NASA TECHNICAL NOTE

NASA TN D-8004

NASA TN D-8004

2. u/u

1.

FRICTION AND WEAR OF TIN AND TIN ALLOYS FROM -100° TO 150° C

Donald H. Buckley

Lewis Research Center
Cleveland, Ohio 44135

3. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • 5. JUNE 1975

1. Report No.
NASA TN D-8004

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
FRICTION AND WEAR OF TIN AND TIN ALLOYS FROM -100° TO 150° C

5. Report Date
June 1975

6. Performing Organization Code

7. Author(s)
Donald H. Buckley

8. Performing Organization Report No.
E-8230

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

10. Work Unit No.
506-16

11. Contract or Grant No.

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

13. Type of Report and Period Covered
Technical Note

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Sliding friction experiments were conducted with an iron (110) single-crystal pin sliding on single and polycrystalline tin and tin alloys. Specimens were examined at various ambient temperatures from -100° to 150° C. Applied loads varied from 1 to 50 grams, and sliding velocity was constant at 0.7 mm/min. Results indicate that the crystal transformation of tin influences friction coefficient. Friction was higher for the diamond structure (gray tin) than it was for the body-centered tetragonal structure (white tin). Bismuth arrested the crystal transformation, which resulted in constant friction over the temperature range -100° to 150° C. Both copper and aluminum enhanced the kinetics of transformation, with aluminum producing a nearly twofold change in friction with the crystal transformation.

17. Key Words (Suggested by Author(s))
Friction; Wear; Tin; Crystal structure; Crystal transformation

18. Distribution Statement
Unclassified - unlimited
STAR Category 26(rev.)

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
13

22. Price*
$3.25

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

FRICTION AND WEAR OF TIN AND TIN ALLOYS FROM -100° TO 150° C

by Donald H. Buckley

Lewis Research Center

SUMMARY

An investigation was conducted to determine the effect of the crystal transformation of tin on the friction and wear behavior of tin and tin alloys. A hemispherical, iron, single-crystal pin (2-mm radius) with a (110) orientation slid on single and polycrystalline tin and tin binary alloys containing 1 atomic percent of bismuth, copper, or aluminum. Experiments were conducted over a range of temperatures from -100° to 150° C. Applied loads varied from 1 to 50 grams, and all experiments were conducted at a constant sliding velocity of 0.7 mm/min. All measurements were made in vacuum (10^{-8} N/m^2) to control environmental effects.

The results of the investigation indicate that friction coefficient is higher for the diamond form (gray tin) than it is for the body-centered tetragonal form (white tin). Bismuth arrested the crystal transformation such that the friction coefficient for the alloy was constant over the temperature range studied. Both copper and aluminum enhanced the kinetics of transformation. With aluminum in tin a nearly twofold change in friction was observed with crystal transformation.

INTRODUCTION

Tin is used in the field of lubrication to reduce friction and wear in mechanical components. It is employed as a thin surface film because of its low shear strength (ref. 1). It also has been used in alloys for bearings for over 50 years (refs. 2 to 4). For example, babbitt-metal bearing linings are frequently tin-base alloys. These materials must frequently operate over a broad temperature range. Despite the extensive use of tin in lubrication, very little fundamental research has been conducted relative to the influence of various physical properties on the friction and wear of tin.

Tin undergoes a crystal transformation at approximately 13° C. This transformation, from a cubic-diamond to a tetragonal structure, could influence friction and wear behavior. The effect of the transformation on the friction and wear behavior of tin has not been measured.

The objectives of this investigation were (1) to determine the effect of the crystal transformation on the friction and wear of tin and (2) to examine the influence of alloying elements on friction in the temperature region of the tin transformation. Single-pass, sliding friction experiments were conducted with a 2-millimeter-radius rider specimen of single-crystal iron (110) orientation contacting tin single crystals (110) and polycrystalline tin and tin alloys. The binary alloys contained 1-atomic-percent aluminum, copper, or bismuth. Sliding velocity was 0.7 mm/min, with applied loads of 1 to 50 grams. Temperatures of experimentation ranged from -100° to 150° C in a vacuum of 10^{-8} N/m^2 (10^{-10} torr).

