EFFECT OF TEMPERATURE ON WEAR RATE OF HOMOPOLAR PULSE CONSOLIDATED ELECTRICAL BRUSH

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Abstract

Binderless copper-graphite composite electrical brushes are being developed using a high-energy, high-rate pulse sintering technique by the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Experiments were done to investigate temperature's effect on the homopolar pulse consolidated (HPC) brush wear rate for an apparent brush current density of 180 A/cm^2, a brush downforce of 44.5 N, and rotor surface sliding speeds of 10 m/s and 40 m/s. At a sliding speed of 10 m/s, it was found that brush wear rate dropped steeply as the brush bulk temperature increased from 80°C to 103°C. Other than this unusual wear finding in this particular sliding speed and temperature range, test results indicated that brush wear rate generally increased with increasing brush bulk temperature. At a sliding speed of 40 m/s, it was found that brush wear rate suddenly increased by several times as the brush bulk temperature approached 149°C. In the case of 10 m/s sliding speed, no stepwise rise in brush wear rate was observed even as the brush bulk temperature reached 156°C.

1. Introduction

The limiting components in continuously operated homopolar motors and generators are the sliding electrical contacts (brushes). Both the sliding contacts and slip rings experience wear, but, since the brush material is usually softer than that of the slip ring, the brushes wear out first. Recent requirements for higher tip speeds and current densities demand more robust brushes. Conventional electrical brushes have limited operating range because of the low melting temperatures of the binders, such as tin and lead. Excessive wear rate has been observed for conventionally sintered copper-graphite brushes at high sliding speed and high current density due to gross melting of the binder material.

In response to the need for an efficient and reliable electrical brush system, binderless homopolar pulse consolidated (HPC) copper-graphite composite electrical brushes have been fabricated with a high-energy, high-rate pulse sintering technique being developed by CEM-

UT. Homopolar generator consolidation is an extremely fast pulse sintering process (about 1 to 3 s) which uses high current to electrically heat the material being consolidated. Because the process is fast, internal oxidation of powder can be minimized. Joule heating occurs due to contact resistance at interparticle interfaces and a dense material with improved electrical, mechanical, and thermal properties can be produced by forging during the rapid heating process.

Wear rate in sliding electrical contacts is the result of many factors, which include contact force, sliding speed, temperature, material properties, surface roughness, and rubbing conditions. In this research, temperature's effect on the HPC brush wear rate was investigated. Electrical and mechanical heating can cause changes in the material properties of the contact surface layer. Fundamental changes may take place in the brush material as the contact temperature reaches a certain level and the surface layers acquire essentially new material properties. These changes can be accompanied by a stepwise rise in wear rate by several orders of magnitude [1]. The combination of elevated temperature and ambient medium exposure can develop an oxide film on the electrical contact surfaces. In some cases, the oxide film is beneficial because it prevents high friction and wear caused by metal-to-metal contact, but in other cases, the oxide is detrimental because it promotes wear.

Quinn [2,3] provided an extensive review of oxidational wear. He proposed that various wear modes could be unified into two major classes, namely mild and severe. Oxidational wear was in the mild wear category in which protective oxide films were formed at the real areas of contact. Contact temperature was important in determining the oxide structure and wear properties of the sliding interface; oxidation occurring more swiftly the higher the temperature.

For high temperature sliding contacts, friction and wear are largely determined by changes in the strength of materials, weldability, and oxide film formation at the sliding interface. As contact temperature increases, loss of material strength and the increase of material weldability usually promote high wear rates. However, the surface oxide films appear to be more important as contact temperature becomes elevated. Peterson et al. [4] ran friction tests with various metals sliding against themselves over a wide temperature range. As the temperature was increased, they found high friction and considerable surface damage resulted until a particular temperature was reached. Above this temperature, a significant drop in the frictional coefficient was observed. They attributed this frictional improvement to the continually reformed soft oxide film in the sliding track. Rabinowicz [5] investigated oxide film lubrication on metal surfaces. He indicated that for an oxide to provide effective lubrication, the oxide must not be much harder than the substrate and the oxide film thickness must be adequate.

