friction coefficients in the range of 0.22 to 0.55 were obtained.

Data showing the effects of sliding velocity on friction for hot-pressed rider specimens containing various percentages of MoS_2 with Cu and Ag are presented in figure 3. In comparing the friction curves (at a load of 269 grams) for the various rider specimens, appreciable decreases in friction with increases in sliding velocity between 1000 and 8000 feet per minute are evident for MoS_2 concentrations of less than 5 percent. In general, with the higher concentrations of MoS_2, the friction forces stabilized and showed little change with variation in sliding velocity. 1220

The data of figure 3 also include points for loads of 519 and 1017 grams as well as for the 269-gram load (the curves are for the 269-gram load). Load apparently has little effect on friction over the range investigated. In all these experiments, however, the data scatter was quite large, possibly masking any effect of load on friction coefficient. Absence of a discernible general effect of load may reflect the lack of homogeneity observed in the hot-pressed specimens. Voids and relatively large inclusions of MoS_2 in the specimens were common.

Concentration of MoS_2. - As shown in figure 4, friction generally decreased with increased MoS_2 concentration. The greatest effect of concentration on friction was observed in the range of concentrations of MoS_2 between 0 and 5 percent. With higher concentrations, the relative effect of the amount of MoS_2 on friction was less; however, a decrease in friction continued with increased concentration.

Enlarged photographs of wear areas produced on specimens of various MoS_2 concentrations during 1 hour of operation at a sliding velocity of 5000 feet per minute and a load of 519 grams are presented in figure 5. Wear runs were made with the 519-gram load because of inability to obtain significant wear data in a reasonable period of time with the 269-gram load used in presenting most of the friction data. Data on the physical measurements of wear on these specimens are presented in figure 6. Because the reproducibility of the weight-loss data was not nearly as good as that for the wear-spot diameter, the weight-loss curve is included only to show the trend and to indicate the general correlation of the two methods of wear measurement. A friction curve is also included in figure 6 for these specimens; this curve is cross-plotted from figure 3. These data show a definite minimum amount of wear with specimens having approximately 10-percent MoS_2. Greater wear of specimens containing more than this amount is attributed to lower specimen strength resulting from the larger proportion of the soft phase (MoS_2) within the

hard matrix. A photomicrograph of a Bierbaum hardness scratch made on the surface of a specimen containing 15-percent MoS_2 is presented in figure 7. Filtered light, used in making this figure, accentuated directional surface disturbances such as the hardness scratch. Comparison of the width of this scratch and data obtained with specimens containing different MoS_2 concentrations indicated there was little difference in matrix hardness of specimens having various ratios of Ag to Cu. Equivalent scratches have been obtained in other materials that had measured Brinell hardness numbers of approximately 150. No physical measurements, such as tensile and compressive tests, were made but increasing the amount of lubricant inclusions (MoS_2) would probably adversely affect the strength of the composite material. A cursory study of the fine network of lines that appear in figure 7 indicated that this network might correspond to the MoS_2 inclusions. A grouping of these network lines would correspond to a relatively large inclusion of MoS_2 that would then be visible under normal lighting, as shown in figure 8. A photomicrograph of a finely abraded surface of a specimen containing 15-percent MoS_2 is presented in figure 8 showing typical dispersion of the solid lubricant under normal lighting.

Surface studies. - When an effective lubricating film (resulting in low friction and no welding) was established between the rider and the steel-disk surfaces, the contacting areas showed characteristic discoloration. This discoloration lowered the reflectivity of the surfaces and, in general, made photomicroscopy more difficult and rendered black and white photomicrographs less significant. In some cases, the common varied lines of discoloration appeared in black and white photomicrographs as indicating severe surface disturbance when in reality no significant surface disturbance existed, as determined from either a visual study or a study of full-color photomicrographs.

Several photomicrographs of wear surfaces of rider and disk specimens after 1 hour of operation at 5000 feet per minute sliding velocity with 519 grams load are given in figure 9. In figure 9(a), the wear surface of a rider specimen containing 95-percent Ag and 5-percent Cu is shown. The photomicrograph shows normal abrasive-type wear, as well as a pit that may have been caused by plucking out of material because of a strong weld between the sliding surfaces. A characteristic surface crack is also shown on the upper part of the photomicrograph. Surface cracks of this nature are common in dry friction with many materials including steel and are probably caused by the high surface stresses resulting from welding. These high surface stresses in the direction of motion produce surface failures in the form of cracks normal to the direction of motion. In consequence, the surface crack of figure 9(a) cannot be considered as resulting from any characteristics peculiar to this material.

The mating disk surface for the rider shown in figure 9(a) is presented in figure 9(b). This disk surface shows a surface weld of the rider material to the steel. Surface welds of this nature were common with all rider specimens containing less than 5-percent MoS_2. The dark spots appearing all over the normal running surface in figure 9(b) were probably caused by oxidation of rider material transferred to the disk.

The wear surface of a rider specimen containing 15-percent MoS_2, 80-percent Ag, and 5-percent Cu is shown in figure 9(c). The apparent surface disturbances in this case consist of the surface discoloration previously discussed and the surfaces of inclusions of MoS_2, indicated in figure 8. No evidence of surface welding or other common forms of lubrication failure was found on this surface or on the mating steel surface shown in figure 9(d). In figures 9(c) and 9(d), surfaces that are considered representative of the contact areas observed in all cases of the satisfactory operation that occurred with concentrations of MoS_2 of 5 percent or higher are pictured. In these cases, surface discoloration of both the rider and the disk occurred; this discoloration was primarily the result of the MoS_2 being transferred from the rider material to form a lubricating film. The lubricating film was quite thin although it had sufficient thickness on the steel surface to include particles of wear debris from the rider matrix. The lubricating film was not perfectly continuous but seemed to cover most of the contacting surfaces. Surface coloration made identification of the film material present comparatively simple.

Examination of the friction, wear, and surface-study data obtained establishes the fact that an optimum concentration of MoS_2 exists that seems to be approximately 10 percent. Above that concentration wear increased, friction decreased only slightly, and no indication of any further desirable effect on surface condition occurred.

In general, by comparison of the friction data obtained in this investigation with that of figure 2 and reference 6, it is indicated that bearing surfaces made of hot-pressed Ag, Cu, and MoS_2 may have suitable friction characteristics at moderate sliding velocities and under conditions of metal-to-metal contact. The data of this investigation also indicate that the solid film lubricant MoS_2 was effective in preventing welding at concentrations greater than 5 percent even under conditions of metal-to-metal contact. This result is in contrast to that for the steel surfaces of reference 5, where welding took place whenever the surfaces were dry and clean.