CRYSTAL TRANSFORMATION

Tin is polymorphic. It exists as the so-called gray tin at temperatures below 13° C and as white tin above this temperature (ref. 5). Gray tin has a diamond type of crystal structure, with each tin atom tetrahedrally coordinated by four other tin atoms. White tin has a body-centered tetragonal structure and appears as a distorted diamond structure. The structure of white tin is shown in figure 1(a). The bonding of a tin atom to four of its neighbors at the corners of a flattened tetrahedron is shown in figure 1(b). Gray tin has a more symmetrical structure than white tin, as can be seen in a comparison of figures 1(a) and (b) with 1(c) and (d). This difference is thought to be due to an electron-zone overlap present in white tin which does not exist in the more symmetrical gray tin (ref. 6).

DEFORMATION

Gray tin atoms can be pictured as stacking sheets composed of continuously linked, "puckered" hexagonal rings of tin atoms parallel to the (111) planes of the crystal. Shear takes place along these planes.

White tin, with its tetragonal structure, slips on (110) planes in the [001] direction at low temperatures. At higher temperatures, slip takes place on the (110) planes, but the direction [111] is the preferred slip direction (ref. 7). The critical resolved shear stress necessary for slip in white tin (110) [001] is less than that for nickel. It is, however, greater than that necessary to initiate slip in the noble metals copper, silver, and gold (ref. 8).

With respect to strain hardening (below the recrystallization temperature), tin behaves more like the hexagonal metals such as cadmium than like the face-centered cubic metals, which strain harden very readily. For both the (100) and (110) orientations of tin, crystals can be strained as much as 500 percent with only about a factor-of-2 increase in shear stress. Face-centered cubic metals such as copper will experience a factor-of-500 increase in shear stress with as little as a 50 percent increase in strain (ref. 7).

APPARATUS

The apparatus used in this investigation was a vacuum system that had built into it the capabilities for the measurement of adhesion, friction, and load. The mechanism for the measurement of adhesion, friction, and load is shown schematically in figure 2.

A gimbal-mounted beam projects into the vacuum system. The beam contains two flats machined normal to each other with strain gages mounted thereon. The end of the rod contains the iron single-crystal pin. By moving the beam inward toward the disk, load is applied and measured by the strain gage. With load removal, if adhesion occurs, the adhesion forces are measured by the deflection of the beam in the direction opposite to which the load is applied (fig. 2). Tangential motion of the pin along the disk surface is accomplished through the gimbal assembly. Under an applied load, friction force is sensed by the strain gage which is normal to that used to measure load.

Multiply wear tracks could be generated on the disk specimen (25-mm diam) surface by translational motion in the horizontal direction. Pin sliding was in the vertical direction (fig. 2).

The vacuum apparatus in which the components of figure 2 were contained also had a low-energy electron diffraction (LEED) system and an Auger spectrometer. The electron beam of both could be focused on any disk site desired. This was accomplished with a disk manipulation device. The vacuum system was a conventional vacsorb and ion-pumped system capable of readily achieving pressures of 10^{-10} torr as measured by a nude ionization gage within the specimen chamber. Sublimination pumping was also used.

The specimens were sputter cleaned by argon ion bombardment. Argon pressure of 10^{-3} torr and an ionization voltage of 1000 volts for a period of 30 minutes were used.

EXPERIMENTAL PROCEDURE

The single-crystal tin disk specimens (99.99 percent pure) were polished on metallurgical papers down to 600 grit. They were then electropolished in a solution of 6 parts glycerol, 2 parts water, 1 part ethyl alcohol, and 1 part perchloric acid. They were rinsed with water and ethyl alcohol and dried with high-purity argon. The specimens were then mounted in the vacuum system against a liquid-nitrogen-cooled, stainless steel coil.

Experimental temperatures below room temperature were achieved by passing either cold nitrogen gas or liquid nitrogen through the coil to which the tin crystal was mounted. Temperature was measured with an iron-constantan thermocouple, and experiments were conducted by starting at -100° C, increasing the temperature to 150° C, and then completing the experimental cycle by cooling back to -100° C. The tin crystal was heated above room temperature by placing a standard infrared lamp against the window of the vacuum chamber. Specimen temperatures of 150° C could readily be achieved by this technique.