Moisture content in sliding environments is critical in reducing brush friction and wear. High wear and friction occur when sliding contact pairs operate in vacuum or dry gas environment. Pardee [6] conducted wear tests by sliding silver-graphite brushes against copper slip rings to determine the minimum moisture levels to prevent dusting (rapid wear) in air, nitrogen, helium, and carbon dioxide. Johnson and Moberly [7] did wear tests with electrographite brushes and copper slip rings. Their tests indicated that the brush wear rate was adversely affected by temperature and dusting occurred if brush bulk temperature exceeded a critical level. They determined that the high wear was a result of desorption of moisture from the contact interface graphite sites which became excessive when the critical temperature was reached. Lee and Johnson [8] evaluated the effects of five different nonoxidizing gas atmospheres in the presence of water vapor on silver-graphite brush performance. They indicated that the effectiveness of water vapor in reducing graphite friction and wear is temperature dependent and only applies to temperatures below 200°C. McNab [9] conducted a thorough review of electric current transfer across sliding surfaces. He indicated that a significant change in the wear rate of graphite-based brushes occurs as the bulk brush temperature approaches 180°C. Above this bulk temperature, wear rate can increase by a factor of 1,000 or more, and a large amount of fine brush particles (6 nm) will be produced.

Chow and Bishop [10] ran wear tests by sliding commercially available CM1S™ copper-graphite brushes on a copper slip ring. Under the operating conditions of a sliding speed of 20 m/s and a brush load of 4.5 N, their experimental results demonstrated that high current densities generated high brush temperatures, which in turn resulted in high contact voltage drops and high brush wear rates. Mokhtar [11] showed experimentally that lower friction is usually associated with harder surfaces due to strong interatomic linking bonds in hard metals. Generally, the hardness of a metal decreases with increasing temperature; hence, wear rate increase would be expected as the sliding contact temperature increases.

From the foregoing, it appears obvious that the temperatures of sliding contact pairs are important in the determination of material properties, oxide film properties, contact loss, and wear rate. Previous experimental works carried out by Carnes [12], one of the authors of this paper, indicated that the HPC brush wear rate decreased with increasing temperature within his testing temperature range, which did not seem to meet conventional expectation. In this research, attempts have been made to investigate temperature's effect on the HPC brush wear rate under certain operating conditions.

2. Measurements and Results

The rotor used in this research is made of AISI 4130 steel and has a diameter of 635 mm and a width of 38.1 mm. It has a maximum operating speed of 200 m/s, and is part of a machine called the sliding electrical contact tester (SECT) which is shown in figure 1. The standard HPC brush sample is a half disc with dimensions of 22.2 mm x 11.1 mm x 7.6 mm. The sliding contact surface of each test brush has a cross-sectional dimensions of 22.2 mm x 7.6 mm. The brush holder is made of pure copper and is connected to the electrical terminal through flexible copper straps. The test brush and brush holder are shown in figure 2. The normal load applied to the brush to maintain contact between the brush and rotor is provided by a nitrogen actuator mounted directly over the brush holder. The SECT rotor is driven by a 400-hp fixed displacement hydraulic motor. The brush current is provided by a dc power supply which can provide a maximum voltage of 250 V and a maximum current of 6000 A. The current loop is completed by a CM1S™ return brush. The actual current level into the SECT is controlled by adjusting potentiometers in a control panel. An inductive proximity probe is fastened above the brush holder to monitor the transient brush wear. Brush temperature, brush holder temperature, voltage drop at the brush interface, brush downforce, rotor speed, brush wear, brush current, cable temperature, and motoring pressure are monitored by a multichannel strip chart recorder and recorded at a fixed sampling rate of 5 s.

To measure brush bulk temperature during the wear test, a thermocouple was embedded into the middle of each test brush. A small hole with a diameter of 0.8 mm was drilled from the center of the brush's semicircular periphery. This drilled hole was 5.6 mm deep and perpendicular to the brush's sliding surface. The thermocouple joint was placed against the bottom of the hole, then the drilled hole was filled with high temperature epoxy. Heat generation at the brush contact interface includes frictional and electrical heating. In order to vary the bulk temperature of the test brushes in wear tests, a high watt density cartridge heater, which has a nominal diameter of 6.35 mm and a length of 38.1 mm, was embedded into the brush holder to provide external heat. The cartridge heater was located close to the brush site to maximize brush heating, and a variac was used to control the amount of resistive heat generated.

The contacting surfaces of the HPC brushes were not preformed to the curvature of the disc before tests. The brushes were tested under the operating conditions of an apparent brush current density of 180 A/cm^2, a brush downforce of 44.5 N, and rotor surface sliding speeds of 10 m/s and 40 m/s. The actual current through each test brush was 304 A. The voltage drop across the SECT was approximately 0.3 ~ 0.4 V, and most of this voltage drop occurred at the brush sliding interface. The rotor surface was cleaned with acetone before each test. Before and after each test, the HPC brush was weighed by an electronic scale to determine the weight lost during the test. Before each test, the brush and brush holder were preheated by the variac-controlled cartridge heater for about 10 min. After dropping the brush on the rotor surface and applying current, the initially cold rotor surface would soak heat from the interface. In a short period of time, the rotor would warm and the temperatures of the brush and brush holder stabilize. The temperatures presented later were determined on an averaged basis. The duration time for each brush wear test was from 0.5 to 2 hours.

