

RESEARCH MEMORANDUM

FRICITION AND SURFACE DAMAGE OF SEVERAL
CORROSION-RESISTANT MATERIALS

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CORROSION-RESISTANT MATERIALS

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SUMMARY

An investigation, in air, of the friction and surface damage of several materials that are resistant to corrosion by liquid metals was made. The values of kinetic friction coefficient at low sliding velocities and photomicrographs of surface damage were obtained. Appreciable surface damage was evident for all materials tested except tungsten carbide. The friction coefficients for the combinations of steel, stainless steel, and monel sliding against steel, stainless steel, nickel, Inconel, and Nichrome ranged from 0.55 for the monel-Inconel combination to 0.97 for the stainless-steel - nickel combination; for steel, stainless steel, monel and tungsten carbide against zirconium the friction coefficients were approximately 0.47. Lower coefficients of friction (0.20 to 0.60) and negligible surface failure at light loads were obtained with tungsten carbide when used in combination with various plate materials.

INTRODUCTION

Liquid metals have potential application as heat-transfer fluids in power plants (reference 1). The extreme corrosive nature of most liquid metals at elevated temperatures introduces many critical design problems. One important problem is obtaining satisfactory materials for sliding surfaces of parts, such as the bearings for pumps. Most common bearing materials are rapidly corroded by liquid metals and the materials that are known to be corrosion resistant have unknown friction properties. Information on the frictional behavior in air and in liquid metals of combinations of otherwise useful materials is needed in the solution of current design problems.

Accordingly, a series of investigations were conducted at the NACA Lewis laboratory in order to study the frictional behavior in air of corrosion-resistant high-temperature materials. The investigations were conducted at room temperature under static and extremely slow-speed sliding-friction conditions using a range of loads with maximum loading sufficient in most cases to cause appreciable plastic deformation of the

surfaces. The materials investigated include combinations of stainless steel, monel, nickel, Inconel, Nichrome, zirconium, tungsten carbide, and carbon steel.

APPARATUS AND PROCEDURE

Apparatus

The friction experiments were performed with the apparatus described in reference 2. This apparatus is shown in figure 1. The principal parts of the apparatus were the rider assembly (shown at the right in fig. 2), which held the ball specimens, and the plate (shown at the left in fig. 2), which the balls contacted. Three ball specimens were securely clamped in positions in the rider holder, which corresponded to the vertices of an equilateral triangle, and a dead weight load was applied at the center of the triangle normal to its plane. The load was assumed supported equally by the three balls. The specimen plate was clamped to the base of the apparatus and the load applied to the rider (fig. 3). Motion between the plate and rider was produced by applying a force through a dynamometer ring on which force-indicating strain gages were mounted (reference 3). The dynamometer ring was connected to the rider assembly by fine music wire. The frictional force was continuously recorded on a photoelectric recording potentiometer. A 1-rpm motor rotating a fine pitch (64 threads/in.) screw resulted in a constant displacement rate of 0.0156 inch per minute.

In order to minimize the effects of vibration, the chamber which contained the apparatus was mounted on a base plate (fig. 1). The table which held the base plate was suspended using commercial flexible mountings.

The apparatus was contained within a chamber having provisions for maintaining an atmosphere of clean dry air. The source of the air, a -70° F refrigerated air line, insured dryness. The temperature of the air was raised to that of the room before circulating through the apparatus. The air was filtered through glass wool contained in the tube that was mounted on top of the chamber as shown in figure 1. Relative humidity in the chamber during the friction experiments was maintained at a value of less than 10 percent.

Specimen Preparation

All plate specimens were cleaned according to the following procedure:

- (1) Ground to a surface finish of 10 to 15 rms
- (2) Abraded lightly under acetone with 4/0 emery cloth

- 2415
- (3) Scrubbed with levigated alumina and water
 - (4) Washed with water to remove adhering alumina
 - (5) Rinsed with triple distilled water
 - (6) Rinsed with 90 percent alcohol
 - (7) Flushed with consecutive rinses of freshly distilled acetone and vapor in Soxhlet extractor
 - (8) Dried in the chamber containing the friction apparatus

The ball specimens used were cleaned by the same procedure as the plates except that steps (1) and (2) were omitted. With this procedure the surfaces were found by electron diffraction to be grease free.

Specimen Materials

The materials used in this investigation were chosen because of corrosion-resistant properties. The plate and ball materials used are shown in table I. The chemical composition and hardness of each material are also listed in table I.

Method of Obtaining Data

According to Amonton's law, the coefficient of friction of dry metals should be independent of load. For this reason, friction measurements were made for each combination of metals with a range of loads (total load on three balls) from 300 to 4200 grams to determine an average value for the coefficient of friction. (Unless otherwise specified, subsequent references to load will refer to total load on three balls.) The frictional force was measured initially for a load of 300 grams; without removing the slider from the plate, additional weights were added to the slider and the frictional force corresponding to this greater load was measured. The load was then reduced to 300 grams and the frictional force remeasured. The procedure was continued until the highest load run had been made. The rider and the plate were kept in contact during the entire test in order to avoid misalignment and contamination from the air. Higher load runs and 300-gram load runs were alternated; the 300-gram load runs gave reproducible results, indicating that the surface damage resulting from one load run did not affect the results of the succeeding ones. For a few material combinations, two values of frictional force were obtained: (1) the force to initiate sliding and (2) the first steady value of kinetic frictional force.

