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Wear and electrical performance of a slip-ring system with silver–graphite in continuous sliding against PVD coated wires

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A B S T R A C T

Sliding electrical contacts transferring current between stationary and rotating components are also tribological systems. Although low contact resistance and noise are prioritised, lower wear rates reduce material usage, and lower friction reduce energy loss. In this paper a slip-ring assembly with wires contacting a silver–graphite ring is investigated with the aim to optimize the wire material to displace all wear to the ring. Uncoated wires and wires coated with nanocomposite Ti–Ni–C or TiN are tested at 100 mA current. Tribofilms, consisting mainly of silver and carbon, form on the wires and a contact resistance of around 0.5 Ω is measured for all wire materials. The properties of the tribofilms control the overall performance and the similarity between them, regardless of wire material, is the reason for the similar contact resistance. The Ti–Ni–C coating wear least on the silver–graphite. Both coatings degrade and wear off during testing, exposing the steel substrate. The steel itself also wears, although not at a rate excluding it as a possible wire material. None of the three surfaces fully displaces wear to the ring only. Considering the performance of the uncoated steel wire, coatings cannot be motivated on behalf of either improved electrical performance or wire protection.

1. Introduction

This paper presents results from a study on how coated spring steel wires perform in a simplified component test set up modelling a slip-ring assembly. This assembly consists of stationary spring wires contacting a rotating v-grooved graphite composite ring. The use of graphite in the ring is an alternative design that has not been described in any publication but those of the authors. This study builds upon work done on the same materials in a more fundamental model test set up with cylinders in reciprocation sliding [1], suggesting coated wires for use in real electrical contact applications. The purpose of the coating is to protect the wire from wear, and this has to be done without causing excessive wear on the silver–graphite ring and, of course, while providing a sufficiently low contact resistance. In this work it is investigated if a nanocomposite Ti–Ni–C coating or a ceramic TiN coating fulfils those requirements. Although the research on hard coatings for electrical contacts is quite extensive, the use of a graphite based material as a counter surface is not found in the literature. The focus is on the electrical performance and the silver–graphite wear rate, but the wires are also analysed for wear, material transfer and tribofilm build up. A more detailed description of the test set up can be found in Ref. [2] where both different ring and different wire materials have been used. More details on the coating deposition and coating analysis of the Ti–Ni–C coating can be found in Ref. [3].

1.1. The slip-ring assembly

A traditional slip-ring assembly consists of a stationary graphite composite brush, which is pressed against a rotating metal alloy slip ring. The graphite helps to lower the friction and some atmospheric moisture is needed to prevent high wear rates. High-speed applications require more graphite and high-current requires more metal [4]. Silver–graphite brushes are common in applications where the current density or the rotational speed is high, as well as when signals are transferred. Different aspects of silver–graphite brushes have been studied extensively by several research groups over the years. Common slip-ring materials are Cu and Ag alloys and it has been concluded that metallurgical incompatibility of the slip-ring metal with graphite gives the lowest amount of wear [5].

Although this traditional system is simple in design, difficulties may arise if the slip-ring assembly needs to be very small. Firstly, manufacturing of millimetre sized brushes is difficult and, secondly, the brushes are worn out quickly, resulting in short service intervals. For the very smallest assemblies a stationary metal

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spring wire in a rotating v-grooved ring may be a more adequate system. The ring is most often metallic; copper, silver and gold alloys are common. Also the wire is most often metallic and it is important that it has high electrical and thermal conductivity, high corrosion resistance, good wear resistance and spring elasticity properties. Silver or gold is used in applications with low voltage, infrequent sliding and in environments detrimental for other contact materials [4]. A less noble metal can be used for applications with a high force, high voltages or continuous sliding which will help to break up any insulating films. As with any metal–metal contact some kind of lubrication is necessary to achieve satisfactory tribological performance. Fluid lubricants are however problematic at high rotational speeds as this may cause hydrodynamic lifting [6]. Different variations of the above described spring wire assemblies can be found in the literature, all with different limitations as to tribological and electrical performance.

In this work the use of a graphite ring is suggested to improve the tribological performance compared to systems using metal alloy rings. Graphite gives low-friction just as with conventional brushes and no additional lubrication is needed. The main advantage is however that the volume of available metal–graphite is increased in comparison to the conventional system with only a few small brushes of metal–graphite. In difference to more common slip-ring systems the silver–graphite in the present work will be going in and out of contact rather than being in contact constantly. It will give the temperature in the silver–graphite a chance to decrease when not in contact with the wire which could influence the electrical performance as well as wear and tribofilm formation. Silver–graphite was chosen for the ring, with signal transfer applications at high rotational speed in mind.

