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AN ANALYSIS OF THE VARIATION IN WEAR LIFE OF HOT PRESSED MOLYBDENUM DISULFIDE-SILVER ELECTRICAL CONTACT BRUSHES IN VACUUM

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ABSTRACT

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Compositions of hot pressed molybdenum disulfide containing metallic additions have shown promise as materials for electrical contact brushes in vacuum; however, the wear life for a given composition has varied from specimen to specimen. The non-reproducibility of these brushes has been analyzed with the major effort being concentrated on a 55.9% MoS_2 - 44.1% Ag (wt) composition. The factors affecting wear duration of both the brush materials and their deposited commutator films have been studied and correlated. An optimum brush composition that should give the best combination of lubrication and electrical conduction properties is defined. The brushes are classified according to their electrical conduction behavior.

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NON-METALLIC MATERIALS BRANCH
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ACKNOWLEDGMENT

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SUMMARY

Compositions of hot pressed molybdenum disulfide containing metallic silver additions have shown promise as materials for electrical contact brushes in vacuum; however, the wear life for a given composition has varied from specimen to specimen. The variation in wear life of a 55.9% MoS_2 - 44.1% Ag (wt) composition was analyzed to determine the contribution of brush composition and fabrication techniques to failure and the mechanism of failure. The wear life of the brushes varies inversely with the volume of free silver at the wear surface. The variable silver concentration in the brush specimens is due to an irregular silver distribution in the hot pressed slug from which the brushes are cut. This arises predominantly from migration of the silver during hot pressing and is not a result of poor mixing or the pre-pressing process.

The surface film of the commutator is rich in silver content for short wear life brushes and low in silver for brushes of long wear life. Arcing as a failure mechanism is associated with the presence of a large silver content. Sulfur can be released independently of arcing.

The brushes studied have the properties of degenerate semiconductors. The analysis indicates that brushes containing a 13.8% to 26% (wt) silver content will give the best combination of lubrication and electrical conduction, the approximate optimum composition being 80.5% MoS_2 - 19.5% Ag. Actual wear testing of brushes of the optimum composition appears to confirm the analysis.

INTRODUCTION

Graphite is a satisfactory material for use as electrical contact brushes in standard brush-commutator applications. However, under vacuum or reduced pressure conditions, these brushes are not suitable because of the rapid breakdown of the lubricating mechanisms. The general description of graphite lubrication is based on the common belief that the fundamental graphite lattice consists of loosely bound layers which possess a low shear strength. This is not the case. Bryant et al. has shown that the graphite lattice has a high interlamellar binding energy (Ref. 1). It may be caused to lubricate under a number of conditions. The condition of most interest is that of air. Graphite crystals exhibit a significantly lower interlayer binding energy in air than in its absence (vacuum). In air, there is an effect of oxygen and water vapor upon the interlayer bonds of the graphite. The energy reduction by oxygen is described as an interaction between the unpaired electrons of oxygen molecules and the π-electrons of graphite. An adsorbed film of water may also prevent π-electron bonding between near-surface graphite layers and thus permit easy cleavage or shear. In the absence of oxygen and water vapor, graphite exhibits high cleavage and is not a satisfactory lubricant for electrical contact brushes. Also, because the commutator loses its oxide layer under vacuum and elevated temperatures, the commutator surface is roughened, which contributes to excessive brush wear.

Because of the reduced pressure and loss of the oxide layer and surface contaminants, the contact voltage drop decreases with a corresponding drop in contact resistance (Ref. 2); circulating currents build up, and arcing results. Arcing cannot be tolerated under reduced pressure conditions since there is no medium of heat transfer. As a consequence, the arcing physically damages the brush and commutator surfaces.

The inadequacy of graphite brushes was first encountered in 1940 with their failure in high altitude military aircraft. To provide a lubricant for the contact surfaces under the conditions of low oxygen and water vapor content, additives of organic materials, molybdenum disulfide, or metallic halides to the standard graphite compositions were tried (Ref. 3). The organics volatilized. The molybdenum disulfide-carbon brushes initially deposited a satisfactory lubricating film, but, with the start of sparking, molybdenum carbide was formed. This caused severe commutator wear.

