WADC TECHNICAL REPORT 54-598

RETAINER MATERIALS FOR AIRCRAFT GAS TURBINE BEARINGS

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MARCH 1955

MATERIALS LABORATORY
CONTRACT No. AF 33(616)-2099
PROJECT No. 3066

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
200 - 29 September 1955

FOREWORD

This report was prepared by the Horizons Incorporated under USAF Contract No. AF 33(616)-2099. The contract was initiated under Project No. 3066, "Gas Turbine Technology", Task No. 73599, "Bearing Materials", formerly RDO No. 506-204, "Bearing Materials", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt R. D. Masteller acting as project engineer.

ABSTRACT

A study of the elevated temperature wear resistance of potential cage materials for aircraft turbojet bearings was conducted using a special wear testing machine to simulate roughly the conditions to which such bearings are subjected in service. All tests were conducted in the Mechanical Metallurgy Department of Horizons Incorporated.

It has been found that:

1. Several alloy compositions have been developed which have superior bearing properties to "S" Monel and iron-silicon bronze. All of the promising materials except one contain silver as a major alloying element.

2. It has been established that the addition of from 2 to 4% silicon is distinctly beneficial to the wear properties of several classes of metallic alloys.

3. It has been shown that the alloy composition can be varied considerably with respect to the strong, load supporting phase as long as silver is contained in the soft matrix.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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RETAINER MATERIALS FOR AIRCRAFT GAS TURBINE BEARINGS

I. INTRODUCTION

The purpose of this research project was to investigate the possibilities of developing improved materials for use as retainers or cages in the rolling contact bearings used to support the rotors in modern military aircraft gas turbines. While it is understood that generally the present materials used for such cages are satisfactory, the evidence indicates that they are operating at their very upper temperature limits with no margin of safety. The most satisfactory cage materials in use are silver plated iron-silicon bronze and silver plated "S" Monel. A wide variety of other metallic materials have been tested in the past, such as brass, bronze, nickel base alloys, and various types of cast irons. The cloth impregnated plastics which have been useful in conventional applications of roller and ball bearings are ruled out by the high ambient temperatures to which the cages are exposed.

While the mechanism of cage failures is not understood exactly, the available evidence indicates that adhesive metal transfer between the cage and race materials plays a major role in the process. The resulting clearance alterations can then lead to failure in several different ways. It is, therefore, evident that a major criterion in the selection of a retainer material is its frictional characteristic and surface stability against hardened alloy steel. A consideration of the mechanism of adhesive friction and wear, as it is presently understood, suggested the use of a two-phase system for the friction surfaces of the cage or retainer. This two-phase system would consist essentially of a hard phase which would limit the size of the true contact area and contribute the desired bulk mechanical properties and a soft, low shear strength phase which would act as a metallic film lubricant.

This philosophy permitted a wide variety of material combinations to be considered, both metallic and non-metallic. The purpose of this report is to present the results of simulated service tests of such material combinations which were considered promising for use in high temperature retainers.

II. LITERATURE REVIEW

On the assumption that the primary problem is galling, one must consider the factors that are responsible for it. The modern theory of friction as developed by Holm (1), Merchant (2), and Bowden and Tabor (3) ascribes its origin almost entirely to minute adhesions or welds between the solid surfaces. Based on this model, one is able to predict semi-quantitatively the conditions for low adhesion and for low friction. The conditions for low adhesion are essentially as follows:

a. The true area of contact should be as small as possible. This generally means that both surfaces should be hard.

b. The materials of the top rubbing surfaces should be as dissimilar chemically as possible.

At low rubbing speeds, even though the friction will not necessarily be low, these conditions are usually sufficient to prevent adhesion. However, at high rubbing speeds, the friction itself, although it does not necessarily result directly in much adhesion transfer of material, does have an important indirect effect. This is because the frictional heat evolved will produce appreciable softening of the surfaces and also accentuate any tendency to weld. Thus, it is most important to keep the friction as low as possible.

It can be shown that the friction coefficient may be expressed in terms of the plastic properties of the rubbing surface materials as follows:

$$f = \frac{s}{p} \qquad (1)$$

where s is the average shear strength of the welds formed and p is the flow pressure of the softer material. The important conclusion from this equation is that the lowest friction will only be achieved in a duplex type of structure consisting of a hard substrate covered with a thin layer of material which forms a very weak bond with the other surface.

A weak bond in turn is achieved primarily through chemical dissimilarity between the two surfaces resulting in low adhesion. However, experiments using radioactive tracers have demonstrated that even between the most dissimilar materials, such as steel and glass,(4) and using the best boundary lubricant,(5) some adhesion and transfer of materials still remains. It is, therefore, further required that the weak bonding layer consist of a material that is inherently weak itself, i.e., it should be soft at the temperature of operation, and have a melting point not much above this temperature, so that any frictional heating will produce a locally liquid surface layer and restrict any further temperature rise.

This is the principle behind all the premium bearing materials for high speed-high load applications today. They all have a duplex structure consisting of two phases, a hard one and a soft one which, on running, provide a hard substrate covered with a thin, soft, easily sheared layer. These two phases may be disposed in a variety of ways. There may be hard particles embedded in a soft matrix as in the babbitts, soft particles in a hard matrix as in copper-lead, layers as in the plated and lead-indium coated silver bearings, or equally dispersed as in powder metallurgy compacts of silver-tungsten, copper-graphite, etc.

The above is the most important requirement for a high performance bearing. There are, in addition, a number of lesser ones such as conformability, chemical and thermal stability, the right degree of surface reaction with the lubricant, and surface fatigue resistance. In the present case, mechanical strength and impact resistance will also be important considerations for the bulk material.

The basic mechanism underlying adhesive wear is not understood in as much detail as that of friction. However, the work of Holm (6) and Burwell and Strang (7) indicates that it also depends on the true area of contact as well as the load and distance of travel. It has been shown that for homogeneous materials, at least, the character of the wear changes markedly above a critical load, becoming self-accelerating and catastrophic, completely destroying the surfaces. This critical load was found to equal approximately the product of the nominal or apparent contact area times one third of the indentation hardness. Below this critical value the wear is mild, steady, and may be predicted from the following equation:

$$V = k \frac{W \cdot L}{p} \qquad (2)$$

where V is the volume of material worn off, W is the load, L the distance of travel, p the flow pressure of the softer metal, and k an empirical constant depending on the pair of materials and the operating conditions. For a given geometry, this then imposes another condition on the hardness of the bearing material substrate.

It appears rather certain from the above that a successful material will have to possess a duplex surface structure. It is very doubtful whether any single material will have all of the requisite properties. On the other hand, a duplex or two-phase material offers a double range of choice of material properties in order to obtain a successful result.

In such a duplex structure, the more critical of the two materials is the softer surface one. If this surface film is appreciably thicker than the surface irregularities and the substrate material is not greatly deformed, the substrate material may be completely protected. In this case, the shearing action occurs only on the surface layer, the friction is low, and the film provides protection until the surface temperature reaches the melting temperature of the film. Experiments conducted to determine the effectiveness of various films give surprising results (8). Indium films on a hard substrate have coefficients of friction of the order of 0.04 up to 155°C, lead films have coefficients of friction of about 0.15 up to 327°C; silver films have coefficients of friction of about 0.25 up to 950°C. These results indicate that films of these metals are operative to within only a few degrees of their respective melting temperatures. It is true, however, that after repeated sliding on these surfaces the films are worn away and the substrate material is the ultimate bearing material. In practice, this difficulty is overcome by dispersing hard particles in a soft matrix, therefore, resulting in a two-phase bearing alloy. This permits the softer metal to be sheared and smeared over the surface. This continuous action provides an effective, protective surface film until the dimensional tolerances have been exceeded. It is by this principle that lead and tin-base babbitt materials operate so successfully.

The commonly accepted viewpoint is that the composition of the hard phase is unimportant so long as it is sufficiently hard to provide a small true contact area, and that it does not interfere with the lubricant action of the softer phase. Thus it has been demonstrated with copper-lead bearing alloys (3) that a surface film of lead is replaced more easily from a dendritic alloy than from a non-dendritic alloy of the same composition. The dendritic alloy is therefore less likely to seize under certain conditions. On the other hand, under severe conditions of sliding, the non-dendritic alloy possesses higher mechanical strength, and at high temperatures its frictional properties are better.

III. THE TEST MACHINE

The essential functions of the machine built for these experiments are that of crudely simulating the service conditions of wear betweem the cage and race components of jet aircraft bearings. It consists of a rotating disc of the same diameter as the inner race land of a 200 mm bearing (a size contemplated for future use). This disc is driven at a linear peripheral speed corresponding to that expected in service, and contacts an arc of the material to be tested having the same radius of curvature as the inner locating surface of the retainer to be used in this bearing. The test specimen can be normally loaded by various amounts against the rotating disc, and the whole assembly is enclosed in a box furnace for heating to the same ambient temperature as that expected in operation. For higher temperature requirements an induction heating unit is used. Oil is supplied to the test surfaces by jets from an oil circulating system and preheated to the temperature expected in actual practice.

A more detailed description of the components of this wear testing machine can be described by consideration of the following items. (See Figure 1).

A. Machine Construction

The rotating components of the machine are composed of the hollow shaft (102) and the test disc (104), the latter corresponding in its dimensions and physical characteristics to the inner race land of the bearing.

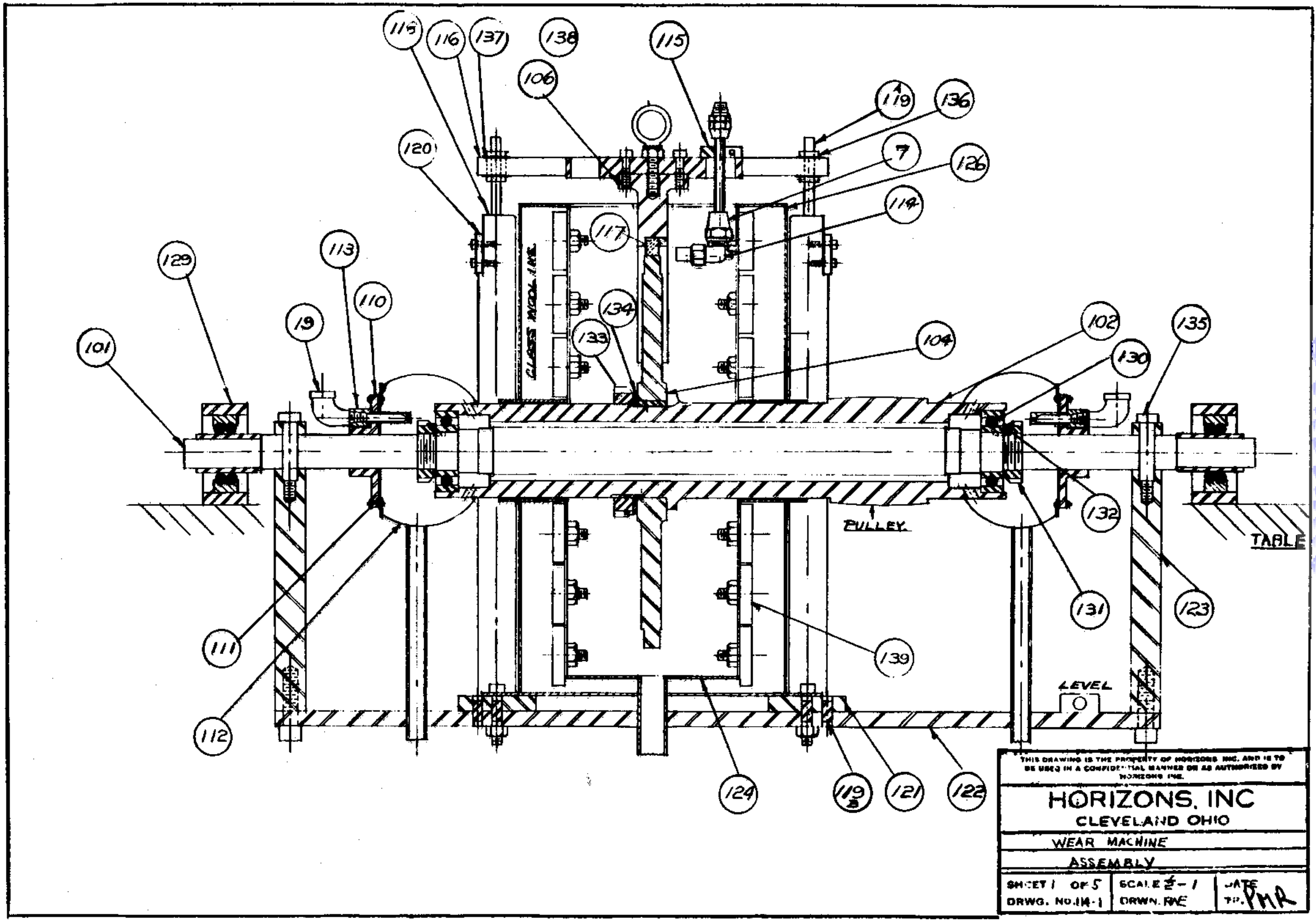


Figure 1 Assembly Drawing of Wear Machine

the bearing.

The hollow shaft (102) is joined to the solid shaft (101) by high-speed ball bearings (130) on each end. The solid shaft (101) is held at the extremities by ball bearing, self-aligning, pillow-blocks. The cradle bar (122) is rigidly connected to the shaft (101) by posts (123) and bolts (135) on both ends.

In the same place, and perpendicular to the bar (122), the guide post supports (121) extend to hold the guideposts (118). The guideplate (116) is able to slide on the four guideposts (118) by means of four roller bushings. The specimen holder (106) is **attached** to the guideplate.

The primemover is a 5 HP, 3600 RPM synchronous motor, with 175% overload rating. The power is transmitted from the motor pulley to the integral shaft pulley of shaft (102) by means of an endless nylo flat belt.

The use of a **synchronous** motor eliminates the use of instantane and totalizing revolution counters. The lateral surface speed of th rotor is 440 ft/sec or rotational speed of 10,000 RPM.

The rotors used were made from SAE 52100 alloy steel for the lower temperature tests (up to 400°F) and A1S1-SAE T-1 tungsten - chromium-vanadium (18-4-1.1%) alloy steel for the higher temperature tests (up to 750°F).

B. Lubrication and Heating Systems

1. Lubrication Circuit for Support Bearings (See Figure 2).

A rotary gear pump, with a bypass valve for quantitativ flow regulation, pumps the oil through a flowmeter and thermometer well. The main supply of oil is then divided into two equal parts by equal lengths of tubing and flexible high pressure hose leading to the jets (113). The oil catches (112), return the oil by gravity flow through the sump and filter to the pump. (See Figure 1).

