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SUMMARY

The effects of processing and compositional variations on the tribological performance of PM212 were investigated. PM212 is a self-lubricating powder metallurgy composite, comprised of a wear resistant metal bonded chromium carbide matrix, containing the solid lubricants barium fluoride/calcium fluoride eutectic and silver. Several composites were formulated which had lubricant, matrix, and processing variations. Processing variations included sintering and hot isostatic pressing. Pins fabricated from the composites were slid against superalloy disks in a pin-on-disk tribometer to study the tribological properties. Several composites exhibited low friction and wear in sliding against a nickel-based superalloy. The good tribological performance by several different composites showed that the composition of PM212 can be altered without dramatically affecting performance.

INTRODUCTION

There is an ongoing need for materials which can be used for sliding bearings and seals requiring operation from room temperature to temperatures as high as 900 °C in oxidizing (air), reducing (hydrogen), and inert (argon, nitrogen) atmospheres. Oil lubrication cannot be used to cover the temperature range in these applications since the upper limit of oil lubricants is 300 to 350 °C (ref. 1). Solid lubricants offer the potential to meet these lubrication challenges. However, the traditional solid lubricants such as molybdenum disulfide (MoS_2) and graphite do not have the temperature capabilities needed.

The limitations of the traditional solid lubricants underscore the need for innovative material systems capable of providing lubrication over a wide range of temperatures. In addition, these systems must be able to withstand corrosive atmospheres. The PS200 and PM200 composites have been developed at NASA Lewis Research Center in response to these needs.

The PS200 plasma sprayed composite coating series and the PM200 series of powder metallurgy composites have been shown to provide low friction and wear over a wide temperature spectrum. PS200 and PM200 composites are comprised of a wear resistant metal bonded chromium carbide (Cr_3C_2) matrix with the solid lubricants barium fluoride/calcium fluoride (BaF_2/CaF_2) eutectic and silver. Silver functions as a low temperature lubricant (up to 500 °C). The BaF_2/CaF_2 eutectic functions as the high temperature lubricant (400 °C and up). The solid lubricant additions provide lubrication by forming a low shear strength film during sliding. The eutectic is used instead of a single fluoride since it has a lower melting point and thus a lower softening temperature. The composite materials function by replenishing the sliding contact

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surfaces with lubricants as wear occurs. In doing so, a film containing the low shear strength lubricants is formed at the sliding interface (ref. 2).

Potential applications for these materials include process control valves, variable temperature control surface bearings, high temperature combustion engine cylinder wall coatings, backup lubricant coatings for gas bearings, and turbine engine seals and bushings (refs. 3 and 4). Tribological properties of PM212 (70 wt % NiCo-Cr_3C_2, 15% Ag, and 15% BaF_2/CaF_2 eutectic) pins in sliding against superalloy disks were reported in reference 5. The PM212 pins were fabricated by the use of cold compaction techniques followed by pressureless furnace sintering. The composite pins were tested over a spectrum of temperatures, sliding velocities, and applied loads and were found to exhibit good tribological properties.

Mechanical and thermophysical properties of PM212 were reported in reference 6. It was found that fully dense PM212 formed by hot isostatic pressing (HIPping) was three times stronger in compression than sintered PM212 which was only 78 percent dense. Several other properties including tensile strength, elastic modulus, thermal expansion coefficient, and thermal conductivity were determined. Most recently, a comparison of the tribological performance of sintered PM212 and HIPped PM212 showed that the HIPped version provided slightly lower friction and wear (ref. 7).

This present investigation focuses on the effect of processing and compositional changes on the performance of the baseline PM212 composite. Alternate composites chosen for this study had unique characteristics, such as matrix only (no added lubricants), only a single lubricant added, single fluoride in place of the eutectic fluoride, additional lubricant compared to baseline, additional unbonded chromium carbide in place of a portion of the metal bonded chromium carbide, and the use of gold instead of silver. A detailed study of the gold containing composite can be found in reference 8.

Two processing routes were used in this investigation; cold compaction followed by sintering and cold compaction followed by HIPping. HIPping yields parts of higher strength and density in comparison to sintering (ref. 6). The two processing routes were chosen to determine if the extra effort associated with HIPping to produce higher density parts would improve tribological performance. Hemispherically tipped pins fabricated from the composites were slid against nickel-based superalloy disks in a pin-on-disk tribometer with temperatures ranging from 25 to 900 °C at a sliding velocity of 2.7 m/s. The intent of the evaluation was to determine if any of the processing or compositional changes had a substantial positive or negative effect on tribological properties. The composite microstructures were compared using optical microscopy, scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS), and density measurement. Additionally, the compressive strengths of the sintered composites were determined at temperatures ranging from 25 to 900 °C.