The brushes that eventually proved to be satisfactory were those containing metallic halide additions (Ref. 3). It was discovered that these brushes would not operate adequately for long periods of time in a space environment. Consequently, in 1960, a research program was initiated in the Engineering Materials Branch of the Marshall Space Flight Center to develop and evaluate materials for use as electrical contact brushes in vacuum (Ref. 4). Materials were tested in an externally driven brush-commutator simulator at a pressure of 10^{-7} mm Hg. Initial evaluation included brush-commutator combinations of copper to copper, bronze or lead to mild steel (1018-hardened), and molybdenum disulfide-copper to mild steel.

The most promising brushes were hot pressed MoS_2 - Cu combinations (Ref. 4). They were fabricated by hot pressing at 871° - 927°C (1600° - 1700°F) at 3,500 psi (Ref. 5). Improvement was noted with each brush containing a successively higher percentage of MoS_2. A test duration of 700 hours was achieved with a 90% MoS_2 - 10% Cu (vol) brush.

Molybdenum disulfide brushes containing metallic silver were evaluated next (Ref. 6). The duration of wear life before failure for any one composition varied from a few hours to several thousand hours. In general, the lack of reproducibility of wear period was observed in the molybdenum disulfide brushes containing silver or copper additions.

The purpose of this study was to investigate and analyze the variation and non-reproducibility in the performance of the molybdenum disulfide brushes with metallic additions. This analysis was concentrated on brushes having a nominal composition of 55.9% MoS_2 - 44.1% Ag (wt) or 73.5% MoS_2 - 26.5% Ag (vol). The work was organized according to three specific areas. The first and second were investigations of the brush materials and the deposited commutator films, respectively. In the third area, an attempt was made to define a compositional range which would give brushes with the best wear life performances. The results are presented in this report.

EXPERIMENTAL

Materials

All brushes used for this investigation were prepared from molybdenum disulfide and metallic silver. Unless otherwise noted, the brushes were fabricated by hot pressing at 927°C (1700°F) at 3,500 psi as described by King (Ref. 5). All references to compositions, listed as either volume or weight percent, refer to starting compositions rather than final compositions.

X-Ray Techniques

The wear surfaces of the brushes were examined by X-ray diffraction for identification of the crystalline phases present. Powdered specimens normally are used; however, in this study, the wear surfaces were used because the reflection of the incident X-ray beam from the wear surface is more representative of the surface structural condition at the time of wear. Powdered specimens removed either tangentially from or normal to the brush wear surface would include subsurface layers which would not be representative of the wear surface at the time of failure. The crystalline phase concentration from one cross-sectional plane to another will also differ. The integrated intensities of the respective reflections were used to calculate the intensity ratios of the crystalline phases present at the brush wear surfaces. The integrated intensity of a reflection for a phase in a multi-phase ceramic depends upon the volume fraction of that phase. The ratio of the integrated intensities for two phases is proportional to the ratio of the concentrations of these phases in the ceramic.

Since the relation of intensity and concentration ratios is based on flat surfaces, assumptions are made in the present work which are adequate for a relative comparison of the volume of one crystalline phase with the other at the wear surface of each brush. The brush wear surfaces have a radius of curvature; however, if all of the samples have the same radius and are mounted in the diffractometer in the same manner, the same error would be introduced into each measurement. For relative comparisons, as in the present case, this error can be assumed to be canceled.

The question of the effect of preferred grain orientation at the wear surface must be considered. Since each surface has been subjected essentially to the same surface load and commutator rotation direction, the ratio should not be affected. Variations in line shape because of grain effects will not affect integrated intensity (Ref. 7).

Powders were collected from the surface films deposited on the copper commutator. These were examined by using the Debye-Scherrer diffraction technique and were exposed up to 15 hours to determine the presence of minor crystalline phases.

Electrical Conductivity - Resistivity Measurements

The electrical conductivity of the brushes was measured in the direction of wear, i. e., the long direction of the brush specimen. The specimens were first machined so that the wear face and the opposite face of the brush were parallel. Each sample was coated with Du Pont silver preparation #4351 so that the potential probe or four-point probe for measuring electrical resistivity could be utilized. This method eliminates the errors that could be introduced by stray electromotive forces at the electrode interfaces.

The silver coating was fired at 250°C (482°F) for five minutes. The surface conductivity of the fired-on silver was much higher than that for air-dried silver. Leads were soldered to the silvered specimens with a soldering pencil by using soft solder. The resistance was measured at room temperature on a Keithley Model 503 milliohmmeter, and the resistivity and conductivity were calculated.

