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SUPER-LAMINAR FLOW BEARINGS AND SEALS FOR PROCESS FLUID LUBRICATED TURBOMACHINERY

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✓ Bearing and Seal Materials for Liquid Metal Lubrication

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ABSTRACT

The obvious problems of selecting materials for high temperature corrosion resistance and strength have masked the fact that many of these liquid-metal lubricated bearing and seal surfaces may fail by seizure long before corrosion becomes a significant factor. Some of the hard, refractory materials, such as the cemented carbides, appear to offer a means for achieving good sliding behavior, corrosion resistance and high temperature strength all in one package. Actually, these materials are pacifiers. Design and fabrication problems generally outweigh the advantages that the cermets offer. In addition, the use of these materials may limit the size of machine components.

One promising approach is to use coatings or surface treatments to protect surfaces in relative motion. The feasibility of this approach has been demonstrated; however, there is a reluctance to use coatings because of quality control problems. Unless this problem is resolved, the design and fabrication of liquid metal lubricated components will continue to be unduly complex and in some instances, will be a source of built-in unreliability.

INTRODUCTION

There is certainly no controversy over the importance of bearing and seal materials in process fluid-lubricated systems. In many cases, materials have been the limiting item in the successful operation of machinery, especially when liquid metals were used as the lubricating fluids. Their poor viscosity characteristics, coupled with the fact that liquid metals have little or no boundary lubricating ability, impose very stringent limitations on the reliability of the bearing systems. Even hydrostatically-supported bearings are in constant jeopardy of failure because of an accidental rub.

There are materials available with good sliding behavior and corrosion resistance in NaK, but their physical characteristics impose many limitations on design and fabrication. The purpose of this discussion is to review briefly the status of the work on bearing materials selection and to recommend an approach to the problem of achieving good sliding characteristics without penalizing the bearing or seal design.

BACKGROUND ON BEARING MATERIALS FOR LIQUID METALS

In the early nineteen fifties, Vail, at the Knolls Atomic Power Laboratory and Basham et al, at Battelle Memorial Institute, both published results of material compatibility tests with NaK (Refs. 1 - 3). Their results are summarized in Table 1. The work done at Battelle was concerned with static tests on valve and seat material combinations in 1500F NaK. The purpose was to determine if welding and transfer would take place. Vail's work at KAPL consisted of basic sliding tests on a large number of material combinations in NaK, at temperatures up to 850F. In both studies, it was found that certain metal-bonded carbides were very satisfactory. Basham also showed that tungsten and molybdenum were promising materials for the valve and seat materials.

Since that time, there have been a number of other investigations made to select bearing material combinations for various liquid metal environments, e.g., Refs. 4 - 9. In general, the conclusions have been much the same. The cemented carbides and tungsten or molybdenum are the most compatible sliding combinations

for liquid metal-lubricated bearings. Stellite Star J has also been added to the list of promising materials. Certainly, these studies were useful since they broadened our knowledge of the behavior of these materials in various liquid metals. However, from the standpoint of the design engineer, who is concerned with building practical machinery, this approach of trying to use solid carbides or refractory metals appears to be the wrong way to attack this problem.

That last statement is backed up by practical experience. Some of the early work on journal bearings operating in NaK was done by Apkarian (Ref. 4) using the cemented carbides which were recommended by Vail as the bearing materials. The same background is still being used to select materials, e.g., Figure 1 shows a cemented carbide thrust bearing which was built by MTI for Aerojet-General under NASA Contract No. NAS 5-417. That bearing ran successfully in the Snap 8 NaK pump for 3000 hours at temperatures from 300-600F. Pivot damage studies have also been run in 600F NaK using various material combinations, including the cemented carbides.