MATERIALS AND PROCESSING

Materials and Processing Selection

Table I summarizes the ten different composites which were formulated for this investigation. PM212 (70 wt % 430NS, 15% Ag, 15% BaF_2/CaF_2 eutectic) is the baseline composite. The 430NS (metal-bonded Cr_3C_2) functions as the wear resistant base material and was tested alone to determine the effect of no added lubricants. It would be expected that without lubricants, friction and counterface wear would be higher throughout the temperature range tested. The 430NS+Ag and 430NS+Eut were chosen to examine the single lubricant condition. It was expected that the silver containing composite would perform adequately only at low temperature and the fluoride containing composite would do so only at higher temperatures. PM212/BaF_2 and PM212/CaF_2 were formulated to study the effect of the single fluorides in place of the eutectic fluoride. The use of a single fluoride offers the potential for cost saving in the processing steps. PM226 had additional silver added to determine the effect of a higher quantity of lubricant. PM221 and PM225 had Cr_3C_2 with no binder metal incorporated substituted in place of some of

the metal bonded Cr_3C_2. This was to determine if the harder nonmetal bonded chromium carbide would improve the wear resistance of the composite.

The silver in PM212 imposes certain limitations on the use of the composite. PM212/Au was formulated with the same composition as PM212 with the silver replaced by the volumetric equivalent of gold. Silver has the lowest melting point of the constituents of the composite (961 °C). Thus, the material cannot be used much above 900 °C. Additionally, silver combines directly with sulfur (a constituent typically found in fuels) to form silver sulfide, even at low temperature. The possibility for stress corrosion cracking of superalloys due to sulfidation attack is a concern. Gold in its metallic state does not combine directly with sulfur (ref. 9). Thus, the potential for sulfide formation with the silver in the composite is eliminated. In addition, by replacing the silver with gold (MP = 1063 °C), the eutectic has the lowest melting point (1050 °C). Hence, the temperature limit for the composite may be higher than 900 °C for limited periods.

Powders and Preparation

The powders used to make the self-lubricating composites are commercially available from several sources. The powder particle sizes ranged from 40 μm to 150 μm (-200 to +400 sieve). The BaF_2/CaF_2 eutectic is a 62/38 wt % blend. The eutectic was formed by prefusing the mixed fluorides in a nitrogen atmosphere at 1100 °C. Then, the eutectic was crushed, and ball milled to produce a fine powder size for use in the composites. The 430NS is a nickel-cobalt bonded chromium carbide powder. The composition of 430NS is as follows: 48 wt % Cr, 28% Ni, 12% Co, 6% C, 2% Mo, 2% Al, 1% B, and 1% Si.

The powders were weighed and combined in the proportions listed in table I for each composition. Each combined batch of powder was loaded into a V-type mixer and blended for 30 min to produce a uniform distribution of the different powders. After blending, the powder batches were ready for the powder metallurgy processing.

Cold Compaction

Cylindrical slugs (13 mm diameter by 32 mm long) were formed using a die press followed by cold isostatic pressing. The blended powder was poured into a steel die lined with graphite sheet foil. An axial load of 35.6 kN was applied which generated a pressure of approximately 281 MPa on the powder in the die. The die pressed cylindrical slugs were then placed in rubber bags. The bags were placed in a chamber which was pressurized to 414 MPa for 5 min. The specimens were removed from the pressure chamber and then the slugs were removed from the rubber bags. This rubber bag-pressure chamber method is the cold isostatic pressing (CIPping) technique. This two stage compaction scheme yielded slugs with green densities ranging from 70 to 80 percent.

Pressureless Sintering

The CIPped specimens were placed into a tube furnace with a dry hydrogen atmosphere, which was used to prevent oxidation of the specimens during the sintering process. The furnace was heated at a rate of 10 °C/min up to 1100 °C, and then held at temperature for 30 min. The furnace was then cooled at a rate of 10 °C/min down to room temperature before the specimens were removed.

Hot Isostatic Pressing

The CIPped specimens were placed into stainless steel cans lined with graphite sheet foil. The unsealed cans containing the CIPped specimens were vacuum annealed at 350 °C. After annealing, the cans were sealed under vacuum using electron beam welding. The sealed cans were placed into a chamber that was simultaneously pressurized and heated. The chamber was heated to 1100 °C at a rate of 6 °C/min and pressurized with argon to 138 MPa at a rate of 0.75 MPa/min. The chamber was held at 1100 °C and 138 MPa for 20 min. Then, the chamber was cooled at a rate of 12 °C/min and depressurized at a rate of 1.5 MPa/min. The specimens were removed from the chamber and then the slugs were removed from the cans.

The specimens processed by the sintering route were made before those by the HIPping route. It was then decided to formulate additional composites (430NS, 430NS+Ag, 430NS+Eut, and PM212/Au). In turn, these composites were only processed by HIPping since that was the technique being used at the time those new composites were formulated.

