SLIDING ELECTRIC CONTACTS IN SPACE: OBSERVATIONS ON EXISTING TECHNOLOGY AND NEW TRENDS IN LOW-SPEED APPLICATIONS

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ABSTRACT

Although it has been generally accepted that slip-rings employing self-lubricating composite brushes provide adequate solutions to the tribological and electrical problems of operating sliding electrical contacts in space there is evidence to suggest possible shortcomings. These shortcomings relate to the susceptibility of the contact materials to contamination and the effects this might have on the electrical performance of the slip-rings. The paper analyses the likely results of surface contamination as it applies to existing slip-ring materials and also looks at the relevant properties of brush materials, particularly those of silver and molybdenum disulphide. Methods of avoiding lubrication in slip-rings for low speed applications are discussed, together with some practical results. The possible advantages of multi-"strand" brushes in high current applications are analysed.

Keywords: Electric Contacts, Vacuum, Dry Lubrication, Contamination.

1. INTRODUCTION

The transfer of electricity across relatively moving parts in spacecraft mechanisms is largely accomplished through the employment of appropriately designed brush/slip-ring systems. Such designs must allow for the special requirements of sliding electrical contacts operating in an environment which is both inaccessible and, in some ways, hazardous. The highest emphasis is thus placed on achieving high mechanism reliability and selecting materials which are suitable for employment in the space environment.

The need for reliability calls for the following requirements:

1. A low wear rate of brush and ring materials so that debris production is kept low thereby ensuring long operating lifetimes and minimising the likelihood of short circuits across adjacent slip-rings.
2. Low contact resistance during power transmission so that power losses and temperature rises due to Joule heating are kept low.
3. Low electrical noise so that interference with associated circuitry can be tolerated.
4. Low friction so that torque requirements are kept low.
5. Contact materials which are unaffected by gaseous or other forms of contamination so that no degradation in performance occurs as a result of pre-flight storage and testing.

Though stringent, these requirements are met by the simplest of devices - the brush/slip-ring assembly. A large measure of this success can be attributed to the employment of monolithic brushes fabricated from self-lubricating composites. The implementation of lubrication in this manner has been shown to offer several advantages, particularly in terms of long-term reliability, over other methods - such as those employing fluid lubrication. Within this technology, composites based on silver and molybdenum disulphide have become established brush materials with silver or gold as corresponding ring materials.

In general, these materials have proved successful in a variety of space applications. Yet despite this there is increasing concern regarding their suitability for their intended tasks. Much of this concern centres on the integrity of the materials in question following their subjection to storage and pre-launch testing. This paper reports observations of anomalous electrical behaviour which have raised doubts over the materials employed and possible reasons for such behaviour are examined. It is argued that an improvement in reliability of low speed slip-rings might be obtained through the withdrawal of lubrication and the implementation of alternative contact materials in novel brush and ring configurations.

TABLE I

ADVANTAGES OF DRY LUBRICANTS OVER LUBRICATING OILS

DRY LUBRICANTS	WET LUBRICANTS
1. REASONABLY HIGH ELECTRICAL CONDUCTIVITY	ELECTRICALLY INSULATING
2. SELF - REPLENISHING	EXHAUSTIBLE SUPPLY.
3. DO NOT POSE A CONTAMINATION THREAT.	OIL VAPOUR CAN CONDENSE ON OTHER COMPONENTS.
4. CHEMICALLY STABLE DURING STORAGE.	DEGRADATION POSSIBLE.
5. WIDE OPERATING TEMPERATURES.	LIMITED TEMPERATURE RANGE OF OPERATION.
6. ACCELERATED TESTING VALID.	NOT FEASIBLE DUE TO TIME-DEPENDENT FACTORS.

2. DEVELOPMENT OF SELF-LUBRICATING COMPOSITE BRUSHES FOR USE IN SPACE

The realisation that graphite and silver-graphitic brushes wear rapidly under high vacuum necessitated the examination of other materials as potential sliding electrical contacts for space applications. The approach taken was to employ contacts of precious metal or precious metal alloys and to lubricate these with either wet or dry forms of lubrication. The notion of implementing dry lubrication by incorporation of solid lubricants in the brush block was first proposed by Clauss and Kingery (Ref 1). In this manner lubricant is continuously made available at the sliding interface for as long as brush wear takes place.

It became clear that, in the main, the advantages of dry lubrication implemented in this manner outweighed those of wet lubrication. A list of comparisons between the two lubricant forms is given in Table 1. The sixth advantage, that of the validity of accelerated testing, was established by Cunningham et al (Ref 2) and is of great significance as real-life testing of mechanisms is generally precluded because of the lengthy duration of most space missions.