A sample holder was constructed to measure the resistivity of the brushes as a function of temperature by using the four-probe technique. The holder and sample were suspended in a small electric furnace whose rate of temperature rise was controlled closely.

The resistance of the surface films deposited on the commutators was determined by measuring the resistance of the surface between slots on the commutator for a given specimen. A number of such areas was measured and then compared for each commutator.

RESULTS AND DISCUSSION

Brush Materials

The nominal starting composition of the brushes used for this study consisted of 55.9% molybdenum disulfide and 44.1% metallic silver (wt). The raw materials were hot pressed into slugs, from which the brushes were cut. The wear lives of these brushes varied from 5.3 to 7,000 hours. X-ray diffraction patterns of the wear surfaces of the brushes showed hexagonal molybdenum disulfide and metallic silver as coexisting crystalline phases. The silver to molybdenum disulfide intensity ratio was determined by comparing the intensity of the major silver reflection with that of the major molybdenum disulfide reflection as given by the American Society for Testing Materials diffraction data cards.

A correlation of the wear lives of the brush specimens and their respective intensity ratios showed that the wear life varied inversely with the volume of silver. As the Ag/MoS_2 intensity ratio increased, the wear life of the brushes decreased. This is shown in Table I. The ratio was 0.1 at 7,000 hours and 1.5 at 5.3 hours. At 51 and 156 hours, the ratios were 0.75 and 0.43, respectively.

TABLE I

STRUCTURAL AND ELECTRICAL DATA FOR BRUSHES

WEAR PERIOD (HOURS)	$\frac{I_{Ag}}{I_{MoS_2}}$	CONDUCTIVITY ($mohm^{-1}$ -cm^{-1})	RESISTIVITY (ohm-cm)
5	1.50	15.15	6.6×10^{-5}
51	0.75	6.26	1.60×10^{-4}
156	0.43	4.76	2.10×10^{-4}
670	0.50	7.27	1.38×10^{-4}
7000	0.10	0.21	4.76×10^{-3}

The results of the electrical measurements listed in Table I show that the electrical conductivity decreased as the volume of silver decreased. The values for the 5-hour and 7,000-hour wear life brushes were 15.15 and 0.21 milliohm^{-1}-cm^{-1}, respectively. Table I also shows that the room temperature resistivities of the brushes range from 10^{-5} - 10^{-3} ohm-cm; the brushes of long wear life have the higher resistivities. The results of the electrical measurements agree with the intensity ratio calculations and indicate that there is a variation in the silver content of the brushes.

Good conductors have resistivities in the vicinity of 10^{-6} ohm-cm with a positive temperature coefficient of resistivity (Ref. 8). Semiconductors are characterized by resistivities in the range of 10^{-2} to 10^{9} ohm-cm and by a negative temperature coefficient. The nominal 55.9% MoS_2 - 44.1% Ag (wt) brushes have resistivities which are intermediate between those of good semiconductors and good conductors and have positive temperature coefficients of resistivity. This is shown in FIG 1, which is a plot of ln σ (conductivity) as a function of T and $\frac{1000}{T}$, the slope of $\left(\frac{\ln \sigma}{T}\right)$ being negative. These brushes can be classified as as degenerate semiconductors. When a semiconductor has an impurity density of 10^{19} per cm^{3}, it acts as a high resistivity metal and is referred to as either a semimetal or a degenerate semiconductor (Ref. 9).

After establishing that the wear life of the brushes was dependent upon the silver content, it was necessary to determine why there was a variation in the silver content from brush to brush. This was accomplished by examining brush specimens prepared by each of the following procedures: (1) cold pressed (pressure only), (2) cold pressed and then sintered in a kiln (temperature only), and (3) hot pressed (temperature and pressure).