If the ball and plate were allowed to experience relative motion for a long period of time, the frictional force would increase considerably because of the accumulation of wear debris in front of the slider. This effect was also observed by Bowden and Tabor (reference 4, p. 92) with other materials. This accumulation of debris would result in an increase in friction coefficient of approximately 0.25; by choosing the first stable value of frictional force, however, these data were found to be reproducible to within ± 0.05 . During the alternate light-load (300 grams) runs the ball specimens passed over the debris accumulation from the preceding run; this also happened intermittently throughout the runs with heavier loads. As a result, wear debris accumulates only to a limited extent before being passed over by the rider; consequently, the effect on friction throughout one experiment was limited and not cumulative.

RESULTS AND DISCUSSION

The friction coefficients obtained for the various combinations of materials are shown in table II. Each coefficient of friction listed is an average value of the coefficients obtained at different loads. These values are therefore the coefficient of kinetic friction at a sliding velocity of 0.0156 inch per minute in the load range from 300 to 4200 grams (100 to 1400 g/ball). The types of surface damage for many of the metal combinations are similar. These different types of surface damage, as noted in table II, are discussed in the Surface Damage section. Although coefficients of friction vary considerably with different metal combinations, it would be very difficult to isolate any particular variable and consider its role in determining the coefficient of friction. Bowden and Tabor (reference 4, p. 78) have shown that some general conclusions may be drawn in the case of dry friction by considering the relative physical properties of the two sliding surfaces. The total frictional force is made up of two separate factors: the force to shear the welds which occur when two clean metals are placed in contact and the force to plow one surface through the other. If it is possible to decrease either of these factors or both, the frictional force and the coefficient of friction will likewise be decreased. These two factors may be reduced in several ways. With a hard-slider softer-plate combination, the hard slider will penetrate the soft plate and cause appreciable plowing; an increase in the hardness of plate will reduce the plowing and therefore reduce the coefficient of friction. This effect is generally observed in table II where harder materials are listed on the right-hand side; for example, SAE 1095 steel against bonded tungsten carbide (hardness Rockwell C-85) gave a friction coefficient of 0.34 while for the combination of SAE 1095 steel and nickel (hardness Rockwell B-62) the friction coefficient is 0.85. As discussed in reference 4, another way in which the friction coefficient may be decreased is to decrease the number of welds which occur between the slider and plate. Similar

materials, for example, stainless steel against stainless steel or a pure metal sliding against a pure metal, will show considerable welding. Welding is characteristic of materials that are mutually soluble. In these experiments the amount of welding that takes place for various combinations usually cannot be estimated. If, however, a film of some contaminant is placed between the mating surfaces, welding can largely be eliminated. This contaminant may be either oxide, grease film (characteristic of uncleaned surfaces), or a lubricant. The variations in friction coefficients in the cases of steel against steel and other material combinations are therefore the result of one or a combination of any of these three considerations: (1) relative hardness, (2) amount of welding, or (3) presence of contaminating films and their breakdown.

Steel Against Steel

A plot of coefficient of friction against load for hardened steel balls sliding on a steel plate is shown in figure 4. These four tests established the average coefficient of friction of 0.79 for steel on steel over the load range from 900 to 4200 grams. Similar values have been obtained by other investigators, for example, a static friction coefficient for steel on steel of 0.78 is presented in reference 5. The plate specimens in the four tests of figure 4 had lapped surfaces (4 to 8 rms); tests were therefore conducted using a steel plate, the surface of which had been ground to duplicate the surface roughness (12 to 15 rms) of the other materials. The friction coefficient for the ground surface is shown in figure 5. The coefficients of friction for the ground surface fall within the experimental limits of the data of figure 4. This is in agreement with the statement by Bowden and Tabor (reference 4, p. 175) that "over a wide range of surface finish, the friction of metals is nearly independent of the degree of surface roughness."

The lower values of the coefficient of friction at light loads were not true load effects but rather, were functions of the slider surfaces. When a continuous run was made with alternate loadings of 300 and 1557 grams, the initial friction coefficient was approximately 0.65, and after continued sliding the friction coefficient increased to approximately 0.79. This increase in friction coefficient may be the result of the breakdown of surface layers of either oxides, cold worked metal, or other contaminating films of the slider specimens, allowing surface welding to occur, the duration of the 1557-gram-load runs was so short that there was insufficient time for an accumulation of debris in front of the slider.

The accumulation of debris (primarily plastically displaced metal) in front of the slider is very pronounced for the heavier loads if sliding is allowed to continue for a long period of time. During the time the debris is accumulating, the friction will increase and the coefficient of friction will approach 1. If the resistance to motion

becomes too great, the slider passes over the top of the debris and the same process is repeated again. A photograph of the wear track resulting from this phenomenon and a diagrammatic sketch for the combination of a steel slider and a nickel plate is shown in figure 6.

Other Material Combinations

Nickel in all tests conducted was found to have high friction coefficients. Except against tungsten carbide, coefficient of friction approaches 1 and welding was apparent at all loads (for example, fig. 6). The friction coefficients for two nickel alloys (Nichrome and Inconel) were lower than for nickel with all combinations of slider material. This decrease in coefficient of friction may be the result of the increase in the hardness of these alloys.