When the tin specimen reached the temperature of the experiment, load was applied. Loads of 1 to 50 grams were employed. Sliding of the iron crystal across the tin surface was then initiated, with a sliding velocity of 0.7 mm/min for a total sliding time of 20 minutes. Each data point at a specific temperature was obtained only after an equilibrium temperature had been achieved.

A polycrystalline tin specimen was prepared by straining a single crystal and then recrystallizing the specimen. This procedure was used to ensure that the single and polycrystalline specimens were from the same lot.

Binary alloys of aluminum, copper, or bismuth in tin were prepared by molding the molten alloy in graphite crucibles. Each alloy contained 1 atomic percent of the solute element in the tin solvent. After they were cut to size the alloys were handled in the same manner as the single crystals of tin.

RESULTS AND DISCUSSION

In sliding on a tin single-crystal surface above and below the transformation temperature (13° C), marked differences in the friction coefficient were observed. There was also a difference in the nature of the friction. In figure 3(a) the friction trace at 24° C, for the tetragonal structure, shows the stick-slip behavior so frequently observed with metals. Adhesion occurs, the friction force increases until the tangential force is sufficiently high to fracture the adhered junction, and friction force drops sharply. The process then starts again (fig. 3(a)). Likewise the friction trace at temperatures above 24° C has the stick-slip behavior shown in figure 3(a).

At -46° C, for the diamond structure of tin (fig. 3(b)), the friction force is higher, but the trace is extremely smooth relative to that seen in figure 3(a) for the tetragonal structure, where there is marked stick-slip. The same relatively smooth friction trace as represented in figure 3(b) occurs at temperatures below -46° C.

The friction coefficient as a function of temperature was measured with sliding in two crystallographic directions on the tin (110) crystal surface. Experiments were started at the higher temperatures because of the possibility that recrystallization would occur with the cooling of the crystals below the crystal transformation at 13° C. The results obtained are presented in figure 4.

An examination of figure 4 indicates that when sliding was in the [001], or low-temperature preferred, slip direction essentially no change in friction coefficient was detected over the range of temperature from 150° to -100° C. Thus, the transformation had no effect upon friction coefficient when sliding was in the [001] direction.

When sliding was initiated in the [111], or high-temperature preferred, slip direction the friction coefficient was markedly less than was observed in the [001] slip direction at all temperatures. An increase in friction coefficient was observed on reducing the temperature beyond the crystal transformation at 13° C. Thus, friction was sensitive to the transformation when sliding was in the [111] direction.

A recrystallization of the tin crystals was anticipated with passage through the crystal transformation at 13° C. With repeated experiments, no evidence of recrystallization with transformation was observed.

It is of interest to note in figure 4 that the friction coefficient for the body-centered tetragonal structure of tin was lower than was observed for the diamond structure. The opposite result was anticipated. Adhesive bonding of tin to iron occurred for both crystalline forms. With sliding, however, shear was more effectively accomplished with the body-centered tetragonal structure. Thus, shear strength and resistance to shear were less for the tetragonal structure. Further, the (110) plane of tin is the preferred slip plane with [001] and [111] being the preferred slip directions. Thus, shear resistance is at a minimum for these orientations (ref. 8).

The width of the wear track generated on the tin crystal surface varied with load and temperature. The variation of wear track width with load at -100° C is presented in figure 5. As the load was increased, the track widened. For a 50-gram load the wear track width was more than twice as wide as it was for a 10-gram load.

The variation of track width with changes in temperature is presented in figure 6. At a fixed load of 10 grams, there was no marked change in track width with temperature from -100° to 15° C. Above 15° C, which was above the crystal transformation temperature, the track width increased linearly with temperature. Below the transformation temperature, tin is a semiconductor and relatively brittle. Thus, changes in temperature there are not expected to exert much influence on surface deformation. Above, the transformation temperature, however, tin is a metal and ductile, deforming with load in a plastic manner. Thus, track width increases with an increase in temperature.