Granted that these cemented carbides have excellent sliding compatibility in liquid metals, there are still many problems involved in the design and fabrication of parts from these materials which discourages their use in machinery. For example, Table 2 compares some of the characteristics of candidate liquid metal lubricated bearing materials with common structural alloys. All of the bearing materials have very low coefficients of thermal expansion and relatively poor shock resistance. In contrast, most of the structural alloys, with the exception of the columbium alloy, have much higher coefficients of thermal expansion. These mismatches in material properties have a strong tendency to force the design engineer to ignore sliding compatibility as a bearing material requirement and to select materials based on other attributes.

For these reasons, MTI has leaned heavily on the use of coatings to provide good bearing surfaces for unconventional fluid-lubricated systems.

EXPERIENCE ON COATINGS FOR BEARING APPLICATIONS

Most of the work which has been done at MTI on using coatings for bearings has been directed toward gas-lubricated bearing systems. However, this work does apply to the problem of liquid metal lubrication. In most of the gas bearing work, the gases were inert and no contaminating oxide films were present to provide surface protection. In addition, these non-reactive gases provided no boundary lubrication. These two conditions apply equally well to lubrication by NaK or by inert gases, although NaK is certainly a more severe case.

Basically, our approach has been to select one base alloy for the shaft, bearings, and any other critical structural members. This alloy is chosen for strength, density, corrosion resistance and any other essential attributes. Then, plasma or flame-sprayed oxide or cermet coatings are used on the journal and bearing surfaces to provide the necessary resistance to sliding damage. These coatings are applied, then ground back to a standard thickness of .003 inches. In this way, problems of matching thermal expansion are minimized. Experience has also shown that these thin coatings are much more capable of withstanding thermal or mechanical shock than are the solid cermets or ceramics.

Even among these so-called wear resistant coatings, there are wide gradations in effectiveness. Under NASA contract, MTI has evaluated some promising gas bearing material combinations for use in an inert environment (Ref. 10). In those tests, a single hydrodynamic tilting pad test bearing was dead weight loaded down against a 1.5 inch diameter test shaft. A photograph of the partially assembled test rig is shown as Figure 2. Capacitance probes, mounted on each side of the pad, were used to monitor lift-off speed, running film thickness and wear. The purpose of those tests was to measure changes in bearing performance as a result of sliding contacts.

In Figure 3, photographs of three different tilting pad bearings are shown after these bearings had been evaluated in start-stop tests. Two of these bearings ran very effectively for 1000 starts and stops at a stress level of 4 psi, based on the projected area of the shaft. These were a nickel-bonded tungsten carbide coated bearing against an Al_2O_3 coated shaft and a chrome

oxide coated bearing against a chrome oxide coated shaft. The contacting surfaces were lightly polished and the capacitance probes indicated less than forty microinches of wear. The third bearing, a hardened M-50 tool steel (60Rc) running against a cobalt-bonded tungsten carbide coated shaft was effective for about 350 starts and stops. At this point, the capacitance probe signals indicated that the bearing performance was beginning to degrade. The test was continued for the full thousand starts and stops, but there the bearing was not lifting effectively at the end of the test. Examination of the bearing surfaces after the test showed that the tool steel had transferred and welded to the carbide coated shaft and that this transferred material was scoring the pad surface in one area.

These same bearing combinations were also subjected to a series of high speed rubs by bringing the shaft up to a stable speed of 60,000 rpm and then impacting the pad against the shaft under various shock loads. Time in contact was on the order of .02 - .05 seconds. The appearance of the bearings after those high speed rub tests is shown in Figure 4. The chrome oxide coated pad running against the chrome oxide coated shaft was still in excellent condition after ninety rubs. The capacitance probe signals indicated that the bearing was operating on a larger film thickness at the end of the test than it was in the beginning. The contacting surfaces were highly polished and smooth.

As was the case in the start-stop tests, the M-50 tool steel pad running against the cobalt bonded tungsten carbide coated shaft was a very poor combination. This test had to be stopped before the full sequence of shock loads could be run because the pad was no longer lifting. The pad was found to be severely cold-worked and the shaft was covered with transferred metal.