The coefficient of friction for all slider materials in combination with zirconium is relatively low (0.44 to 0.49). This may be the result of several factors. Zirconium is not only harder than the other plate materials (except bonded tungsten carbide) but also acquires, in air, a thick oxide film which reduces the amount of welding. Even though this oxide film is apparently easily ruptured during sliding, the effect may be considered beneficial because the film will not be completely removed by the passing of the slider and also because this oxide film immediately reforms and protects the surface against further wear.

Using tungsten-carbide sliders in combination with various plate materials also resulted in low friction coefficients. The coefficient of friction increased during the runs to much higher values at the end. This increase in friction with continued sliding of tungsten-carbide sliders has been explained by Shooter (reference 6). Initially, the surface is not damaged and material is not removed from either the slider or the plate, because no mass surface welding occurs (for example, fig. 7(a)); therefore the frictional force is principally the force necessary to plow the slider through the material. With prolonged sliding and higher loads, however, some of the plate material becomes transferred to the tungsten carbide slider. When this transfer takes place the frictional force will increase because the material which has become attached to the slider will then weld to the plate material. The frictional force has then increased by an amount necessary to shear the metal-to-metal welds. In figure 8, photomicrographs of a plate specimen (stainless steel) and a slider (tungsten carbide) after sliding several hundredths of an inch are shown. Considerable material has been removed from the plate and has become welded to the slider.

When tungsten carbide sliders were used in combination with a bonded tungsten carbide plate material, friction coefficients of approximately 0.20 were obtained. This is in the range reported by Shooter (reference 6). No surface damage was observed on either the tungsten carbide balls or the bonded tungsten carbide plate.

When stainless steel is used as a slider material, higher friction coefficients than for other slider materials frequently result (table II). Other investigators (reference 4, p. 81) have attributed the poor frictional behavior of stainless steel to a homogeneous structure which readily allows welding with other material.

Surface Damage

Photomicrographs of the various wear tracks are shown in figure 7. These wear tracks are characteristic of all the various types of sliding encountered. The type of surface damage for each metal combination is shown in the table II. The types of surface damage are defined as follows:

Type a (fig. 7(a)). - Type a surface damage is a combination of a very hard slider against relatively soft plate: for example, tungsten carbide slider against steel plate. There is very little welding and consequently little damage to surfaces initially. The slider is not damaged.

Type b (fig. 7(b)). - Type b surface damage is a combination of a hard slider against a softer plate: for example, SAE 1095 steel against SAE 1020 steel. In this example the two materials are similar in composition. The plate specimen is damaged by considerable welding to the slider, which greatly increases the amount of surface damage.

Type c (fig. 7(c)). - Type c surface damage is a combination of materials of similar hardnesses; for example, monel against stainless steel. Material is removed from the slider and is left welded to the plate material. With stainless-steel sliders, material was removed from the ball but the appearance of the plate indicated that mass welding was taking place.

Type d (fig. 7(d)). - Type d surface damage is a combination of similar materials; for example, stainless steel against stainless steel. There is severe damage to both the slider and plate. Large welds occur and whole areas are torn from both the slider and plate. Damage is much more severe than that of type c.

Type e (fig. 7(e)). - Type e surface damage is a combination of zirconium with various sliders; for example, zirconium against steel. Zirconium attains by exposure to air a relatively thick oxide film. During sliding this oxide film is easily ruptured; however, enough oxide remains to partly protect the surface.

SUMMARY OF RESULTS

Friction and surface damage of several materials that are resistant to corrosion by liquid metals was studied in air and the following results were obtained:

1. The friction coefficients of various metal combinations were determined to be:

Slider (ball)	Plate						
	Nickel	SAE 1020 steel	Nichrome	AISI 347 stainless steel	Inconel	Zirconium	Bonded tungsten carbide
Friction coefficient, μ							
Tungsten carbide	0.55	0.36-0.40	----	0.35-0.60	----	0.49	0.20
SAE 1095 steel	.85	.79	0.85	.67	0.79	.44	.34
Monel	.95	.85	.78	.68	.55	.48	----
18-8 stainless steel	.97	.80	.91	.96	.65	.47	----

2. Surface failure occurred with all metal combinations except with tungsten carbide sliding on bonded tungsten carbide.

3. Nickel used in combination with various sliders gave high friction coefficients and severe surface damage.

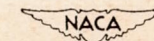
4. Zirconium, because of its hardness and formation of a relatively thick oxide film, gave low coefficients of friction. This oxide film was easily ruptured during sliding.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, October 19, 1951.

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5. Campbell, W. E.: Studies in Boundary Lubrication. Trans. A.S.M.E., vol. 61, no. 7, Oct. 1939, pp. 633-641.
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TABLE I - TYPICAL COMPOSITION AND HARDNESS OF MATERIALS



Materials	Composition	Rockwell Hardness
Plate Specimen		
Nickel	Nickel	B-62
SAE 1020 steel	0.20 percent C; 0.45 percent Mn; 0.04 percent max P; 0.05 percent max S	B-65
Nichrome V	80 percent Ni; 20 percent Cr	B-72
AISI 347 stainless steel	17-19 percent Cr; 9-13 percent Ni; 2.5 max Mn; 1.5 max Si	B-80
Inconel	75 percent Ni; 0.5 percent max Cu; 0.5 percent Si; 0.15 percent C; 12.15 percent Cr; 0.1 percent Mn; 9.05 percent Fe	B-81
Zirconium	Zirconium	B-83
Bonded tungsten carbide	Tungsten carbide plus 2 percent cobalt	C-85
Ball Specimen		
18-8 stainless steel	18 percent Cr; 8 percent Ni	B-70
Monel	67 percent Ni; 30 percent Cu; 1.4 percent Fe; 1.0 percent Mn	B-83
SAE 1095 steel	0.95 percent C; 0.40 percent Mn; 0.04 percent max P; 0.05 percent max S	C-60
Tungsten carbide	Tungsten carbide	C-85