2. Lubrication Circuit for Wear Tests (Figure 3).

A rotary gear pump, with a bypass valve for quantitative flow regulation, pumps the oil through an immersed cooling coil, flowmet and thermometer well. This supply of oil is divided into two parts as above and returns through jets (114) by way of the furnace (124) to sump, filter and pump (see Figure 1). The oil used during all tests was Esso Turbo Oil 15, which conformed to MIL-L-7808 specifications.

3. The Heating System (Figure 1)

The furnace consisting of a lower and upper part (124, 126) is mounted on the cradle bar (122) and covers the rotating disc

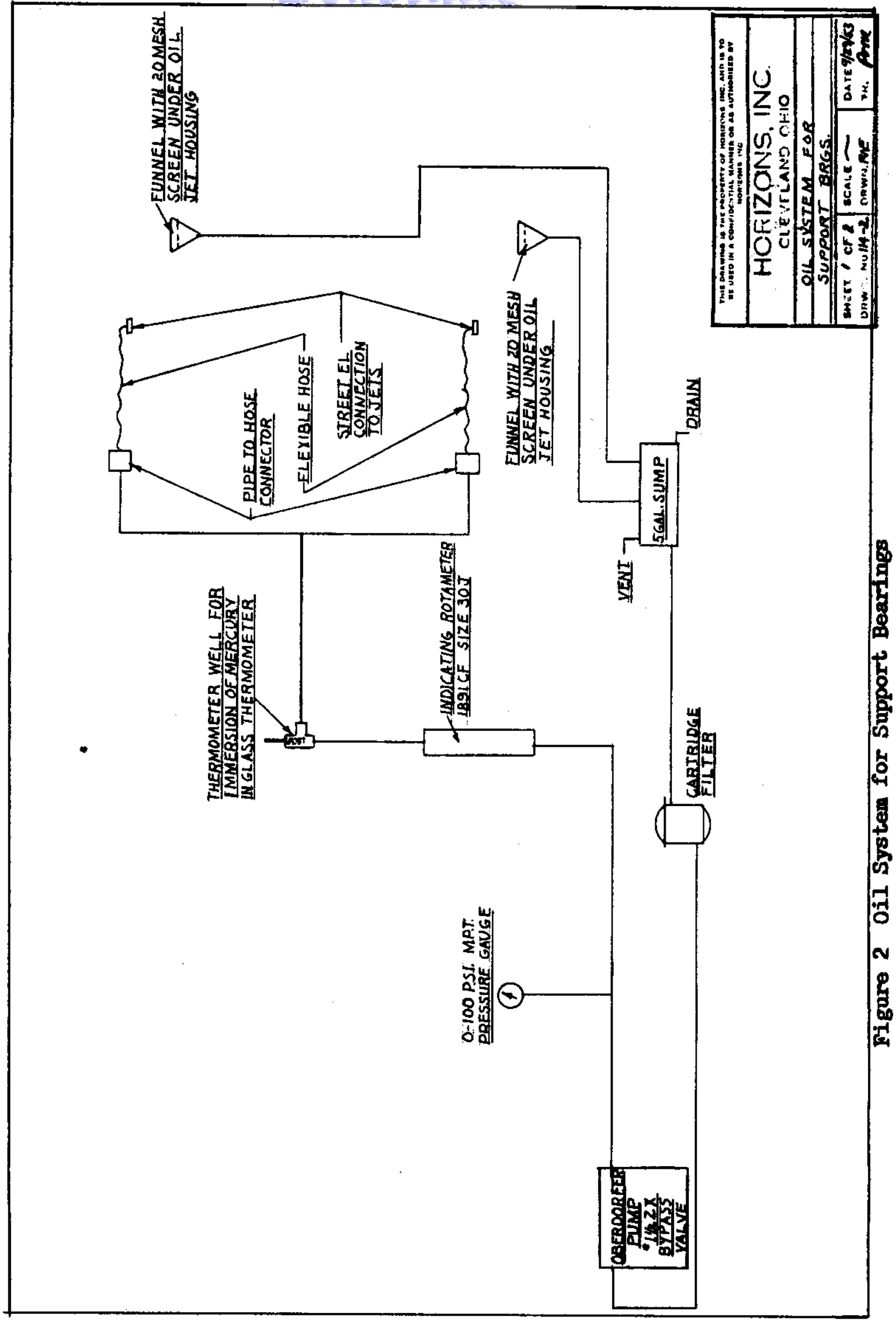


Figure 2 Oil System for Support Bearings

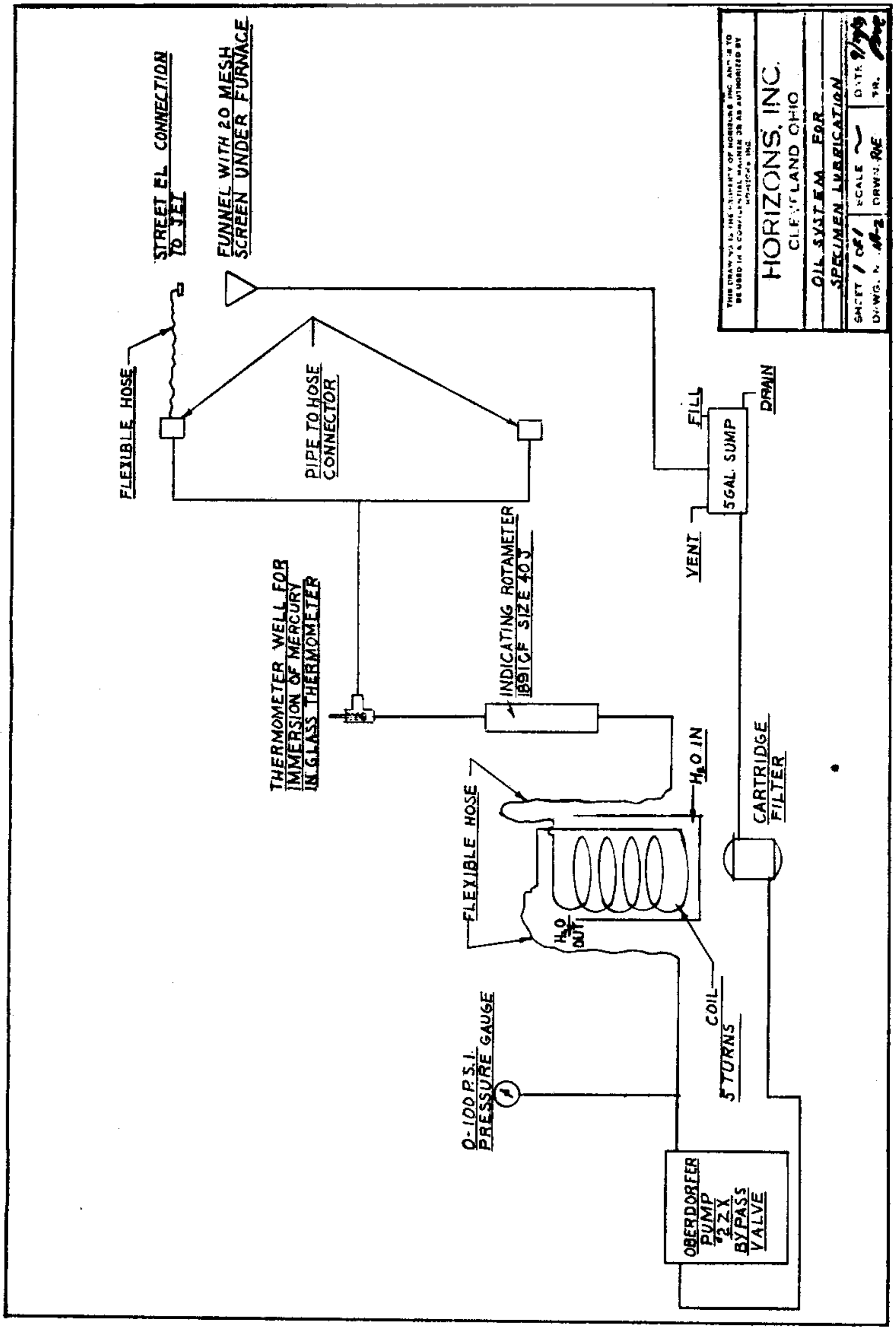


Figure 3 Oil System for Specimen Lubrication

(104). Each half of the furnace contains six strip heaters with individual temperature control for upper and lower part.

The furnace was initially designed to serve two purposes: to maintain an ambient temperature of up to 500°F for the testing atmosphere surrounding the disc (104) and the test specimen (117), and also to heat the oil for the jets (114) so that its incoming temperature would be about 250°F. However, under actual testing conditions the strip heaters provided an ambient temperature of only 350°F and caused decomposition of the oil that splattered on the hotter furnace walls. Therefore, it was necessary to provide an additional heat source for tests conducted at temperatures up to 500°F. Figure 4 shows the nichrome resistance heater insulated by a Vycor glass tube inserted in a milled groove at the top of the specimen holder. By controlling the power input by means of a variable auto-transformer the specimen temperature was controlled accurately and the resulting specimen temperature during actual testing could be predicted with good accuracy for each material tested.

For temperatures above 500°F a pan-cake type coil of 3/16 inch copper tubing was wound as an induction heater. (See Figure 5). Since the oil decomposes at temperatures around 400°F it was deemed practical to heat the disc or rotor in a direct manner in order to supplement the resistance heater and strip heaters. Temperatures up to 750°F were easily obtained by this procedure.

C. Temperature and Friction Measuring Instrumentation

1. Temperature Recording

In order to record the transient temperature changes during a test run, an Esterline-Angus chart recorder driven by a multivolt D.C. amplifier was employed. This recorded temperature data from the specimen-rotor interface thermocouple. (See Figure 4).

2. Friction Measurements

Friction forces were measured by use of a calibrated brass ring with **SR-4** wire resistance strain gages connected so that the outputs added and temperature dependence cancelled. This gage was mounted as the restraining member to the cradle bar (122).

IV. EXPERIMENTAL PROCEDURE

The experimental test procedure consists in principle of placing a heated test specimen in contact with the outer periphery of a rapidly rotating hardened steel disc, and letting wear of the specimen proceed for a prescribed period of time. The temperature measurements on the specimens are made by means of a chromel-alumel thermocouple inserted into a small hole drilled into the sides of the specimens (see Figure 4).

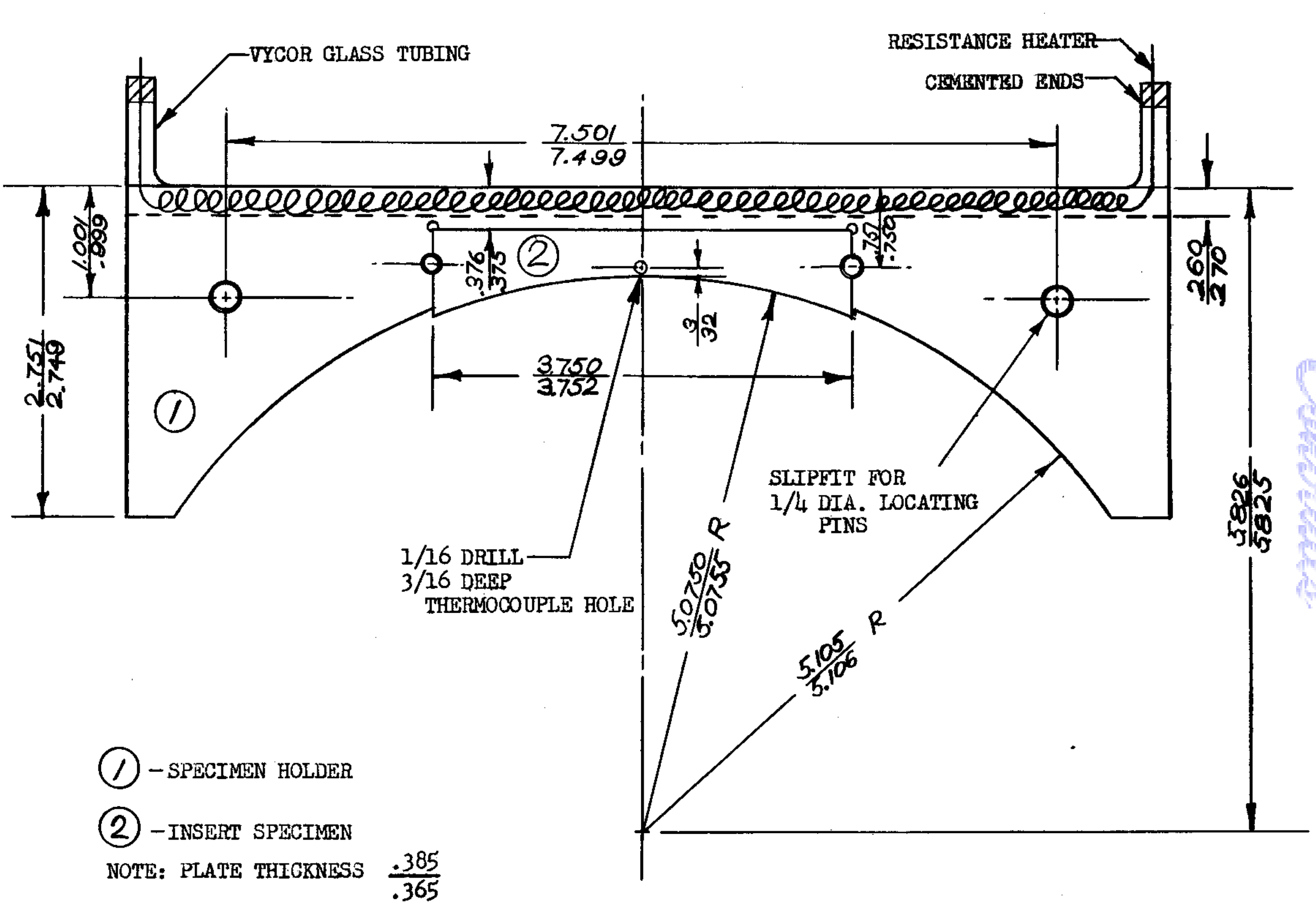


Figure 4. Specimen Holder and Vycor Tube Heater

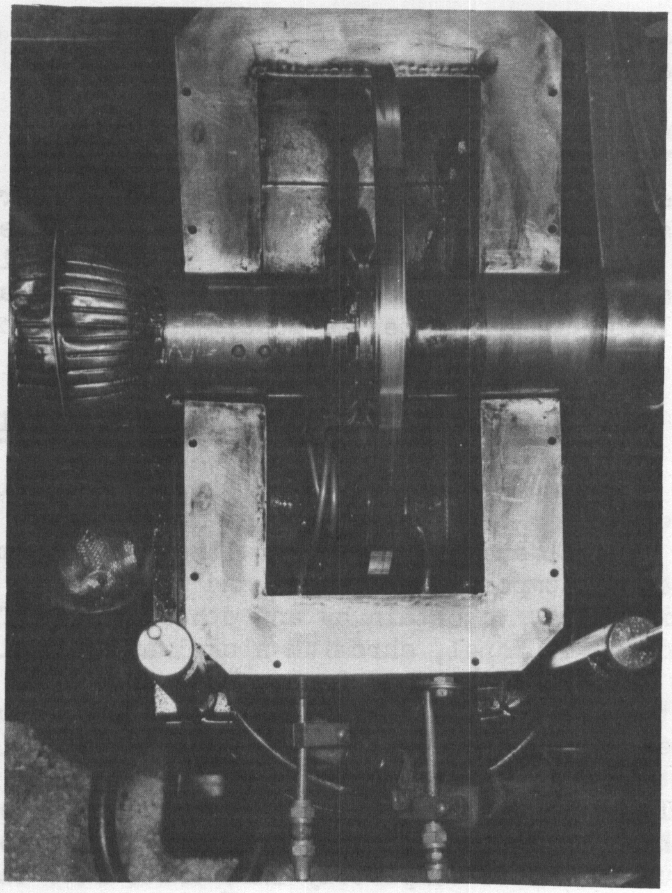


Figure 5 Position of Induction Coil in Furnace

Prior to starting the rotor, the specimen and oil are heated to the desired starting temperature. To obtain the higher temperatures, it is necessary to heat the rotating disc by means of the attached induction heating unit. Friction coefficients are calculated from the displacement forces as determined from the SR-4 wire resistance gage load cell.