The tungsten carbide coated pad running against an Al_2O_3 coated shaft showed a gradual deterioration in running performance throughout the test. After ninety rubs, the probe signals indicated that intermittent contact was taking place between the pad and the shaft. Examination of the test specimens showed that a smooth film of the binder metal was smeared on the Al_2O_3 coated shaft. The carbide-coated pad was severely abraded, either by the transferred metal or by

carbide grains being torn out of the pad surface.

Similar results have also been obtained with nickel and cobalt bonded tungsten carbide coated pads running against the same coatings on the shafts.

From the results of these tests the self-mated chrome oxide coating was selected as being the most promising material for good sliding behavior. This coating has since been used successfully in a number of gas and water-lubricated machinery applications.

MTI EXPERIENCE ON COATINGS FOR LIQUID METAL LUBRICATED BEARINGS

When a decision was required on the bearing materials for the NaK lubricated test rig, which was being built by MTI under AEC Contract No. AT(30-1)3363, three coatings were selected for preliminary evaluations of their corrosion resistance to NaK. The selection was based on our previous experience of the sliding compatibility of these materials in inert environments. These coatings were:

- a) Chrome oxide
- b) Chrome oxide, undercoated with molybdenum to improve the adherence of the oxide.
- c) Cobalt-bonded tungsten carbide.

The coatings were sprayed on one end of a hardened, cylindrical, 410 stainless steel test specimen which was part of a dumbbell tensile test bar. The geometry and dimensions of the specimens are shown in Figure 5. The coatings were then ground back to a standard thickness of .003 inches. This specimen configuration was used so that some measure of the bond strengths of the coatings could be obtained before and after exposure to NaK. To determine the coating bond strength, the coated face of the specimen was cemented to the other half of the tensile test bar with an epoxy resin. The bar was then pulled on a tensile test machine. Normally, the break will occur at the interface between the coating and the substrate since this bond is rarely as strong as the epoxy joint. Figure 6 is a

photograph of some typical test specimens showing the type of coating failure which should normally occur. By comparing the bond strength of control specimens with the bond strength of specimens which have been exposed to NaK, a measure of the resistance of the coatings to attack by the liquid metal can thus be obtained. This bond strength test, coupled with visual observation of the condition of the coating on the surface, is a reasonable measure of the resistance of the coating to corrosive attack.

The first test was a 300 hour static test with the specimens immersed in NaK at 200F. The specimens were then removed, examined and subjected to the tensile test. Table 3 gives the bond strength values for the control specimens (which had not been exposed to NaK), and for the specimens which had been exposed to 200F NaK. Two discrepancies were noted. First, the bond strength of the chrome oxide coating, which was undercoated with molybdenum, actually increased by a significant amount after exposure to the 200F NaK. At this time, we have no explanation for this behavior.

The second discrepancy was the fact that the joints broke at the epoxy when the tungsten carbide coated specimens, which had been exposed to NaK, were tested. At that time, it was felt that this was simply the result of a poor epoxy joint. However, repeat tests gave essentially the same results and in no case were we able to get good adhesion between the epoxy and any of the carbide coated specimens after the carbide coatings had been exposed to NaK. It is possible that the NaK had reacted with the carbide surface or the metal binder to form a film which did not make a good bond with epoxy. This introduced some uncertainty into the test results but time did not permit us to resolve this.

There was no visible indication of corrosion on any of the test specimens.

The second part of the screening study consisted of a series of fifty hour tests in 600F NaK. After each fifty hour cycle, the specimens were removed, washed and examined. The reason for removing the specimens every fifty hours was to see if the formation of caustic, as the result of exposure to air, would cause more corrosion than the continuous immersion in NaK.

After the first fifty hour test at 600F, the chrome oxide coatings were found to be completely disintegrated. Not only had the coating separated from the surface, the particles of chrome oxide had also separated from each other and had ended up in the bottom of the basket as fine debris. The molybdenum undercoat was still intact on the specimen which had been undercoated. A photograph of one of the chrome oxide coated specimens after this test is shown in Figure 7.