Surface studies of the disk specimens after operation with the hot-pressed rider show that MoS_2 is transferred from the rider material to form a lubricating film similar to that described in reference 7, which states that lead is extruded (from copper-lead bearings) to form an effective lubricating film on steel surfaces. A chemical spot test indicated that the film present on the rubbed surface contained molybdenum. The spot test used is described in reference 8 and involved the use of ammonium hydroxide to dissolve the molybdenum compound. This solution was then absorbed on filter paper that was acidified in fumes of concentrated hydrochloric acid. A drop of sodium thiocyanate solution was then added and, in those cases where molybdenum was present, a brown-red color appeared. The intensity of color depended on the original concentration of molybdenum. A further check was made by the addition of stannous chloride, which will discolor the solution if the color is due to iron. The results of the check substantiated the indication that molybdenum and not iron was predominately present in the film material. The matrix material of rider specimens having less than 5-percent MoS_2 showed immediate surface welding to the steel when operated at high sliding velocities. Because lubrication by thin solids requires a film of finite thickness, the process of gradual running-in of such surfaces would probably increase the thickness of a transferred film of MoS_2. This MoS_2 film would protect the surfaces against failure during subsequent operation at higher sliding velocities.

SUMMARY OF RESULTS

Hot-pressed bearing materials containing molybdenum disulfide MoS_2, silver Ag, and copper Cu, formed in cylinders with hemispherical contacting ends, were operated against rotating dry steel disks at sliding velocities between 75 and 8000 feet per minute and with loads of 269, 519, and 1017 grams. Under these conditions, the following results were observed:

1. The bearing materials investigated functioned by a transfer of solid lubricant (molybdenum disulfide MoS_2) from within the structure of the rider to the interface between the rider and the steel slider; this transfer resulted in the formation of an effective lubricating film on the steel surface.

2. Of the bearing compositions investigated, the one containing 10-percent molybdenum disulfide MoS_2, 85-percent silver Ag, and 5-percent copper Cu was shown to have the best performance characteristics with regard to both friction and wear. Lower concentrations of MoS_2 resulted in higher friction, greater wear, and, in

most cases, surface failure by welding. Concentrations of MoS_2 above 10 percent resulted in a slight decrease of friction; however, wear increased, probably because the higher concentration of MoS_2 lowered the physical strength of the material.

3. Sliding velocities up to 8000 feet per minute did not influence the friction values to any appreciable degree although the trends showed some deviation when less than 5-percent molybdenum disulfide MoS_2 was included in the materials.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 18, 1949.

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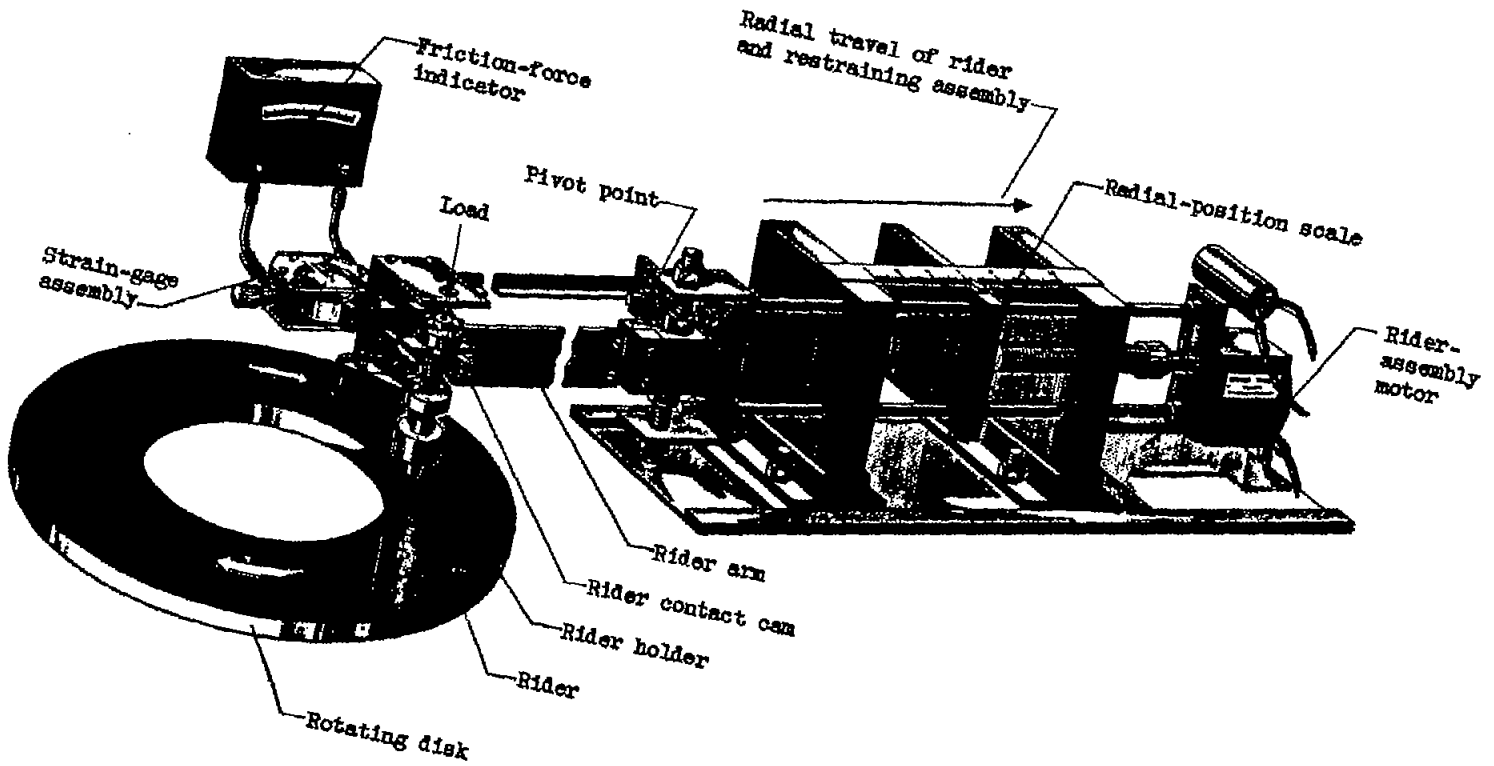


Figure 1. - Schematic diagram of sliding-friction apparatus.