Structural examination of the unfired cold pressed specimens by X-ray diffraction revealed that the silver was well distributed throughout the specimens. The cold pressed specimens were then sintered in an electric kiln at 927°C (1700°F) and examined for silver distribution. It was found that the silver migrated toward the lower surface of the specimens (relative to their position in the kiln). The upper portion was rich in MoS_2. This was also observed visually, the upper portion having the macroscopic characteristics of MoS_2. Excessive silver migration occurred when the MoS_2-Ag compositions were densified in the absence of increased pressure. The excessive silver migration did not occur when the composites were subjected to both increased temperature and pressure during sintering; however, some migration occurred. In specimens that are hot pressed at

3,500 psi but at lower temperatures, some redistribution occurs. This redistribution increases with increasing processing temperature. At 927°C (1700°F), the redistribution is sufficient to produce an irregularity of silver in the slug so that there is a variation in the silver content among the brushes which are cut from the slug. The nominal 55.9% MoS_2 - 44.1% Ag (wt) brushes cut from the same slug hot pressed at 927°C (1700°F) at 3,500 psi had wear lives that ranged from 5.3 to 4,400 hours. This also indicates that there is a variation in the silver content of the brushes cut from the same slug.

To confirm the above observations, a microscopic examination was made. Light microscopy showed that the silver in the brushes hot pressed at 927°C (1700°F) was distributed as localized concentrations throughout a molybdenum disulfide matrix (FIG 2). This suggests that during hot pressing there is a migration of silver to the locations of lowest free energy. The silver forms an aggregate whose shape tends to be that of a spheroid in which the total surface energy is minimized. It is conceivable that this shape is being approached since some of the strain energy present is being relieved by plastic flow during sintering. The concentrations of silver are elliptical. The surface shown is the one that would contact the commutator during wear testing. This is normal to the pressure plane of the hot pressed slug from which the brushes are machined.

Commutator Surfaces

In this investigation, the commutator surfaces were studied to see if a correlation could be observed between the deposited films and brush materials. X-ray diffraction techniques were used to determine the crystalline phases of the surface films deposited on the commutators by the brushes during wear testing. Films deposited by the nominal 55.9% MoS_2 - 44.1% Ag (wt) brushes contained molybdenum disulfide and silver as principal co-existing crystalline phases. Brushes of short wear life deposited films that were rich in silver. These films contained small amounts of cuprous sulfide (Cu_2S) in addition to MoS_2 and Ag. Brushes of long wear life deposited films that contained MoS_2 as the major crystalline phase and that were low in silver content.

The resistances of the commutator films were measured, and the results are shown in Table II. Molybdenum disulfide films and the copper commutator surfaces have resistances of 400 and 270 milliohms, respectively. The resistances of the wear brush films are between these two values. Films deposited by brushes having wear duration of 7,000 and 51 hours have resistances of 350 and 290 milliohms, respectively. These results agree with the X-ray structural findings and show that the silver content plays an important role in the wear life of the brushes.

TABLE II

RESISTANCE OF COMMUTATOR FILMS

Film	Resistance (milliohms)
MoS_2	400
Cu Commutator Surface	270
7,000-hour	350
51-hour	290
Start of arcing	320

To obtain additional information and verify the above results, the powdered residue that collected in the test apparatus during wear testing of the brushes was analyzed by X-ray diffraction. The residue collected from brushes of long wear life contained MoS_2 as the major crystalline phase. Also, the amount of residue collected from these brushes was small, which indicated that the material transfer was slow. The residue collected from brushes of short wear life contained large pieces of material that appeared to have resulted from rupture of the film. This residue contained silver as the major crystalline phase. The wear of these brushes was heavy and was accompanied by arcing.

To determine the effect of arcing on the wear life of the brushes, brush samples were removed from the test apparatus at the start of arcing and examined. The brush wear surface had a large silver volume, the silver to molybdenum disulfide intensity ratio being 1.7. The resistivity along the length of the brush was 0.065 milliohm-cm. The commutator film showed silver as the major crystalline phase. These results verify previous findings, i.e., brushes of high silver concentration have short wear lives.

Metallic material transfer by arcing during contact has been discussed by Holm (Ref. 10). If the contact voltage can reach the melting voltage at the metallic contact spots, the molten metal can be transferred since the temperature of the contact surface is above that of the bulk material. The material loss is usually from the anode since the arc causes evaporation and transfer of the metal. The transfer is roughly proportional to the quantity of electricity that has passed through the arc.

The melting voltage of silver is given as 0.37 volts and the minimum arc current and voltage as 0.4 amperes and 12 volts, respectively. The test voltage and current for the brushes being analyzed exceed these minimum values. If the required concentration of silver is present, transfer of metal to the commutator surface is possible. It has also been observed in this analysis that, with arcing and heavy wear, one brush (probably the anode) wears at a much faster rate than the other.