The cobalt-bonded tungsten carbide specimens had a dark film on the surface, but the coatings were still intact. These carbide coated specimens were then put back for another fifty hours. After this second run, there was a faint suspicion of pitting starting to appear on the surfaces. This could have been due to the fact that the NaK had washed out some grinding debris which had been embedded in the surface. In retrospect, this explanation seems reasonable since the pitting never became any worse.

The tests were suspended temporarily at this point while a new set of specimens was obtained. This time, 410 stainless specimens with a nickel-bonded carbide coating (25% WC, 7% Ni + mixed W-Cr carbides) were prepared. This nickel-bonded carbide is known to be more corrosion resistant than the cobalt-bonded material. In addition, a tilting pad bearing with this nickel-bonded carbide coating on a 416 stainless substrate was also included. This pad bearing had been ground and lapped to a 1-3 rms finish for some previous tests. It was included here because the highly polished surface would make it easier to see if the coating was actually pitting.

Finally, a type 316 stainless flat with an Al_2O_3 coating was also evaluated just to see if NaK would attack the Al_2O_3 . The Al_2O_3 coating was as-sprayed.

The specimens described above, plus the two cobalt-bonded tungsten carbide specimens which had already been subjected to the two fifty hour cycles in 600F NaK, were then run through three more fifty hour cycles at 600F in NaK.

At the end, the specimens were washed and examined. The appearance of the surfaces is summarized in Table 4. Figure 8 is a photograph of the polished carbide

coated specimen and the Al_2O_3 coated flat after the test. The carbide coated pad appeared to be in very good condition, perhaps a little duller than before the test but certainly not pitted. The Al_2O_3 coated flat had discolored badly and looked much rougher. However, the coating was still intact. This test should be repeated with an Al_2O_3 coating which has been ground back to a smooth finish. The result does not prove that Al_2O_3 is unsuitable, in fact, Al_2O_3 has been reported to be resistant to NaK at much higher temperatures but it does indicate that there maybe some questions as to the ability of the coating to withstand corrosion by NaK.

The shiny cylindrical specimen, with the threaded end, which is also shown in Figure 8, is a test sample of 6061 T-6 aluminum alloy that had been plated with .0002 - .0003" of electroless nickel. This aluminum specimen had gone through the five 50 hour cycle tests at 600F with no apparent corrosion taking place.

Table 5 summarizes the results of the bond strength tests on the carbide-coated specimens before and after exposure to 600F NaK. Once again, poor epoxy bonds were obtained on the specimens which had been exposed to NaK, particularly with the cobalt-bonded carbide. However, the results do indicate that the losses in bond strength, if any, were not large.

Based on the results of these static corrosion tests, the nickel-bonded tungsten (W-Cr) carbide coating was selected as being the best choice for the bearing and journal surfaces in the MTI NaK loop. As far as sliding behavior was concerned, this coating was known to be satisfactory for start-stop operation. Its ability to withstand high speed rubs was not outstanding, but seemed to be adequate for several lightly-loaded momentary contacts. The corrosion resistance of the carbide coating appeared to be suitable at temperatures up to at least 600F.

This conclusion of the suitability of the carbide coatings for use in 600F NaK was also shown by Wallace (Ref. 6) who had evaluated cobalt-bonded tungsten carbide coatings for their sliding behavior in NaK at 600F, and had found that these coatings had good wear resistance.

Figure 9 is a photograph of the shaft and pads from the MTI NaK test rig. The journals and pad surfaces have the nickel-bonded carbide coating. Although the number of operating hours on this facility is still low, these bearings have been run in water, alcohol and NaK. As far as sliding behavior is concerned, the coatings appear to be very satisfactory.

One point which should be emphasized here is the capability of these coatings for protecting larger areas such as face seal and thrust bearing surfaces. There is no limit to the diameter of a part as far as the application of coatings is concerned.