TABLE II - FRICTION COEFFICIENTS FOR SEVERAL COMBINATIONS OF MATERIALS

Slider (ball)	Plate													
	Nickel		SAE 1020 steel		Nichrome		AISI 347 stainless steel		Inconel		Zirconium		Bonded tungsten carbide	
	Rockwell hardness													
	B-62		B-65		B-72		B-80		B-81		B-83		C-85	
	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage	Friction coefficient μ	Type of damage
Tungsten carbide (Rockwell C-85)	0.55	(a)	0.36 - 0.40	(a)	----	---	0.35 - 0.60	(a)	----	---	0.49	(a) (e)	0.20	---
SAE 1095 steel (Rockwell C-60)	.85	(b)	.79	(b)	0.85	(b)	.67	(b)	0.79	(b)	.44	(e)	.34	---
Monel (Rockwell B-83)	.95	(c)	.85	(c)	.78	(c)	.68	(c)	.55	(c)	.48	(e)	----	---
18-8 stainless steel (Rock- well B-70)	.97	(c)	.80	(c)	.91	(c)	.96	(d)	.65	(c)	.47	(e)	----	---

Type of damage (as illustrated in fig. 7):

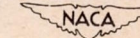
^aVery hard slider on relatively soft plate.

^bHard slider on softer plate.

^cPlate and slider of similar hardness.

^dPlate and slider of similar materials.

^eVarious sliders on zirconium.



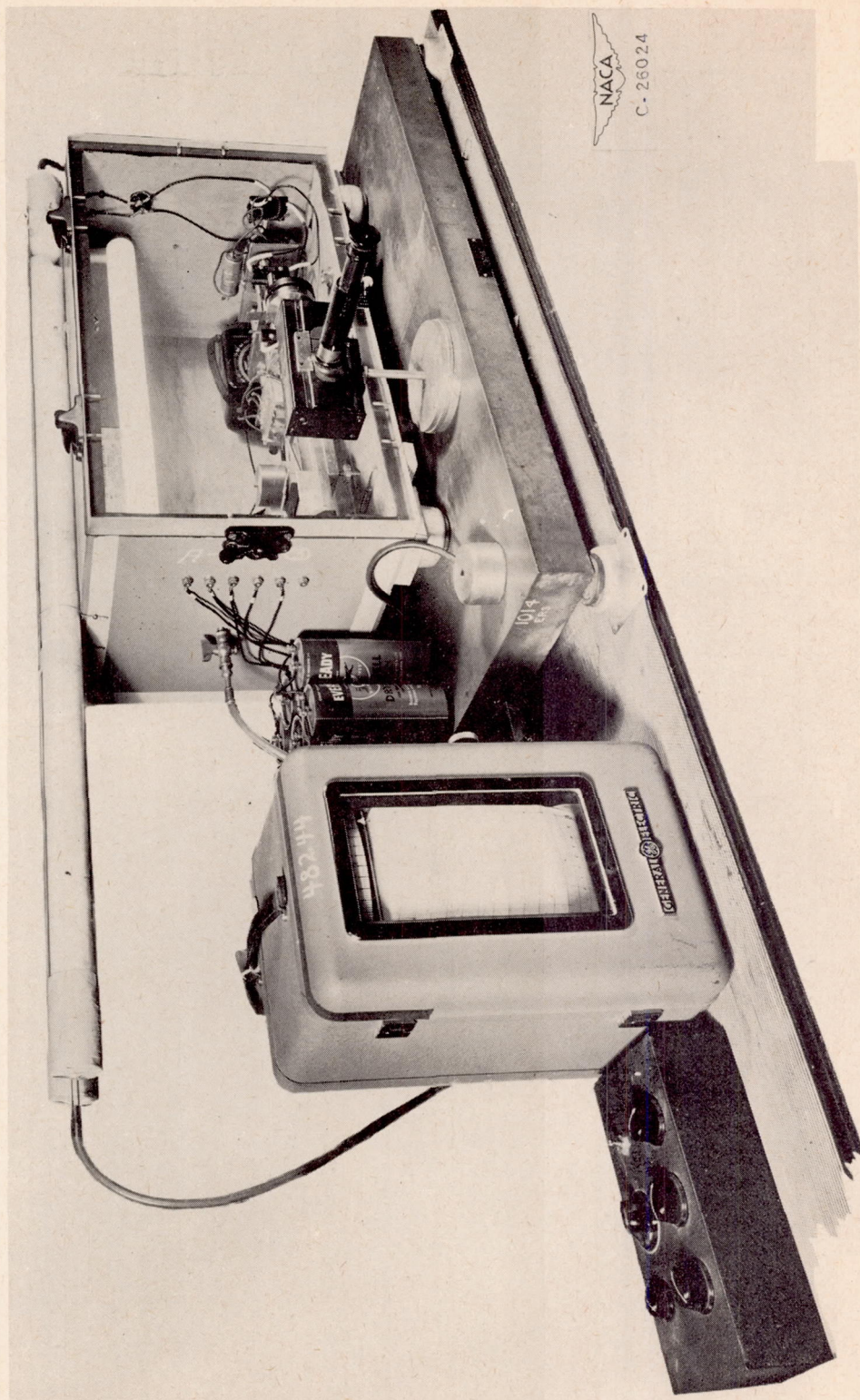


Figure 1. - - Static-friction apparatus.