In Clauss and Kingery's work composite brush material containing silver, molybdenum disulphide and copper was prepared by cold pressing of a powdered mixture of the constituents followed by sintering in vacuum (Ref 1). It was established that the near optimum composition, as judged from measurements of contact-resistance, electrical noise and contact wear, was 82.5% to 85% by wt. silver; 15% to 12.5% by wt. MoS_2 ; 2.5% by wt. copper. Other metal dichalcogenides have since been examined as lubricants for composite brushes (Refs 3 and 4) but none has given rise to any significant improvement in contact performance, either tribologically or electrically, over that obtained with molybdenum disulphide - this despite the latter's comparatively high electrical resistivity (Ref 5). Since Clauss and Kingery's work in the mid-Sixties the

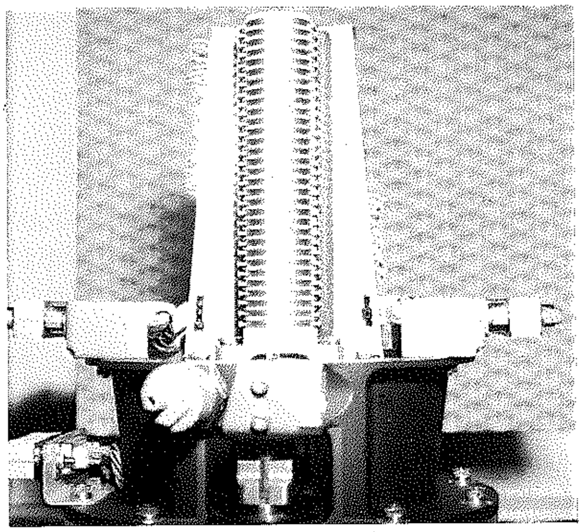

Fig 1. Slip rings of a solar array drive mechanism (European Communications Satellite)

material combination of silver, molybdenum disulphide and copper proposed by them has become an established brush material for space applications, albeit with slight variations in component concentrations.

Such brushes are normally employed in conjunction with silver or gold plated rings. Typically an arrangement of slip-rings within a satellite mechanism consists of an array of spring-supported brushes held against a series of shaft-supported rings. Such an arrangement is depicted in fig 1. The slip- ring assembly pictured is that of a solar array drive mechanism (SADM) of a European Communications Satellite. These electrical contacts are used for the transfer of electicity at both signal levels (mA) and power levels (amps).

3. OBSERVATIONS OF ANOMALOUS ELECTRICAL BEHAVIOUR

There is little doubt that the employment of Ag/MoS_2 based composite brushes in low speed, satellite applications has become firmly established and that this reflects the adequate performance afforded by them. However, whilst a satisfactory tribological and electrical performance is generally obtained there is evidence that such contacts, on occasion, exhibit anomalous electrical behaviour and that this has created doubt regarding contact reliability. This view is supported by the following observations made at ESTL.

i) Observations of Contacts Having a Negative Coefficient of Resistance

Routine thermal vacuum testing of solar array drive mechanisms of geostationary satellites shows that in general slip-ring contacts employing composite brushes exhibit a positive thermal coefficient of resistance. This is illustrated in fig 2a in which the voltages developed across slip-rings of a typical SADM for a fixed current flow (3 amps) are seen to

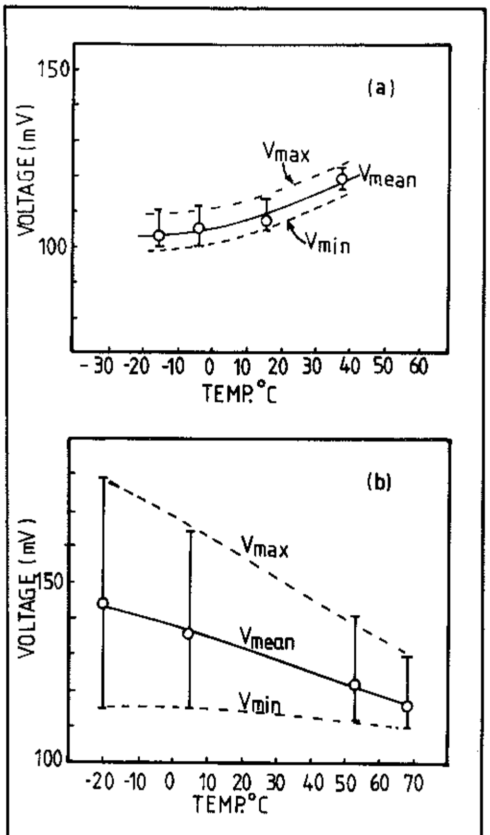

FIG. 2 VOLTAGES (mean, max, min) ACROSS SLIP-RING PAIRS VS. TEMP. (UNDER VACUUM; CURRENT=3amps). (a) NORMAL CHARACTERISTICS (b) ANOMALOUS CHARACTERISTICS.