During wear testing, it was noted that a discoloration of the commutator surface was associated with arcing. To determine if molybdenum disulfide contributed to this discoloration and to study its behavior as a brush material in a vacuum, a set of 100% MoS_2 brushes was wear tested. To start rotation of the commutator, a test voltage of 52 volts was required for the brushes without silver as compared to 15 volts for the silver-containing brushes. This would be expected in view of the higher resistance of MoS_2 arising from its semiconductive nature. A shiny black film indicative of MoS_2 dry film lubrication was first deposited on the commutator. With increasing time (10 minutes), the commutator surface on each side of the film assumed a dark blue tarnish which blended into a lavender tarnish as the edge of the commutator was approached. Next, the edges of the black film disappeared as metallic copper appeared, and another black film was deposited on the metallic copper. The black film then turned gray, and, with the color change, the magnet no longer could drive the commutator. The total test time was 20 minutes.

The commutator had to cool before rotation would start again. With the start of rotation, a black film was first deposited which, in turn, assumed a gray color. With this change, the magnet could no longer drive the commutator. There was no visible evidence of arcing.

The experimental results indicate that the discoloration can arise from a mechanism other than arcing. A metal spot in a non-contaminated atmosphere will tarnish when exposed to a sulfur-containing atmosphere (Ref. 7). With repeated contact, a sulfide film is formed which will grow with accelerated temperature until decomposition occurs. This can leave a white powder on the surface. If cooling is rapid enough after decomposition, the surface remains metallic.

With the MoS_2 brushes of this study, some sulfur appears to be released, especially from the edges of the film since the copper tarnishes. By the time the second MoS_2 film is deposited, a temperature is reached where some decomposition occurs. This leaves a grayish residue with a high coefficient of friction which opposes the action of the magnetic drive.

This experiment demonstrates the possibility of the release of sulfur from the molybdenum disulfide. The release of sulfur from the silver-containing brushes of short wear life is shown by the Cu_2S that is formed. This does not appear to be the case with the brushes of long wear life.

Optimum Brush Compositions

In view of the brush material and commutator surface results, an attempt was made to determine an optimum brush composition. The brushes with a wear life of 7,000 hours had a silver to molybdenum disulfide intensity ratio of 0.1 on a volume basis. This indicates that a brush with the approximate composition 90% MoS_2 - 10% Ag (80.5% MoS_2 - 19.5% Ag by weight) would give the best combination of lubrication and electrical conduction properties. If the optimum composition was in this vicinity, brushes of lower and higher silver content should be, respectively, non-metallic and metallic in conduction behavior, which was found to be the case. A composition of 74% MoS_2 - 26% Ag (wt) had a positive temperature coefficient of resistivity or a negative coefficient of conductivity. A composition of 86.2% MoS_2 - 13.8% Ag (wt) had a negative coefficient of resistivity or a positive coefficient of conductivity. A comparison shows that the metallic to non-metallic conduction transition occurs within the range of 13.8% to 26% (wt) of silver (FIG 3).

The plot of ($\frac{\ln \sigma}{1/T}$) of the 74% MoS_2 - 26% Ag body can be compared with that of the 55.9% MoS_2 - 44.1% Ag which had a 7,000-hour wear life (FIG 1). The values of conductivity are quite close, being in the range of 1 to 2 x 10^2 ohm^{-1}-cm^{-1}. The slopes are the same; the temperature dependence is quite low.

The plot of ($\frac{\ln \sigma}{1/T}$) of the 86.2% MoS_2 - 13.8% Ag body is shown in FIG 3 with that of the 100% MoS_2 composition. The conductivities lie within the same order of magnitude, and both have the negative coefficient of resistivity characteristic of non-metallic conduction. Since both follow an Arrhenius plot, there is an activation process involved. The activation energies of the 100% MoS_2 and the 86.2% MoS_2 compositions are 0.27 and 0.20 eV, respectively.

This evidence suggests that a composition containing a minimum amount of silver may give the molybdenum disulfide the electrical conduction required for use as an electrical contact without losing the lubrication properties of the hexagonal structure. Without this metallic addition, as was shown, the value of the electrical resistance of the MoS_2 is too large for the MoS_2 to be used as a dry film lubricant.