With this set-up, the wires could easily become the weak link if not made sufficiently wear resistant. All wear should be displaced to the ring, where a stable wear rate is acceptable as there is a fairly large amount of material to wear from. A spring steel wire is employed to satisfy the need of spring properties to ensure persistent contact with the ring. Wear resistant coatings are used for wire protection. The use of coatings for wear resistant electrical contacts has been considered previously. Rudolphi et al. [7] concluded in 1997 that coatings give higher contact resistance than metal to metal contacts and that the best use of coatings could be in low current or signal applications. Several coatings have since been investigated for electrical contact applications, among them Ti–Ni–C nanocomposites [1,8,9]. During magnetron sputtering of these coatings, the weak carbide forming metal, Ni, will form a metastable solid solution with (Ti,Ni)C grains in an amorphous-carbon (a-C) matrix as shown by Lewin et al. [8]. It was also shown that coatings with a high amount of a-C matrix show good tribological properties and good static electrical properties. Ti–Ni–C coatings against silver in reciprocating sliding have been shown to result in contact resistances of around 200 $\mu\Omega$ and a coefficient of friction stabilising around 0.15 [9].

1.2. The combination of tribological and electrical performance

Continuously sliding electrical contacts are tribo-electrical systems. Current is transferred between two surfaces in relative motion and sufficiently low contact resistance is the most important characteristic of the system. Tribological aspects of friction and wear are important for reliability and improved component life-time, but they are seldom given priority. Hard materials often contribute with wear resistance and, due to small contact areas, a low coefficient of friction [10]. For electrical contacts, large contact areas are desired, as the contact resistance is inversely proportional to the conducting area [11]. This is why the most common materials for electrical contacts are soft noble metals which give large real contact areas and form a minimum of insulating tarnish films. It is common to allow for a small amount of wear in order to remove insulating films and maintain metal to metal contact. However, it is then important to limit the amount and size of the wear debris to avoid shortages and electrical noise [6].

In order to achieve a well-functioning sliding electrical contact it is necessary to look not only at the contact resistance but also on the noise of the contact. Contact noise has been defined in ASTM B615 as “the varying voltage across a pair of electric contacts due to conditions at their interface”. When signals are transferred, variations in the output signal, i.e. noise, might be interpreted as true variations in the signal and hence give rise to errors. In most applications, a low variation of the resistance is thus far more important than the absolute resistance [12].

In the field of tribology it is well known that two mating surfaces in sliding contact will affect each other and possibly react with each other and the surrounding atmosphere and form tribofilms. The situation is no different in sliding electrical contacts; tribofilms will form and become decisive not only for the friction and wear but also for the contact resistance. Unless the atmosphere can be controlled and oxygen free, it is thus important that the elements present in the surface interface either are inert to oxygen or govern the formation of a tribofilm with acceptable resistivity.

2. Experimental

2.1. Materials

A spring steel wire, with a diameter of 0.45 mm, was used both as substrate for the coated specimens and uncoated as a reference specimen. It has a principal alloying composition of 0.90 wt% C, 0.67 wt% Mn and 0.25 wt% Si and, in addition to that, some small amounts of other alloying elements. It was polished manually before coating deposition to an R_a value below 100 nm. However, occasional scratches from the drawing process may still remain.

The Ti–Ni–C coating was deposited using dc magnetron sputtering from a composite target. Prior to deposition, the wires were plasma etched for 30 s and coated with a thin Ti bonding layer to improve the adhesion of the Ti–Ni–C coating to the steel. The substrates were biased to -50 V and no external heating of the wires was employed. TiN was deposited using reactive electron beam evaporation of Ti in a nitrogen atmosphere. An argon plasma and a bias of -110 V on the wires were used both for pre-etching and for assisting the deposition process.

The silver–graphite in the ring is a commercial silver–graphite[1] with a silver content of 14 vol% and small additions of MoS_2 (Molykotes microsize). Note that despite being referred to as silver–graphite, the main constituent of this material is graphite. Pressed and heat treated from powders, it contains silver particles with an average size of about 36 μm. The resistivity of this silver–graphite is 11 $\mu\Omega$ m (measured according to DIN IEC 413.402) and it has a hardness of 100 $HR_{10/60}$ (measured according to DIN IEC 413.303 which is a measurement method particularly developed for brushes, using a 10 mm ball at 60 kg load performed as a Rockwell test). Both these values are given by the manufacturer. Nanoindentation measurements in the silver and graphite phases separately indicate a hardness of 0.6 GPa in the silver and 0.2 GPa in the graphite.

[1] Available from CarbexAB, Vadstena, Sweden. www.carbex.se.