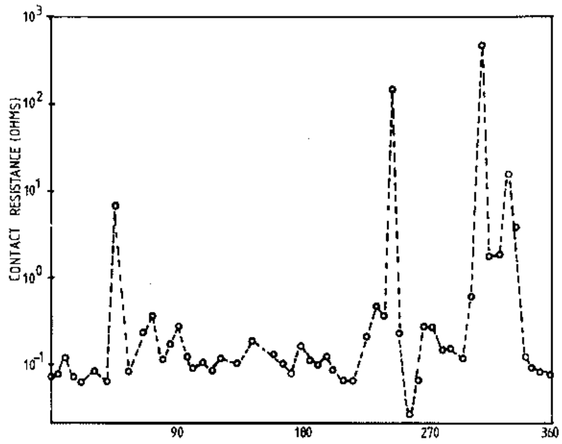

FIG. 3 VARIATION IN CONTACT RESISTANCE ACROSS BRUSH/RING INTERFACE WITH RING POSITION (MOD BAPTA ASSEMBLY AFTER STORAGE)

increase with increasing temperature. The voltage levels depicted represent the mean, minimum and maximum voltages recorded during one slip-ring revolution at the indicated temperature. An increase in contact resistance with increasing temperature as observed here is characteristic of 'metallic' conduction. On occasion however, the converse behaviour has been observed. An example of this is shown in fig 2b wherein the voltage drop, and therefore the contact resistance, is seen to decrease with increasing temperature. Such behaviour is characteristic of electrical conduction through a semiconductor and may indicate the presence of semiconducting material at the sliding interface. This has important implications with regard to electrical transfer particularly at low currents and will be discussed in section 4.

ii) Observations of High Contact Resistance

An examination of the electrical characteristics of a slip-ring unit known to have undergone prolonged storage has revealed evidence of high contact resistances. The slip-ring unit in question formed part of a SADM which had previously been subjected to accelerated life-testing at ESTL (Ref 3) and which subsequently was stored for some five years under clean room conditions. Measurements of contact resistance were made at each brush/ring interface at several ring-shaft positions. An example of data thus obtained corresponding to one of the rings is shown in fig 3. It is observed that as several ring positions there exist large excursions in resistance (measured for a current flow of 50 mA) corresponding to increases in contact resistance of up to 200ohms.

4. THE EFFECTS OF CONTAMINATION AND INTERFACIAL FILMS ON ELECTRICAL PERFORMANCE

To an extent all electrical contact materials are effected by the environments in which they are manufactured, tested and operated. In applications intended for space usage it can, with some justification, be said that the principal threat to contact integrity occurs during ground testing and pre-launch storage. In space and, to a lesser extent, within the satellite interior the greatly reduced pressures of gases (Ref 7) provide, from the view point of electrical performance, a more benign environment in which to operate sliding electrical contacts: whereas on earth the likelihood of contamination due to adsorption of airborne gases is greater. It is pertinent therefore to consider the vulnerability of each component of contact materials to contamination when exposed to laboratory air. In doing this, the intention is not to produce specific explanations of the observations described in the preceding section, but rather to consider what effects might lead to or contribute to such behaviour.

Silver

The tendency of silver surfaces to form tarnish layers is widely known. This susceptibility and the chemical nature of the

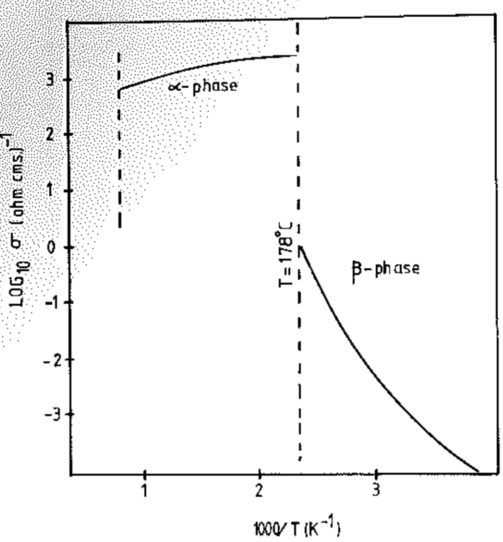

FIG.4 ELECTRICAL CONDUCTIVITY, σ, OF Ag_2S VS. INVERSE TEMPERATURE (AFTER JUNOD ET AL)

