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SOME OBSERVATIONS ON PHENOMENA AFFECTING WEAR OF BEARING MATERIALS IN SLIDING CONTACT IN SODIUM AND ARGON AT TEMPERATURES UP TO 1200°F

by

E. S. Sowa, K. C. Tsao, C. Fiala,
and C. J. Divona

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Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
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and C. J. Divona

Reactor Engineering Division

July 1969

*The University of Wisconsin

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ABSTRACT

Vee blocks of four bearing materials: Type 304 stainless steel, Clarite T-1, Stellite 19B, and molybdenum, were installed in a modified Falex machine and loaded (75 lb) against Carboloy 78B shafts rotated at 20 rpm for 2-hr periods in static sodium and argon at 300, 500, 700, 900, and 1200°F, respectively. Use of Carboloy shafts restricted wear to the vee blocks.

A generalized equation was developed and simplified in an attempt to establish a parametric relationship of the variables affecting the relative wear of these materials. Variations in values of the wear coefficient and a constant reflected the interactions between the vee block-shaft assemblies and the test environments.

Plots of volumetric wear versus time are presented to show the effects of sodium lubrication, "wetting," and formation of oxide coatings on wear of Type 304 and molybdenum at various temperatures. Retention of MoO_3 as molybdate for molybdenum in sodium results in marked improvement in wear resistance over identical specimens in argon.

Recordings of drive-motor current input superimposed above wear plots of Type 304 and Stellite 19B show a correlation between time variation in friction coefficient in regions of "abnormal" wear and a more stable value in regions of "normal" wear.

I. INTRODUCTION

Operational experience with prototype liquid metal fast breeder reactor (LMFBR) power plants in the U.S. has revealed many problems with system performance. These problems must be understood more fully, resolved by research and development, or compensated for in design if the programmatic goal of a safe, reliable, and economic LMFBR utility industry is to be achieved.

One particularly pressing problem is wear in in-core components, such as control-rod drives or refueling mechanisms, whose intended functions are performed by moving elements such as grapples, bearings, guides, and seals. In operation, the surfaces of these elements are in continuous or intermittent sliding contact while immersed in the high-temperature primary sodium coolant or exposed to the inert gas blanket maintained above the coolant. Excessive wear of load-bearing surfaces in existing refueling mechanisms, for example, has caused malfunctions ranging from unacceptably high-friction torques to galling and complete seizure of the facing materials.

It is recognized that the advent of economic LMFBR central station power will depend, to a large degree, on the ability to schedule refueling and maintenance operations consistent with maximum plant availability. It is also recognized that this ability will depend, in part, on the availability of bearing materials that will minimize or eliminate malfunctions of the refueling mechanism and consequent cost penalties incurred by nonproductive in-core residence of the fuel. Therefore, considerable effort has been expended in test programs designed to evaluate the relative wear behavior of potential bearing materials in sliding contact with each other during exposure to sodium environments at anticipated operating temperatures.[1,2] However, very little effort has been focused on surface-interaction phenomena which influence wear behavior of materials in dynamic contact or the basic material properties which may cause these phenomena to develop.

On the premise that surface-interaction phenomena are dependent on fundamental properties of the contacting materials, experimental-analytical studies were initiated to: (1) determine the nature of this dependence; (2) identify the material properties which govern surface interaction behavior in terms of parameters; and (3) develop a correlation which will aid designers of in-core mechanisms in the selection of appropriate bearing materials (or combinations thereof) for service in sodium or inert gas at specified conditions.

Owing to funding restraints, the full extent of these objectives was not attained. However, four bearing materials were tested in continuous sliding contact in static sodium of known purity and in argon at temperatures from 300 to 1200°F. Analysis of the data yielded a number of significant observations. A simplified correlation was evolved which is of sufficient merit to warrant a more comprehensive program.

II. EXPERIMENTAL

A. Equipment for Wear Test

The wear tests were performed in a Falex machine modified to evaluate candidate bearing-material combinations in static or dynamic sodium at temperatures up to 1200°F. With reference to Fig. 1, the machine operates as follows.