Sliding on the tin single-crystal surface at 23° C resulted in recrystallization in the wear track. This is shown in the photomicrograph of figure 7. Grain boundaries were present in the wear track. Tin recrystallizes at -4° C. The sliding and associated strain supply the necessary energy for recrystallization. The recrystallization was confined to the wear track itself and did not extend beyond it.

Friction experiments were conducted with polycrystalline tin and alloys of tin. Binary tin alloys containing 1-atomic-percent bismuth, copper, or aluminum were examined. Coefficients of friction were measured over the range of temperatures from -100° to 150° C. The results obtained in these experiments are presented in figure 8.

An examination of figure 8 indicates that there was a change in the friction coefficient of polycrystalline tin at the transformation temperature. Just as with the single-crystal results of figure 4 for the (110) [111] orientation, friction increased with transformation from the body-centered tetragonal to the diamond structure. The friction coefficient of polycrystalline tin was, at all temperatures, higher than those observed for the single-crystal orientations of figure 4. This observation is consistent with friction results for hexagonal metals in their single and polycrystalline forms (ref. 9).

Bismuth added to tin completely eliminated the crystal transformation in tin, as shown by the friction data of figure 8. No change in friction coefficient was observed as the alloy passed through the crystal transformation region.

Aluminum and copper both increased the kinetics of the otherwise sluggish transformation from the body-centered tetragonal form to the diamond form of tin (ref. 9). With both copper and aluminum a marked change in friction coefficient was observed as these alloys passed through the crystal transformation. The presence of aluminum in tin produced a nearly twofold decrease in the friction coefficient with the transformation from the diamond form of tin to the body-centered tetragonal form. Thus, the data of figure 8 indicate that the effects of the crystal transformation in tin on friction coefficient can be controlled by proper alloying.

A wear track on the copper-tin alloy is shown in figure 9. There is a "cellular" structure to the alloy. The wear track is intermittent in moving across this structure.

CONCLUSIONS

Based upon the experimental results obtained in this investigation of an iron single crystal sliding on single and polycrystalline tin and tin alloys at various temperatures from -100° to 150° C, the following conclusions were drawn:

1. The crystal transformation from the body-centered tetragonal structure (white tin) to the diamond structure (gray tin) resulted in an increase in friction for both single-crystal (110) [111] and polycrystalline tin. The friction behavior also changed from a stick-slip character for white tin to smooth for gray tin.

2. Alloying the metals bismuth, copper, or aluminum with tin altered friction behavior in the region of the crystal transformation. Bismuth arrested the crystal transformation, which resulted in a constant friction coefficient at temperatures from -100° to 150° C. Both copper and aluminum enhanced the kinetics of transformation and accounted for a marked increase in friction with transformation. The greatest effect was

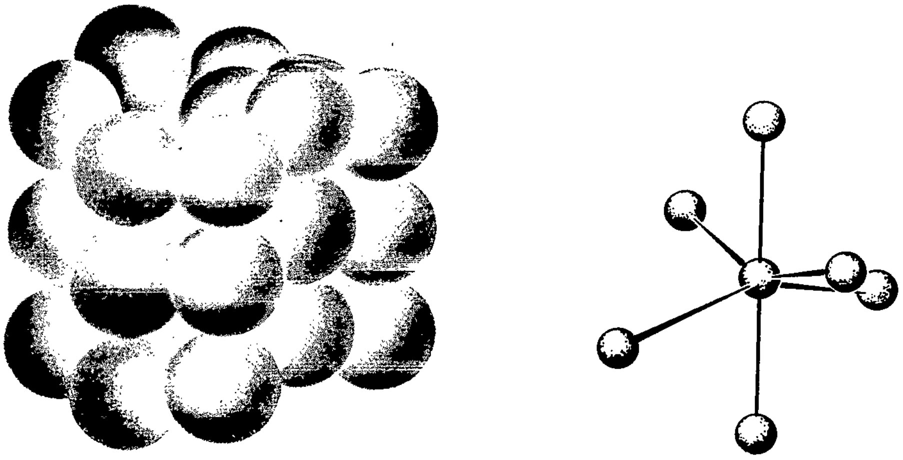
seen with aluminum. Alloying generally decreased the friction coefficient of tin at all temperatures.