resultant tarnish layer vary according to the environment to which the metal is exposed. Thus outdoor exposure leads to tarnish layers containing, in the main, silver sulphate and silver chloride whereas indoors silver is more likely to react with hydrogen sulphide to form silver sulphide (Refs 8,9). It is further known that the rate of growth of silver sulphide on silver increases with increasing concentration of hydrogen sulphide and that, generally, an increase in relative humidity also leads to enhanced film growth (Ref 8).

Analyses of films formed on silver under normal laboratory conditions indicate the principal tarnish product to be Ag_2S (Refs 8 and 9), this being a low temperature phase stable up to 178°C whereupon it transforms to Ag_2S. In the β phase Ag_2S exhibits a metal-like character in that its electrical conductivity decreases with increasing temperature whereas the β form displays an increase in electrical conductivity with increasing temperature (fig 4) and is considered a semi- conductor (Ref 10).

In the temperature range of slip-ring operation in geosynchronous satellites (and that of thermal vacuum testing on earth), silver sulphide would assume its semiconducting form. If present at the contact interface it would impart its highest resistance at the lower end of the temperature range (fig 4), ie. under eclipse conditions. This resistance would be lower on power slip-rings (as opposed to signal slip rings) because of the additional heat generated there as a result of electrical power dissipation. In addition to changes in resistance within the body of the film there would arise barrier resistances at metal-semiconductor interfaces (Schottky barriers). Such junctions could exhibit rectifying properties and again these would impede electrical flow to a greater extent at low currents as the barrier resistance decreases with increasing current flow.

Two further properties of silver sulphide call for mention. First Ag_2S is an ionic crystal in which the positive silver ions have high mobility. Secondly, its conductivity is sensitive to the degree of stoichiometry and increases with silver content (Ref 11). These two properties are thought to give rise to time and polarity dependent impedances on sulfided, silver contacts (Ref 12). The resistance of such contacts was observed to change following a reversal in polarity of the applied voltage. This change in resistance had two components: an instantaneous change and a time-dependent change, the latter occuring over a period of some minutes. Depending on whether the polarity reversal brought about an increase or decrease in contact resistance the effect was attributed to either depletion or enhancement of silver concentration (through the field-induced movement of silver ions) within the silver sulphide film.

Summarising the possible effects the presence of Ag_2S has on contact characteristics we have:

i) A contact resistance exhibiting a negative coefficient of resistance.

ii) High contact resistance, particularly at low currents.

iii) Time and polarity dependent contact resistances.

It is important to realise that the validity of the above statements holds only for thicknesses of Ag_2S film in excess of a certain minimum. For film thicknesses less than about 20Å electronic conduction is likely to occur by means of electron tunneling which will take precedence over all other conduction processes and give rise to near ohmic ("metallic") behaviour. This is a significant factor which could bear on contact performance if, for example, under the action of sliding and shearing, the Ag_2S film thickness became progressively reduced. The softness of silver sulphide when present on pure silver (Ref 13) coupled with its low shear stress would certainly favour smearing of such films and a consequent reduction in thickness.

Molybdenum Disulphide

In contrast to silver and its compounds there is little experimental data available on the effects of contamination on the electrical properties of molybdenum disulphide. Indeed this lack of knowledge extends to the properties of intrisic MoS_2 in that there is considerable uncertainty regarding its true value of electrical resistivity. Thus Lansdown (ref 14) in a review of MoS_2 properties reports that measured values of the electrical resistivity of MoS_2 vary by factors of up to 10^9. Since it is generally

TABLE 2

EFFECT OF INTERFACIAL FILM ON CONTACT RESISTANCE

FILM TYPE	THICKNESS	EFFECT ON CONTACT RESISTANCE, R
SEMICONDUCTOR/INSULATOR	< 20Å	OHMIC CHARACTERISTICS/ LOW R
β Ag_2S	>20Å	HIGH R AT LOW CURRENT, LOW TEMPERATURE dR/dT NEGATIVE (T- TEMPERATURE) TIME AND POLARITY DEPENDENT R
DRY MoS_2	> 20Å	HIGH R AT LOW CURRENT, LOW TEMPERATURE dR/dT NEGATIVE
MOIST MoS_2	> 20Å	HIGH R

accepted that MoS_2 has semiconducting properties (its electrical resistivity decreases with increasing temperature ref 14) much of this disagreement may originate from variations in sample purity as the resistivity of semiconductors is extremely sensitive to impurity concentration.