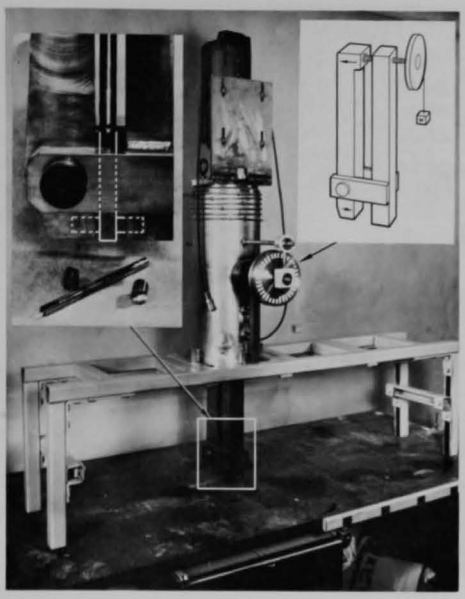

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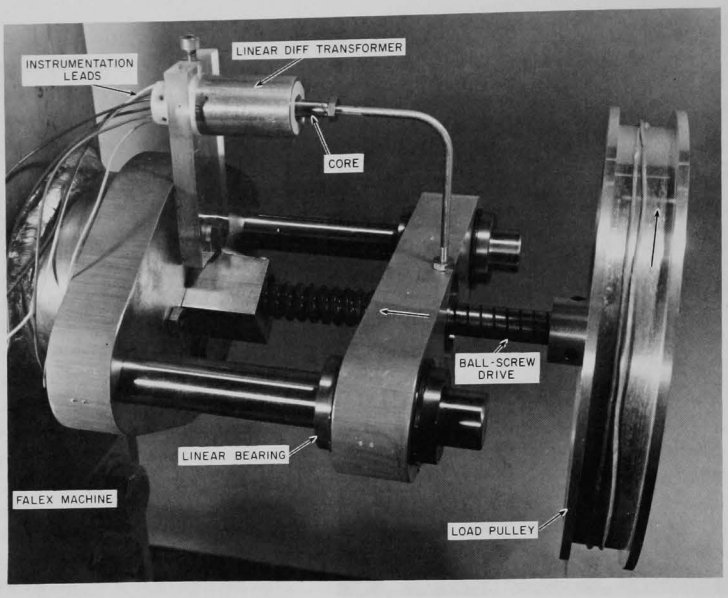
Fig. 1. Modified Falex Machine for Evaluating Wear Properties of Candidate Bearing Materials in Sodium up to 1200°F. Insets show (left) vee blocks, shaft extension, and supporting structure which are immersed in the sodium, and (right) simplified sketch of lever-loading assembly.

The tubular body is flange-sealed to an opening in an electrical-resistance-heated vessel containing static sodium or in a sodium-recirculating loop. This body supports a motor-drive shaft and two loading levers that extend through a flooded stainless steel packing into the sodium. Water-cooling coils around the body produce a temperature drop which results in a reflux return of condensed sodium from the region of the packing. This arrangement eliminates condensation and deposition of sodium on the upper shaft seal and loading levers.

The lower extremities of these levers squeeze two vee blocks against a central rotating shaft extension immersed in the sodium. Both vee blocks and shaft extension represent the materials being evaluated; they can be removed and replaced with similar configurations of other like and unlike materials. Rotation of the shaft extension is imparted by the drive shaft of a constant-speed, dc motor atop the tubular body. Squeezing of the vee blocks against the shaft extension is accomplished by a lateral thrust applied to the upper end of one loading lever by an assembly mounted on the side of the tubular body (see inset in Fig. 1).

This assembly (see Fig. 2) consists of a lead screw-ball nut drive, a load pulley, and a linear, differential transformer. One end of the lead screw extends through a bellows seal and bears against the loading lever. The other end is attached to the load pulley. Throughout the test, constant pressure is maintained on the lever by a weight suspended from the pulley. Rate of wear of the test specimens is recorded electronically by forward motion of the screw and drive housing which, in turn, moves the core in the transformer. Calibration of the assembly indicated that the recorded minimum movement of the core corresponded to a linear wear displacement of 0.000018 in.



112-6658 A

Fig. 2. Lever-loading Assembly Installed on Side of Falex Machine. Weight suspended from load pulley maintains constant pressure of lead screw against lever (and test specimens) inside machine (see insets in Fig. 1). Lever displacement with specimen wear is recorded by a transformer, the core of which is driven by the lead screw-ball housing. Minimum core movement corresponds to a linear wear displacement of 0.000018 in.

In addition to recording rate of wear, the machine can be used to measure the frictional coefficients of the test specimens. Friction is determined from the changes in current required to drive the constant-speed, dc motor. Also, the onset of galling is clearly evident by the torque behavior of the motor and the fluctuations in the wear readout. Finally, by replacing the dc motor with an impulse drive, the machine can be used for start-stop wear studies.

B. Test Specimens

Four materials were tested: Type 304 stainless steel, molybdenum, Stellite 19B,* and Clarite T-1.* These materials were selected because of their availability, their usage in current bearing applications, and/or their desirable properties. Each material was fabricated into vee blocks, 5/8 in. in OD and 11/16 in. long, with a 90° vee angle in one end. The angles on all vee blocks were machined to a surface finish of 50 μin.

*Analysis, in weight percent: Stellite 19B--29.50-32.50 Cr, 9.50-11.50 W, 3 Ni, 3 Fe, 1.3-2.10 C, 1 Si, 1 Mo, balance Co; and Clarite T-1--18W, 4 Cr, 1.10 V, 0.73 C, balance Fe.

In each test, two vee blocks of like materials were loaded against a rotating shaft extension (of 3/8-in. OD and $1\frac{1}{2}$ in. long) of Carboloy 78B,* which was ground and heavy-honed to the same surface finish as the vee blocks. Carboloy 78B was selected because of its excellent high-temperature hardness and compatibility with sodium. In operation, the material differential between the shaft and vee blocks limited the surface interactions such that wear effects were minimized. Because of the hardness characteristic of the shaft material, the data recorded by the transformer was confined predominantly to wear of the vee blocks.

C. Test Procedure

Three pairs of Clarite T-1 vee blocks, and two pairs each of Stellite 19B and molybdenum vee blocks were loaded against Carboloy 78B rotating shafts for 2 hr, respectively, in static sodium and in argon at temperatures of 300, 500, 700, 900, and 1200°F. Because of its demonstrated poor performance as bearing material in inert gas atmospheres, tests with two pairs of Type 304 stainless steel vee blocks were confined to the sodium environments.

The basic test procedure, identified as Phase I tests, was as follows:

(1) Position vee blocks in lower ends of loading levers, and attach Carboloy shaft extension to drive motor shaft, of the Falex machine (see inset in Fig. 1).

(2) Insert lower end of machine into test vessel; seal machine to vessel.

(3) Interconnect evacuation and electrical system to vessel; energize electrical-resistance-heating coils around vessel. Evacuate and preheat vessel interior simultaneously for 2-3 hr. Disconnect evacuation system.

(4) Load vessel with sodium (8.7 gal) via valve-isolated piping from adjacent EBR-II mockup primary tank. (The oxygen content of the sodium in this tank was 30 ppm.) Close isolation valve.