Superalloy Disks

The disk specimens used for the pin-on-disk testing were made of the nickel-based superalloy R41. R41 has excellent high temperature oxidation resistance and strength and is a commonly used aerospace material. The weight percent composition of the major components of R41 is as follows: 55% Ni, 19% Cr, 10% Mo, 10% Co, 3% Ti. Several trace elements are present in the alloy. R41 is precipitation hardened to a nominal hardness of R_c 35 to 40 at room temperature.

Machining Techniques

The cylindrical slugs produced from both the CIP-sinter and CIP-HIP routes were fabricated into hemispherically tipped pins. The slugs were centerless ground to obtain a cylindrical diameter of 9.53 mm. 4.76 mm hemispherical radii were placed on both ends of the pins using diamond grinding. The diamond grinding technique is used to prevent the softer phases (silver, gold, and fluorides) from being selectively removed from the ground surface (ref. 10). In addition, only clean water is used as a coolant. Machining oils are not used so that contamination of the composite is minimized.

Specimens were also made into small cylinders and blocks to allow for density determination by weight and measure. Additionally, small cylindrical pins (5 mm in diameter and 10 mm in length) were made of the sintered composites for compressive strength testing.

The superalloy disks were machined using standard techniques. The fabricated disks had a diameter of 63.5 mm and a thickness of 12.7 mm. After machining to size, the disks were lapped to an average surface roughness of 400Å CLA.

Metallographic Preparation

Cross sections of the composites were prepared by mounting the samples in epoxy. The mounted samples were diamond sawed to expose the cross section of the composite. The cut surface was then diamond polished using a sequentially finer grit to a final paste grit size of 0.5 μm.

EXPERIMENTAL AND ANALYTICAL METHODS

Specimen Preparation

The composite pins were heated in an oven for 3 hr at 200 °C and 60 mm Hg absolute pressure to remove any residues from the processing, handling and machining operations. The pins and disks were then cleaned with ethyl alcohol, wet scrubbed with 0.1 μm grit size alumina powder, rinsed with deionized water, and dried with compressed air.

Tribological Testing

An induction heated pin-on-disk tribometer was used for this investigation. The tribometer generates a 51 mm diameter wear track on the rotating disk while holding the pin in a fixed position. The surface temperature of the disk specimen was measured with an infrared pyrometer and a continuous readout of the friction force was made on a chart recorder from a temperature compensated strain gage bridge transducer.

Tests were performed at a sliding velocity of 2.7 m/s (1000 rpm) at temperatures of 25, 350, 760, and 900 °C. The composite pins were slid against the R41 superalloy disks. A new set of specimens was used for each temperature. The test load was 4.9 N and the atmosphere was air with relative humidity of 35 to 50 percent at 25 °C. The 4.9N load was chosen to facilitate comparison with previous work (refs. 5 to 7) and is considered a typical load for sliding bearing and seal applications.

One test was performed for a duration of 70 min at each temperature for each sintered and HIPped composite. An exception was the 25 °C tests of the sintered composites, which were split into three segments (10, 20, 40 min) to study how wear varied with time.

Friction Analysis

The friction coefficient is determined by dividing the measured frictional force by the normal load force on the pin. The average friction coefficient for each test run is determined by averaging a sampling of 35 uniformly spaced (every 2 min) data points recorded throughout the test. An overall average friction coefficient for each composite is calculated by averaging the individual average friction coefficients at the four different test temperatures. The range of the four averages is used to represent the variation that was present.

Wear Analysis

After the test run, a photomicrograph is taken of the pin wear scar to determine the volume removed. A stylus surface profilometer is used to measure the wear track profile on the disk. Typically, four measurements of the wear track area are averaged. The area of the wear track cross section is multiplied by the track circumference to determine the wear volume. Figure 1 shows a pin wear scar and a disk wear track profile scan for one of the tests performed.

Wear factors were computed for both the pin (K_{pin}), and the disk (K_{disk}). Briefly, the wear factor is equal to the volume removed due to wear during sliding divided by the product of the normal load and the total sliding distance. Wear factors higher than 10^{-4} $mm^3/N\text{-}m$ are considered unacceptably high for most applications and those less than 10^{-6} $mm^3/N\text{-}m$ are considered very low.

Wear surfaces of the disk were analyzed using EDS for transfer films formed from sliding against the composite pins. Optical microscopy was used to observe general features of the wear surfaces at lower magnification.

Microstructural

Metallographically polished surfaces of the composites were examined using optical microscopy, SEM, and EDS. The EDS system is an integrated part of the SEM. Settings used on the SEM were 20 kV accelerating voltage, 6.0×10^{-10} A probe current, and 39 mm working distance. Key elements were identified using x-ray mapping with the EDS system. Optical micrographs of the composites were obtained using vertical illumination on a metallographic microscope. The analyses helped to compare and characterize the microstructures based on elemental distribution and surface topography.