Because of these semiconducting qualities we might expect MoS_2, as with Ag_2S, to be more resistive at low temperatures and offer greater resistance to current transfer when current flow is relatively low.

The only atmospheric contaminant known with any certainty to degrade the electrical (and tribological) characteristics of MoS_2 under ambient conditions is moisture. This is observed to promote the formation of a viscous film at the contact interface when MoS_2 composite brushes are run in air (ref 15) which gives rise to higher friction and higher contact resistance (up to 8ohms).

Copper

Some brush manufacturers, particularly in Europe, include a small quantity of copper (2.5% by wt) in the Ag/MoS_2 brush composite material. The inclusion of copper is intended to harden the silver (through alloying) and bring about an improved wear performance. It is unclear as to how this amount of copper affects - if at all - the tarnishing properties of the silver-copper alloy, though there exists evidence to suggest it relevant. Thus Simon et al (ref 16), in a study of the contamination of pure silver and silver-copper alloys in synthetic air containing controlled quantities of H_2O and H_2S, found the principal tarnish product on silver-copper alloys containing 10% Cu to be copper sulphide. In view of this it is of interest to note that copper contacts contaminated with copper sulphide display non-ohmic behaviour (ref 17) consistent with the properties of a metal-semiconductor type junction.

A summary of the predicted effects of interfacial films on contact performance (electrically) is given in Table 2.

5. NEW SLIP-RINGS FOR LOW SPEED APPLICATIONS

Based on the foregoing discussion we can conceive situations in which MoS_2, in pure or

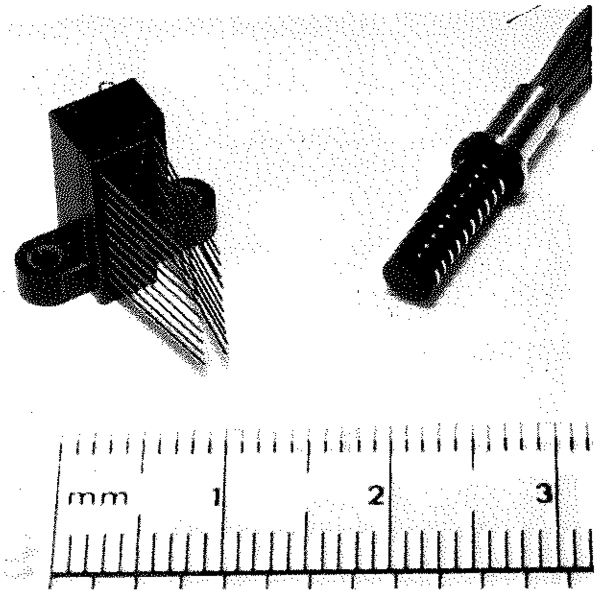

Fig 5. Miniature Signal Slip-ring Assembly

contaminated form, or tarnished silver could give rise to adverse contact performance. It follows that contact susceptibility to the formation of anomalously high resistances is likely to be reduced if:

i. the need for lubrication is removed such that there are no poorly conducting lubricant films at the sliding interfaces

ii. contact materials are replaced by metals or metal alloys which are better able to resist tarnishing and the build up of resistive surface films.

If lubricants are to be eliminated then ways of reducing the consequent increases in frictional torque and contact wear must be sought. In the case of low speed applications where the total sliding distance is low this may be possible but the approach taken towards achieving this goal will differ according to whether the application is intended for low current (signal) or high current (power) transmission.

5.1 Signal slip-rings

Slip-rings of solar array drive mechanisms of geostationary satellites undergo relatively few ring revolutions in the operational lifetime of the satellite (typically 4000 revolutions in 10 years). Typically, slip-rings of radius 1cm are employed such that total sliding distances are in the order 250 metres. Without lubrication the production of wear debris over such sliding distances is likely to reach unacceptably high levels. However, in the case of low current slip-rings the total sliding distance undergone can be very much reduced by use of slip-rings of decreased diameter. In this manner, wear, even in the absence of lubrication, is maintained at acceptable levels. Furthermore since the dissipation of Joule heat is negligible at low current contacts, relatively high contact resistances can be tolerated and light brush loads are thus warranted. This