(5) Pressurize vessel interior with argon; adjust regulator to maintain ambient atmospheric pressure throughout test. Measured purity of the argon showed an average of 22 ppm H_2O and 15 ppm O_2.

(6) Heat vessel (and sodium) to desired temperature.

*Carboloy 78B--83 WC, 9 Co, 8 TiC.

(7) Load vee blocks against Carboloy shaft by suspending a 1/2-lb weight from the load pulley. The mechanical advantage of the mechanism results in a constant load of 75 lb.

(8) Adjust linear differential transformer voltage output to zero.

(9) Start test-shaft drive motor and adjust speed to 20 rpm or a lineal velocity of 0.39 in./sec. (During test, motor speed was monitored via voltage output from an attached dc generator.)

(10) Check out all instrumentation and monitoring equipment for proper operation.

(11) Activate data-acquisition system to sample data at 1-min intervals during each 2-hr test run.

(12) Upon completion of test series, allow sodium to cool to 300°F; disconnect electrical heating system. Enclose lower end of machine and test vessel in telescoping plastic bag; flood interior of bag with argon; disconnect machine from test vessel; seal plastic bag around test vessel; remove and replace test vee blocks and shaft extension.

(13) Insert and seal machine to clean test vessel (six vessels were available); repeat steps (3) to (11).

In some instances, the sodium was allowed to cool to 300°F, whereupon the same specimen assembly was exposed to a second series of tests; these are identified as Phase II tests.

Phase I and Phase II tests also were performed with specimen assemblies in argon. With the exception of Step (4) and phases of Step (12) related to sodium contamination, the procedures were identical to that described above.

D. Data-acquisition System

On being activated, this system recorded linear wear displacement; drive-motor rpm; drive-shaft torque as determined from current input to the motor; and bulk vee-block temperature, all at 1-min intervals during each test run. These data were punched on tape in 6-level bioctal flexowriter code for computer processing or graphical analysis. The latter is performed rapidly by a Hewlett-Packard X-Y plotter, which can be programmed to produce graphs of pertinent parameter relationships. Graphs were produced in this manner and examined prior to each successive run, since they also provided advance warning of a potentially abortive test run.

Subsequently the data were processed with a CDC-160A computer which yielded volumetric wear as a function of time, frictional coefficient, and temperature. An appropriate correction also was made to compensate for thermal expansion between test temperatures.

E. Results

1. Clarite T-1

Wear of the Clarite T-1 vee blocks was significantly more erratic and pronounced in argon than in sodium. As shown in Fig. 3A, the wear was very low and uniform in sodium at 300 to 700°F, increasing gradually at 900°F, with only slight positive variations indicative of increased wear at 1200°F. In contrast (see Fig. 3B), the vee blocks in argon experienced marked positive and negative variations in wear at temperatures up to and including 900°F. At 1200°F, the wear rate increased sharply, indicative of severe galling of the vee blocks.

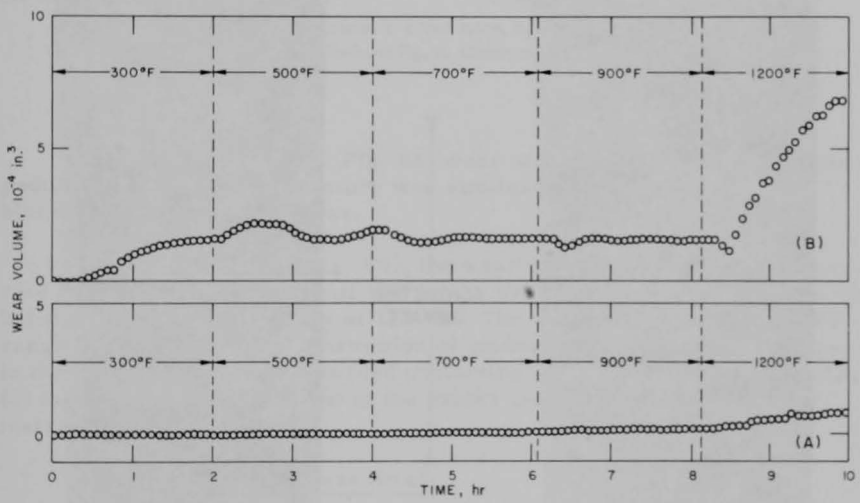
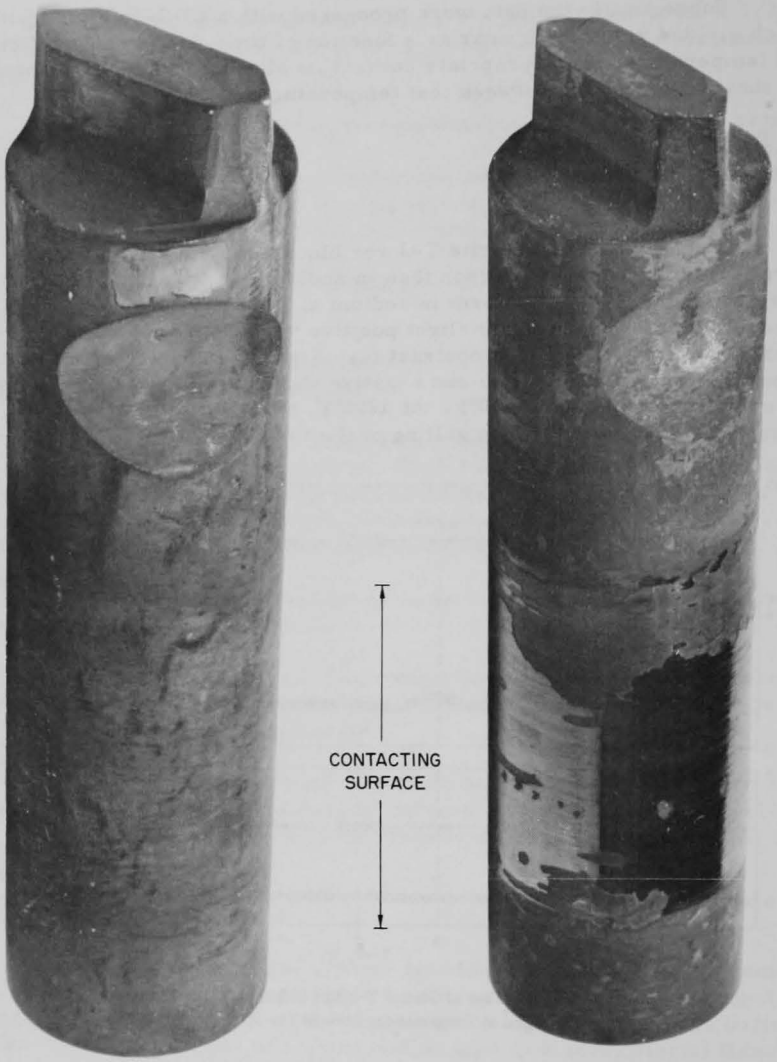