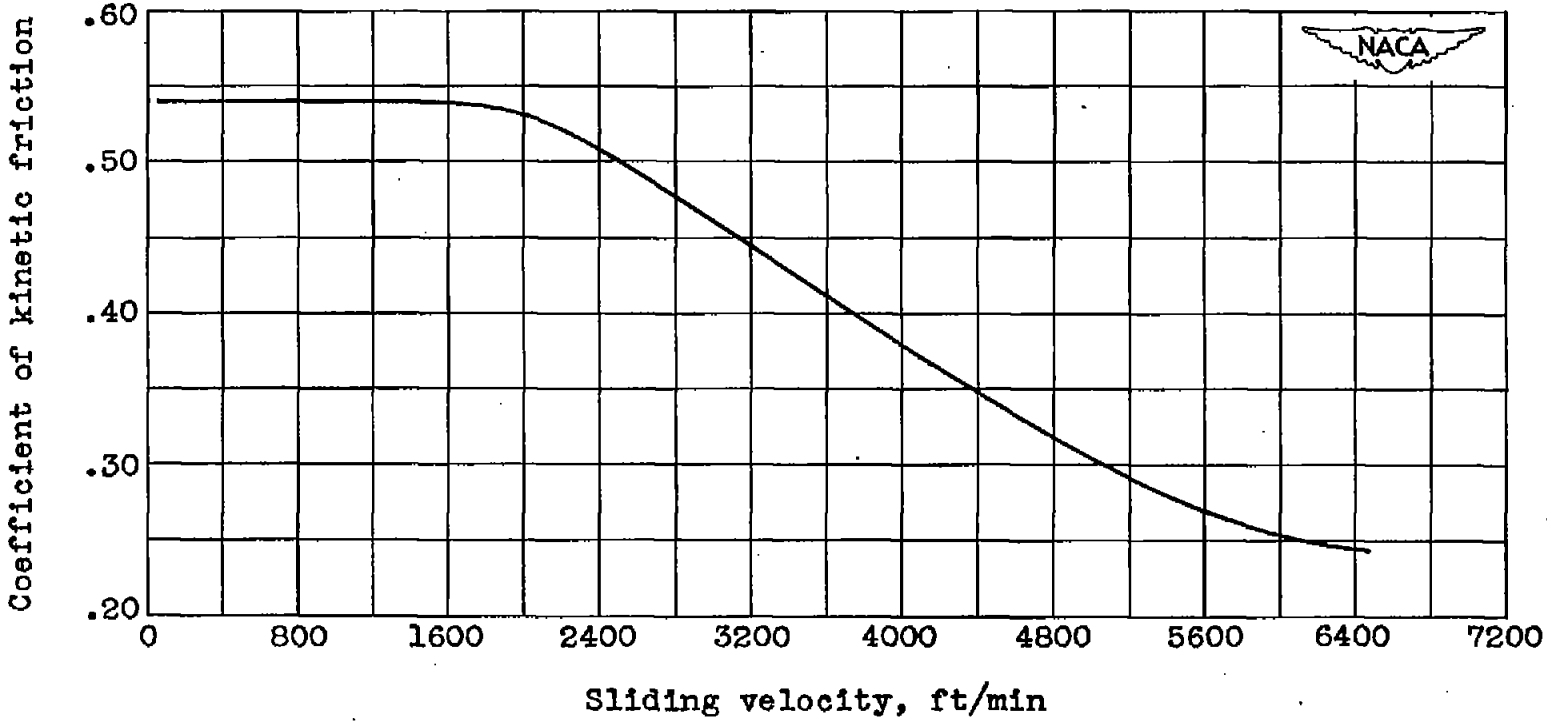
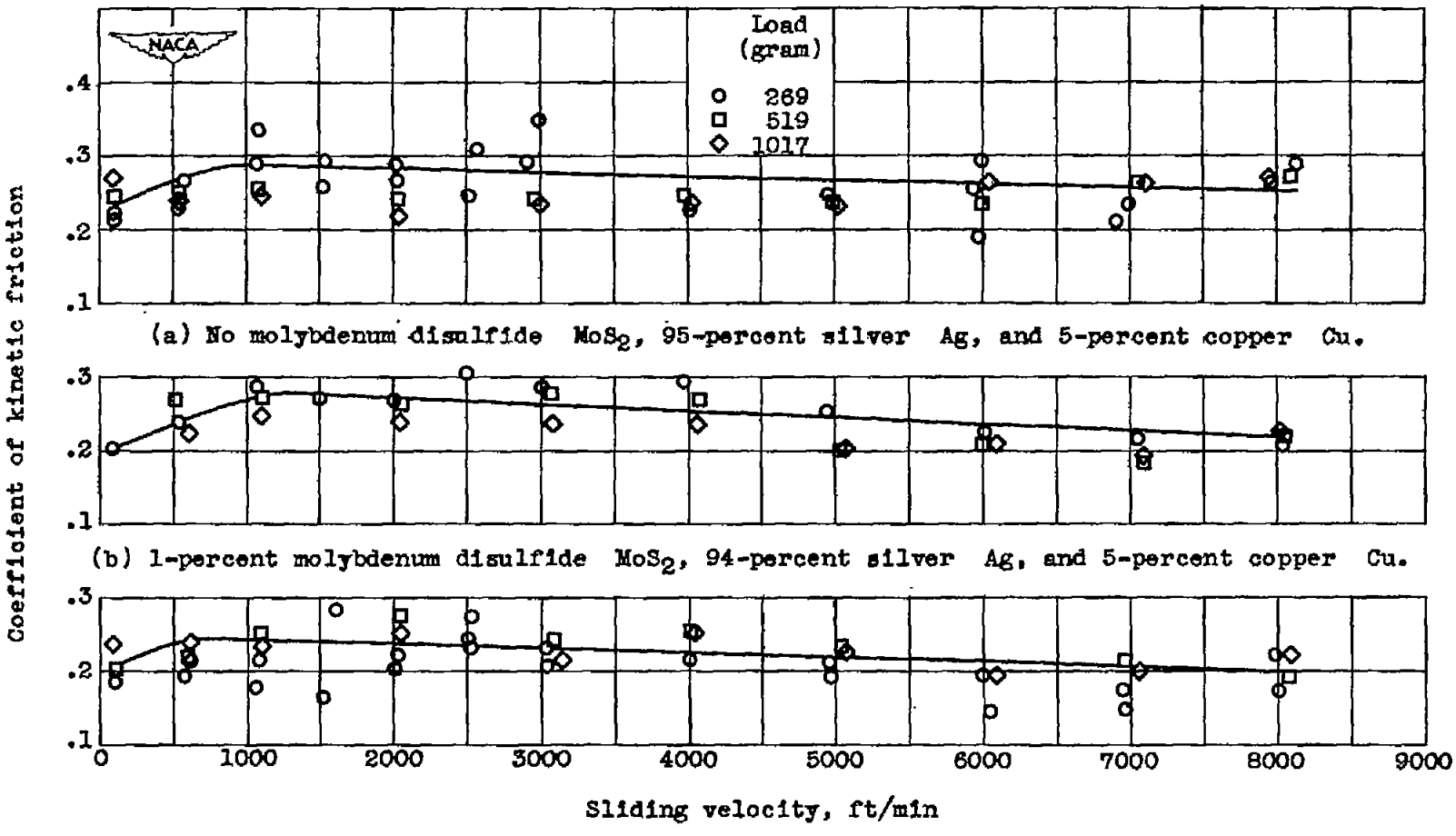