In view of this, brushes of 80.5% MoS_2 - 19.5% Ag were wear tested in a vacuum. A set of brushes and their commutator film that has run for 2,085 hours have been analyzed. The wear brush surfaces and commutator films have characteristics that were predicted. Tarnishing of the commutator occurred over the period of testing without interruption of the test. The stoppage of the test was not caused by the brush specimens but is believed to have been caused by the specimen holder which appeared to have prevented material transfer and, thus, caused stoppage of the test.

CONCLUSIONS

In a program to evaluate materials for use as electrical contact brushes in vacuum, molybdenum disulfide containing metallic additives has shown promise. However, the wear life test results for a particular composition have not been reproducible since they vary from a few hours to several thousand hours. The non-reproducibility has been analyzed. Most of the analysis was concentrated on brushes having a nominal starting composition of 55.9% MoS_2 - 44.1% Ag (wt).

The analysis has shown that the primary contribution to the variation in wear life is a variation in the silver content of the brushes caused by silver migration during processing. The wear life of the brushes varies inversely with the volume of silver at the wear surface.

The surface film deposited on the commutator by the short wear life brushes is rich in silver as is the brush wear surface; the silver content is minimized for brushes of long wear life.

A large silver concentration on the brush wear surface provides the conditions for the initiation of arcing and the melting, evaporation, and transfer of the silver to the commutator surface. The silver deposition on the commutator surface results in destruction of the lubricating film and stoppage of the wear test.

The variable silver concentration in the brush specimens comes from an irregular silver distribution in the hot pressed slug from which the specimens are cut. This is not a result of poor mixing or of the pre-pressing process; during hot pressing, there is migration of the silver so that it is distributed in localized concentrations throughout the molybdenum disulfide matrix.

Investigation of the 100% MoS_2 brushes shows that sulfur can be released, and decomposition of the lubricating film can occur independently of arcing.

The nominal 55.9% MoS_2 - 44.1% Ag brushes can be classified as semimetals or degenerate semiconductors. They have resistivities in the range of 10^{-5} to 10^{-3} ohm-cm and positive temperature coefficients of resistivity; the brushes of longer wear life have the higher resistivities.

Based upon the results of this analysis, it appears that a brush containing 13.8-26% (wt) silver should give the best combination of lubrication and electrical conduction properties, the approximate optimum composition being 80.5% MoS_2 - 19.5% Ag.

FUTURE WORK

Additional work is planned to extend the study of the molybdenum disulfide-silver system to optimize the electrical properties and to improve the wear life reliability. This will include studying the effects of such processing variables as time, temperature, and hot pressing pressure on the electrical and physical properties of the brushes. The effects of the initial particle size and purity of the raw materials will be studied also. Other material systems, based on compounds structurally similar to molybdenum disulfide and with metallic additives for increased conductivity, will be investigated to determine if they possess inherent advantages over the MoS_2-Ag system.