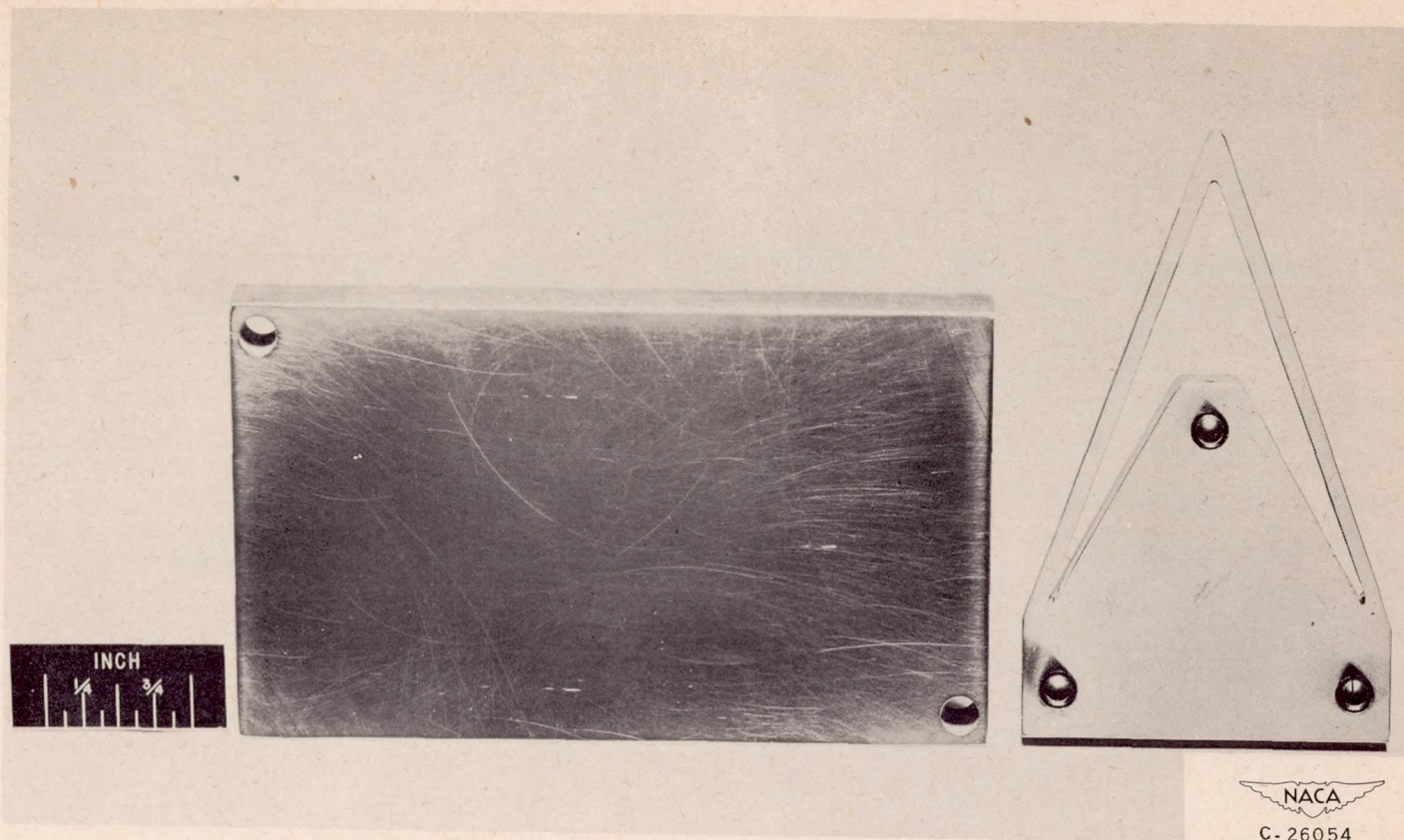


Figure 2. - Static-friction plate specimen and rider specimens in rider holder.