The detailed discussion of the various phases of specimen preparation and data evaluation are discussed below.

A. Preparation of Material

The cast alloys used for testing were either purchased from appropriate sources or alloyed by use of the available equipment. In all cases a complete chemical analysis of these alloys was acquired in order to substantiate the compositions. Metallographic inspection was also employed to eliminate the possibility of inhomogeneous structures.

1. Development of a Sintering and Infiltration Procedure

One method of acquiring a two-phase alloy, besides casting them directly, is by means of powder metallurgy. By sintering a metal powder compact and infiltration with a lower-temperature melting metal a number of compositions can be had which would be difficult, and therefore, expensive, to obtain by any other means. Trial mixes were initially made up of Monel, chromium-nickel and nickel powders and compacted at 14 tons per square inch. They were then sintered at appropriate temperatures in a hydrogen atmosphere furnace. The sintered compacts were measured and weighed for density determination and the proper amount in pure sheet form of the lower melting constituent, in this case silver, was added to fill all vacancies. Upon reheating to 50°F above the melting temperature of silver it was found that the silver had melted but failed to completely infiltrate into the metal compacts.

A modification in the metal powder mixes was then tried by a 10% by weight addition of silver powder. This acted very well as a wetting agent for the silver and resulted in an infiltrated specimen with a final density of slightly under 90 percent.

Finally, it was found that by calculating the density of the pressed metal powder compact and adding the required silver sheet for infiltration, and sintering and infiltrating in one operation, a final density of above 98 percent was obtained. This was done repeatedly irrespective of any silver powder addition. By combining the two steps the formation of any oxide coating on the metal powder was minimized and complete wetting of the molten silver was at a maximum.

The step-by-step procedure for making the infiltrated specimens was:

1. Metal powder mix made up according to Table I.
2. **Placed in die shown in Figure 6.**
3. Compressed with a load of 60,000 lbs or 14 tons psi.
4. Taken out of die and density calculated.
5. Placed in Globar heated furnace under a dry hydrogen atmosphere as shown in Figure 7 with a surplus amount of silver.
6. Sintered and infiltrated at respective temperature for two hours.
7. Apparent density measured.
8. Machining of specimen from compact according to Figure 4.
9. Metallographic examination of scrap surfaces nearest wear surface of specimen.

B. Thin Film Coatings

1. Plating

Electroplating specimens with silver **were obtained by use of** a variable power source with a piece of silver sheet as the anode and the specimen as a cathode. The specimen was thoroughly cleaned by immersion in a commercial cleaning solution. A strike solution and plating bath of the following composition were used:

Strike Solution

Silver Cyanide	0.5-0.7 av. oz./gal.
Sodium Cyanide	8.0-10.0 av. oz./gal.

Plating Solution

Silver Cyanide	4.0 av. oz./gal.
Potassium Cyanide	7.0 av. oz./gal.
Potassium Carbonate	6.0 av. oz./gal.
Brightener (in new bath)	1/8 fl. oz./gal.

By accurately timing each operation a silver plate of 0.002 inch was obtained on Fe-Si-bronze specimens.

2. Bonding of Teflon

A sintered iron specimen was coated with Teflon in the following manner:

a. Surface dipped in "Triton" X-100.
b. Dried in a forced convection air oven.
c. Baked and sintered at 700°F.
d. Same procedure repeated for application of second coat.

Each coat was 1 mil thick and the resulting Teflon coating was 2 mils thick. Multiple dips, with baking in between dips, resulted in good

TABLE I COMPOSITION OF SPECIMENS MADE BY POWDER METALLURGY TECHNIQUES BEFORE AND AFTER SINTERING AND SILVER INFILTRATION

	Before Infiltration Weight Per cent Composition							After Infiltration Weight Per cent Composition							
					$MoSi_2$										
No.	Cr	Ni	Monel	Si	Mo	Si	% D	Cr	Ni	Monel	Si	Mo	Si	Ag	% D
1	48.0	48.0		4.0			64.0	25.8	25.8		2.1			46.3	98+
2	46.0	46.0		8.0			63.6	24.7	24.7		4.3			46.3	98+
3	45.0	45.0			6.3	3.7	63.7	24.3	24.3			3.4	2.0	46.0	98+
4			96.0	4.0			69.8			62.3	2.5			35.2	98+
5			92.0	8.0			72.6			61.0	4.9			34.1	98+
6			90.0		6.3	3.7	75.4			61.0		4.3	2.5	32.2	98+
7		96.0		4.0			75.0		64.7		2.6			32.7	98+
8		92.0		8.0			75.1		61.9		5.4			32.7	98+
9		90.0			6.3	3.7	74.5		59.8			4.2	2.5	33.5	98+

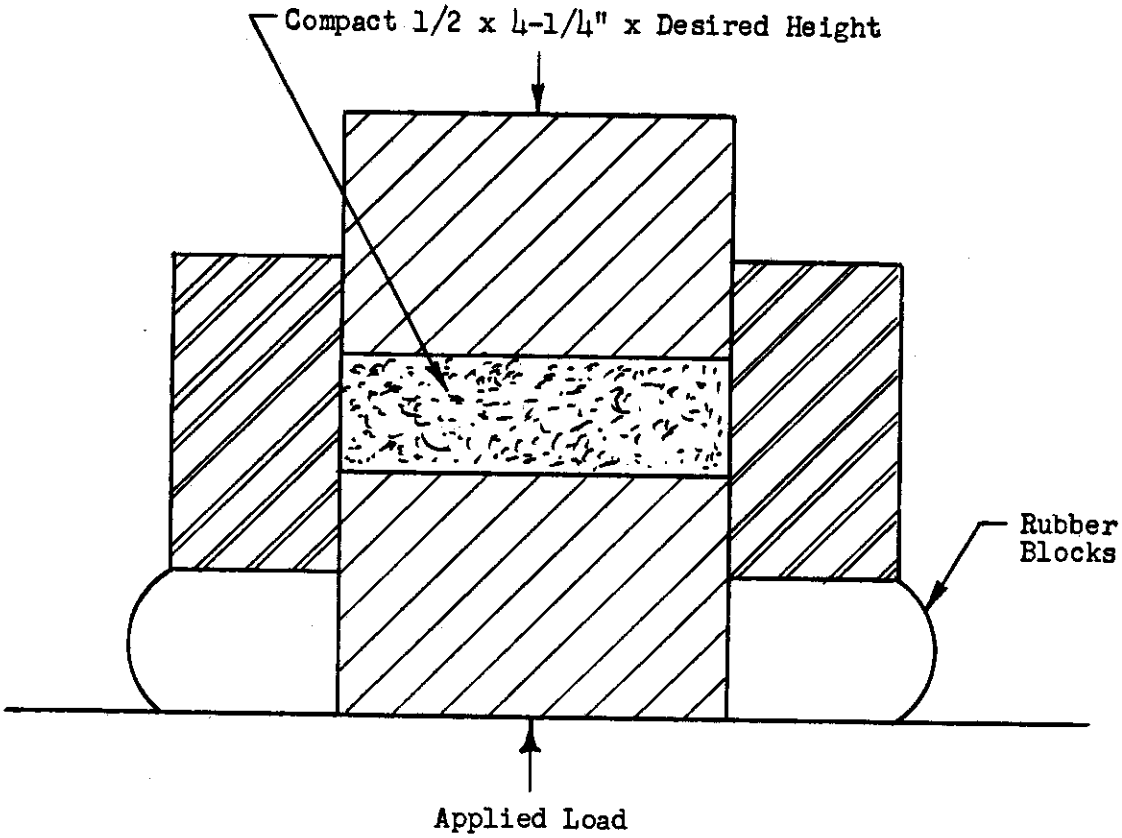


Fig. 6 - Sectional View of Compacting Die for Pressing Metal Powders.

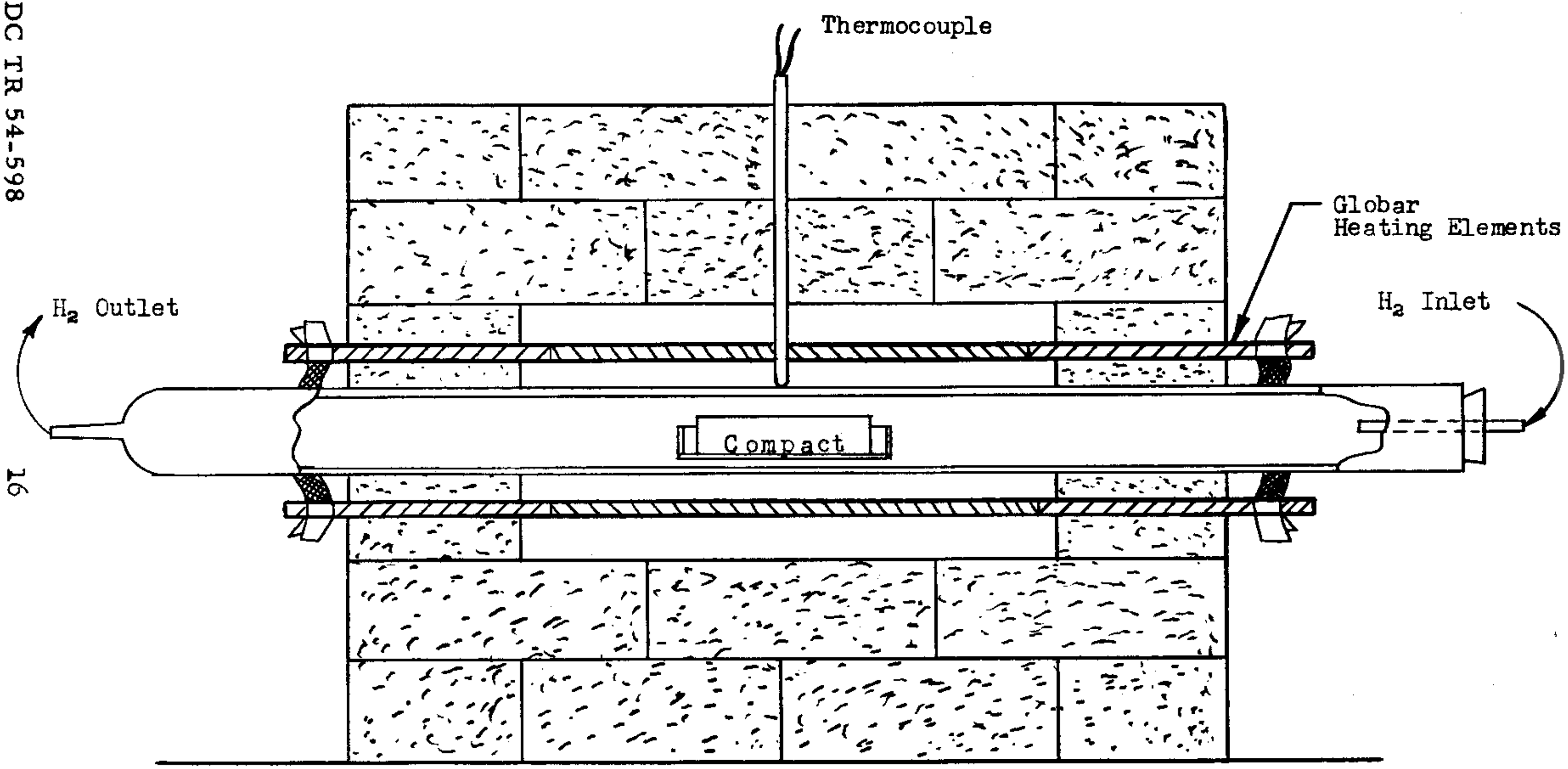


Fig. 7 - Hydrogen Atmosphere Furnace for Sintering and Infiltrating **Wear** Test Specimens.

homogeneity and showed no indication of a laminar structure.

3. Graphite Coating

An iron-silicon bronze specimen was coated in the following manner with graphite:

- a. Surface dipped in "dag 213" which consists of colloidal graphite suspended in an epoxy resin.
- b. Baked at 400°F for 30 minutes in a forced convection air furnace.

C. Mean Base Testing Temperature Determinations

The transient temperatures which occurred at the specimen's surface were recorded. The curves obtained of temperature vs. time were evaluated by accurately measuring the areas under these curves with an OTT compensating planimeter having a unit range of 0.01 inch. By dividing the areas by the unit of time, the average testing temperature of each test conducted was determined.

D. Wear Measurements

Measurements of the specimen before and after each run were made in a reproducible manner. Measurements were taken across the center of the specimen as shown in Figure 8. By this means an accurate measurement of the wear which occurred during each test run was obtained.