Density Measurement

The densities of the composites in both HIPped and sintered forms were determined by weight and volume measure. Measured density was compared to theoretical maximum density to determine the porosity level present after processing. Density and porosity levels of PM212 have previously been established using liquid porosimetry and weight and volume measure techniques (ref. 6).

Compressive Strength Determination

Compression tests were performed using cylindrical specimens of the sintered alternates. The tests were conducted at 25, 350, 760, and 900 °C in air on a load testing rig at a strain rate of 2.1×10^{-4} s^{-1}. Three tests were performed at each condition. Reference 6 contains the complete experimental methodology for the compressive strength measurements and analysis.

RESULTS

Tribological

Since only one 70 min test was performed at each temperature for each composite, the test-to-test variation for a specific composite at a given temperature cannot be stated. However, from the tests performed, overall performance across the temperature range can be compared. Table II shows how the composites performed in overall friction coefficient relative to one another. The listed values represent the average friction coefficients based on the tests performed at the four different temperatures. For a more detailed presentation of the data, see reference 11. The PM226 sintered alternate, which contained additional silver compared to the baseline PM212, had the lowest overall average friction coefficient (0.31) of the sintered composites. Sintered PM212 had the highest overall average friction coefficient (0.38) of the sintered composites. The HIPped 430NS+Ag composite had the lowest overall average friction coefficient (0.25) of the HIPped composites. The HIPped PM212/CaF_2 had the highest overall average friction coefficient (0.33) of the HIPped composites. The overall averages had variations ranging from ± 0.03 to ± 0.11.

Table II also lists the results for the pin and disk wear factors. It can be seen that the wear factors were primarily in the 10^{-6} to 10^{-5} mm^3/N-m range. K_{pin} ranged from 8.8×10^{-6} to 7.5×10^{-5} mm^3/N-m and K_{disk} spanned -4.5×10^{-6} to 5×10^{-5} mm^3/N-m. The negative wear factor represents transfer buildup on the disk from the pin. In general, K_{pin} was lower for the HIPped composites than for the sintered. The average wear factors typically had a variation up to an order of magnitude about the average.

Figure 2 illustrates the how wear varied with time for the sintered composites at room temperature. This includes both the composite pins and the R41 disks. The plots show a decline in wear factor with sliding distance. This decline is more pronounced for the disk than for the pin.

The friction coefficient was slightly higher (≈0.5) during the first few minutes of sliding Thereafter, the value decreased, and remained at nearly a constant value.

Microstructural and Mechanical

The presence or absence of pore space was determined by measuring the density. Table III contains the theoretical and measured densities for the composites by both sintering and HIPping. The percent of theoretical density achieved ranged from 52.9 percent (430NS) to 81.8 percent (PM226) for the sintered alternates. Every composition except PM212/Au, the gold containing composition, HIPped to full density. The causes of residual porosity in PM212/Au from HIPping are elaborated upon in reference 8. Briefly, it appeared that gas entrapment may have prevented PM212/Au from achieving full density.

Table IV summarizes 0.2 percent offset compressive yield strength results obtained for the sintered alternates at the four temperatures investigated. In general, the strength decreases with increasing temperature. Figure 3 is a plot of the 0.2 percent offset compressive yield strength versus percent residual porosity after sintering. The plot contains strength data at 25°, 350°, and 760 °C. The strength decreases as residual porosity level increases. The strength data at 900 °C were all very low and do not clearly correlate with residual porosity level.

DISCUSSION

There was considerable overlap in the overall performance (across the temperature range tested) for both friction coefficients and wear factors for the different composites. Clearly, many tests would be required to clearly define the exact performance characteristics of a single composite. Figure 4 contains a histogram of the individual test average friction coefficients for all of the composites, both sintered and HIPped. This plot shows that a variety of changes may be made to the baseline PM212 composite without dramatically affecting frictional performance at the conditions tested. This is realized since the histogram shows an approximate average friction coefficient of 0.3 with a range of 0.15 to 0.45. Numerically, the mean is 0.31 and the standard deviation is 0.07. The wear factors have more overlap then the friction coefficient. Without more repeat testing, it can only be said that K_{pin} for all composites at all temperatures tested primarily ranged from 10^{-6} to 10^{-5} $mm^3/N\text{-}m$. This is the same for disk wear, except that its range was from -10^{-5} to 10^{-5} $mm^3/N\text{-}m$ (negative sign on a wear factor indicates buildup) . The overall wear factors typically had a variation spanning an order of magnitude.

The objective of this investigation was to screen a large number of composites to obtain general trends due to compositional and processing changes. Therefore, repeat testing was not used to accurately quantify the performance of each individual composite. Nonetheless, for screening purposes, useful information can be extracted from the results regarding composite choice. The PM212/BaF_2 composite had nearly equal performance to the baseline PM212 composite. The use of a single fluoride eliminates the time consuming process of making the eutectic fluoride. The 430NS+Ag was one of the best performing composites overall, in both friction and wear, and from low to high temperature. The use of this composite would eliminate the need for one of the constituents (fluoride) all together.