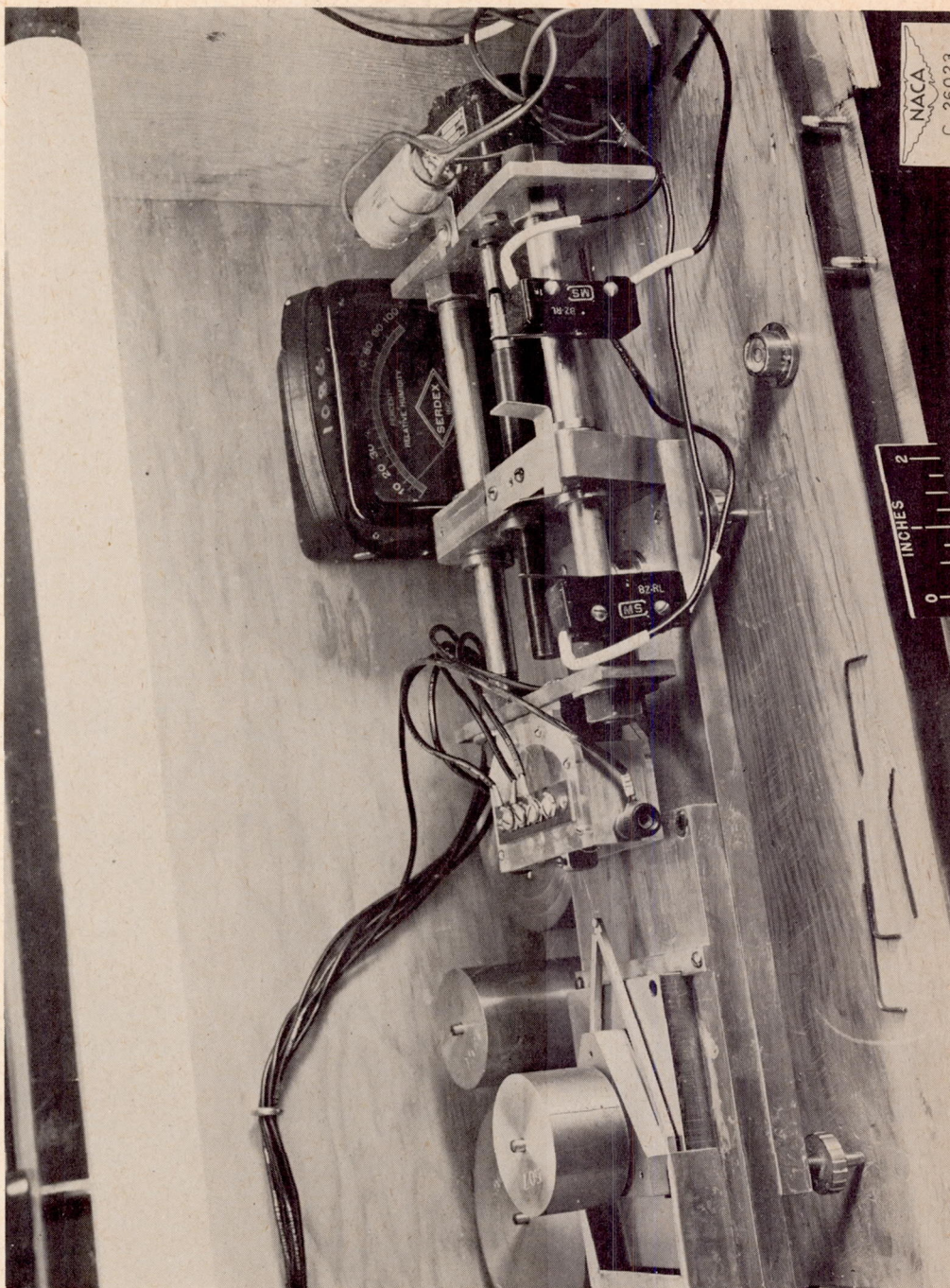


Figure 3. - Basic static-friction apparatus.