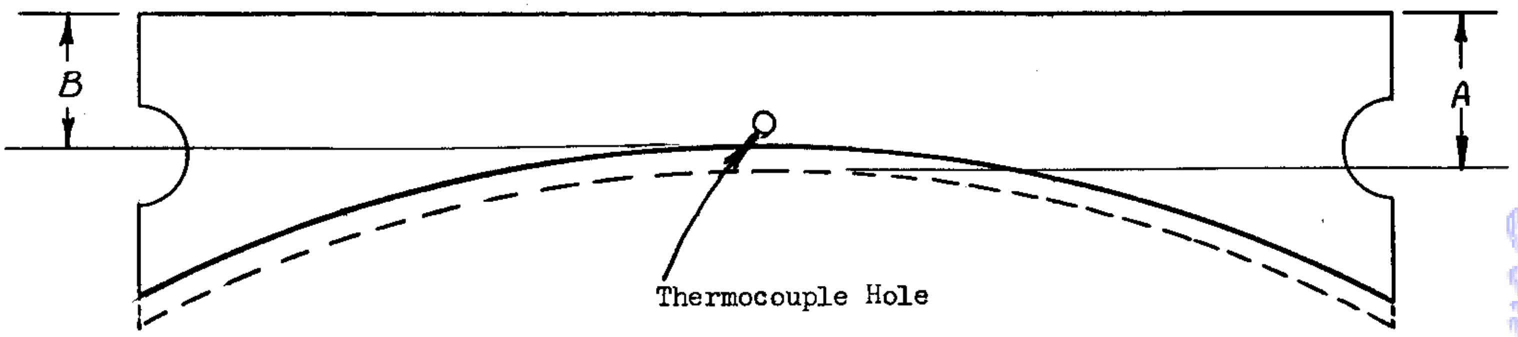
E. Qualitative Data Tabulation

A metallographic examination of the structure of each material tested was made to insure against any composition or structure irregularities. During the tests, the degree of vibration was noted at various time intervals until severe vibration was evident and made continuance of the tests impracticable. The degree of vibration was contingent on either the amount of pickup on the rotor or the degree of scoring taking place. It was calculated that a pickup causing 0.001 inch variation of the diameter of the disc was sufficient to cause the specimen and specimen holder to break specimen contact under the test conditions. Therefore, whenever severe vibration was evident the test was terminated.

The specimen and disc were then examined for uniformity of wear distribution, degree of galling, scoring, etc. The disc was then cleaned up with fine emery paper and checked with a dial indicator for diameter variation. If the diameter variation approached 0.001 inch it was reground to specifications before the next test was run.

F. Heat Treatment of Discs

The SAE 52100 alloy steel discs were fully hardened and tempered. They were fully hardened by heating to 1550°F and oil quenched. Since the soak back temperature required for testing the bearing



A = Initial Measurement of Specimen

B = Measurement of Specimen After Test

A - B = Wear of Specimen

Fig. 8 - Method Used for Measuring Wear

retainer materials was established to be 750°F, the discs were tempered at 750°F for two hours. The resulting hardness of the discs was Rockwell "C" 47.

The discs used for the higher temperature tests were machined from A1S1-SAE T-1, tungsten-chromium-vanadium (18-4-1.1%) alloy steel. It was fully hardened by heating to 2350°F and oil quenched. A double tempering procedure was used. It was tempered at 1100°F for two hours, allowed to cool, and retempered again at 1100°F for two hours. The resulting hardness of the disc was Rockwell "C" 60.

Samples of the two alloys were examined micrographically after hardening and tempering. The structures were found to be homogeneous and properly tempered.

V. RESULTS

The results obtained on the initial group of materials tested are shown in Table II. They are listed generally in the order in which they were tested.

The final group of materials tested consisted of silver infiltrated metal powder compacts. The composition of the metal powder mixes and compact densities, and the resulting compositions and densities after silver infiltration are given in Table I. The results obtained on this group of materials are shown in Table III. The wear rates as a function of testing temperature of these materials are shown in Figures 9, 10, and 11. A comparison of the wear rate properties as a function of temperature of the two most promising experimental materials with iron-silicon bronze and "S" Monel is shown in Figure 12.

A few additional materials were tested in order to obtain some comparative data (see Figure 13 and Table IV). These materials were selected by utilization of the results obtained and on the basis that they might exhibit good wear behavior.

VI. DISCUSSION OF RESULTS

A. Factors Affecting Wear Behavior

The initial tests were conducted under very severe conditions. No auxiliary loading device was used since the 23 pound weight of the specimen holder was considered to be an adequate starting load. It was used on some of the tests conducted with the SAE 52100 alloy steel disc. The temperature range obtained with this procedure was small (220-350°F). The only heat source used at this time was the stripheaters in the furnace and the resistance heaters in the specimen holder. The friction was high enough to maintain a testing temperature of 220°F with an "S" Monel specimen. The effect of the heat sources raised the

TABLE II WEAR TEST RESULTS ON BEARING MATERIALS OF SEVERAL CATEGORIES

	Material	Treatment	Specimen Temp	Results		
Standards	"S" Monel (4% Si)		280°F ↓ 380°	Wear in 4.8 hrs:	.03" ↓ .13"	No pick-up on rotor Some pick-up
	Bronze, Fe-Si		210° ↓ 380°	Wear in 4.8 hrs:	.02 ↓ .07	Pick-up on rotor, leading to severe vibration
	Bronze, Fe-Si	silver plated	330°	Silver plate worn thru < 67 min.		
			430°	" " " " in 6-1/2 min.		
Irons	Nodular iron		280-350°	High friction. Some scoring of rotor and pick-up.		
	Ni-resist cast iron		280-350°	High friction. Some scoring of rotor and pick-up.		
	Iron, sintered	MoS_2 impreg. (4%)	280-350°	High friction. Some scoring of rotor and pick-up.		
Coatings	Iron, sintered	teflon coated	---	Coating wore off immediately.		
	Bronze, Fe-Si	graphite in epoxy coating	280°	Coating wore off < 5 min.		
Miscellaneous	Bronze, Pb		220-280°	Pick-up at 280°F. Worse than Fe-Si bronze.		
	Inconel, (13% Cr, 7% Fe)		380°	Scored rotor and pick-up in 10 min.		
	Ni-Cr (50-50) sintered	MoS_2 impreg.		Scored rotor < 2 min.		
	"S" Monel, sintered (2.2% Si)	Ag impreg.	350°	More pick-up on rotor than plain "S" Monel. Less scoring.		
	Cu-Al-Ag alloy		280°	Ran very smoothly but picked up on rotor very much. Then severe vibration.		

TABLE III WEAR TEST RESULTS ON BEARING MATERIALS MADE BY POWDER METALLURGY TECHNIQUES

Materials	Treatment	Specimen Temp °F	Wear Rate in/hr	Remarks
25.8% Cr-25.8% Ni 2.1% Si-46.3% Ag	All Ag Infiltrated	240 535	0.004 0.022	Some vibration and scoring
24.7% Cr-24.7% Ni 4.3% Si-46.3% Ag		290 490	0.008 0.014	Severe vibration and scoring
24.3% Cr-24.3% Ni 5.4% MoSi$_2$-46.0% Ag		205 600	0.001 0.010	Severe vibration and scoring
62.3% Monel-2.5% Si 35.2% Ag		175 650	0.004 0.042	Vibration due to excessive pick-up on disc. High wear rate. No scoring
61.0% Monel-4.9% Si 34.1% Ag		395 440	0.016 0.024	Vibration due to excessive pick-up on disc. High wear rate. No scoring
61.0% Monel-6.8% MoSi$_2$ 32.2% Ag		205 510	0.010 0.034	Vibration due to excessive pick-up on disc. No scoring
64.7% Ni-32.7% Ag 2.6% Si		190 620	0.002 0.019	Slight vibration at high temperature. No scoring
61.9% Ni-5.4% Si 32.7% Ag		185 640	0.001 0.013	Some vibration at all times and scoring
59.8% Ni-6.7% MoSi$_2$ 33.5% Ag		310 640	0.004 0.016	Slight vibration at high temperature. No scoring

TABLE IV WEAR TEST RESULTS OF MISCELLANEOUS MATERIALS

Materials	Treatment	Specimen Temp °F	Wear Rate in./hr.	Remarks
Cast Inconel	Alloys	450	0.026	Some vibration due to pick-up on disc. No scoring.
58.0% Ag-30.3% Cu 7.7% Al-4.0% Si		650	0.026	Some vibration due to pick-up on disc. No scoring.
93.5% Mg-6.0% Ag 0.5% Zr		535	0.180	Excessive wear with heavy pick-up on rotor.
Mallory D-52 95.0% Ag-5.0% CdO		600	0.020	Severe vibration and scoring.
Elkonite G-14 66.7% WC-33.3% Ag		615	0.009	No vibration or scoring.

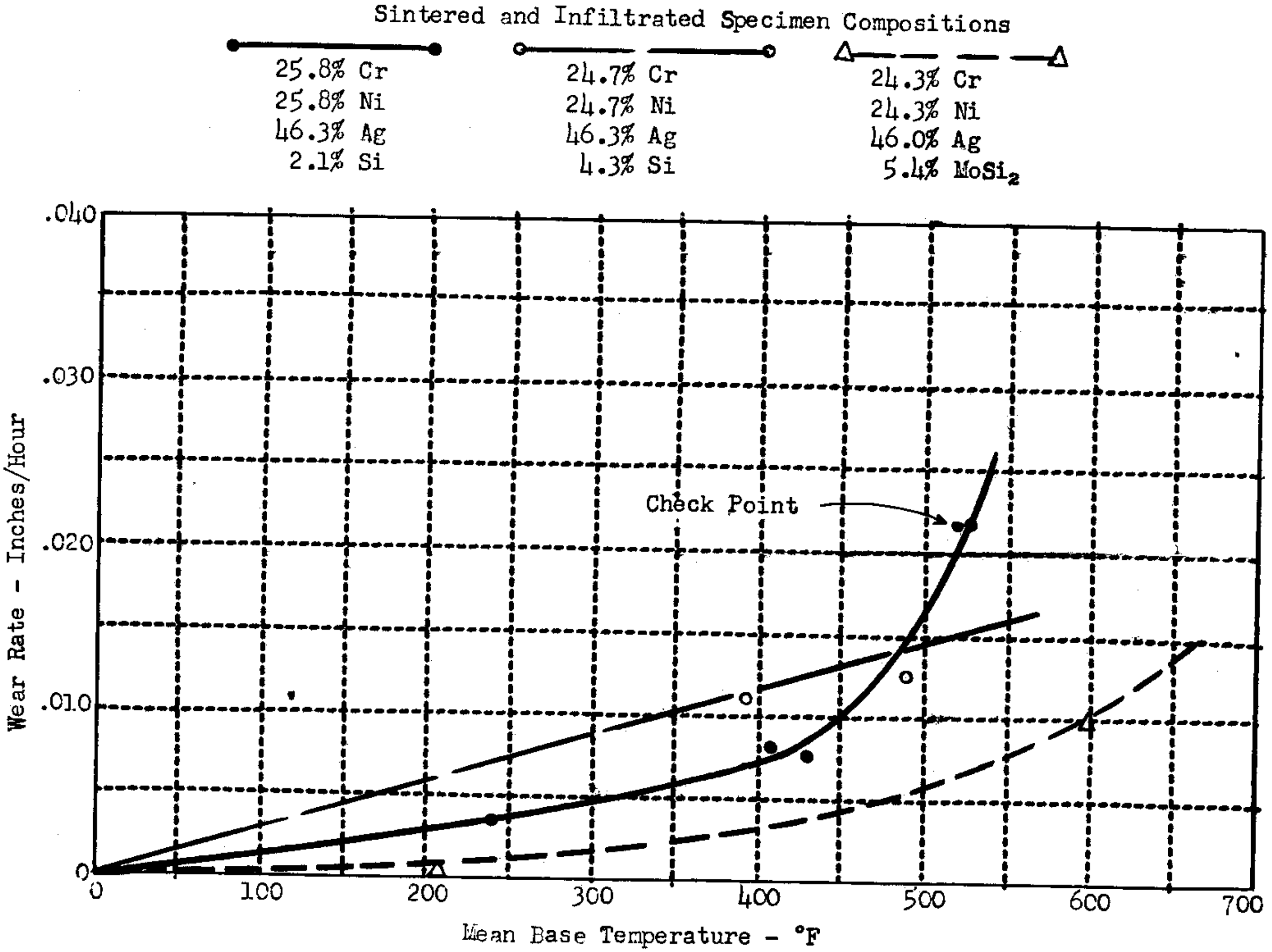


Fig. 9 - Wear Rate as a Function of Temperature for Ag-Cr-Ni-Si or $MoSi_2$ Specimens.