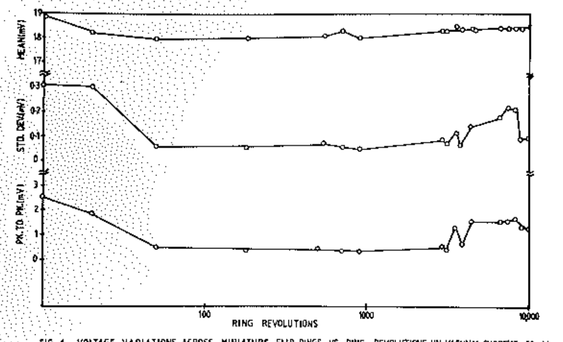

FIG. 6 VOLTAGE VARIATIONS ACROSS MINIATURE SLIP-RINGS VS. RING REVOLUTIONS (IN VACUUM; CURRENT = 50mA)

further alleviates the problem of wear and additionally ensures, in combination with a small ring diameter, low frictional torque.

A slip-ring assembly whose design is based on the adoption of these notions is shown in fig. 5. The assembly comprises an epoxy brush block supporting ten pairs of metal alloy brush wires and a slip-ring shaft consisting of ten gold-alloy plated V-grooved rings set within an epoxy core. Brush wires are manufactured from a commercial metal alloy (Ney OroG) which the manufacturers claim to be resistant to tarnish and corrosion. The arrangement provides each ring with a complement of two brushes such that an element of redundancy is obtained. Each ring has a diameter of 3.5mm such that the total sliding distance over 10 years amounts to 45 meters (operating at 1rev/day). The contact load is of the order of a few grams per contact wire.

The above slip-ring assembly was tested at ESTL under high vacuum over 10,000 revolutions at a speed of 30 revs/hr. Throughout the test a satisfactory electrical performance was observed with no large variations in contact resistance. This is illustrated in fig 6 in which the mean voltage drop and noise voltages (in terms of standard deviation and peak to peak of sampled voltages) developed across one of the slip-ring pairs examined are plotted against number of ring revolutions. Examination of brush surfaces by means of scanning electron microscopy following testing revealed shallow wear scars of imperceptible depth in areas where rubbing had occured (fig 7). These areas were distinguishable from vicinal areas by the accumulation of small quantities of wear debris along wear scar peripheries. There was no evidence of ring wear.

Miniature, un-lubricated slip-rings are thus observed to be capable of satisfactory electrical transmission and give rise to little contact wear. The ability of the alloys employed (as contact materials) to withstand the formation of electrically sensitive films during ground testing and storage is however untested and remains unproven. There is an important distinction to be drawn here between a material's ability

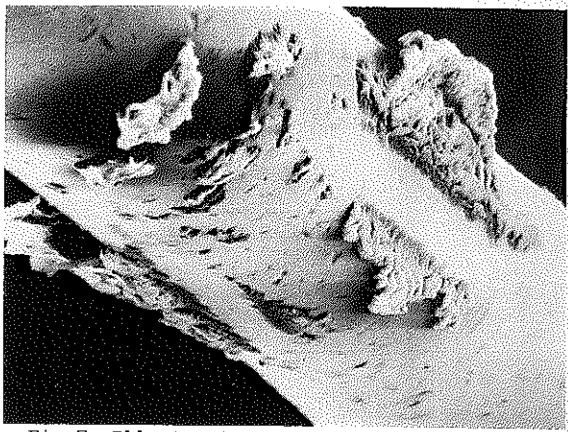
Fig 7 Illustrating wear scars and debris build-up on gold-alloy brush wire

to resist tarnishing and that material's ability to inhibit the growth of electrically resistive films. 'Tarnish-resistance' implies a rate of growth of tarnish layers which is very low yet finite. However, thinner tarnish layers do not necessarily signify lower contact resistance, for as Abbott (ref 13) has shown the resistance of contacts contaminated with a tarnish layer of given composition and thickness is dependent on the substrate on which it is formed. Thus for example silver alloy contacts, though exhibiting greater tarnish-resistance, are shown to be considerably more resistive electrically than pure silver contacts when Ag_2S films of a given thickness are present at the contact interfaces.

The above underlines the caution which should accompany the introduction of new contact materials and emphasises the importance of thorough testing prior to the acceptance of such materials.

5.2 Power slip-rings: the potential of metallic fibre brushes

It has been shown how the effects of increased torque and wear consequent upon the removal of lubrication from low current slip- rings can be overcome through reductions in ring size and brush loads. Such an approach, however, is not feasible in the case of power slip-rings employing monolithic brushes as such actions would bring about substantially higher operating temperatures due to increased I^2R losses.