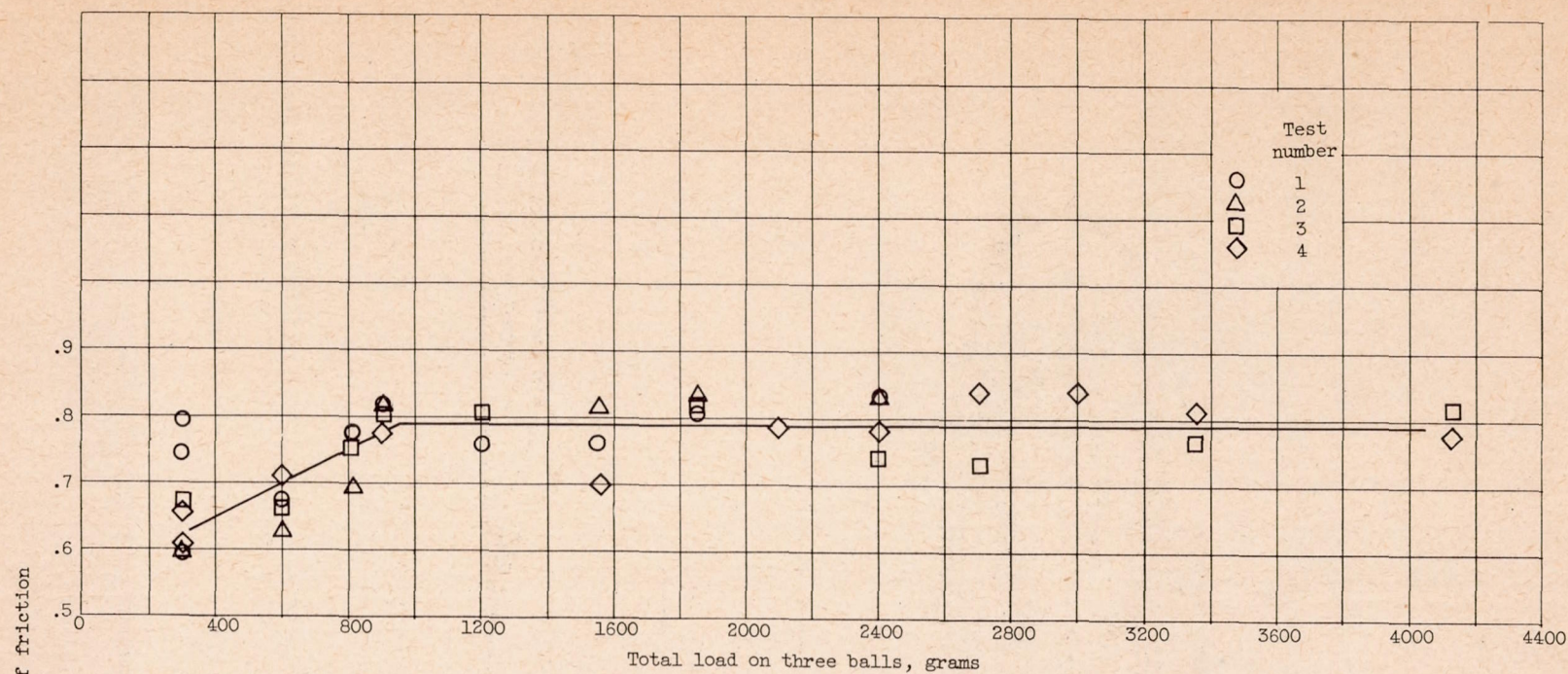


Figure 4. - Effect of load on coefficient of friction for hardened steel balls sliding on steel.

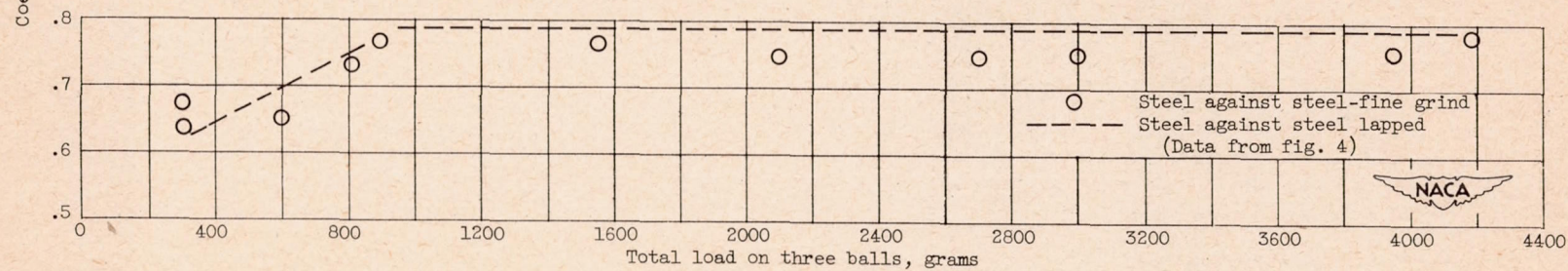
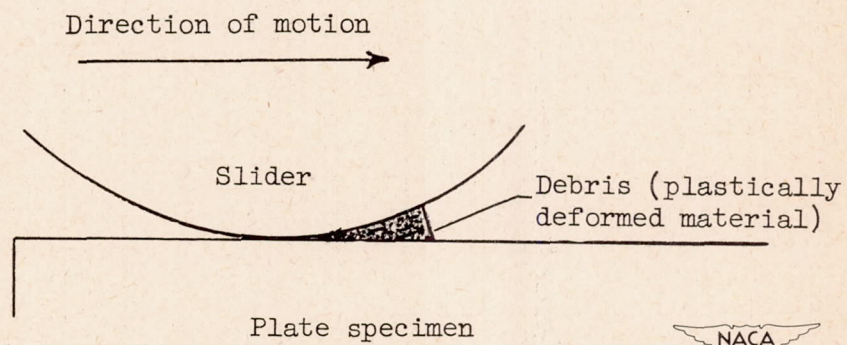
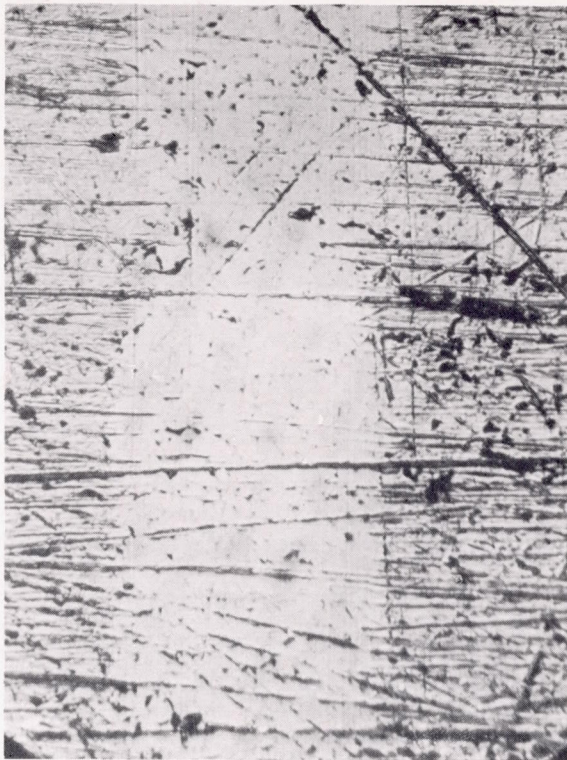


Figure 5. - Effect of load on coefficient of friction for hardened steel balls sliding on ground steel surface.



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Figure 6. - Wear track showing accumulation of wear debris in front of slider for steel against nickel. Load (on three balls), 4200 grams; X200.