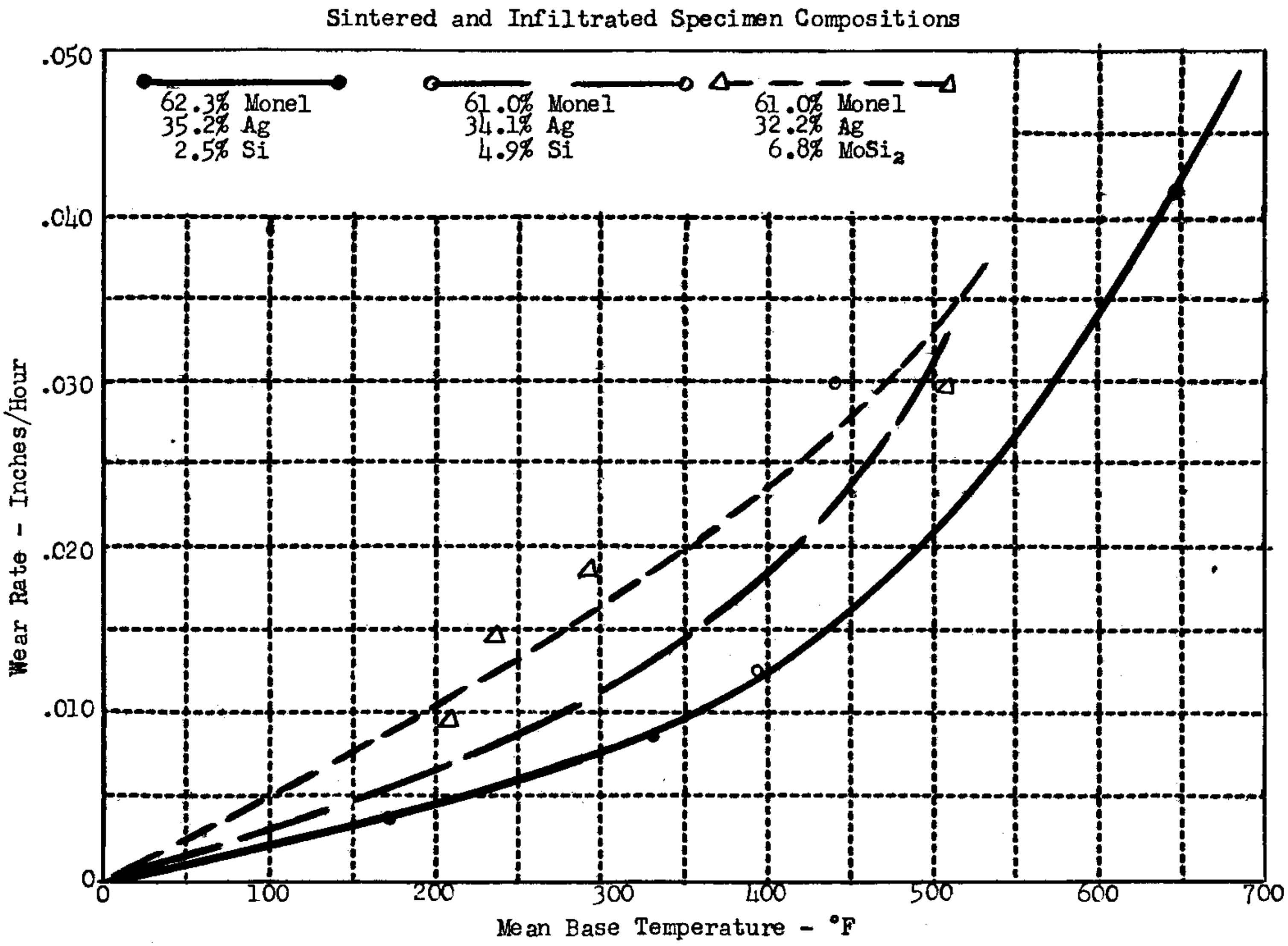


Fig. 10 - Wear Rate as a Function of Temperature for Ag-Monel-Si or $MoSi_2$ Specimens.

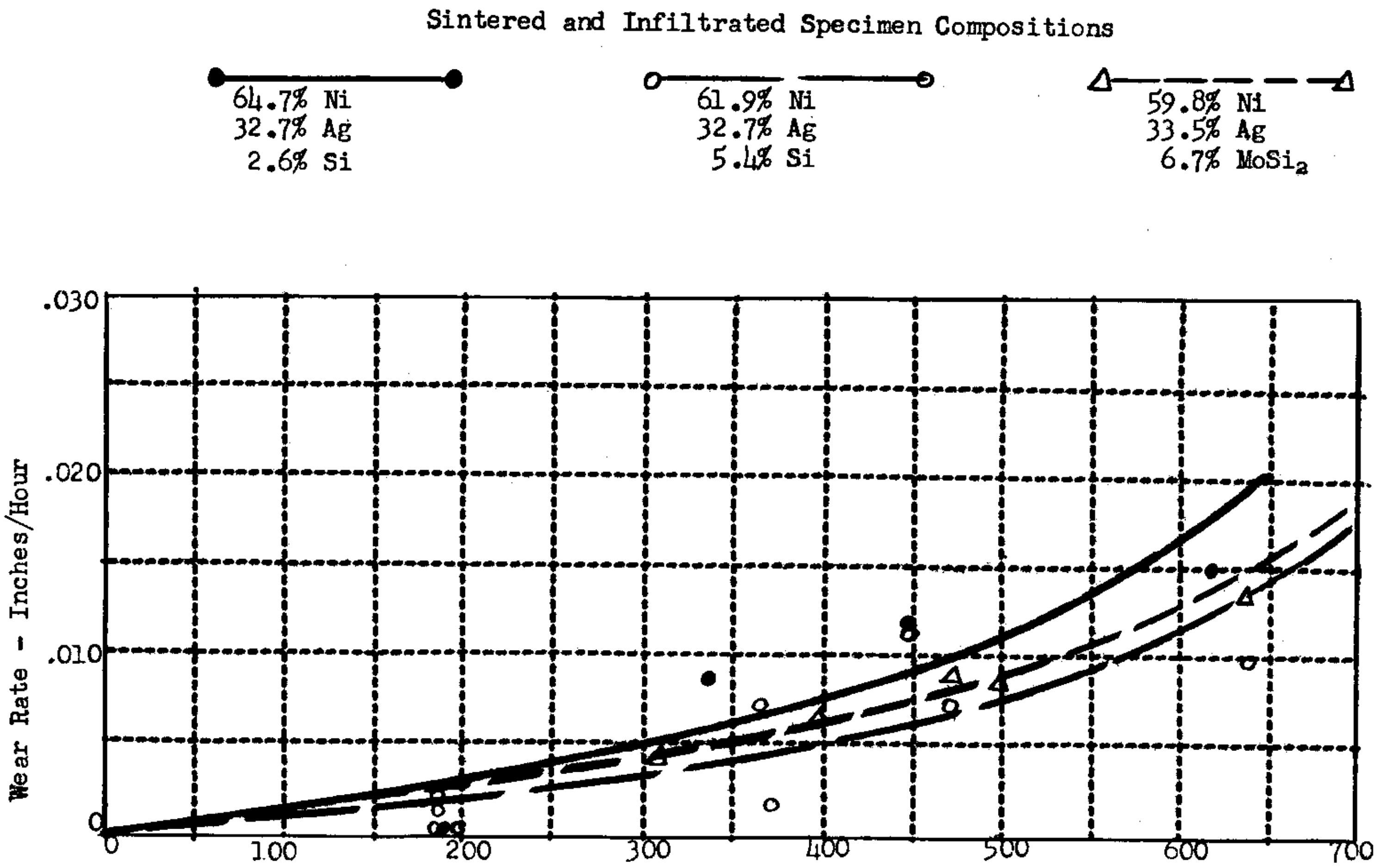


Fig. 11 - Wear Rate as a Function of Temperature for Ag-Ni-Si or $MoSi_2$ Specimens.

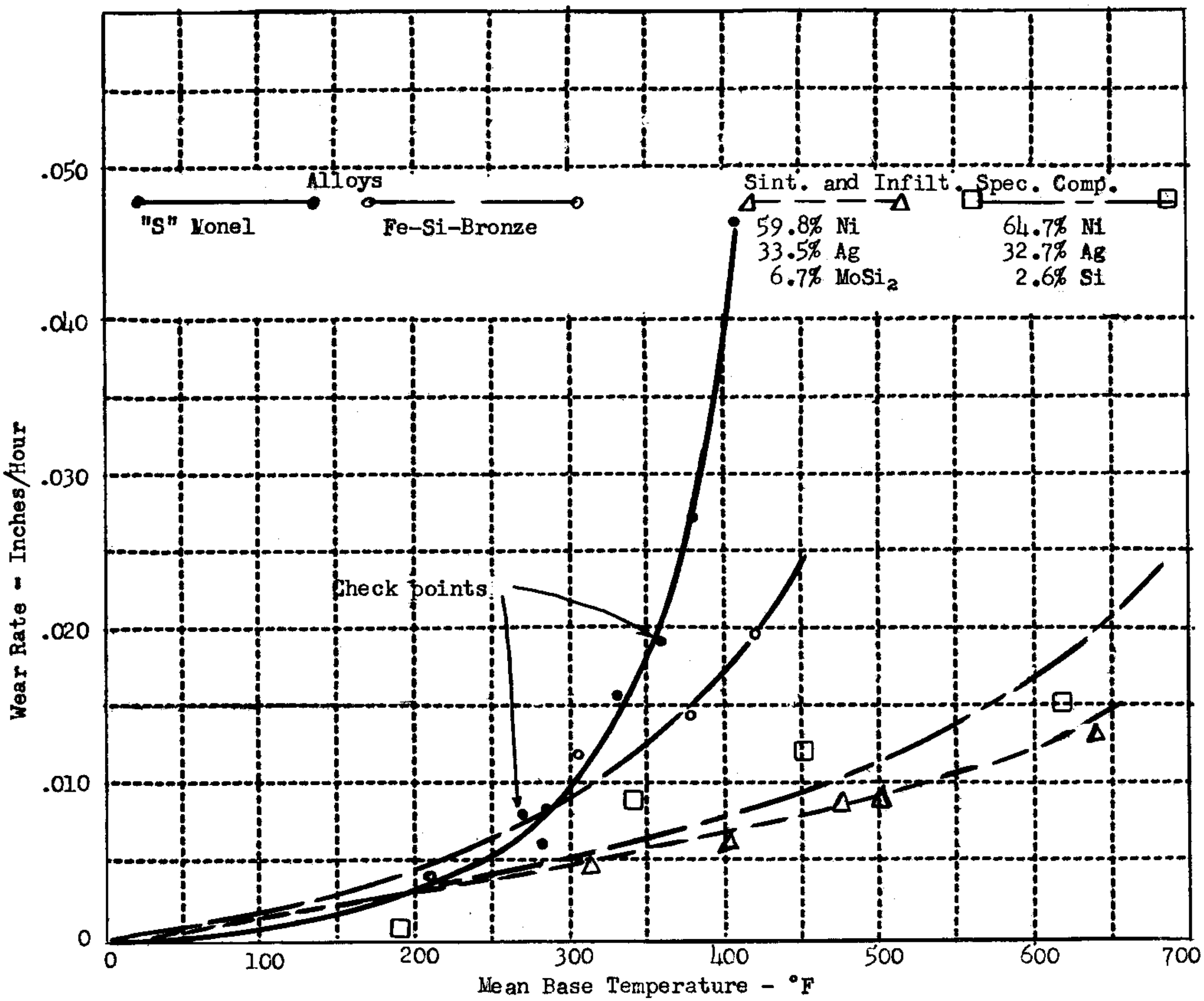


Fig. 12 - Comparison of Standard Materials to Newly Developed Materials with Respect to Wear Rates as a Function of Temperature.

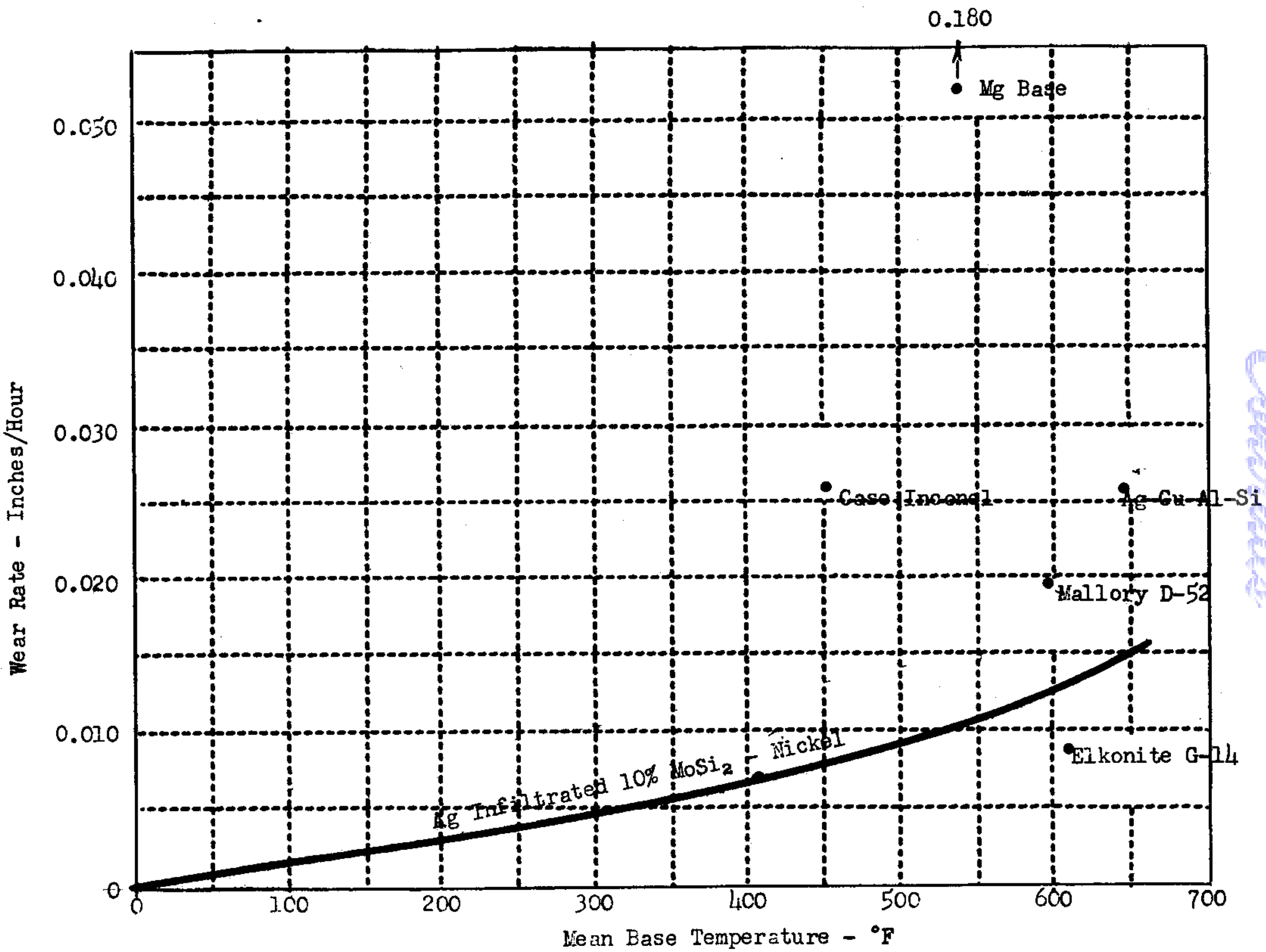


Fig. 13 - Comparison of the Wear Rates at High Temperatures of Various Materials to the Silver Infiltrated Nickel with 10% $MoSi_2$ Material.

temperature to only 350°F, with temperature peaks of up to 700°F. The lubrication was kept at a high flow level and the sliding surfaces were lubricated as well as possible under the existing conditions. Since the heat obtained from friction alone was fairly high the surface high spots were at a temperature above the transformation temperature of the discs when induction heating was used.

A heating and cooling cycle of the surface peripheral layer of the disc took place during the test; as the surface came in contact with the specimen, extreme localized heating at the high spots occurred with successive quenching from the oil. One of the SAE 52100 alloy steel discs actually had a sector of the wheel crack and break off completely (see Figure 14). This was probably due to a small fatigue failure on the surface followed by incipient cracking, due to the change in the residual stress pattern in the rotor.