3. Wear track width was relatively constant with increases in temperature to the crystal transformation temperature. Above the crystal transformation temperature (white tin) the wear increased with increases in temperature in a linear manner.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 21, 1975,
506-16.

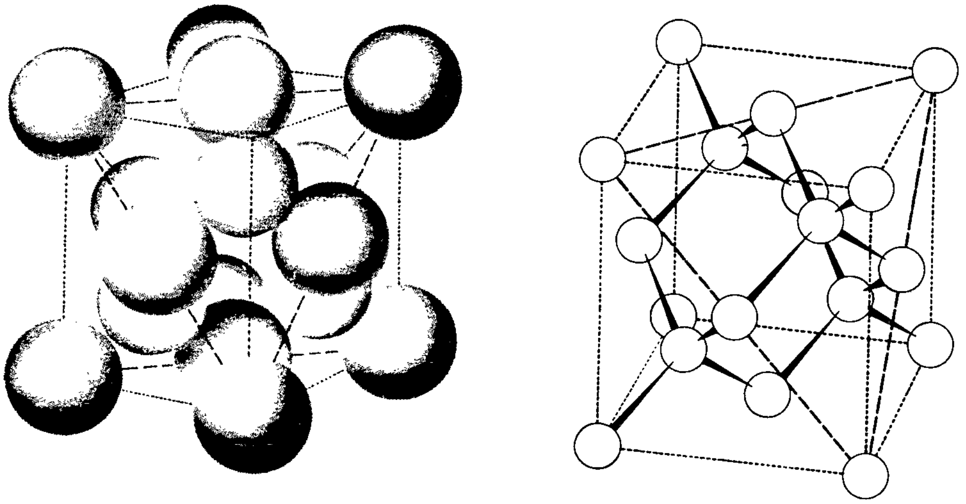
REFERENCES

1. Peterson, M. B.; Florek, J. J.; and Murray, S. F.: Consideration of Lubricants for Temperatures Above 1000° F. ASLE Trans., vol. 2, no. 2, 1960, pp. 225-234.
2. Ellis, O. W.; and Karelitz, G. B.: A Study of Tin-Base Bearing Metals - I. ASME Trans., vol. 50, 1928, pp. 10-13.
3. Karelitz, G. B.; and Ellis, O. W.: A Study of Tin-Base Bearing Metals - II. ASME Trans., vol. 52, pt. 2, 1930, pp. 87-99.
4. Freeman, J. R., Jr.; and Brandt, P. F.: The Effect of Impurities on the Compressive Strength and Brinell Hardness of Babbitt Metal at Normal and Elevated Temperatures. ASTM Proc., vol. 24, pt. 1, 1924, pp. 253-258.
5. Metals Handbook. American Society for Metals, 1948.
6. Azaroff, Leonid V.: Introduction to Solids. McGraw-Hill Book Co., Inc., 1960.
7. Schmid, Erich; and Boas, W.: Kristallplastizität, mit Besonderer Berucksichtigung der Metalle. J. Springer, Berlin, 1935.
8. Barrett, Charles S.: Structure of Metals, Crystallographic Methods, Principles, and Data. 1st ed., McGraw-Hill Book Co., Inc., 1943.
9. Buckley, D. H.; and Johnson, R. L.: The Influence of Crystal Structure and Some Properties of Hexagonal Metals on Friction and Adhesion. Wear, vol. 11, 1968, pp. 405-410.



(a) White tin.