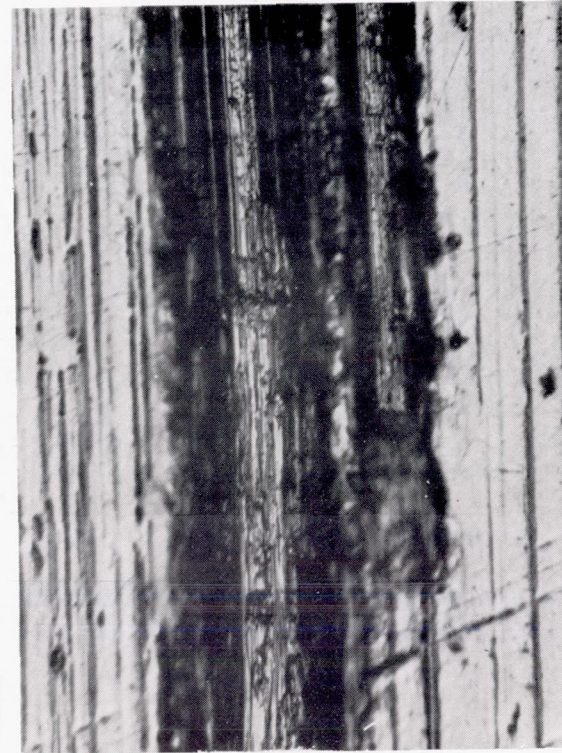
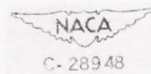
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(a) Damage type a, very hard slider (tungsten carbide) against softer plate (SAE 1020 steel); coefficient of friction μ , 0.36.

(b) Damage type b, hard slider (hardened steel) against softer plate (SAE 1020 steel); coefficient of friction μ , 0.79.

Figure 7. - Photomicrographs of different types of wear track on plates, produced by sliding together of various metal combinations. Load, 4200 grams; X200.



(c) Damage type c, materials of similar hardnesses (monel against stainless steel); coefficient of friction μ , 0.68.

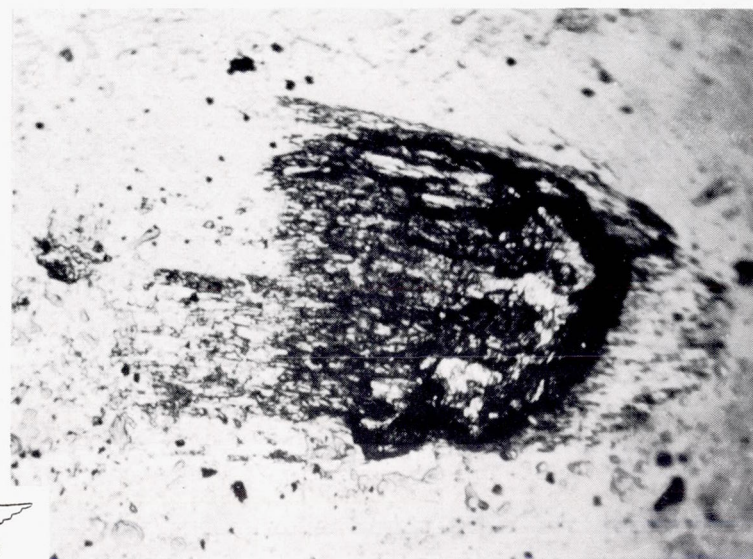
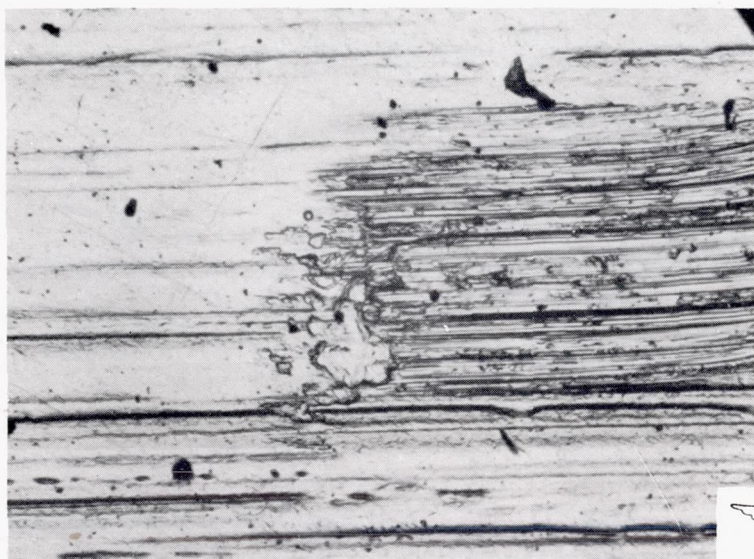
(d) Damage type d, similar materials (stainless steel against stainless steel); coefficient of friction μ , 0.96.

Figure 7. - Continued. Photomicrographs of different types of wear track on plates, produced by sliding together of various metal combinations. Load, 4200 grams; X200.



(e) Damage type e, (steel against zirconium); coefficient of friction μ , 0.44.

Figure 7. - Concluded. Photomicrographs of different types of wear track on plates, produced by sliding together of various metal combinations. Load, 4200 grams; X200.



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(a) Wear track on stainless-steel plate.

(b) Mating surface of tungsten carbide slider after sliding
several hundredths of inch.

Figure 8. - Photomicrographs of wearing surfaces of tungsten carbide slider and stainless-steel plate.