Evidence of the formation of a peripheral martensitic structure as a surface layer is shown in Figure 15. The microhardness values obtained radially through this section are shown in Figure 16. The martensitic layer is approximately 0.008 inch deep. This boundary between the martensite and tempered martensite microstructure indicates that at this depth the temperature obtained was approximately the transformation temperature of SAE 52100 alloy steel (1550°F). Therefore, the rotors were rehardened and tempered by induction heating and the testing procedure was changed in order to obtain less severe testing conditions.

Because of the large transient temperature peaks and the high frictional heat obtained, it was decided that the normal load would be the logical condition to change in order to keep all other conditions uniform. The hydrodynamic effect of the lubricant was checked by counterweighting the specimen holder as the disc was rotated and sufficiently lubricated. By watching the temperature drop which coincided with a change in sound at a definite load, the lubricant was found to be able to support 6 to 7 pounds normal load. A counterweight of 12 1/2 pounds was then employed in all the following wear tests so that the effective normal load on the specimen was, therefore, about 4 1/2 pounds.

This procedure made it necessary to alter one other condition in order to obtain mean testing temperatures up to 750°F. The oil flow through the jets was decreased in order to obtain the required temperatures. This change was not considered to be detrimental to the wear behavior of a material for two reasons. First, the oil flow was in excess of what was required for lubrication purposes, and therefore, only the excess amount of lubricant was decreased. Secondly, the flash temperature of the lubricant is 430°F. At testing temperatures above this its presence is probably of no avail except as a quenching media. These changes had the desired effect of lowering the transient temperature peaks during subsequent test runs, and additionally did not affect the wear behavior of a given material at any specified temperature. This is shown by check points plotted in Figures 9 and 12.

Figure 14 SAE 52100 Alloy Steel Disc with Broken Section

Neg. No. 502B

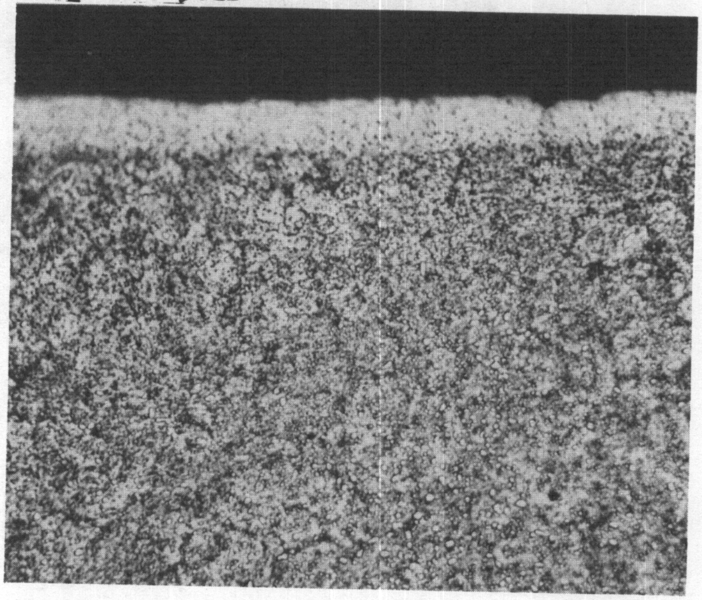


Figure 15 Photomicrograph of SAE Alloy Steel Disc Showing Peripheral Martensitic Layer

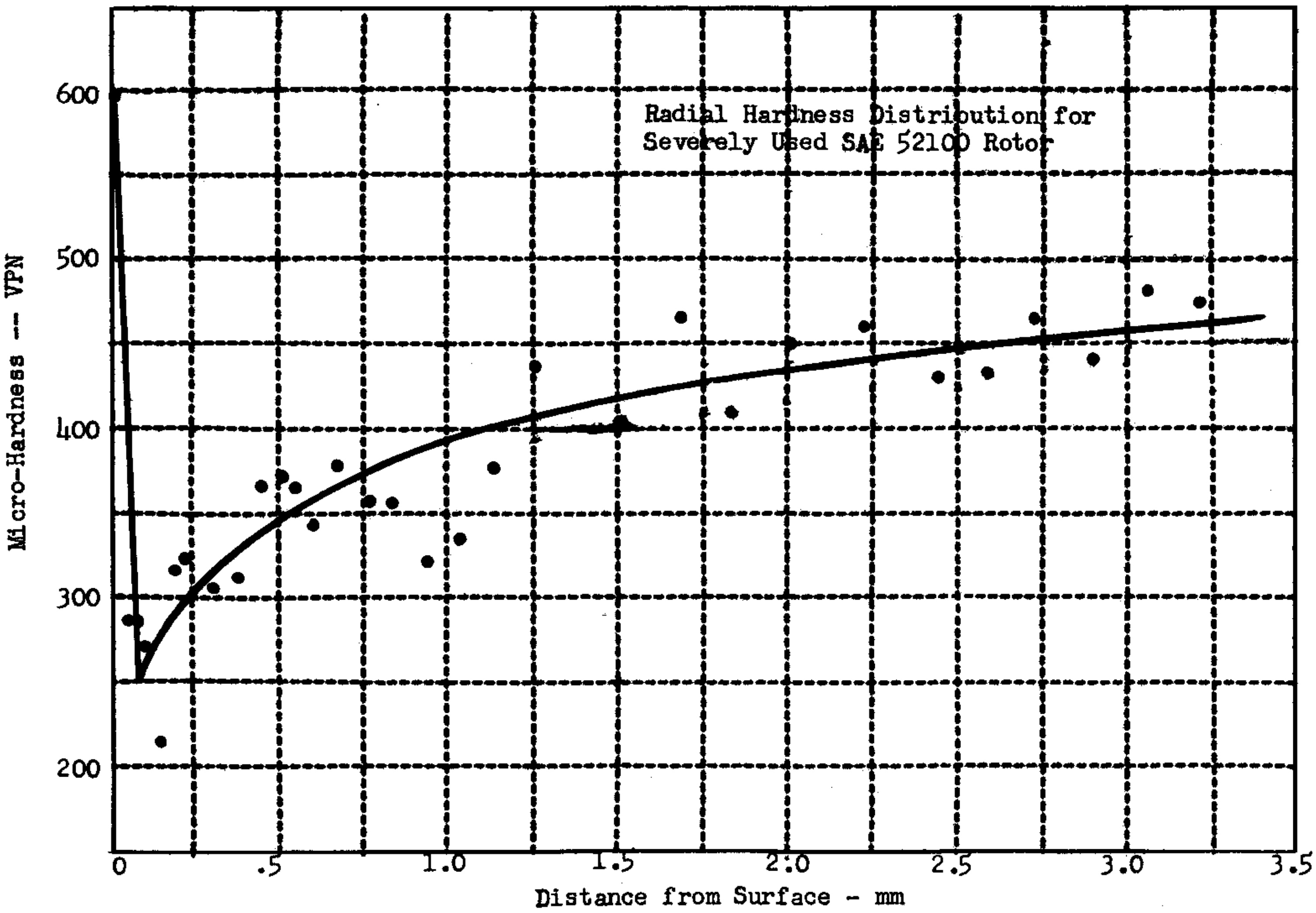


Fig. 16 - Radial Hardness Distribution of Severely Used SAE 52100 Alloy Steel Disc.

For the tests conducted above 450°F the AISI-SAE T-1 alloy steel disc was used successfully.

B. Criteria for Evaluating Wear Characteristics

Because of the complex nature of galling, the evaluation of test results in a program of the type being discussed is of necessity not a simple problem. Hence, it is felt that there is no single property which, when measured on the test machine used, necessarily gives an accurate indication of the susceptibility of the material being tested to cause failure. Rather, the results of the tests of each material are largely in the nature of a collection of observations of one or more characteristics which would be detrimental to the performance of the bearing and tend to lead to trouble in service. In some instances, it is excessive wear of the test retainer material; in others it is pickup of the retainer material on the rotor, thus leading to severe vibration. In still other cases there is either scoring of the rotor surface, excessively high friction, or excessive temperature rise. Obviously, any of these conditions, if severe, militate against successful performance under the critical conditions imposed by the type of service.

1. Wear Rate as a Function of Temperature

It was found by the results obtained on those materials which showed a well-defined wear rate that the wear rate accelerates with temperature. In some cases the wear rate is but a small fraction of the wear rate at higher temperatures. Initially during a test the temperature of the pre-heated specimen dropped until the quenching effect of the lubricant was overcome, and then a rise in temperature occurred until the equilibrium testing temperature was obtained. The time required for this temperature to be reached varied from one to five minutes. In order to establish a wear rate for a mean testing temperature the wear testing time and temperature was omitted for this initial fluctuation and the wear was calculated for only that period of time and that mean base temperature when the temperature reached its equilibrium. An example of a time-temperature curve is shown in Figure 17. This was considered to be an accurate method of obtaining the wear rate as a function of temperature since the initial wear was so very small. In some cases, however, the initial wear was also taken into account if the temperature rise was gradual for a large portion of the test run.

As shown in Figure 17, the temperature fluctuations of the specimen were quite large even after the nominal testing temperature was attained. The degree of this fluctuation varied with the material being tested and with the testing temperature. For example, some specimen materials showed differences from peak to minimum temperatures of 150°F during a test run, while others maintained a practically constant temperature. The exact reasons for this phenomenon are not known, but it is suspected that the cause is intermittent galling of high spots similar to a "running in" process.

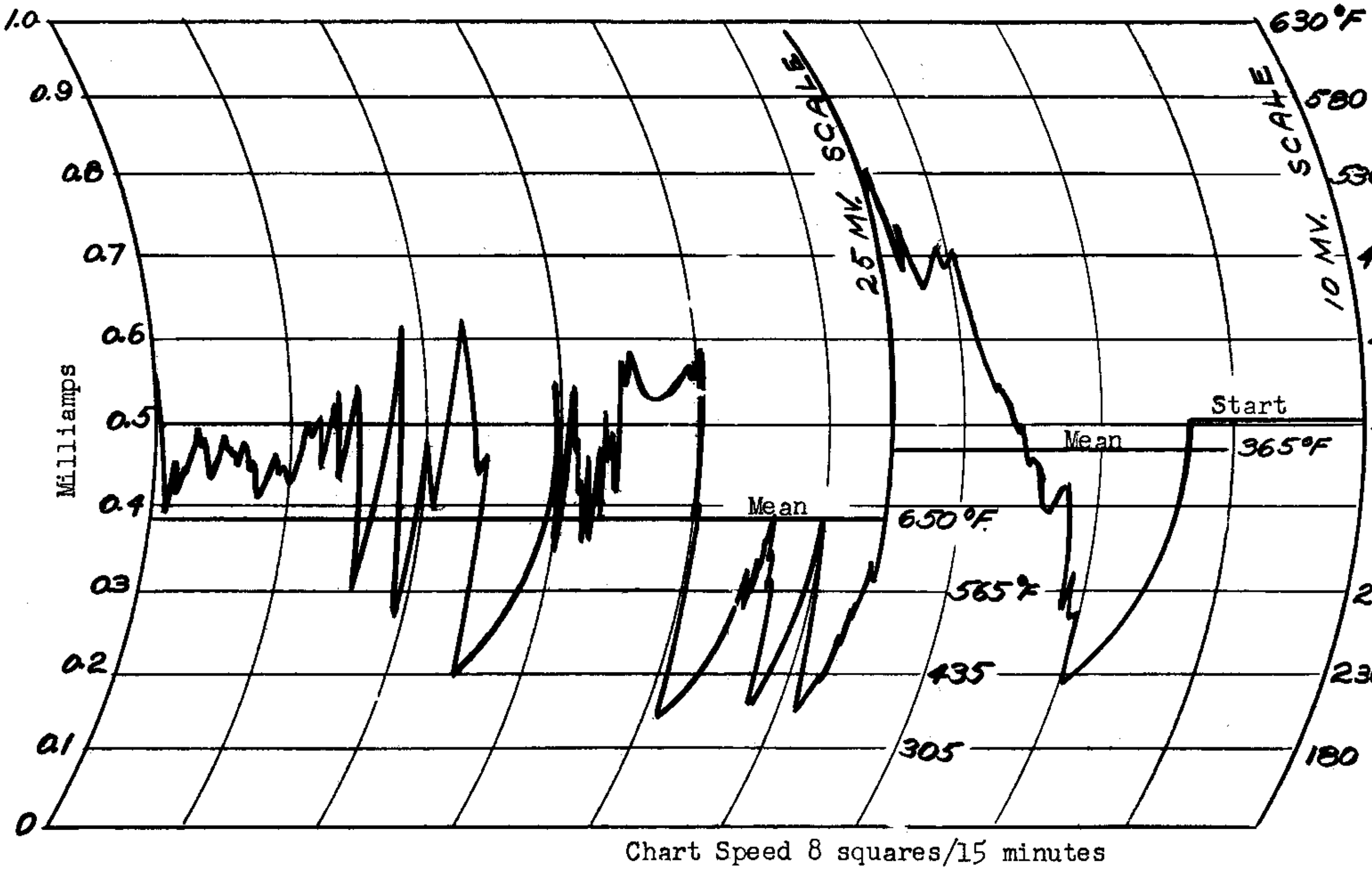


Fig. 17 - Time vs. Specimen Temperature Curve Obtained for Ni-Ag-$MoSi_2$ Specimen Showing Initial Temperature Fluctuations.

The periodic, relatively low temperatures probably represent intervals of constant low wear rate similar to a worn-in bearing surface.

2. Vibration

The vibration of the specimen holder during a run was caused by the diameter variation of the disc. When this variation exceeded a critical limit (approximately 0.001 inch) the specimen and specimen holder broke contact with the disc and vibration occurred. The most common cause of this diameter variation as previously stated was metal transfer of the cage material to the disc during testing. In some cases, scoring of the disc was also a cause of vibration. The degree of scoring was evaluated both from the appearance of the surface of the disc as well as the surface of the wear specimen.

C. Coatings

For reference purposes and to arrive at a standard for subsequent tests, runs were made with specimens of iron-silicon bronze, and silver-plated iron-silicon bronze (0.002 inch silver plate). Runs were made with an oil temperature of 200°F and average specimen temperature of 350°F. The following results were obtained for these two materials.

The iron-silicon bronze specimens showed breakdown after an average of 3 1/2 minutes running with galling, wear, and pronounced pick-up on the disc. The behavior of this material was dependent on temperature. One specimen was run at a temperature of 360 to 365°F, and at the end of one hour was not worn appreciably, although some scoring was evident. However, when the temperature of the specimen was increased to 380°F, very severe galling occurred with considerable vibration due to scoring and pick-up on the disc. Tests on the iron-silicon bronze composition were thus discontinued as it obviously was not suitable for a standard material at 500°F.