Figure 2. - Effect of sliding velocity on coefficient of kinetic friction for dry steel surfaces. (Fig. 5 of reference 5.) Loads, 269 to 1017 grams (initial Hertz surface stress, 126,000 to 194,000 lb/sq in.).

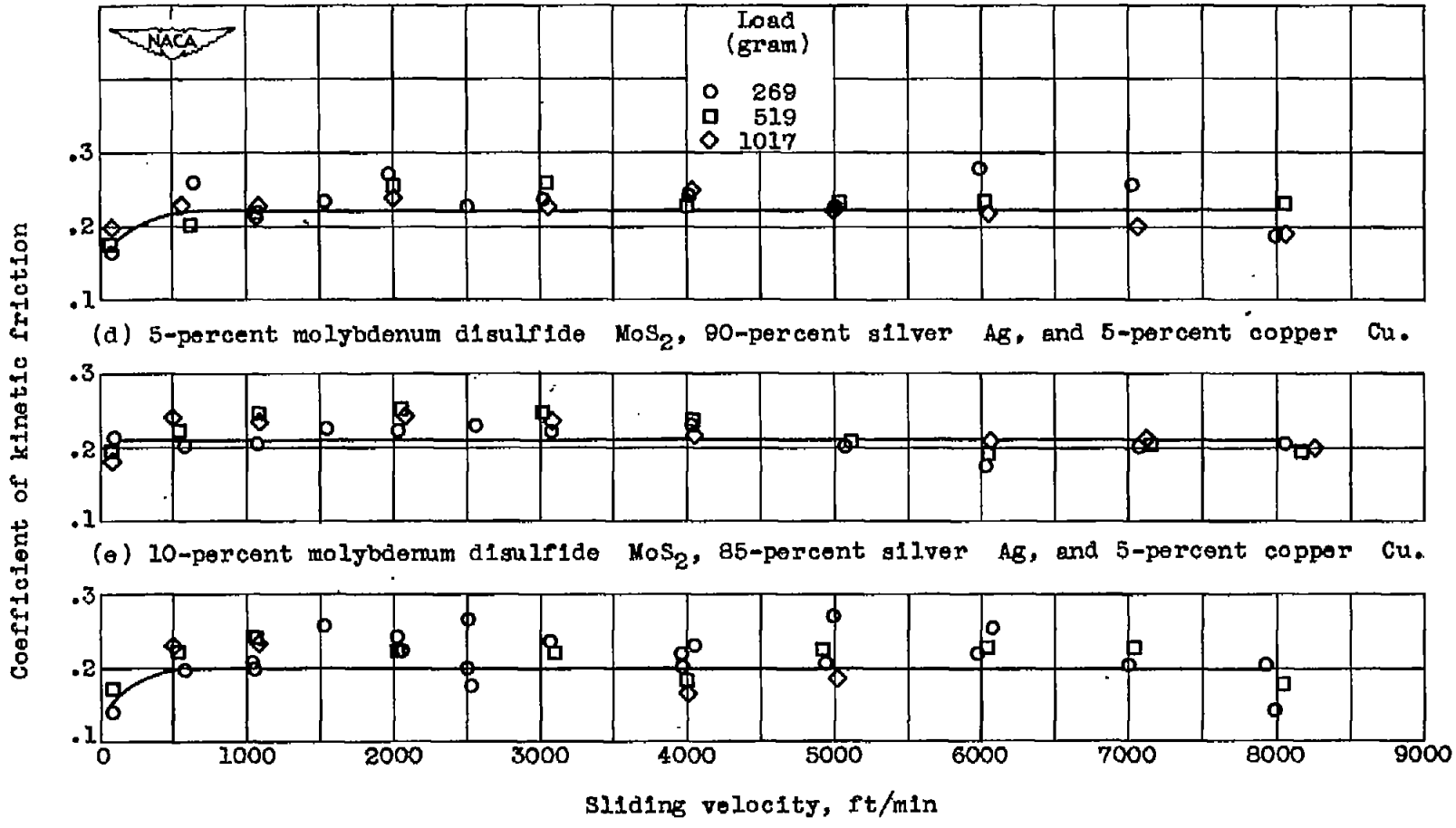


(a) No molybdenum disulfide MoS_2, 95-percent silver Ag, and 5-percent copper Cu.

(b) 1-percent molybdenum disulfide MoS_2, 94-percent silver Ag, and 5-percent copper Cu.

(c) 3-percent molybdenum disulfide MoS_2, 92-percent silver Ag, and 5-percent copper Cu.

Figure 3. - Effect of sliding velocity on friction of hot-pressed rider specimens containing various concentrations of molybdenum disulfide MoS_2, silver Ag, and copper Cu at various loads. Curve is for 269-gram load.