Previous tests with plasma sprayed coatings have shown a dependency on both the silver and fluoride lubricants for lubrication over the entire temperature range (ref. 3). In those tests, a superalloy pin was slid against a disk coated with the composite. The configuration was opposite for the tests in this investigation; composite pin on superalloy disk. In the tests conducted for this investigation, oxide formation on the disk surface may have played a key role in providing lubrication at high temperature without the need of the fluoride high temperature lubricant. The oxides formed on nickel-based superalloys have been shown to have a beneficial, lubricious effect (ref. 12). In the tests performed in refer-ence 3, oxidation of the pin contact area would have been inhibited since the wear surface on the superalloy pin was in direct contact with the coated disk.

On the other hand, oxide formation on the superalloy disk wear track in this investigation would not have been inhibited, since the wear track was exposed to air except for the brief moment as it passed under the pin with each revolution. Therefore, specimen geometry and the chemical nature of the surrounding atmosphere are important variables for the material combinations studied. It was shown in reference 2 that both high and low temperature solid lubricant components are needed in reducing and inert atmospheres where lubricious oxides are not formed.

In Table III, some of the achieved densities were as much as 3.5 percent higher than theoretical. The propagated error associated with calculating the density based on the measured dimensions and mass was less than 1 percent. It is likely that the additional error may have come from non-uniform powder distribution in the section used for density measurement. Small deviations from the stated composition of the powders used may also have contributed error. Thus, when a measured density is within ±3 percent of the theoretical, it can be considered as essentially fully dense.

The strength-porosity relationship in figure 3 illustrated the importance of achieving low porosity levels to produce a composite of high strength. However friction and wear properties do not show this same strong dependence on porosity level. The exception may be at very high temperature, for the porosity level in HIPped PM212/Au may have contributed to the higher wear encountered at 900 °C. Friction coefficients and pin wear factors are slightly lower with the HIPped composites (table II). Hence, if the extra strength associated with full density parts is not required for a certain application, full density processing should not be used. This is because the HIPping process used to produce full density parts is much more labor and time intensive than the sintering process.

The relative insensitivity of the tribological performance points to the fact that the test methodology was inadequate to distinguish tribological differences among the composites. When tested in a different manner, the performance could differ significantly. For example, a case where there was no disk oxidation or one with less surface heating (lower speed). On the other hand, there is a benefit if used in conditions similar to those tested. It may permit a material to be selected based on some other important design criteria, such as yield strength, density, or porosity.

CONCLUSIONS

1. Several chromium carbide-based self-lubricating composites produced by sintering and HIPping have shown low friction and wear in sliding against a nickel-based superalloy. These composites can be used as sliding bearing and seal materials in operation from 25 °C to temperatures as high as 900°C.

2. The good performance by several different composites in an air atmosphere showed that the composition of PM212 can be altered without dramatically affecting performance. This may indicate that stringent quality control on the composition itself may not be required if used in similar conditions to those tested.

3. Composites with less complex compositions than the baseline PM212 showed equivalent or better performance. Utilization of these compositions would reduce the labor and/or raw materials required.

4. Gold has been shown to be a suitable substitute for the silver in PM212. In several cases, the friction and wear of HIPped PM212 and PM212/Au were within scatter of each other. Sulfide formation that is possible with silver is not possible with gold. Thus, PM212/Au is recommended for critical applications requiring chemical stability.

6. For the sintered composites, yield strength decreased as porosity level increased.

7. Composite wear at 25°, 350°, and 760 °C did not show a dependence on porosity level. The exception was HIPped PM212/Au which had higher wear at 900 °C than full density HIPped PM212.

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TABLE I.—COMPOSITIONS OF THE TEN COMPOSITES BY WEIGHT PERCENT

Composite	430NS	Ag	Eutectic	Cr_3C_2	Au	BaF_2	CaF_2
430NS	100.0	-----	-----	-----	-----	-----	-----
430NS+Ag	82.0	18.0	-----	-----	-----	-----	-----
430NS+Eut	82.0	-----	18.0	-----	-----	-----	-----
PM212	70.0	15.0	15.0	-----	-----	-----	-----
PM212/Au	62.0	-----	13.0	-----	25.0	-----	-----
PM212/BaF_2	65.3	13.9	-----	-----	-----	20.8	-----
PM212/CaF_2	70.0	15.0	-----	-----	-----	-----	15.0
PM221	18.2	15.0	15.0	51.8	-----	-----	-----
PM225	40.0	15.0	15.0	30.0	-----	-----	-----
PM226	59.5	25.8	14.7	-----	-----	-----	-----