Tests on the silver-plated iron-silicon bronze specimens indicated that a major improvement was accomplished by the presence of silver. The tests were run at temperatures of 330°F and 430°F, with the plating worn through after less than 67 minutes and 6 1/2 minutes of testing, respectively. As long as the plating was intact, however, the friction was low and the vibration was nil, reflecting low pick-up and scoring of the disc. The only drawback for silver plating under the presented testing conditions would be that it does wear off, thus rendering the material ultimately no better than its substrate.

Two materials were drawn from the category of strong metallic substrates coated with non-metallic polymer or lacquer films. The two examples were sintered iron coated with Teflon and iron-silicon bronze coated with an epoxy resin in which graphite was dispersed. The latter was a proprietary composition which was reported to be able to withstand 500°F. In both cases the coatings wore off practically immediately and it seemed apparent that such organic materials could not stand these severe mechanical and thermal conditions.

This coupled with the adverse results of the silver plated specimen as mentioned above made it necessary to conclude that coatings would only be valuable for run-in purposes under these conditions of wear. However, if any material is found to perform well, temporarily as a coating, it would seem preferable to disperse it throughout the retainer material rather than simply having it on the surface, and this was the philosophy that was followed. In particular it was concluded from the results obtained with coatings that silver might have considerable merit as a dispersed soft phase. This point was investigated and the results obtained are discussed fully later in this report.

D. Cast and Wrought Materials

The following tests were conducted in order to obtain an indication of what materials or group of materials have the more desirable bearing characteristics. If this could be established, development of new materials would be greatly facilitated.

1. Iron Base

This group of materials may be considered together since they all performed quite similarly (see Table II). These materials consisted of nodular iron and Ni-resist cast-iron. These were characterized by unusually high friction, as well as both scoring and pick-up on the disc. This is not surprising considering their ferrous base which would be expected to gall or weld a ferrous disc and apparently the presence of graphite was not adequate to overcome this tendency.

2. Nickel and Copper Base Alloys

Specimens were prepared from several wrought and cast nickel-base alloys for wear tests. Included in this category were "S" Monel, Inconel, and cast Inconel. Similarly, two copper-base alloys were tested, including an iron-silicon bronze and a lead bearing bronze.

The results of wear tests on "S" Monel at various temperatures were superior to those obtained on iron-silicon bronze in some respects. Although the former showed a greater increase in wear rate with increasing temperature than the latter, there was less metal transfer and subsequent vibration with the "S" Monel composition. The relative wear rates of these materials as a function of temperature are shown in Figure 12. Since they are both standard cage materials in present day bearings, the other materials tested on this program are compared to them in other graphs.

A specimen of Inconel was tested at a nominal temperature of

380°F. This test resulted in a severely scored disc and considerable metal transfer to the disc in a short running time. A specimen of cast Inconel, containing about 3% silicon was tested and it was found to be far superior to Inconel in its wear behavior. The latter test was characterized by no vibration, low wear rate, no scoring of the rotor and very little metal transfer to the disc. This test was conducted at a nominal temperature of 450°F, and the wear rate is plotted for comparison with other materials in Figure 13.

A few tests were conducted with a lead bearing bronze containing about 1 1/2% lead. The results obtained indicated that this material was of little potential value at higher temperatures, so further testing was discontinued.

3. Miscellaneous Alloys

The next material tested was a copper-aluminum-silver alloy. This was an attempt to reproduce a babbitt type of structure in a higher temperature matrix material. In this case the tin or lead matrix has been replaced with silver in which are dispersed hard crystals of the intermetallic copper-aluminum compound. The photomicrograph of this alloy is shown in Figure 18a, with its composition and hardness. The operating temperature of this test was 280°F. Initially it performed very smoothly but the wear rate was high, and at the end of five minutes severe vibration, due to disc pick-up, terminated the test.

Because of the previously noted effects of silicon on the wear behavior of several alloys, a second alloy of the above type with an addition of 4% silicon was induction melted and cast. The photomicrograph in Figure 18b, shows the structure of this alloy. Three phases are evident, and consist of a silver-rich phase, a copper-aluminum phase (light grey), and a silicon-rich phase (dark grey). The performance of this specimen in a wear test at 650°F was better than the first alloy with no silicon. The wear rate was about .026 inches per hour which compared favorably at this temperature with other promising compositions. Time was not available for more extensive tests of this material, but continued investigation would seem most desirable.

A magnesium base alloy containing 6.0% silver and 0.5% zirconium was tested at 535°F. The material ran fairly smooth against the disc, but a wear rate of about 0.180 inch/hour was obtained, which greatly exceeded the wear rate of other materials tested.

A silver base alloy containing cadmium oxide was tried in the wear testing machine. This specimen wore at a low rate but caused severe vibration and scoring of the rotor. Results are tabulated in Table IV.

An electrical contact alloy was obtained from the P.R. Mallory Company (Elkonite G-14) which contained about 65% tungsten carbide

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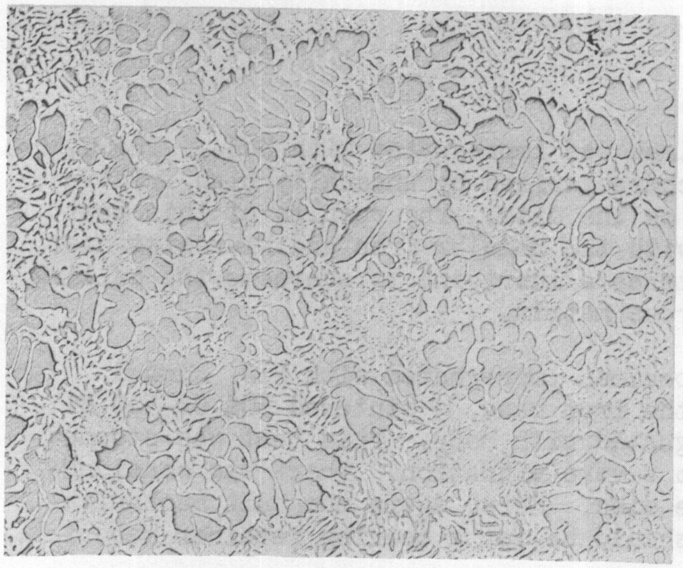

a. Alloy

Al - 7.2%
Cu - 32.8%
Ag - 60.0%

Matrix is silver rich phase
VPN - 130 Average

Grey areas are copper rich γ_2 phase.

VPN - 367 Average

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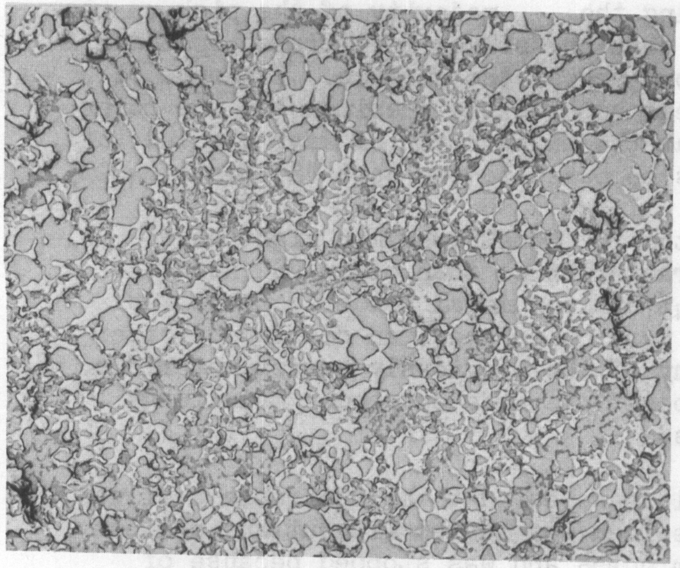

b. Alloy

Al - 7.7%
Cu - 30.3%
Ag - 58.0%
Si - 4.0%

Matrix - Ag rich plus Cu
VPN - 129 Average

Fine precipitate of Ag and Cu-Al phase
VPN - 248 Average

Grey areas are Cu-Al phase
VPN - 489 Average

Dark spots are Silicon rich phase
VPN - 890 Average

Figure 18 Photomicrographs of Cu-Al-Ag and Cu-Al-Ag-Si Induction Melted Alloys.

and 35% silver. This specimen, which was tested at 615°F, showed a very low wear rate of 0.009 inch per hour and no vibration or scoring of the disc. Time was not available for additional tests of this alloy.

E. Sintered Materials

A sintered iron specimen was impregnated with MoS_2. The wear test run of this specimen was characterized by unusually high friction, as well as scoring and pick-up on the disc. The results of this test were similar to those obtained with the nodular iron and Ni-resist cast iron. The MoS_2 was not adequate as a lubricant to overcome the galling or welding tendency of the ferrous matrix.

Since the sintered iron specimen impregnated with MoS_2 showed high friction probably due to the iron base, a sintered 50% Cr-50% Ni compact was prepared and impregnated with MoS_2. This test was stopped in less than two minutes due to severe vibration. There was considerable pick-up and scoring on the disc. Here, again the bulk mechanical properties were not what they should be for a bearing retainer material.

A silver infiltrated "S" Monel specimen was tested at 350°F. The pick-up on the disc was slightly greater than that obtained for the plain "S" Monel, however, the disc was considerably easier to clean with emery paper indicating the majority of the pick-up was silver. It could also be seen that the silver infiltrated specimen temperature was much more uniform across the surface. Evidence of this was the lack of scored areas both on the specimen and the rotor. (see Figure 19). It may be that the higher rate of wear was due to a lower silicon content (2.0%) as compared to the cast "S" Monel (4.0%).

Since the silver infiltrated "S" Monel specimen might have displayed even better wear characteristics than plain "S" Monel, a 48% chromium, 48% nickel, and 4% silicon metal powder compact was infiltrated with silver. This particular specimen displayed better overall wear properties than any of the previously tested materials. Therefore, a new series of compositions made by powder metallurgy techniques suggested themselves.

Since the presence of silicon appeared to be desirable a silver infiltrated chromium-nickel specimen was tested without any silicon addition. The test lasted 55 minutes and was stopped because of steadily increasing vibration. The disc was severely scored and pick-up was excessive. This verified the previous results that a silicon addition was beneficial, though the optimum silicon content or the effect of various percent additions remained to be determined.

Three groups of materials were made up with silicon contents of 4 and 8% and a 10% $MoSi_2$ content. The metal powder mix compositions and compact densities before and after silver infiltration are shown in Table I.

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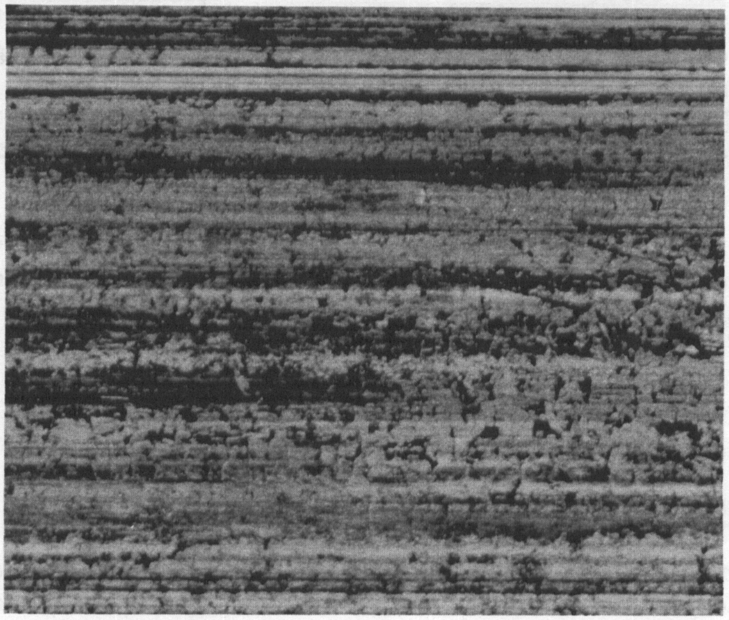

Silver Infiltrated

"S" Monel

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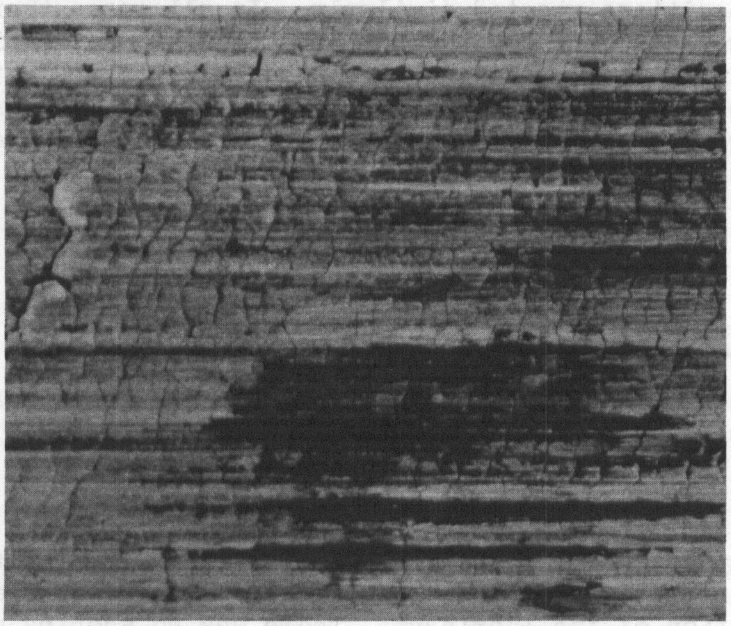

Plain

"S" Monel

Fig. 19 Macrographs Showing Worn Surfaces of Plain "S" Monel and Silver Infiltrated "S" Monel Specimens.

1. Chromium-Nickel Base Compacts

When the first silver infiltrated chromium-nickel-silicon compact was tested slight vibration was noted. However, the wear rate was very low with only very slight vibration and scoring on the disc during the test. Further tests were conducted at temperatures up to 535°F. The vibration or scoring did not increase noticeably and the wear rate remained at a low level in comparison to plain "S" Monel.

The 8% silicon addition and 10% $MoSi_2$ addition to the compact mix proved to adversely affect the wear characteristics. These tests were accompanied with severe vibration and scoring throughout the temperature range of testing.

The wear rate versus mean base temperature relation of these tests is shown in Figure 9.