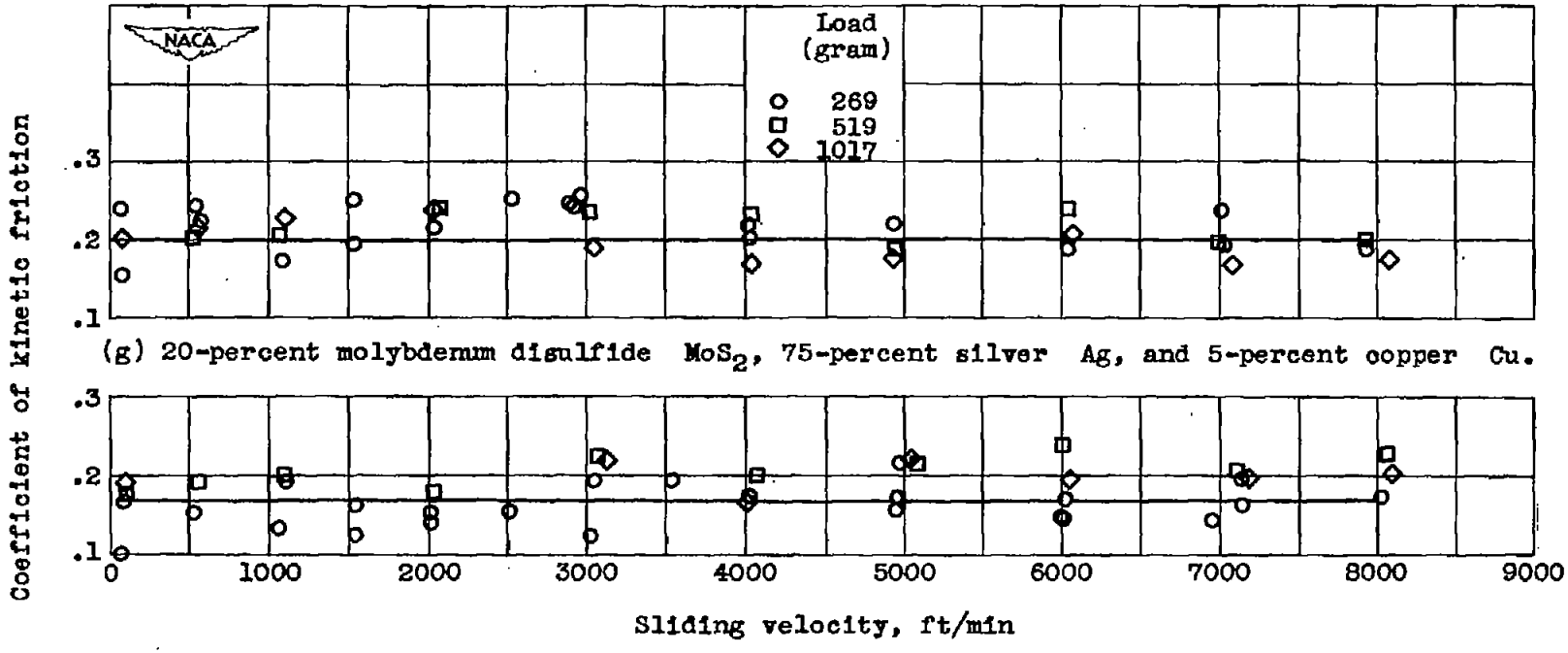


(d) 5-percent molybdenum disulfide MoS_2, 90-percent silver Ag, and 5-percent copper Cu.

(e) 10-percent molybdenum disulfide MoS_2, 85-percent silver Ag, and 5-percent copper Cu.

(f) 15-percent molybdenum disulfide MoS_2, 80-percent silver Ag, and 5-percent copper Cu.

Figure 3. - Continued. Effect of sliding velocity on friction of hot-pressed rider specimens containing various concentrations of molybdenum disulfide MoS_2, silver Ag, and copper Cu at various loads. Curve is for 269-gram load.



(g) 20-percent molybdenum disulfide MoS_2, 75-percent silver Ag, and 5-percent copper Cu.

(h) 35-percent molybdenum disulfide MoS_2, 60-percent silver Ag, and 5-percent copper Cu.

Figure 3. - Concluded. Effect of sliding velocity on friction of hot-pressed rider specimens containing various concentrations of molybdenum disulfide MoS_2, silver Ag, and copper Cu at various loads. Curve is for 269-gram load.