Fig. 3. Relative Wear of Clarite T-1 Vee Blocks in (A) Sodium and (B) Argon at Temperatures from 300 to 1200°F

This was confirmed on subsequent examination of the specimens. A large amount of Clarite material had been transferred and burnished onto the contacting surface of the Carboloy shaft. No doubt, gradual transfer and buildup of the Clarite material onto the shaft accounted for the marked variations in wear at 300-900°F, and ultimate accelerated wear at 1200°F. There was no evidence of Clarite material buildup on the shaft operated in sodium. The post-test appearance of the shafts and vee blocks are shown in Figs. 4 and 5.



X 7.5
(A)

112-9357

X 7.5
(B)

112-9359

Fig. 4. Appearance of Carboloy 78B Shafts Operated for a Total of 10 hr at 20 rpm against Clarite T-1 Vee Blocks in (A) Sodium and (B) Argon at Temperatures from 300 to 1200°F. Shiny, scale-like material on shaft (B) shows extent of Clarite T-1 buildup. (Photographically reduced by 30%.)

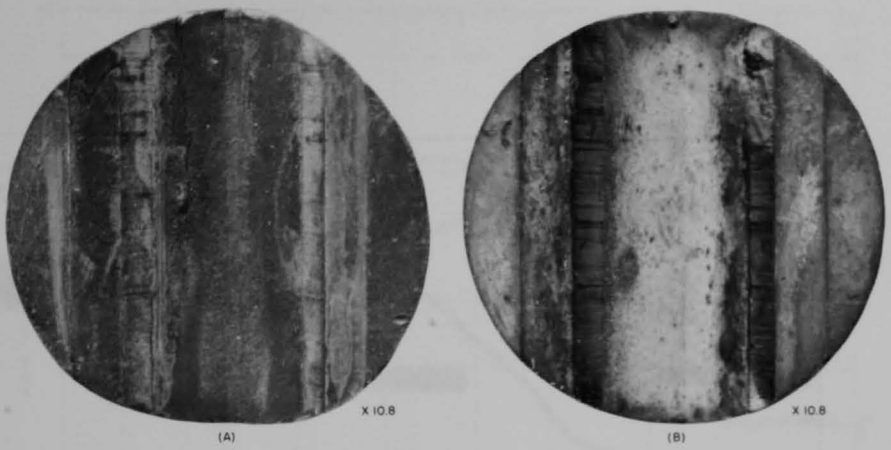


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Fig. 5. End Views of Clarite T-1 Vee Blocks Operated against Corresponding Carboloy 78B Shafts in Fig. 4. (Photographically reduced by 55%.)

2. Stellite 19B

As evidenced by Fig. 6A, wear of the Stellite 19B vee blocks in sodium at each test temperature was similar to that of the Clarite T-1 blocks, but to a lesser degree.

In argon (see Fig. 6B), the wear proceeded at a much higher rate than for the Clarite, until 900°F. At 900°F, the wear rate leveled off, but then varied considerably at 1200°F. The behavior in the 900-1200°F range is attributed to: (1) formation of oxides (from contaminant oxygen in the blanket gas) which afforded protection and/or lubrication at 900°F; (2) formation and detachment of the oxides from the underlying metal matrix at 1200°F.

3. Type 304 Stainless Steel

This vee block-shaft assembly was exposed to two consecutive series of tests in sodium. The results are denoted Phase I and Phase II in Figs. 7B and 7A, respectively.

During the Phase I tests at 300-500°F, the sodium acted as a lubricant, and wear of the vee blocks was restricted to a low rate, but still higher than that for either Clarite T-1 or Stellite 19B. At 700°F, there was a sharp increase or "break" in the wear rate, indicating that surface conditioning or "wetting" had occurred. In the transition zone, from 900 to 1200°F, the wear rate decreased slightly, possibly as a result of oxide formation. Minor positive and negative variations in wear readings were observed during the balance of the test at 1200°F.