TABLE II.—TRIBOLOGICAL SUMMARY FROM THE PIN-ON-DISK TESTS

Sintered composite	Friction coefficient[a]	Kpin, $mm^3/N\text{-}m$	Kdisk, $mm^3/N\text{-}m$
PM212	0.38 (.34 to .44)	$3.4x10^{-5}$[b]	$2.1x10^{-6}$
PM212/BaF_2	0.34 (.27 to .37)	$2.9x10^{-5}$	$5.4x10^{-6}$
PM212/CaF_2	0.34 (.23 to .43)	$3.4x10^{-5}$	$4.5x10^{-6}$
PM221	0.37 (.27 to .44)	$7.4x10^{-5}$	$2.8x10^{-5}$
PM225	0.37 (.24 to .44)	$5.4x10^{-5}$	$1.6x10^{-5}$
PM226	0.31 (.26. to. 37)	$1.7x10^{-5}$	$8.4x10^{-6}$
HIPped composite	Friction coefficient[a]	Kpin, $mm^3/N\text{-}m$	Kdisk, $mm^3/N\text{-}m$
430NS	0.31 (.23 to .42)	$8.8x10^{-6}$	$5.1x10^{-5}$
430NS+Ag	0.25 (.16 to .32)	$9.5x10^{-6}$	$1.7x10^{-5}$
430NS+Eut	0.31 (.28 to .38)	$8.9x10^{-6}$	$8.3x10^{-6}$
PM212	0.30 (.26 to .40)	$1.3x10^{-5}$	$2.0x10^{-6}$
PM212/Au	0.30 (.24 to .33)	$2.6x10^{-5}$	$7.6x10^{-6}$
PM212/BaF_2	0.30 (.27 to .33)	$1.5x10^{-5}$	$5.1x10^{-6}$
PM212/CaF_2	0.33 (.27 to .42)	$2.5x10^{-5}$	$-4.5x10^{-6}$[c]
PM221	0.30 (.26 to .36)	$1.9x10^{-5}$	$2.2x10^{-5}$
PM225	0.27 (.23 to .32)	$1.4x10^{-5}$	$7.6x10^{-6}$
PM226	0.27 (.21 to .34)	$1.3x10^{-5}$	$8.2x10^{-6}$

[a]Values in parentheses are the range of the coefficients for this composite.
[b]Varition for K's was typically one order of magnitude.
[c]Negative number indicates buildup occurred on disk.

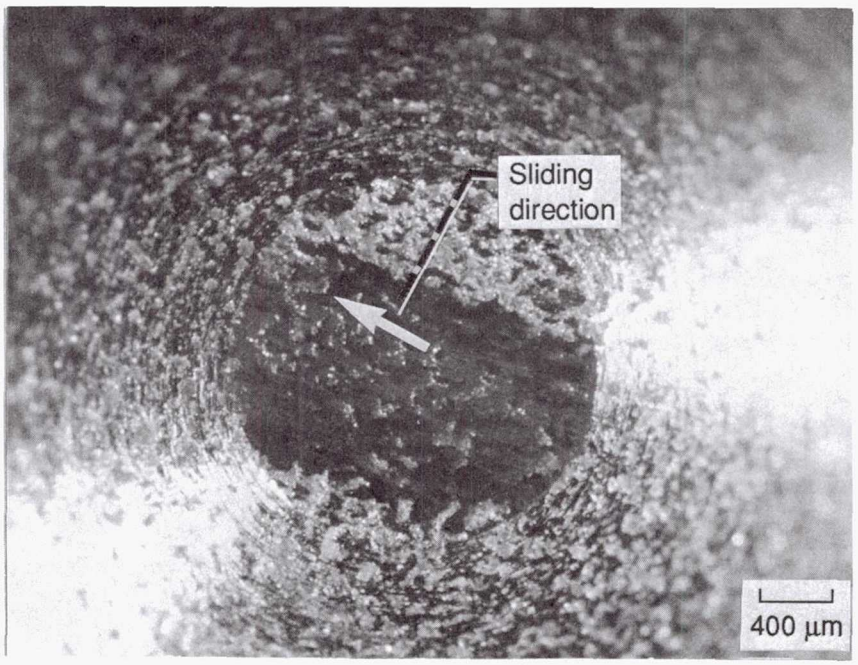
TABLE III. – DENSITY RESULTS FROM SINTERING AND HIPping

Composite (sintered)	Theoretical density, g/cm^3	Measured density, g/cm^3	Percent of theoretical achieved
430NS	6.99	3.70	52.9
PM212	6.61	5.20	78.6
PM212/BaF_2	6.70	5.36	80.0
PM212/CaF_2	6.19	4.18	67.6
PM221	6.46	4.25	65.7
PM225	6.52	4.26	65.4
PM226	6.85	5.60	81.8
Composite (HIPped)	**Theoretical density, g/cm^3**	**Measured density, g/cm^3**	**Percent of theoretical achieved[a]**
430NS	6.99	7.23	103.5
430NS + AG	7.44	7.58	101.9
430NS + Eut.	6.19	6.32	102.1
PM212	6.61	6.70	101.4
PM212/Au	7.48	6.34	84.8
PM212/BaF2	6.70	6.76	100.9
PM212/CaF2	6.19	6.25	101.0
PM221	6.46	6.32	97.8
PM225	6.52	6.53	100.1
PM226	6.85	6.94	101.3
PM221	6.46	6.41	99.3
PM225	6.52	6.55	100.4