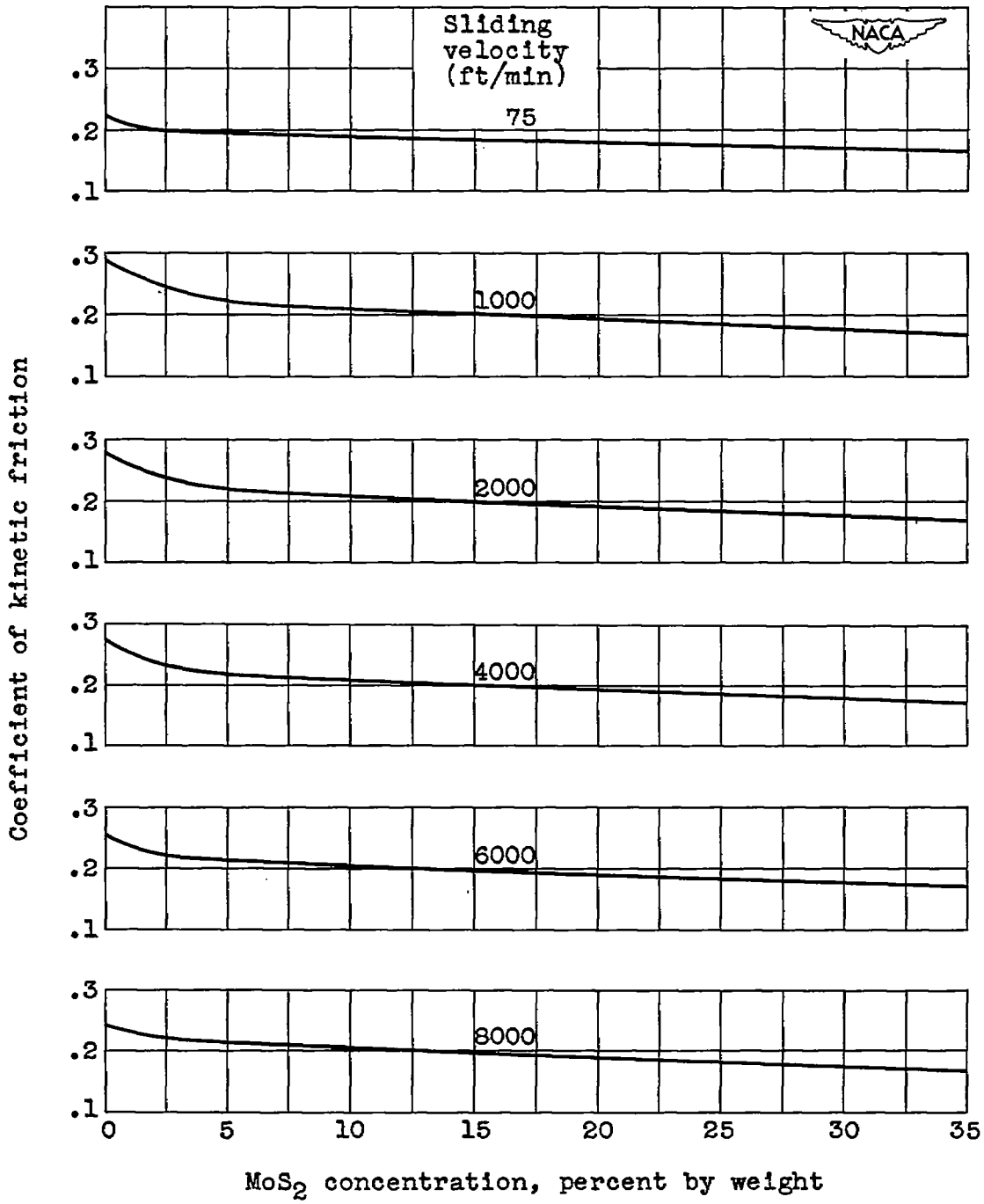


Figure 4. - Effect of molybdenum disulfide MoS_2 concentration on friction of hot-pressed bearing materials at various sliding velocities. Load, 269 grams; material, molybdenum disulfide MoS_2, silver Ag, and copper Cu. (Cross plot of fig. 3.)

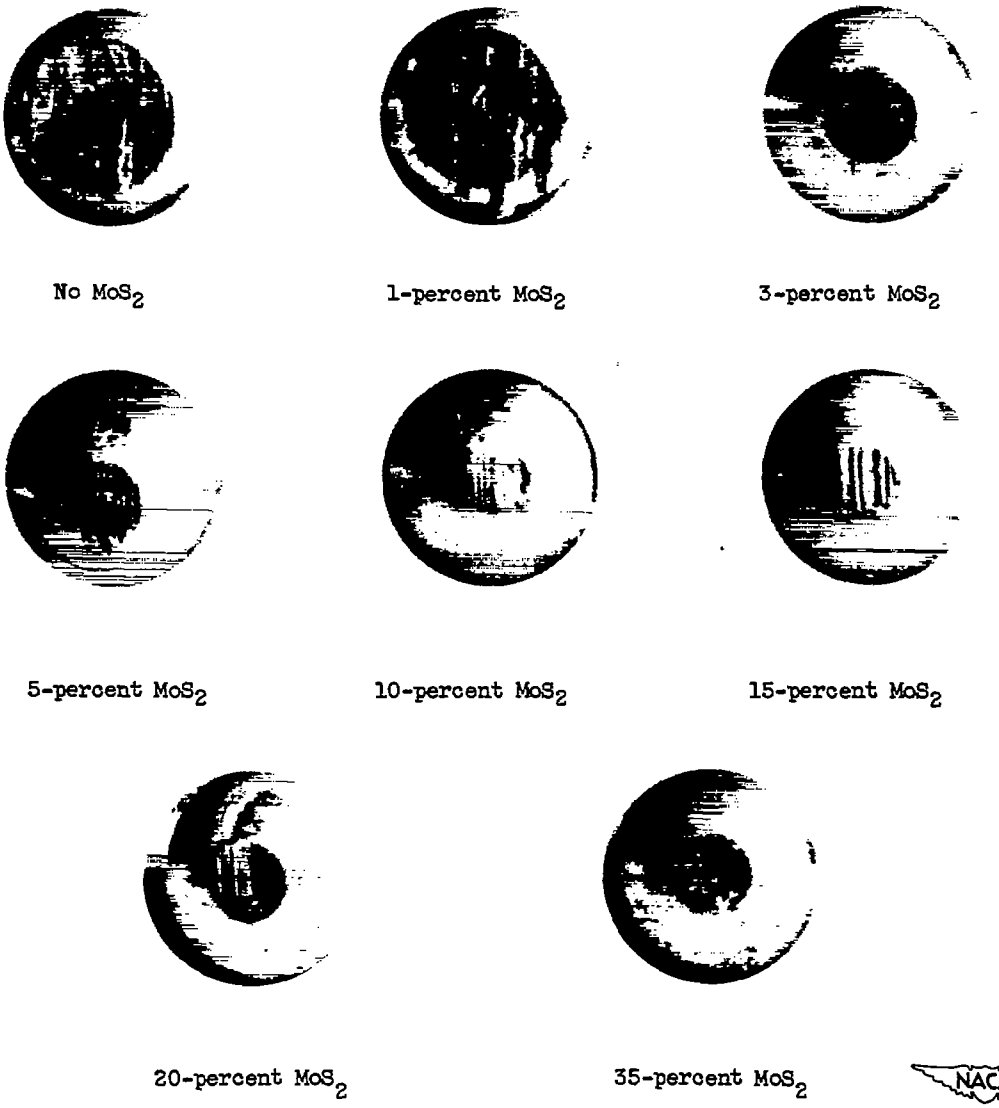


Figure 5. - Riders showing effect of molybdenum disulfide MoS_2 concentration on wear of hot-pressed bearing materials containing silver Ag and 5-percent copper Cu; operation for 1 hour; load, 519 grams; sliding velocity, 5000 feet per minute. X3.