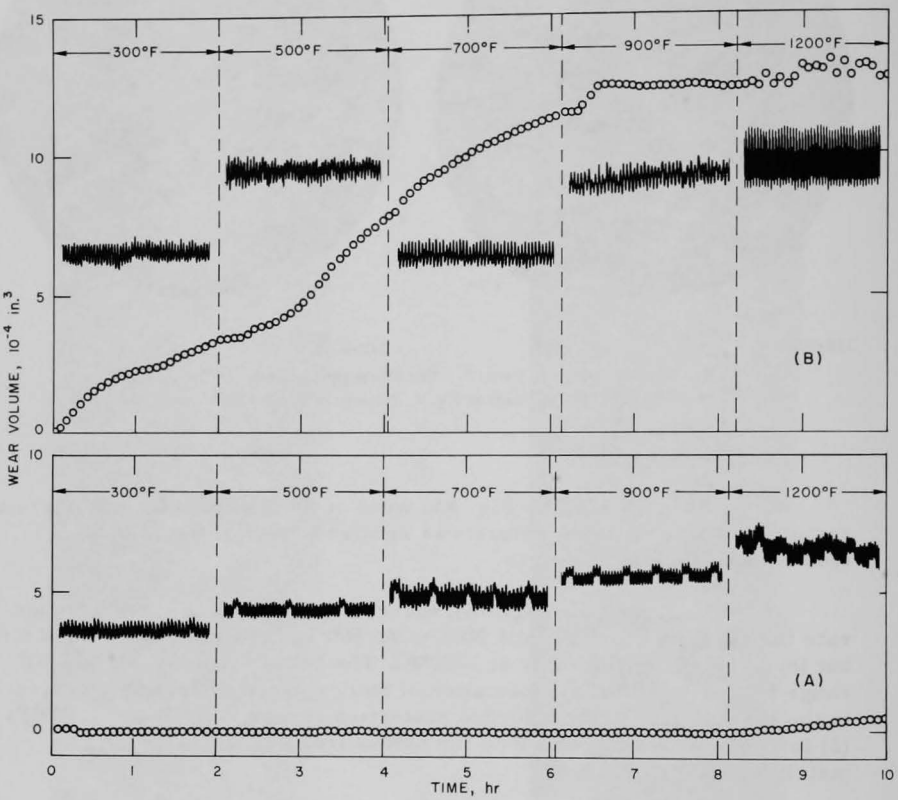

Fig. 6. Wear Behavior of Stellite 19B Vee Blocks in (A) Sodium and (B) Argon at Temperatures from 300 to 1200°F

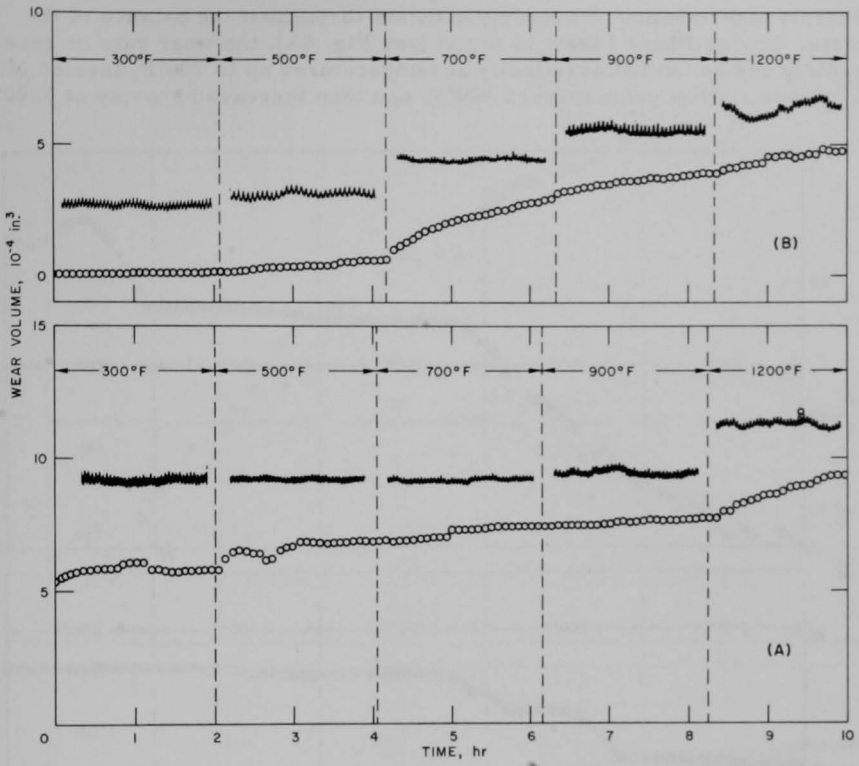

Fig. 7. Wear Behavior of Type 304 Stainless Steel Vee Blocks during (A) Phase II and (B) Phase I Tests in Sodium at 300-1200°F

Upon completion of the Phase I tests, the sodium was allowed to cool to 300°F. At that time, the Phase II tests were started. As shown in Fig. 7A, there was no sharp "break" in the wear rate. Despite some variations in the range from 300 to 500°F, it remained reasonably low and fairly constant up to and including 900°F. The low wear rate now is most likely the result of protection by an oxide coat. In any event, this protection did not prevail at 1200°F, as indicated by the marked increase in wear.

4. Molybdenum

Phase I and Phase II tests were conducted with pairs of molybdenum vee blocks in sodium and in argon. Unlike the Phase I test behavior of Type 304 stainless steel in sodium, the "break" in the wear rate for molybdenum occurred at a lower temperature, i.e., 500°F (see Fig. 8B), and then increased steadily up to 700°F. At 700°F, the wear rate decreased

sharply and remained reasonably constant throughout the balance of the tests. During Phase I tests in argon (see Fig. 8A), the wear rate increased rapidly and somewhat erratically at temperatures up to 700°F, leveled off at a constant low value through 900°F, and then increased sharply at 1200°F.