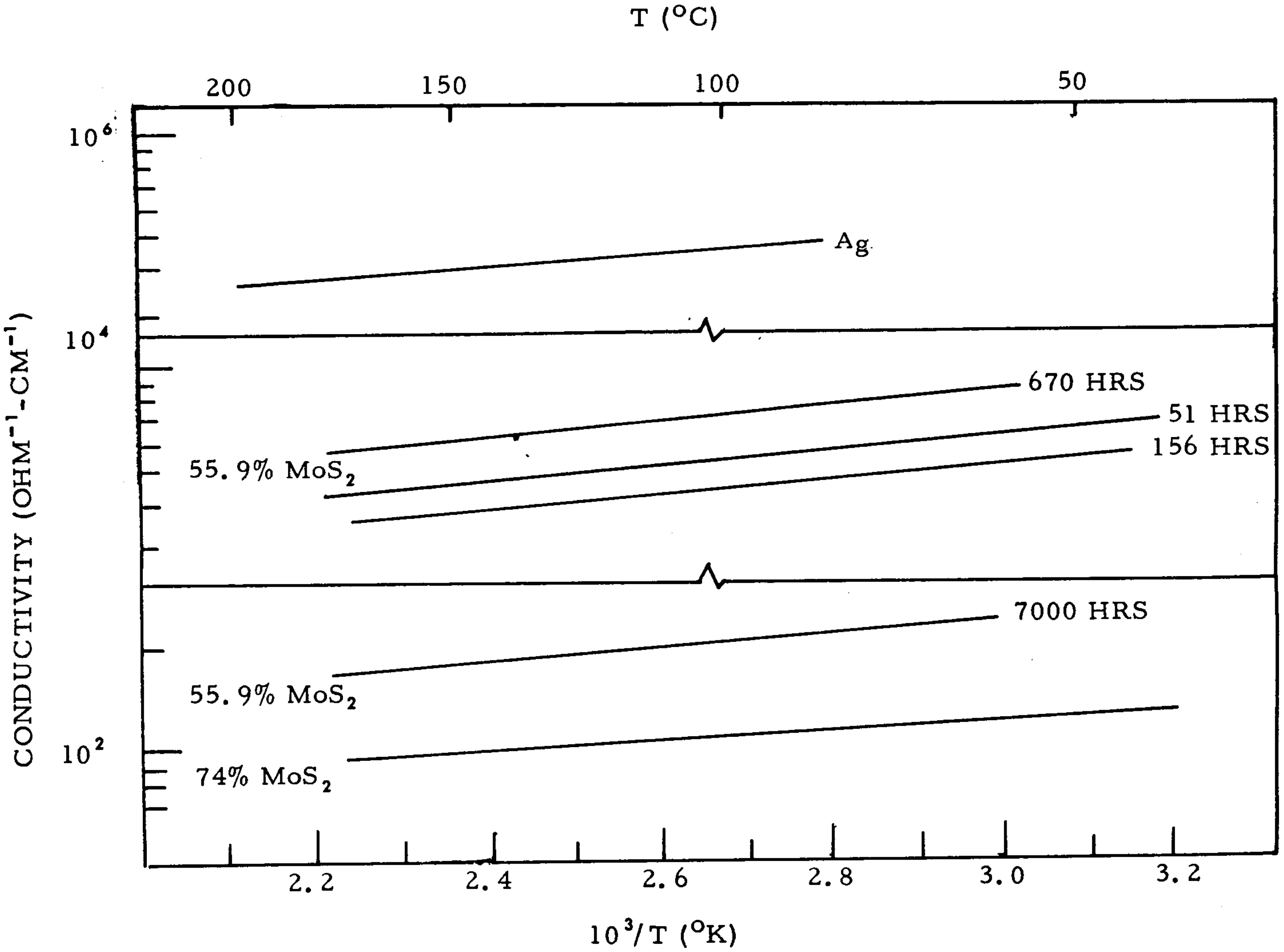

FIGURE 1

CONDUCTIVITY OF METALLIC SILVER AND THE 55.9% AND 74% MoS_2 COMPOSITIONS AS A FUNCTION OF 1/T

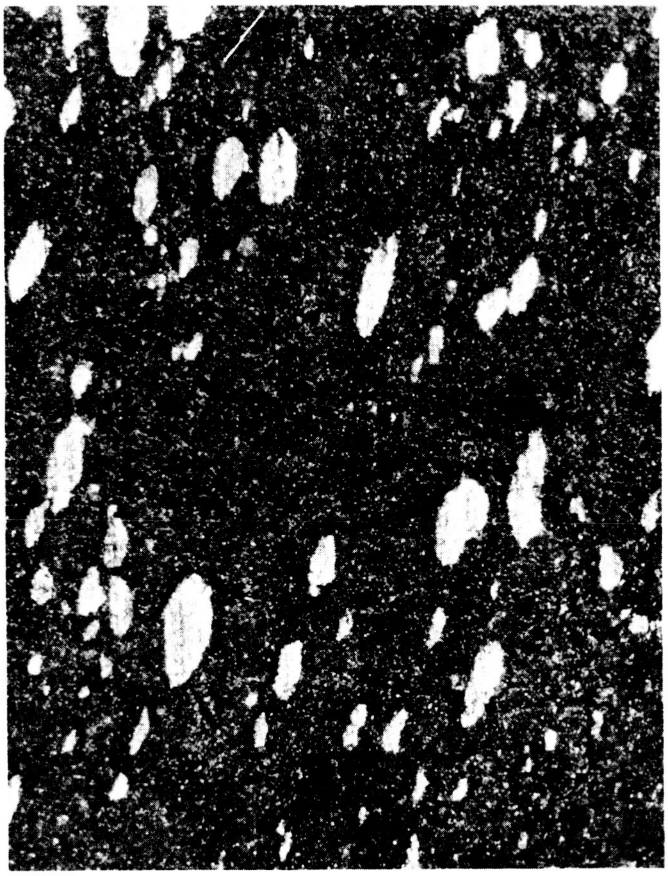

FIGURE 2

Microphotograph of the 55.9% MoS_2 - 44.1% Ag Composition (X200)