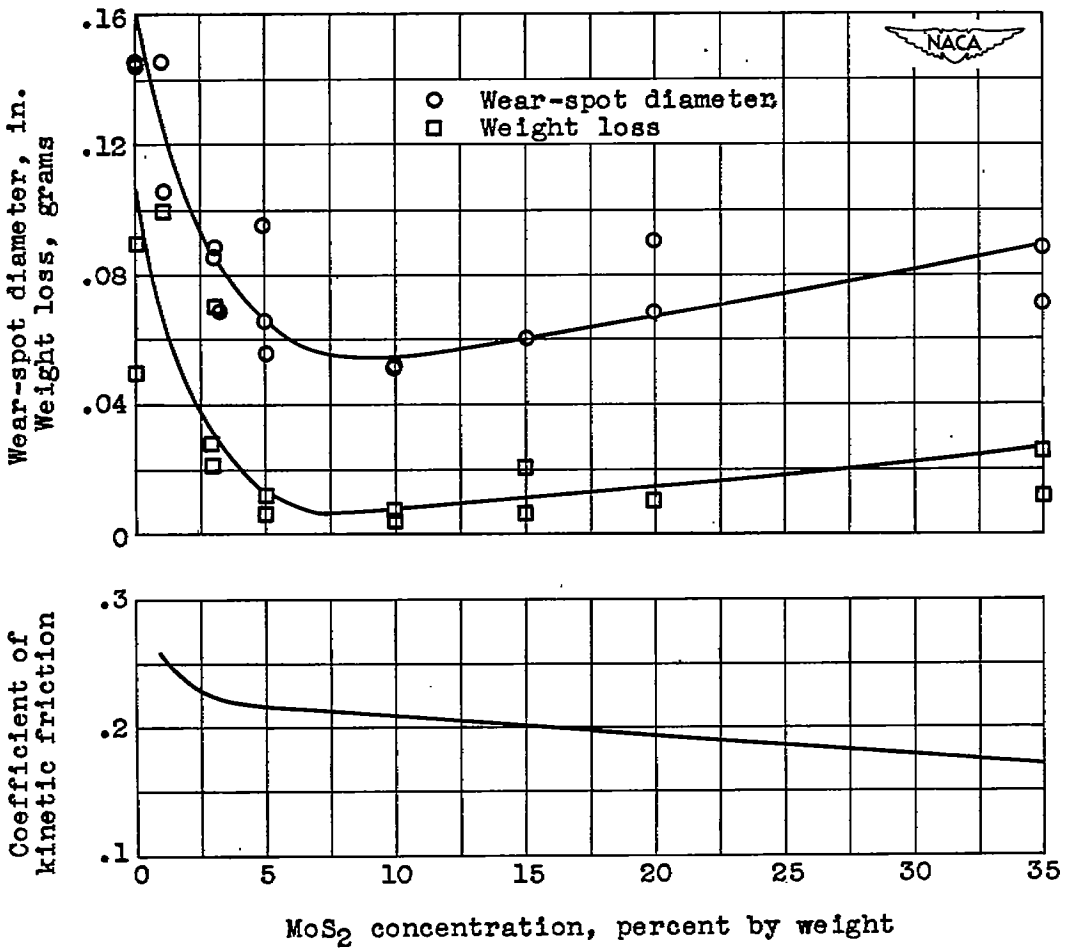


Figure 6. - Effect of molybdenum disulfide MoS_2 concentration on wear and friction of hot-pressed bearing materials. Operation for 1 hour; load, 519 grams; sliding velocity, 5000 feet per minute; material, molybdenum disulfide MoS_2, silver Ag, and 5-percent copper Cu. (Friction curve cross-plotted from fig. 3 at sliding velocity of 5000 ft/min.)

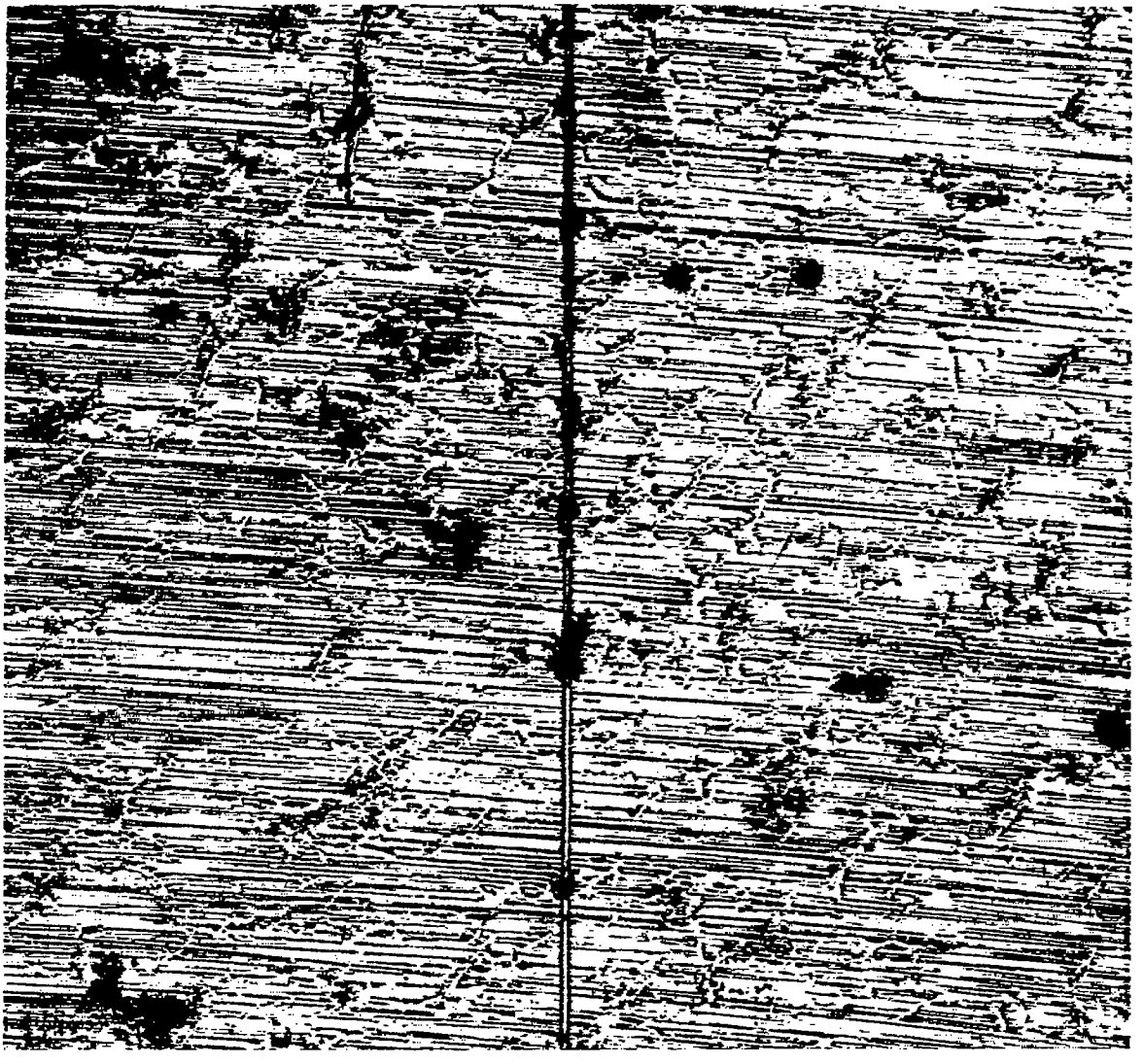


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Figure 7. - Photomicrograph of Bierbaum hardness scratch on finely abraded surface of hot-pressed bearing material containing 15-percent molybdenum disulfide MoS_2, 80-percent silver Ag, and 5-percent copper Cu. Green filter. X100.