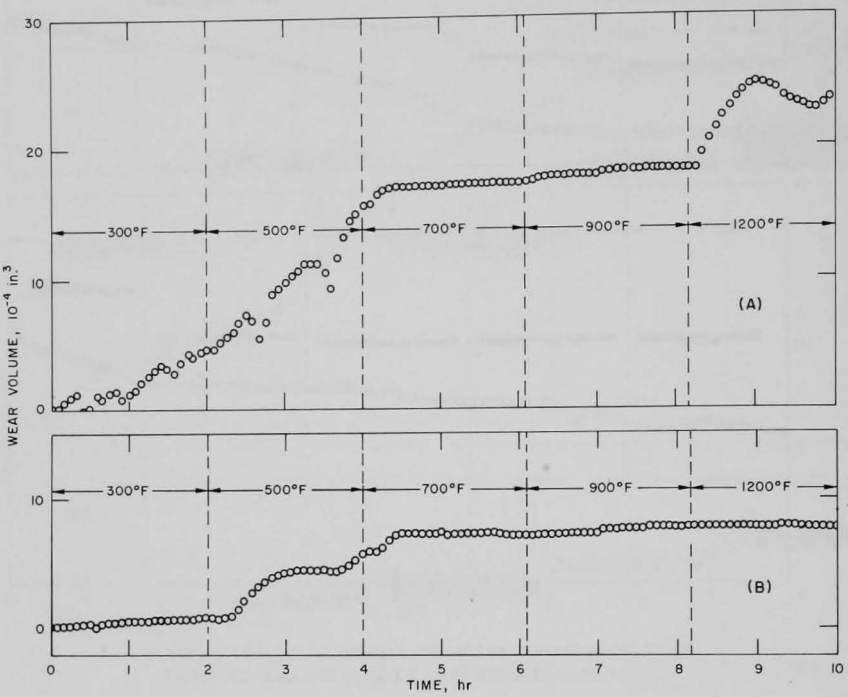

Fig. 8. Wear Behavior of Molybdenum Vee Blocks during Phase I Tests in (A) Argon and (B) Sodium at 300-1200°F

The trends in these plots lead to the conclusion that oxide formation, starting at 700°F, plays a vital role in protecting or lubricating molybdenum bearings in either sodium or argon environments. In sodium, the protection is extended to 1200°F, undoubtedly by the formation of molybdate. On the other hand, argon at 1200°F approximates the sublimation temperature of MoO_3; consequently a corrosive-wear process must occur.

This observation is supported by the results of Phase II tests with the same configuration (see Fig. 9). Here again, the wear trends are similar to those in Fig. 8. Of particular significance is the relatively low wear rate of molybdenum in sodium at all test temperatures.

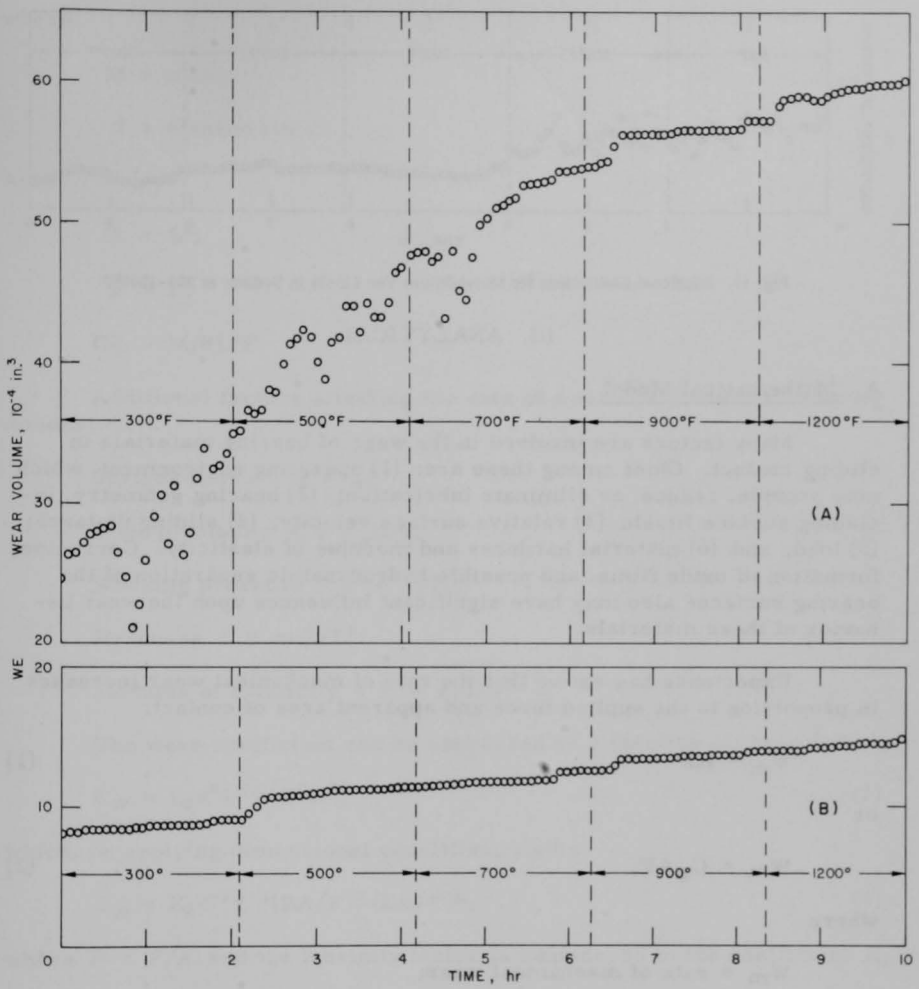

Fig. 9. Wear Behavior of Molybdenum Vee Blocks during Phase II Tests in (A) Argon and (B) Sodium at 300-1200°F

In all of the foregoing tests, the frictional coefficient decreased progressively with increased temperature. Figure 10 shows a typical plot, in this instance, for molybdenum in sodium.