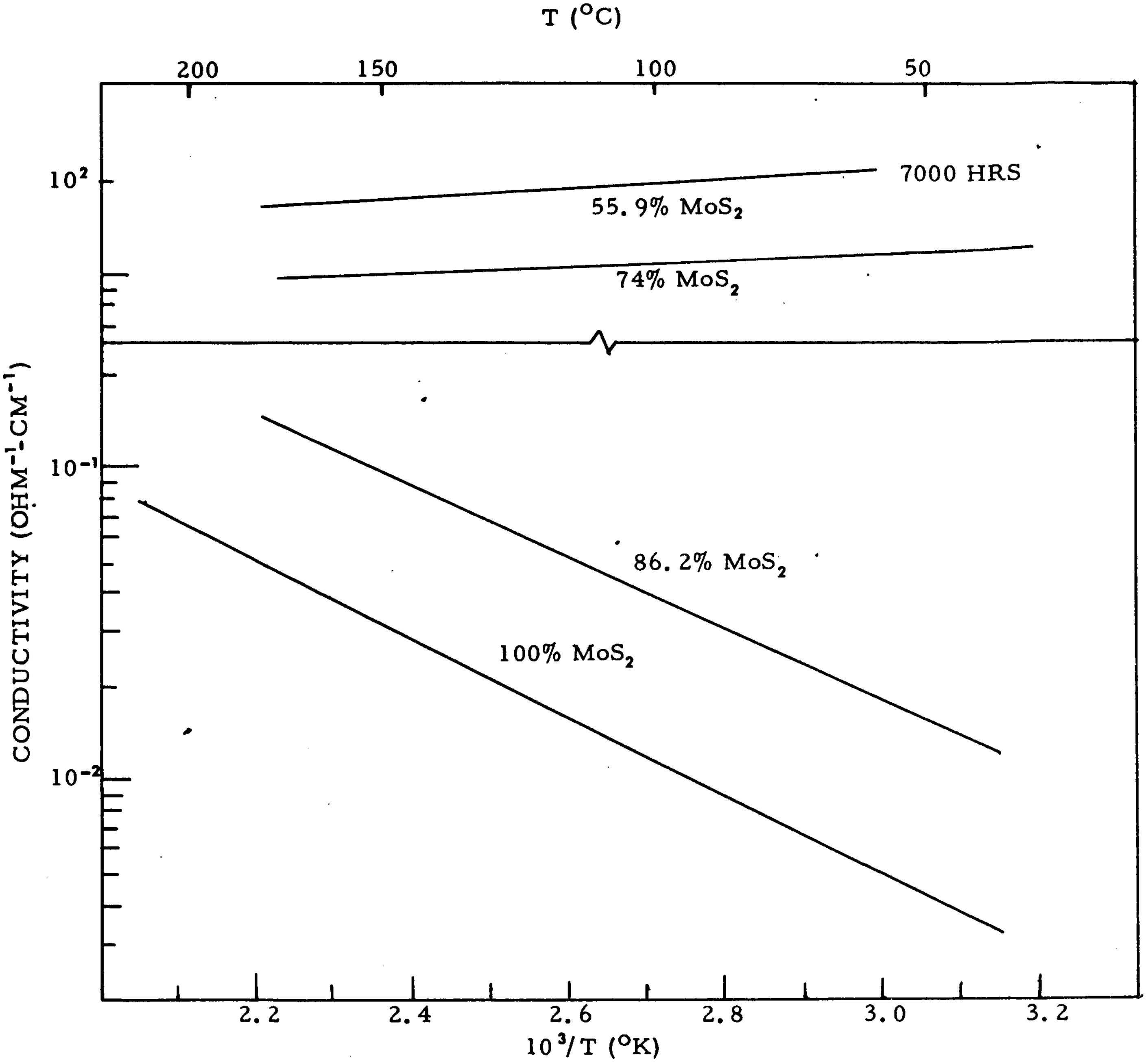

FIGURE 3

CONDUCTIVITY OF THE 100%, 86.2%, 74%, AND 55.9% MoS_2 COMPOSITIONS AS A FUNCTION OF 1/T

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By Dr. Donald R. Ulrich

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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