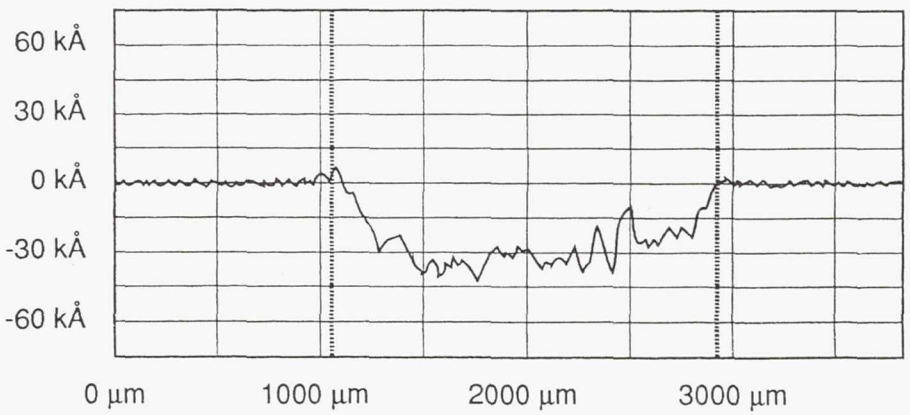
[a]Values over 100 percent are indicative of experimental error.

TABLE IV. – 0.2 PERCENT COMPRESSIVE YIELD STRENGTH [MPa] OF THE SINTERED COMPOSITES

Composite	Temperature			
	25 °C	350 °C	760 °C	900 °C
PM212	346.1	333.7	95.1	20.0
PM212/BaF_2	268.9	246.8	82.7	9.7
PM212/CaF_2	78.6	62.7	49.6	24.1
PM221	120.0	101.4	77.9	26.2
PM225	86.9	80.0	66.9	27.6
PM226	348.2	269.6	108.9	30.3

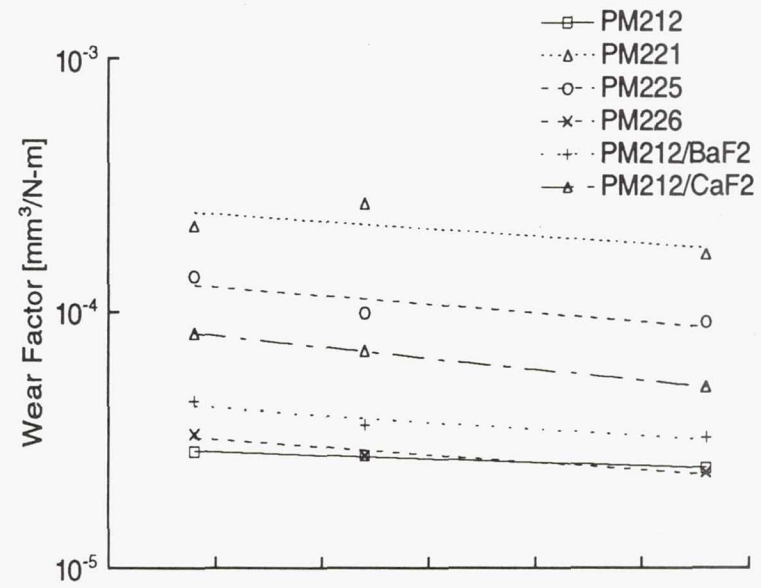


(a) Pin wear.

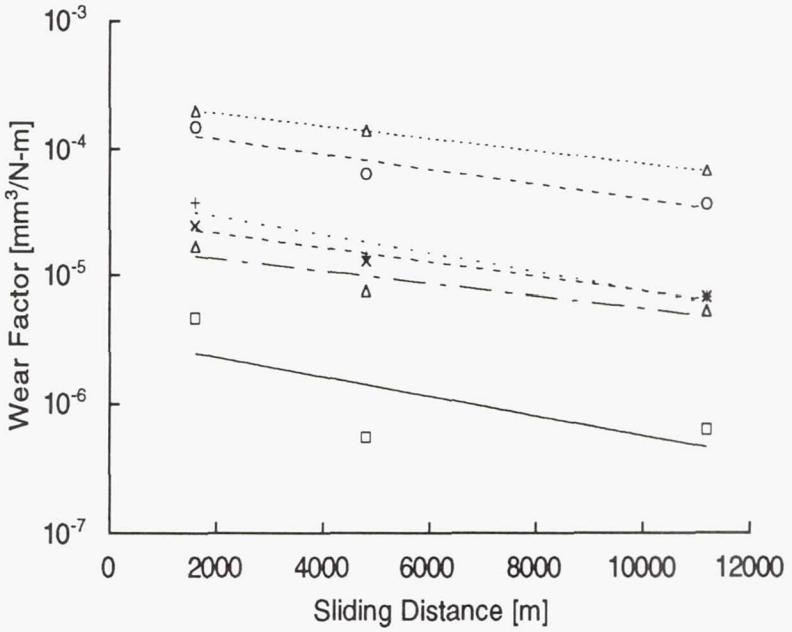


(b) Disk wear track profile.