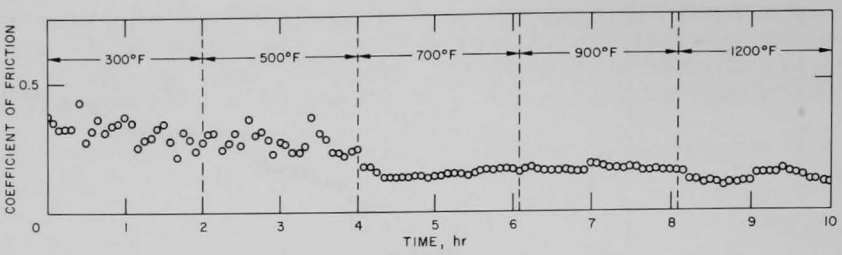

Fig. 10. Frictional Coefficient for Molybdenum Vee Blocks in Sodium at 300-1200°F

III. ANALYTICAL

A. Mathematical Model

Many factors are involved in the wear of bearing materials in sliding contact. Chief among these are: (1) operating environment, which may provide, reduce, or eliminate lubrication; (2) bearing geometry, including surface finish; (3) relative surface velocity; (4) sliding distance; (5) load; and (6) material hardness and modulus of elasticity. Corrosion, formation of oxide films, and possible hydrodynamic separation of the bearing surfaces also may have significant influences upon the wear behavior of these materials.

Experience has shown that the rate of mechanical wear increases in proportion to the applied force and apparent area of contact:

$$W_m \propto AF \tag{1}$$

or

$$W_m = C_w AF, \tag{2}$$

where

W_m = rate of mechanical wear;

A = apparent area of contact;

F = applied force;

C_w = coefficient of wear.

For purposes of dimensional analysis, let

$$W_m = M/\theta,$$

where

M = mass;

θ = elapsed time.

Also,

$A = L^2$;

$F = F$;

$C_W = M/\theta L^2 F$.

Additional factors affecting the rate of wear are given the following dimensions:

Surface finish = $\epsilon = L$;

Sliding velocity = $V = L/\theta$;

Working pressure = $P = F/L^2$;

Hardness = $B = F/L^2$;

Modulus of elasticity = $E = F/L^2$.

The wear coefficient can be expressed as a function of these factors:

$$C_W = K_2 \epsilon^a V^e P^f B^g E^h, \tag{3}$$

which, on applying dimensional equalities, yields

$$C_W = K_2 \epsilon^{-2} V^{-1} (BA/F)^g (EA/F)^h, \tag{4}$$

where $P = F/A$, and the lubricity factor is considered in the coefficient K_2.

Initial simplification of Eq. (4) was afforded by the experimental conditions. For example, sliding velocity was low and constant in all tests. This tends to diminish hydrodynamic lubrication to a small factor. Also, the high-temperature hardness of the shaft material limited the wear predominantly to the vee blocks. Finally, the contacting surfaces of all vee blocks were machined to the same initial finish; hence, this parameter was not variable.

As a result of these simplifications,

$$C_W = K_3(BA/F)^g(EA/F)^h. \tag{5}$$

A further simplification results from the relationship between hardness and elastic modulus,[3] such that B = 0.009E. Thus on substitution in Eq. (5)

$$C_W = K_4(BA/F)^v. \tag{6}$$

Equation (6) was used to treat the experimental results. Deviations from the equation would be indicative of changing relationships inherent in the coefficient K_4.

B. Results

Wear coefficients were calculated using data from two tests (Phase I and II) with Type 304 stainless steel and one test with Stellite 19B. Briefly, the contact area A in Eq. (6) was calculated from the recorded lineal displacement d of the loading lever:

$$A = 0.780 \cos^{-1} \frac{0.2199 - d}{0.2199}. \tag{7}$$

Since the mass worn away is directly proportional to the vee-block volume removed, the wear coefficient was calculated on a volume basis; consequently, values are expressed in in.^{3}/(min)(in.^{2})(lb). Finally, the coefficient K_4 was calculated assuming that the exponent v is -1; this is apparent from the linearity of the experimentally determined wear curves (see Figs. 6 and 7). The results are listed in Table I.

TABLE I. Calculated Coefficients for Type 304 Stainless Steel and Stellite 19B

Experiment	Temp, °F	Wear Coeff (C_W), in.^{3}/(min)(in.^{2})(lb)(x 10^8)	Coeff K_4 from Eq. (6), x 10^6
Type 304 SS (Phase I)	1200	3.0	6.9
	900	3.4	6.6
	700	11.0	17
Type 304 SS (Phase II)	1200	5.6	13
	900	1.0	3.8
	700	1.9	4.6
Stellite 19B	1200	3.6	9.2
	900	0.80	2.0

IV. DISCUSSION

As mentioned in the Introduction, the full extent of the experimental-analytical study objectives was not attained due to budgetary restraints. First, only ten wear tests were performed with four materials in sodium or argon as described, and there was a pronounced variation among the respective test data. Second, data from only three of these tests were employed to check out the simplified wear equation that was derived. Here again there was considerable variation between the corresponding wear coefficients that were calculated.

Despite the limited scope of these studies, two significant observations can be made with regard to the marked variations in the respective data. First, volume properties of candidate bearing materials and the ensuing surface interactions between these materials in sliding contact not only govern their selection, but also dictate the sodium environment in which the bearing can be used, i.e., submerged or in the vapor phase. Second, the absolute magnitude of the coefficient of friction does not have a direct relationship to the wear of the materials, but wear is reflected in the behavior of the coefficient.