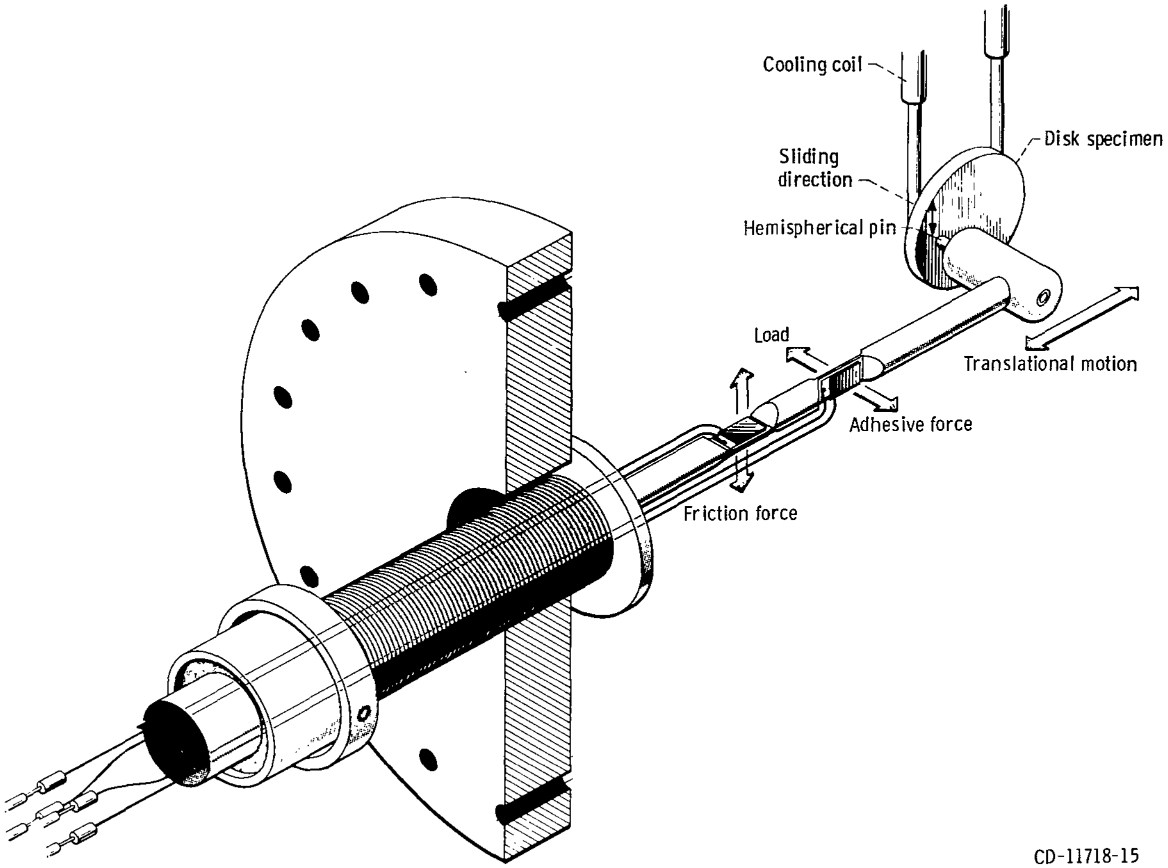
(b) Bonding in white tin.



(c) Gray tin.

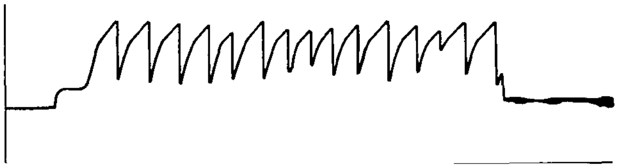
(d) Bonding in gray tin.

Figure 1. - Structure and bonding in the two crystalline forms of tin.

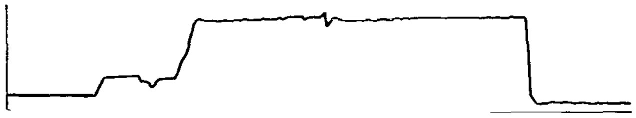


CD-11718-15

Figure 2. - High-vacuum friction and wear apparatus.



(a) Temperature, 24° C; white tin.



(b) Temperature, -46° C; gray tin.

Figure 3. - Friction traces for iron (110) sliding on a tin (110) single-crystal surface at 24° and -46° C. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 10^{-8} N/m^2 (10^{-10} torr).