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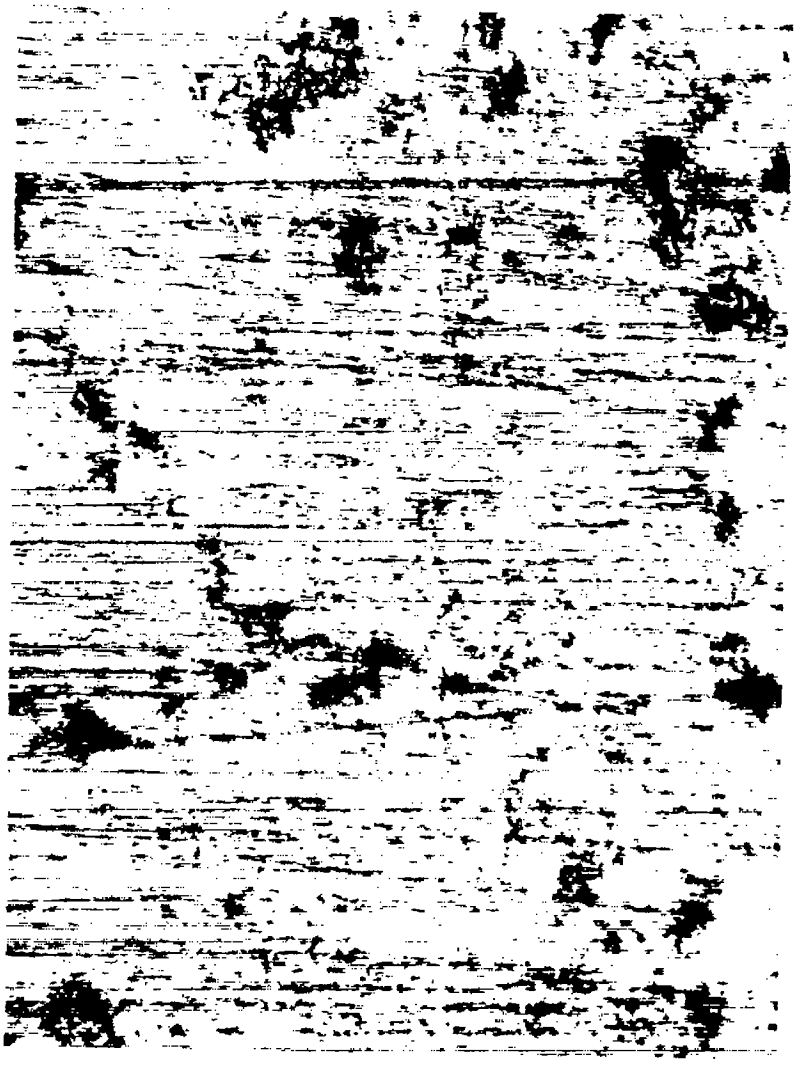

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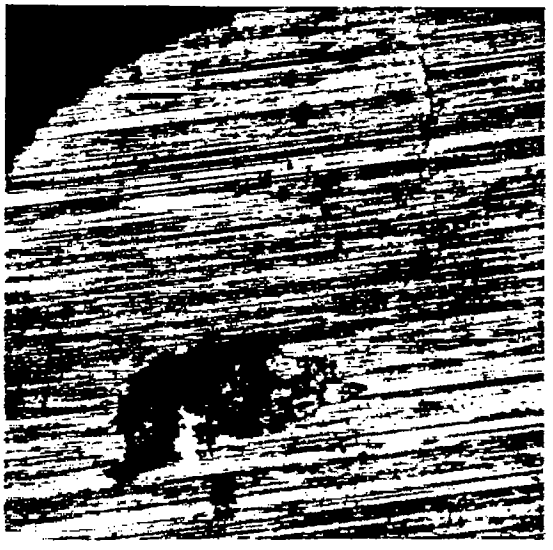
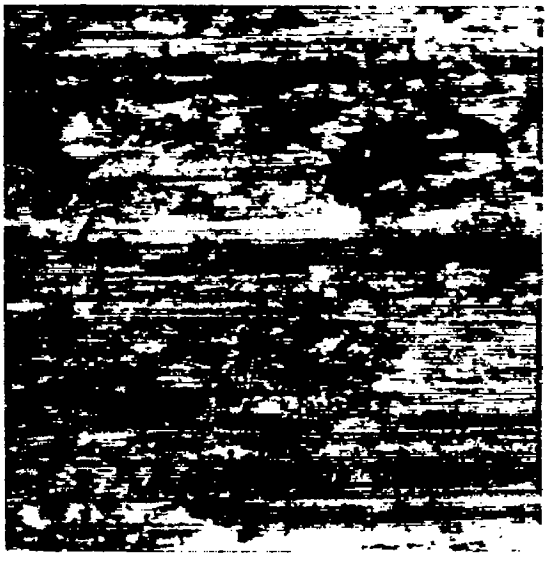
Figure 8. - Photomicrograph of finely abraded surface of hot-pressed bearing material showing dispersion of molybdenum disulfide MoS_2 as dark areas. Material, 15-percent molybdenum disulfide MoS_2, 80-percent silver Ag, and 5-percent copper Cu. X100.



(a) Wear surface on rider containing 95-percent silver Ag and 5-percent copper Cu.

(b) Mating wear surface on steel disk operating with rider shown in figure 9(a).



(c) Wear surface on rider containing 15-percent molybdenum disulfide MoS_2, 80-percent silver Ag, and 5-percent copper Cu.

(d) Mating wear surface on steel disk operating with rider shown in figure 9(c).

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Figure 9. - Photomicrographs of representative wear areas on hot-pressed bearing-material rider specimens and mating steel disk surfaces after 1 hour of operation. Load, 519 grams; sliding velocity, 5000 feet per minute. Figures 9(a) and 9(b) are representative of surfaces that failed, observed with molybdenum disulfide MoS_2 concentrations less than 5 percent. Figures 9(c) and 9(d) are representative of satisfactory surfaces observed with molybdenum disulfide MoS_2 concentrations of more than 5 percent. X100.

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