PROBLEM AREAS IN THE USE OF COATINGS FOR PROCESS FLUID LUBRICATION

Up to this point, all of the emphasis has been placed on the attributes of plasma or flame-sprayed coatings. They do have certain disadvantages, chiefly in the area of quality control. By varying the techniques used to apply the coatings, it is possible to get wide variations in coating properties and adherence. This point was also discussed by Wallace (Ref. 6), who concluded that a vigorous development effort was required to define a standard coating procedure which would insure reliable bearing surfaces. Most of the techniques available at the present time for evaluating the bond strength and integrity of the coatings are destructive in nature. It is necessary to coat test specimens or coupons at the same time that the machine elements are being coated and then to use these specimens for the coating evaluations. This introduces considerable uncertainty as to the condition of the coating on the actual machine parts. Non-destructive techniques have been proposed to determine coating adherence. These include ultrasonics, thermal or infra-red evaluations and eddy current flux field applications. Each of these is a development problem, but the feasibility of using each of these techniques has been demonstrated.

There are other problems in selecting the best coating for a given application and in establishing reasonable temperature limitations for the coatings but this information can be developed in a straightforward manner.

CONCLUSIONS

Flame or plasma-sprayed hard coatings offer many significant advantages in simplifying the design and fabrication of process fluid lubricated bearing and seal components. This is particularly true for large diameter parts where mismatches in the thermal expansion coefficients of materials may otherwise pose insurmountable difficulties. The effectiveness of certain of these coatings in protecting the surfaces against sliding damage in inert environments has been demonstrated in a number of practical applications. All of the test results which have been obtained to date show that these coatings can also be used effectively for liquid metal-lubricated systems.

The major drawback to the use of coatings is a lack of adequate quality control.

Ultimately, the choices boil down to these two:

Either we live with the solid cermets and refractory metals and accept the design problems and limitations which these materials impose, particularly for larger bearings and seals, or we learn to use coatings and develop the necessary quality control procedures which can ensure a reliable product.

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TABLE 1
PROMISING COMBINATIONS FOR NaK

S. J. Basham - Battelle
Valve-Seat Tests in 1500F NaK

Molybdenum vs. Molybdenum

Molybdenum vs. Cobalt-Bonded
Tungsten Carbide

Tungsten vs. Tungsten

Tungsten vs. Cobalt-Bonded
Tungsten Carbide

D. B. Vail - KAPL
Sliding Tests in 850F NaK

Cobalt-Bonded Tungsten
Carbide vs. Itself

Nickel-Bonded Titanium
Carbide vs. Cobalt-Bonded
Tungsten Carbide

TABLE 2
TYPICAL CORROSION RESISTANT BEARING AND STRUCTURAL
MATERIALS FOR LIQUID METAL SERVICE

	Coefficient of Thermal Expansion in./in./°F x 10 ⁻⁶	Density - Pounds Per Cu.In.	Mechanical Shock Resistance
<u>BEARING MATERIALS</u>			
Cobalt-Bonded Tungsten Carbide	2.38	0.54	Poor
Nickel-Molybdenum Bonded Titanium Carbide	3.7	0.22	Poor
Tungsten	2.5	0.70	Fair
TZM (Mo-Base)	2.7	0.37	Fair
Stellite Star J	6.8	0.316	Fair-Poor
<u>STRUCTURAL MATERIALS</u>			
347 Stainless	9.3	0.29	Good
410 Stainless	5.7	0.28	Good
Columbium - 1Zr	3.82	0.31	Good
Haynes 25	9.4	0.33	Good

TABLE 3

RESULTS OF BOND STRENGTH TESTS BEFORE AND AFTER EXPOSURE TO 200 F NAK FOR 300 HOURSALL TESTS IN DUPLICATEA. Control Specimens Which Were Not Exposed to Nak