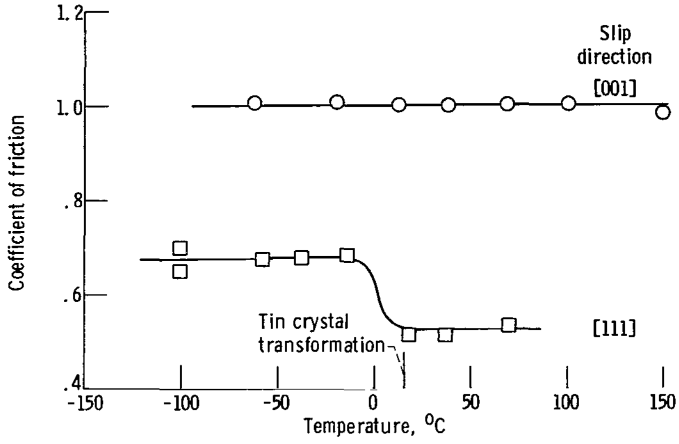


Figure 4. - Coefficient of friction for iron (110) sliding on a tin (110) single-crystal surface. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 10^{-8} N/m^2 (10^{-10} torr).

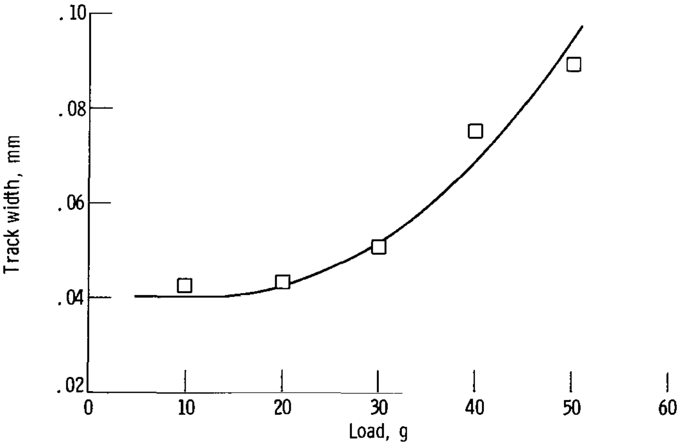


Figure 5. - Track width on tin single-crystal surface as function of load. Sliding velocity, 0.7 mm/min; pressure, 10^{-8} N/m^2 (10^{-10} torr); temperature, -100° C; rider, iron (110); single pass.

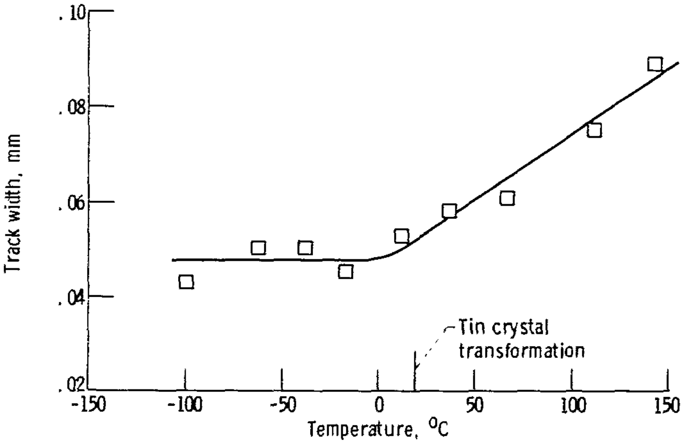


Figure 6. - Track width on tin single-crystal surface as function of temperature. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 10^{-8} N/m^2 (10^{-10} torr); rider, iron (110); single pass.