2. Monel Base Compacts

A corrective addition of silicon to the Monel powder was made to bring the amount of silicon up to 4 and 8% of the metal powder compact so as to simulate the plain "S" Monel specimen composition. The 10% $MoSi_2$ addition was added to the Monel powder which also contained 2.2% silicon and compacts of this mixture were infiltrated with silver. The silver matrix improved the wear properties considerably. All three compositions reacted similarly. In all cases there was no scoring. The tests were smooth until the pick-up on the disc was sufficient to cause vibration. The 8% silicon addition to the metal compact improved the wear rate, and the 10% $MoSi_2$ addition wore only slightly more at higher temperatures than the former. In all cases the wear characteristics were superior to plain cast "S" Monel.

The wear rate versus mean base temperature relation of these specimens is shown in Figure 10.

3. Nickel Base Compacts

Since nickel is the major element in Monel and is a major element in the chromium-nickel compacts, compacts of nickel plus silicon powder were silver infiltrated and tested.

The 4% silicon addition resulted in better wear rates at all temperatures than any of the above mentioned materials. It displayed only slight vibration at temperatures above 400°F. This was probably due to the decomposition of the lubricant. There was no scoring or pick-up other than a thin film of silver on the disc. The behavior of the specimen containing $MoSi_2$ was even better. The wear rate was lower at high temperatures. The 8% silicon compact had an even lower wear rate, but slight vibration and scoring was evident throughout the testing temperature range. It appears that this composition was inferior due to the higher silicon content.

The wear rate versus mean base temperature relation of these specimens is shown in Figure 11.

F. Mechanical and Physical Properties of the More Promising Materials

Some of the experimental materials were considered of sufficient interest to compare mechanical properties such as hardness and tensile strength with conventional materials. The hardness values were determined using either Rockwell B or E scales. These are listed in Table V, along with tensile properties.

No regular relationship was observed to exist between hardness and wear resistance, but this was expected in the cases of the sintered and infiltrated compositions. Here, microhardness values of the hard and soft phases were considered of some significance. These values are shown for several of the silver infiltrated compositions in Figures 20, 21, and 22, together with photomicrographs of the structures. The tensile strengths of the silver infiltrated compositions show a well defined relationship to the microhardness values obtained on the soft, silver-rich phase. Thus the silver infiltrated Monel compacts had tensile strengths of 34,000 to 65,000 psi, while the nickel base specimens had strengths of 19,000 to 28,000 psi. Corresponding microhardness values were 40-60 VHN for the nickel base and 75-90 VHN for the Monel base specimens. This hardening and strengthening effect was caused by alloying of the silver matrix with copper from the Monel.

VII. CONCLUSIONS

From the results of the large number of comparative wear tests conducted on this program, the following conclusions can be inferred.

1. Several alloy compositions have been developed which have superior elevated temperature wear resistance compared with standard bearing cage alloys such as "S" Monel and iron-silicon bronze. All of the promising materials except one contain silver as a major alloying element.

2. It has been established that the addition of from 2 to 4% silicon is distinctly beneficial to the wear properties of several classes of metallic alloys, whether cast or fabricated by powder metallurgy techniques. The function of the silicon has not been exactly established, nor is it clear as to whether it is best added in the elemental form or as a compound such as molybdenum disilicide.

3. It has been shown that the alloy composition can be varied considerably with respect to the strong, load supporting phase as long as silver is contained in the soft matrix. For instance, promising

TABLE V MECHANICAL PROPERTIES OF MATERIALS

Specimen	% Elongation	Tensile Strength psi.	Rockwell "B" Hardness
Ag infilt. (Ni + 4% Si)	---	22,100	14
" (Ni + 8% Si)	3.42	28,570	19
" (Ni + 10% $MoSi_2$)	2.70	18,670	45
Ag infilt. (Monel + 4% Si)	5.75	53,990	52
" (Monel + 8% Si)	1.53	34,360	69
" (Monel + 10% $MoSi_2$)	3.15	65,160	88
Ag infilt. (Cr-Ni + 4% Si)	1.00	15,620	48
" (Cr-Ni + 8% Si)	0.71	9,950	57
" (Cr-Ni + 10% $MoSi_2$)	0.12	16,290	60
S-Monel			105
Fe-Si-Bronze			71
Cast Inconel			74
Mg base 6.0% Ag 0.5% Zr			25
Ag-Cu-Al-Si			101
Elkonite G-14			109
Inconel			86
Mallory D-52	(Rockwell "E" Scale)		37

Neg. No. 604

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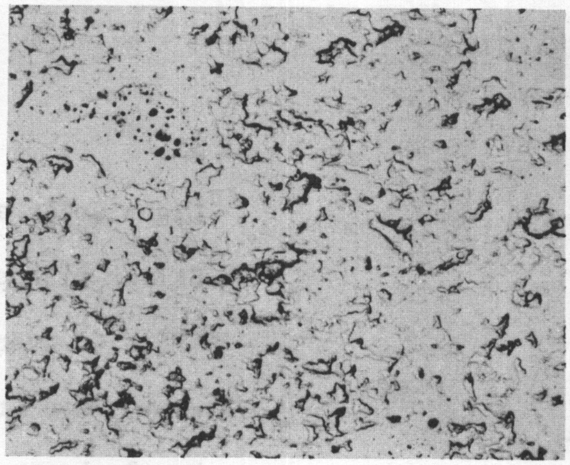

150X

4% Si

Cr-Ni Phase

VPN - 570 Average

Ag rich Matrix

VPN - 94 Average

Neg. No. 645

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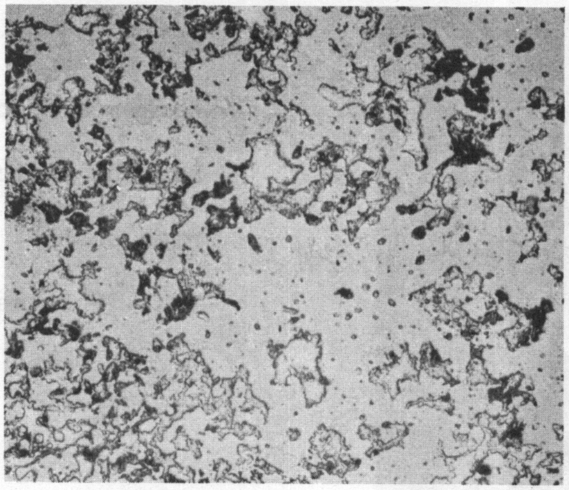

250X

8% Si

Si rich phase

VPN - 760 Average

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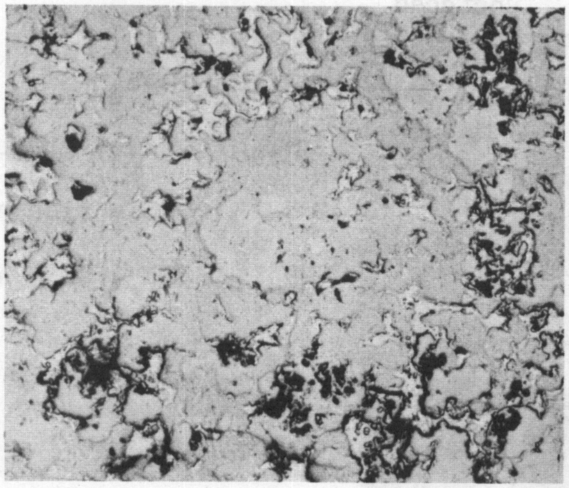

250X

10% $MoSi_2$

$MoSi_2$ rich phase

VPN - 1050 Average

Figure 20 Photomicrographs of Silver Infiltrated 50% Cr-50% Ni Compacts with 4 and 8% Si Contents and 10% $MoSi_2$ Content

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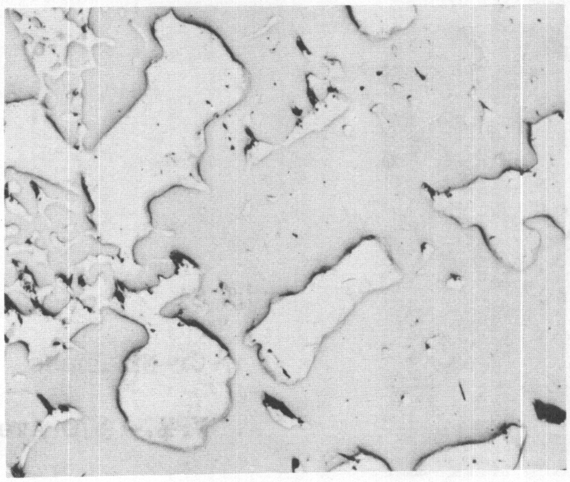

150X

4% Si

Light areas are the Silver-rich phase

VPN - 80 Average

Grey areas are the Monel phase

VPN - 360 Average

Neg. No. 687

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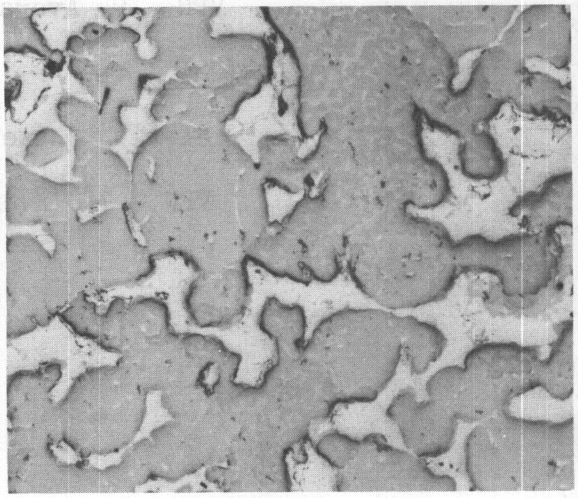


150X

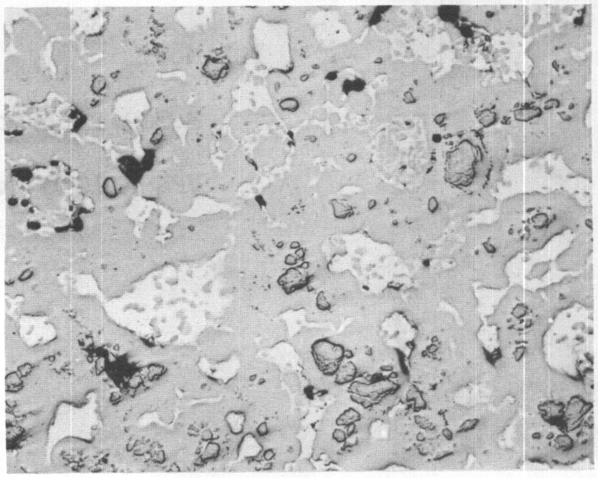
8% Si

Darker splotches are the silicon rich phase

VPN - 760 Average

Neg. No. 688

Unetched



150X

10% $MoSi_2$

Darker grains are $MoSi_2$ rich phase

VPN - 1190 Average

Figure 21 Photomicrographs of Silver Infiltrated Monel Compacts with 4 and 8% Si Contents and 10% $MoSi_2$ Content.

Neg. No. 685

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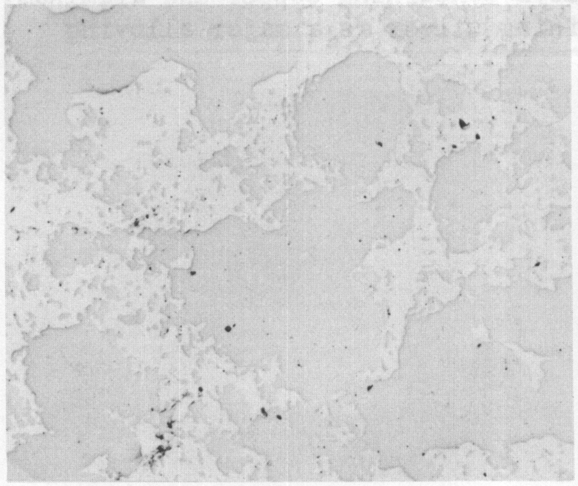


150X

4% Si

White Phase is

Silver rich

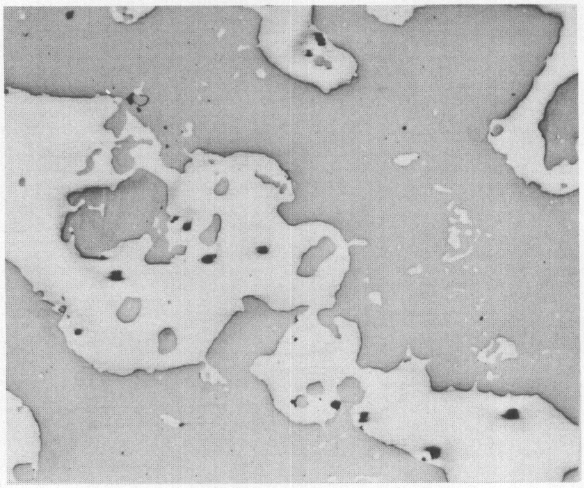
VPN - 70 Average

Grey Phase

is Nickel

Neg. No. 674

Unetched



150X

8% Si

VPN - 305 Average

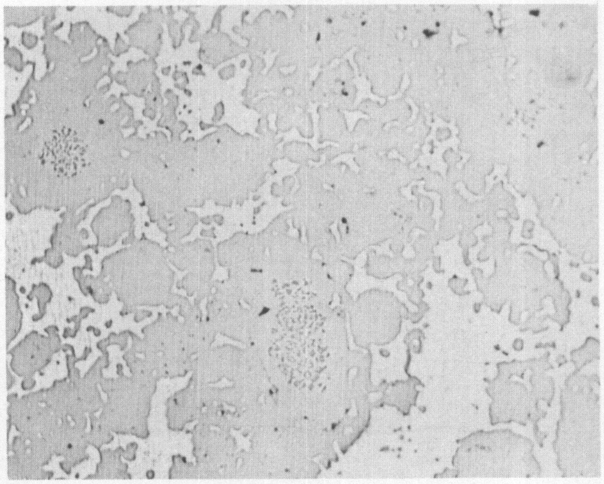
Darker Grey Phase

is Silicon rich

VPN - 770 Average

Neg. No. 647

Unetched



250X

10% $MoSi_2$

Fine precipitate is

Nickel + $MoSi_2$

VPN - 315 Average

Figure 22 Photomicrographs of Silver Infiltrated Nickel Compacts with 4 and 8% Silicon Contents and 10% $MoSi_2$ Content.

results have been obtained with nickel base alloys formed by powder metallurgy techniques, with cast alloys containing copper and aluminum, and with tungsten carbide, all containing silver as a major alloying element.

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