Much of the heat evolved through operation of monolithic brushes occurs at the contact interface where electrical energy is dissipated in constriction and film resistances: the constriction resistance arising from the asperity like nature of contacting points and the film resistance being attribu- table to the presence of interfacial films of lubricant and/or contamination. However both resistive components could, in theory, be reduced substantially through the replacement of monolithic brushes with metallic fibre brushes.

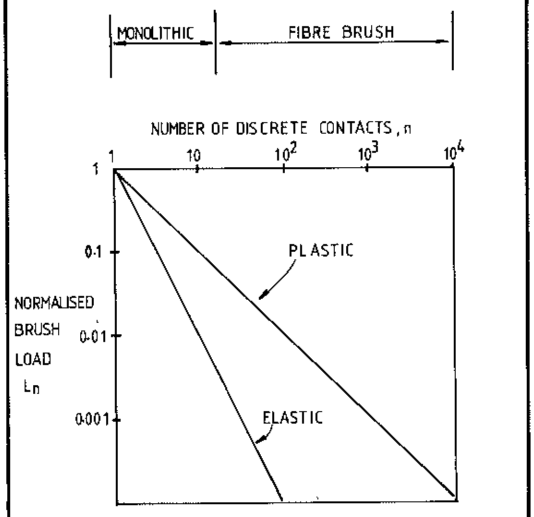

FIG 8 ILLUSTRATING HOW THE BRUSH LOAD REQUIRED TO PRODUCE A GIVEN CONSTRICTION RESISTANCE DECREASES WITH INCREASING NUMBER OF CONTACTS.

This arises from the fact that for a given contact load the constriction resistance decreases with increasing number of contacting points. It is known that monolithic brushes give rise to only a small number of points at which contact is made - typically this lies in the range 1 to 20 (Ref 18) - whereas the number of contacts available from a fibre brushes is as large as the number of metal fibres contacting the ring and this can be made to be many hundreds or more. A brief examination of the underlying principles of contact theory serves to illustrate this dependence of constriction resistance on number of contacts.

The constriction resistance, Rc, associated with a single asperity contact is given by:

$$Rc = \frac{\rho}{2a} \qquad (1)$$

where ρ is the electrical resistivity of the contact material and a is the radius of the contact area, assumed circular.

The value of 'a' is dependent on whether contact deformation is plastic or elastic.

For plastic deformation,

$$a = \sqrt{\frac{L}{\pi H}} \qquad (2)$$

where L is the contact load and H the hardness of the contact materials.

Substituting (2) in (1) gives

$$Rc = \frac{\rho}{2}\sqrt{\frac{\pi H}{L}} \qquad (3)$$

Now assume 'n' identical contacts sharing the load L equally such that the load per contact is L/n.

The constriction resistance per contact =

$$\frac{\rho}{2}\sqrt{\frac{\pi H n}{L}} \qquad (4)$$

such that the total resistance of 'n' such contacts contacts in parallel =

$$\frac{\rho}{2}\sqrt{\frac{\pi H}{nL}} \qquad (5)$$

Thus constriction resistance is proportional to $n^{-\frac{1}{2}}$. In a similar manner it can be shown that if contact deformation is elastic then the constriction resistance is proportional to $n^{-\frac{2}{3}}$. Constriction resistance therefore decreases rapidly as the number of contacting spots is increased. It follows from equation 5 that the load L required to produce a given constriction resistance also decreases rapidly with 'n' and it can be shown that,

for plastic contact deformation, $L \propto \frac{1}{n}$ (6)

for elastic contact deformation, $L \propto \frac{1}{n^2}$ (7)

Based on equations 6 and 7, fig 8 plots the normalised brush load, Ln, required to give a fixed constriction resistance as a function of number of contact spots (the load is normalised such that for a single point contact the required load is unity). The graph illustrates that, depending on the number of fibres employed and the mode of contact deformation, fibre brush loads of upto a factor 10^3 less than monolithic brush loads can be employed without incurring increases in constriction resistance above that obtained with the monolithic brush. It seems reasonable to expect therefore that by employing fibre brushes the brush load can be decreased to a point where lubrication is deemed unnecessary, thereby eliminating a component of film resistance.

Considerable attention is now being paid to the potential use of fibre brushes in terrestrial applications (Ref 18, 19, 20) in which transfer of high currents at high speeds is called for. The technology would appear to exist for producing metallic fibres of the requisite dimensions and stiffness and the manufacture of brushes having thousands of fibres per square centimetre (Ref 18). Some interest is currently being shown in the application of these concepts to space slip-rings. It remains to be seen, however, whether metallic fibre brushes will be fully exploited for this purpose.