Type of Coating	Tensile Stress at Break	Average Tensile Stress	Percent of Area Broken Away
Cobalt Bonded Tungsten Carbide on 410 Stainless	3080 psi 3900	3490 psi	About 40%
Chrome Oxide on 410 Stainless	1650 psi 1470	1560 psi	About 20% Less than 10%
Chrome Oxide with Molybdenum Undercoat on 410 Stainless	1920 psi 2000	1960 psi	Almost complete separation

B. Specimens After 300 Hour Exposure to Nak at 200F

Cobalt Bonded Tungsten Carbide on 410 Stainless	2175 psi 2560	2367 psi	Surfaces did not fail, break occurred at epoxy
Chrome Oxide on 410 Stainless	1625 psi 1700	1662 psi	About 10% Most of coating
Chrome Oxide with Molybdenum Undercoat on 410 Stainless	2975 psi 3150	3062 psi	Almost complete separation

TABLE 4
APPEARANCE OF TEST SPECIMENS AFTER STATIC CORROSION TESTS IN NAK AT 600F

Coating	After One 50 Hour Test	After Two 50 Hour Tests	After Three More 50 Hour Tests
Chrome Oxide on 410 Stainless Steel	Coating Disintegrated	Not Run	Not Run
Chrome Oxide plus Molybdenum Undercoat on 410 Stainless Steel	Chrome Oxide Disintegrated, Molybdenum intact	Not Run	Not Run
Cobalt-Bonded Tungsten Carbide on 410 Stainless Steel	Dark film, easily washed off	Faint suspicion of pitting	Dark film, easily washed off. Same as after first two 50 hour tests
Nickel-Bonded Tungsten (W-Cr) Carbide on 410 Stainless Steel	Not Run	Not Run	Covered by dark film, easily washed off. No damage visible
Nickel-Bonded Tungsten (W-Cr) Carbide on 416 Stainless Steel, Lapped to High Polish	Not Run	Not Run	Covered by dark film, easily washed off. Still shows high polish
Al ₂ O ₃ Coating on 316 Stainless steel	Not Run	Not Run	Coating still intact but it is black and appears to be rougher

TABLE 5
RESULTS OF BOND STRENGTH TESTS BEFORE AND AFTER EXPOSURE TO 600F NAK

A. Control Specimens Which Were Not Exposed To Nak

Type of Coating	Average Tensile Stress	Percent of Area Broken Away
Cobalt-Bonded Tungsten Carbide on 410 Stainless	3490 psi	About 40%
Nickel-Bonded Tungsten (W-Cr) Carbide on 410 Stainless	>4500 psi	Epoxy bond failed before coating

B. Specimens After Exposure To 600F Nak

Cobalt-Bonded Tungsten Carbide on 410 Stainless	>2180 psi ^(a)	Surfaces did not fail, break occurred at epoxy
Nickel-Bonded Tungsten (W-Cr) Carbide on 410 Stainless	>3800 psi ^(b)	Surfaces did not fail, break occurred at epoxy

(a) After five 50 hour tests

(b) After three 50 hour tests

Fig. 1 Cemented Carbide Thrust Bearing

Fig. 2 Disassembled View of Test Rig Showing
Test Shafts and Tilting-Pad Bearing

M-50 STEEL

CHROME OXIDE

TUNGSTEN CARBIDE

Fig. 3 Tilting Pad Bearings After 1000 Starts and Stops in Argon Atmosphere at 4 psi

M-50 STEEL

CHROME OXIDE

TUNGSTEN CARBIDE

Fig. 4 Tilting Pad Bearings After High Speed Rubs at 60,000 rpm in Argon Atmosphere

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Fig. 6 Tensile Test Specimens Showing Typical Coating Failures

Fig. 7 Chrome Oxide Coating After Exposure to 600F NaK

Fig. 8 Appearance of Test Specimens After Exposure to NaK at 600F

Fig. 9 Shaft and Tilting Pad Bearings from MTI NaK Test
Showing Coatings on Journal and Pad Surfaces