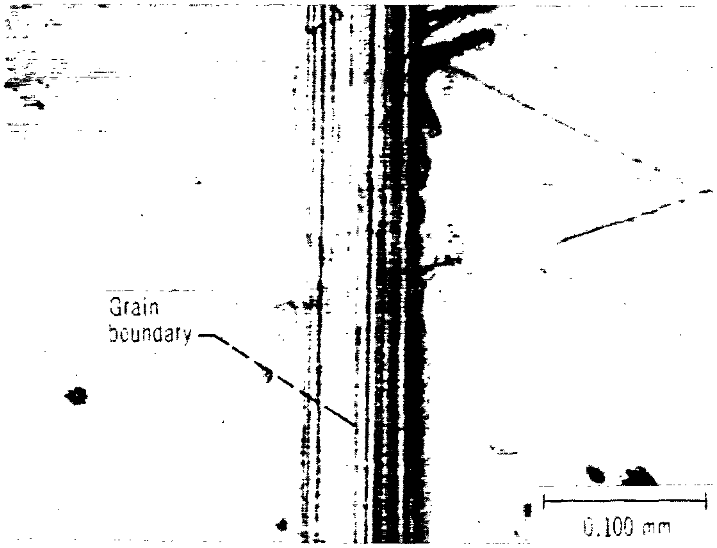


Figure 7. - Wear track on tin (110) single-crystal surface made by sliding an iron (110) crystal across that surface. Sliding velocity, 0.7 mm min; load, 10 g; pressure, 10^{-8} N m^2 (10^{-10} torr); temperature, 23° C.

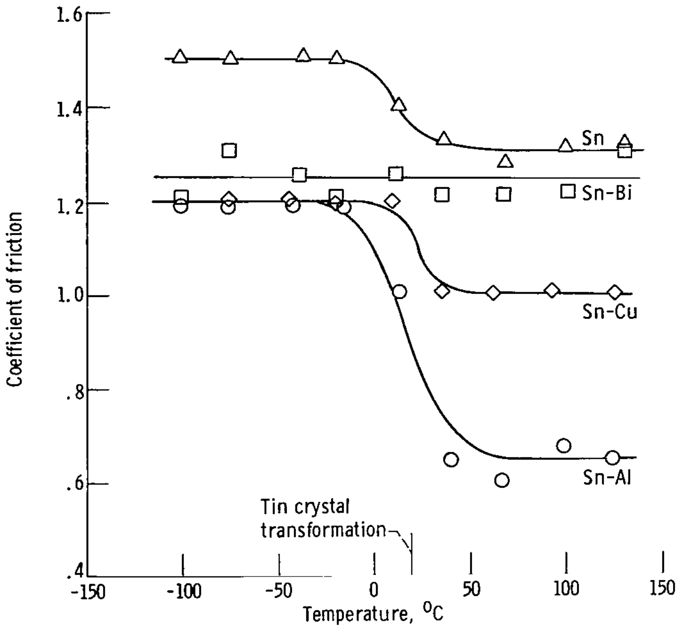


Figure 8. - Coefficient of friction for polycrystalline tin and tin alloys at various temperatures. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 1.33×10^{-8} N/m^2 (10^{-10} torr).

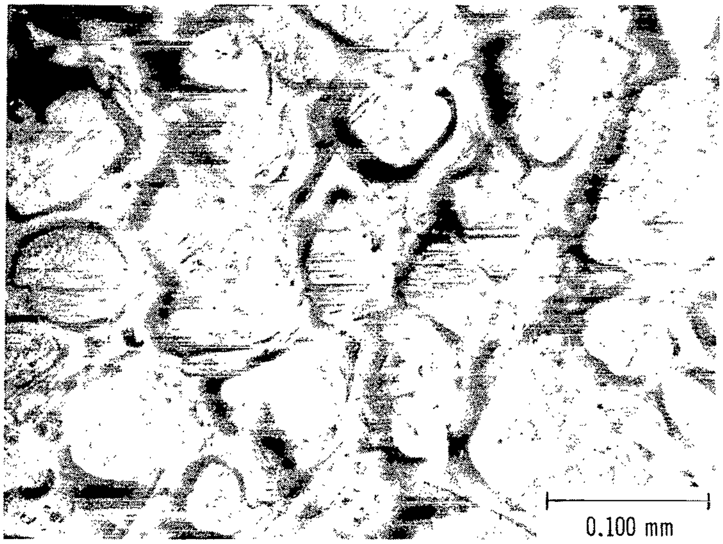


Figure 9. - Wear track on copper-tin alloy surface made by sliding an iron (110) crystal across that surface. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 10^{-8} N/m^2 (10^{-10} torr); temperature, 23° C.

NASA-Langley, 1975 E-8230

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

SPECIAL FOURTH-CLASS RATE
BOOK

648 001 C1 U C 750620 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

> *"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*
>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546