With respect to the first observation: In Table I, the calculated wear coefficient for Type 304 stainless steel in sodium at 700°F (Phase I) is about three times the value computed for sodium at 900 and 1200°F. The higher value reflects the onset of "wetting" without the presence of a protective oxide coating. With the formation of oxide at the higher temperatures, the value of the wear coefficient decreases. The protection afforded by the oxide coating prevailed through the range from 700 to 900°F in the Phase II tests. At 1200°F, the wear coefficient increased sharply, reflecting a decrease in hardness of the stainless steel. Thus the wear process varied, with controlling factors varying between surface interactions and volume properties of the bearing material. In the case of Stellite 19B, the wear coefficient at 900°F was lower than that for Type 304, but approached the value for the stainless steel at 1200°F. This indicates that the oxide-forming mechanism is not as effective for the Stellite as it is for the stainless steel.

With respect to the second observation: Examination of the theory of adhesive wear[3] results in the following course of reasoning. Two adjoining materials under load produce deformation of the contacting surface asperities in elastic and plastic modes until the load is supported in equilibrium. As one surface slides over the other, opposing surface atoms are brought into contact with each other and atomic bonds are formed at the asperities. Further movement of the surface results in breaking of these bonds and formation of new ones. The raising and lowering of the energy levels of these surface atoms produces heat of friction, which is also equal to the work done in sliding the surfaces over each other:

$$Q = \overline{F}s = \sum_{0}^{t} n_a \Delta t, \tag{8}$$

where

$\overline{F}$ = average force applied parallel to the sliding surfaces;

s = distance traveled in time t;

n_a = number of bonds formed and broken in time interval Δt.

The energy of formation of these bonds is a function of the surface energies of the interacting materials. Consequently, the absolute magnitude of the coefficient of friction does not have a direct relationship to the wear of the material. However, as sliding contact continues, more bond formations occur at the contact asperities until the transverse force exceeds the bulk shear strength of the material. When this happens, the asperity is detached from the underlying matrix. Upon detachment, the material of the asperity (which has been stressed within the elastic limit) relaxes and the detached portion either transfers to the opposite surface or is removed as a wear fragment. This energy required to deform and detach the fragment must be added to the function shown in Eq. (8).

To be consistent with this line of reasoning, progressive "normal" wear of the sliding surface should require an energy input which will be an average over a large number of statistical variations occurring throughout a specific series of tests. Also, the required power will be an average over the range of variation of the frictional coefficient as the bonds are formed and the asperities are detached. Incidence of increased wear will necessitate a higher power input since a greater number of asperities are detached. In addition, the tendency for larger fragments to detach at that time should reflect a larger variation in power input.

The foregoing statements are supported by the composite plots in Figs. 6 and 7. As mentioned earlier, power input was measured by recording the current drawn by the dc drive motor. These recordings are shown above the corresponding wear curves for each temperature range. In the case of Stellite 19B in sodium (see Fig. 6B), the wear rate is very low, the corresponding recordings are regular with minor variations, and the band width is relatively narrow up to 1200°F. At 1200°F, the bandwidth increases and, at the same time, a superimposed modulation of the band is clearly visible. The corresponding wear curve indicates a definite increase in wear rate.

For Stellite 19B in argon, the band is much wider, with more variation in the modulation up to 1200°F. This also is associated with a high but reasonably steady wear rate. At 1200°F, the band width increases significantly and the corresponding wear data show considerable scatter. However,

the wear rate is not particularly excessive, so the modulation envelope does not show a high variation. Formation and breakdown of protective oxide coating is obviously occurring.

In the Phase I tests of Type 304 stainless steel in sodium (see Fig. 6A), the band width is considerably narrower than that recorded for Stellite 19B. This reflects the lower strength of the stainless steel. A few variations occur at 300°F. At 500°F a definite variation in band width occurs, with a corresponding higher wear rate. With the onset of "wetting" at 700°F, the band width narrows, but line variations become more numerous. At this time, the wear rate increases markedly. The decrease in band width is probably caused by more frequent detachment of smaller fragments. At 900°F, the wear rate decreases slightly, and the power input recording resembles the one at 500°F. (The wear rates at 500 and 900°F are almost the same, as can be seen from the slopes of the respective wear curves.) At 1200°F, the wear rate begins to increase; this increase is evidenced by the wide variations in the required power input recording.

In the Phase II tests (see Fig. 6B), "wetting" was not encountered; hence the wear rate is fairly constant and there are only minor variations in the power input up through 900°F. However, increased wear at 1200°F is again evidenced by considerable variation in the required power input.

V. CONCLUSION

These modified Falex wear studies have demonstrated only a few of the phenomena, i.e., lubrication, formation of surface compounds, and surface wetting, which affect the wear behavior of bearing materials in continuous sliding contact in sodium and argon up to 1200°F. Also the absolute magnitude of the friction coefficient does not have a direct relationship to normal wear, but a correlation does exist between the variation of coefficients with time in regions of abnormal wear.

The validity of these observations is subject to the results of a more comprehensive investigation. One objective would be an expanded wear-test equation which would reflect surface reactions and wear rates in terms of equation coefficients. Supporting tests should include start-stop modes of operation to yield data of interest to designers of control-rod drive mechanisms.

In addition, the effect of different levels of impurity in the sodium can exert a considerable influence upon the materials interactions. The significance of such influence should be investigated.

Finally, concurrent or independent research should delve into the merits of motor current input as a means of monitoring operating drives for approach to excessive wear conditions.

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