Figure 1. Wear measurements of pin and disk specimens.



(a) Pin run-in behavior.



(b) Disk run-in behavior.

Figure 2. Wear variation with time for the sintered composites at 25°C.

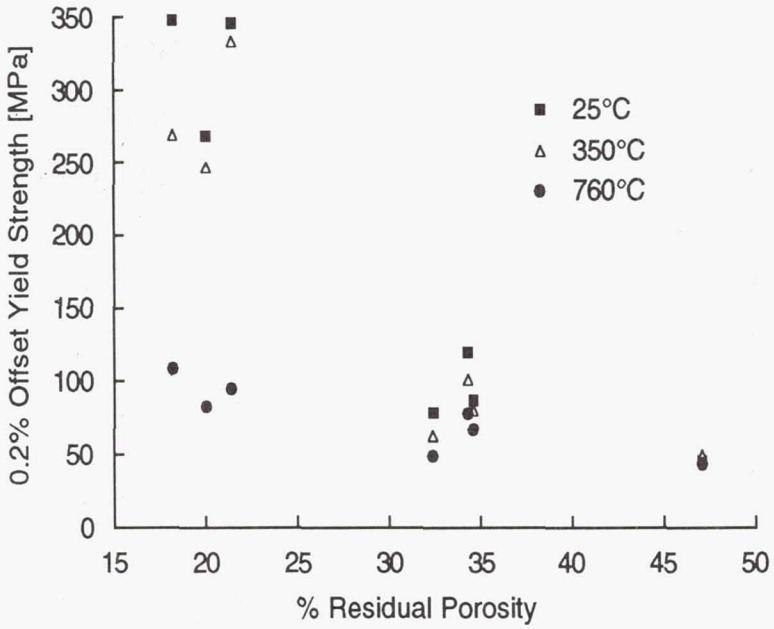


Figure 3. Yield strength decreases as residual porosity increases in the sintered composites.

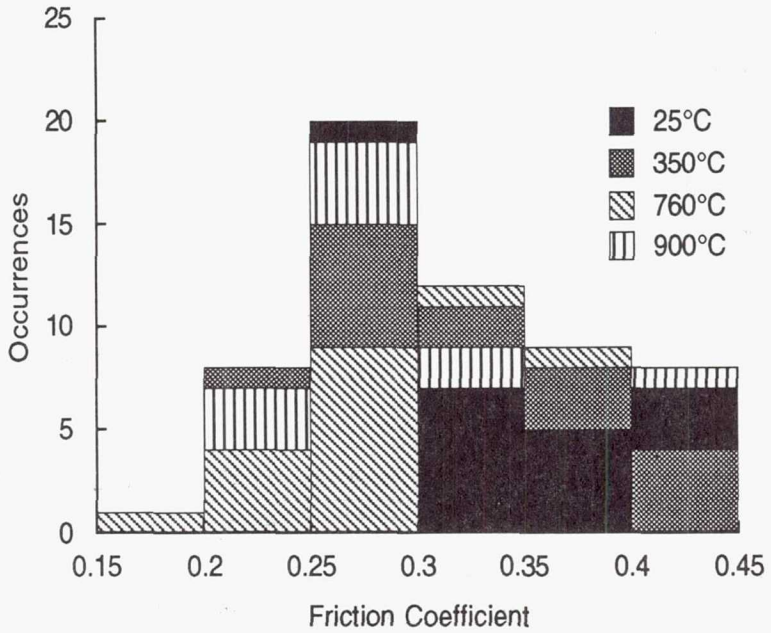


Figure 4. Histogram of individual test average friction coefficients for sintered and HIPped composites.

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13. ABSTRACT ***(Maximum 200 words)***

The effects of processing and compositional variations on the tribological performance of PM212 were investigated. PM212 is a self-lubricating powder metallurgy composite, comprised of a wear resistant metal bonded chromium carbide matrix, containing the solid lubricants barium fluoride/calcium fluoride eutectic and silver. Several composites were formulated which had lubricant, matrix, and processing variations. Processing variations included sintering and hot isostatic pressing. Pins fabricated from the composites were slid against superalloy disks in a pin-on-disk tribometer to study the tribological properties. Several composites exhibited low friction and wear in sliding against a nickel-based superalloy. The good tribological performance by several different composites showed that the composition of PM212 can be altered without dramatically affecting performance.

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