6. CONCLUDING REMARKS

It has been shown how evidence derived from both experimental observations and theoretical considerations supports the view that sliding electrical contacts employing silver/molybdenum disulphide composite brushes are capable of anomalous electrical behaviour. Such behaviour includes the development of high contact resistances and contacts which exhibit a negative temperature coefficient of resistance. It is thought that such effects arise as a consequence of the susceptibility of silver or that of molybdenum disulphide to atmospheric contamination, or as a result of the electronic properties of intrinsic MoS_2 or some combination of these. On this basis it is argued that an improvement in contact reliability might be obtained by operating low speed slip-rings without lubrication and employing alternative contact materials such as alloys which are better able to resist tarnishing. The reservation is held that such tarnish-resistant materials must be shown to be capable of withstanding the development of electrically-resistive films as a result of atmospheric exposure. Miniature slip-rings operating without lubrication are shown to be effective for low current, signal transmission. It is shown how, in principle, metallic fibre brushes are capable of high current transmission at low brush loads such that lubrication may be unnecessary.

7. REFERENCES

1. Clauss F J and Kingery M K 1967, Sliding electrical contact materials for use in ultrahigh vacuum, J Spacecraft Vol 4.
2. Meeks G R, Christy R I and Cunninham A C 1970, Accelerated vacuum testing of long life ball bearings and slip-rings, 5th Aerospace Mechanisms Symposium N.A.S.A. Goddard Flight Center June 1970.
3. Lewis N E et al 1975, Friction, wear and noise of slip ring and brush contacts for synchronous satellite use, Proc. First European Space Tribology Symposium, Frascati, April 1975.
4. Dalley K R and O'Donnell P J 1975, Design and performance of electrical contacts for use in ultrahigh vacuum, Proc. First European Space Tribology Symposium, Frascati April 1975.
5. Boes D J 1964, New solid lubricants: preparation, properties and potentials, IEEE Trans. Aerospace vol 2 457.
6. Parker K 1979, Thermal Vacuum Qualification and Accelerated Life Tests on a British Aerospace Dynamics Group Modified OTS Drive (MOD BAPTA), ESA (ESTL) 41.
7. Robbins E J 1975, Tribology tests for satellite application: simulation of the space environment, Proc First European Space Tribology Symposium, Frascati, April 1975.
8. Crossland W A and Knight E 1973, The tarnishing of silver-palladium surfaces and its effects on contact resistance in low energy circuits, Proc. Holm Seminar on Electric Contact Phenomena, Chicago 1973.
9. Crossland W A et al, 1973, The accelerated tarnish testing of contacts and connectors employing silver alloy contacts, Proc. Holm Seminar on Electric Contact Phenomena, Chicago, 1973.
10. Junod P et al 1977, Metal-non-metal transition in silver chalcogenides Philosphical Magazine Vol 36 No 4 941-958.
11. Hebb M H 1952, Electrical conductivity of silver sulphide, J Chem Phys Vol 20 185-190.
12. Russ G J 1970, Electrical characteristics of contacts contaminated with silver sulfide film, IEEE Trans. Pts, Mats and Pckgng vol PMP-6 No 4 129-137.
13. Abbott W H 1970, The effects of substrate on the contact resistance of tarnish films, Proc. Holm. Conf. on Electric Contacts, Chicago 1970 21-25.
14. Lansdown A R 1974, Molybdenum Disulphide Lubrication. ESRO CR-402.
15. Glossbrenner E W 1970, Poly-Scientific's Role in Space, Ploy-Scientific Division.
16. Simon D et al 1979, Study of the reactivity of silver, copper, silver-copper and silver-palladium alloys, used in telephone relay contacts, Electric Contacts 1979 Illinois Inst. Tech Chicago 55-59.
17. Tamai T 1979, Electrical conduction mechanisms of electric contacts covered with contaminant films, Surface Contamination: Gen, Det, Control Symp Proc. 2 967-981.
18. Adkins C M and Kuhlmann-Wilsdurf D 1979, Development of high performance metal fibre brushes I - Background and manufacture, Electric Contacts 1979 Illinois Inst. Tech. Chicago.
19. McNab I R 1980, Recent advances in electrical current collection, Wear vol 59 259-276.
20. Reichner P 1979, Metallic brushes for extreme high current applications, Electric Contacts 1979, Illinois Inst. Tech. Chicago 191-197.