During two wear tests carried out at under 40 m/s sliding speed, the brush wear rates (tracked by the inductive proximity probe) suddenly increased by several times as the brush bulk temperatures approached 149°C. These sudden rises were accompanied by sudden brush temperature increases. These stepwise rises in brush wear rates may not be as severe as the dusting phenomenon described in [1,7,9], but the brush bulk temperature of 149°C seems to be the transition temperature for movement of HPC brush wear from the mild wear regime to the severe wear regime [2,3] under these conditions. Two typical experimental plots (without and with external heating from the cartridge heater) showing the transient brush wear for the initial half hour of sliding are shown in figures 3 and 4, and the corresponding channel measurements are included in table 1. For the test results shown in figure 3, the average brush bulk temperature and brush wear rate are 125.6°C and 65.7 mm^3/hr, respectively. For the test results shown in figure 4, the average brush bulk temperature and brush wear rate are 140°C and 93.4 mm^3/hr. The experimental results of the tests to determine HPC brush wear rates as functions of brush bulk temperatures, taken at 40 m/s rotor surface speed, are plotted in figure 5. To make the temperature dependent brush wear rates at low temperatures more easily observed, the wear data are replotted in figure 6 by dropping the high wear rate data. Voltage drops under these operating conditions range from 0.18 V to 0.25 V.

By changing the rotor surface speed to 10 m/s and maintaining the same brush current density and downforce, the temperature dependent brush wear rates were re-examined. Under these testing conditions, no stepwise rise in brush wear rate and temperature was observed even as the brush bulk temperature reached 156°C. Apparently, the transition from mild to severe brush wear is dependent upon the sliding speed. Lower interface heating rates seem to make severe brush wear occur at a higher critical brush bulk temperature. Figures 7 and 8 are two typical experimental plots (without and with external heating from the cartridge heater) showing the transient brush wear for the initial half hour of sliding, and the corresponding channel measurements are included in table 1. For the test results shown in figure 7, the average brush bulk temperature and brush wear rate are 81.7°C and 23.5 mm^3/hr, respectively. For the test results shown in figure 8, the average brush bulk temperature and brush wear rate are 87.8°C and 18.1 mm^3/hr. The experimental brush wear rates vs. brush bulk temperatures, taken at 10 m/s rotor surface speed, are shown in figure 9. Voltage drops under these operating conditions range from 0.12 V to 0.26 V.

3. Discussion

In the case of 40 m/s sliding speed, within the testing temperature ranges shown in figures 5 and 6, it appears that HPC brush wear rate increases with increasing brush bulk temperature as described in [10,11]. This finding can also be verified by comparing the transient brush wear rates shown in figures 3 and 4 at different brush bulk temperatures. The considerable increase in brush wear rate in figure 5, when the brush bulk temperature approaches 149°C, may be due to the very high localized contact spot temperature caused by the high brush bulk temperature and the high mechanical and electrical interface heating.

In the case of 10 m/s sliding speed, the brush bulk temperature dependent wear rate curve, shown in figure 9, is very interesting. The wear rate data seem to scatter in the temperature range of 60°C to 75°C, and rise to a peak at about 80°C. Brush wear rate then drops steeply as the brush bulk temperature increases from 80°C to 103°C. As brush bulk temperature increases from 103°C to 160°C, the wear rate increases again. The decrease in wear rate as brush temperature increases in the temperature range of 80°C to 103°C, also supported by comparing figures 7 and 8, is probably due to work hardening of the brush. As mentioned earlier [6,7,8], the water vapor content in the environment is important in reducing brush wear rate. It may therefore be possible that the moisture content near the sliding interface area becomes optimal as the brush bulk temperature approaches 103°C. After this water vaporization temperature, moisture depletion at the sliding interface causes wear rate to increase as brush material softens at higher temperature.

Brush wear rate measured at the sliding speed of 10 m/s did not experience an abrupt rise as it did at 40 m/s sliding speed even when the bulk temperature reached 156°C. It was calculated that the brush interface heat generation, including both mechanical and electrical loads, at 10 m/s sliding speed was about 37% of that produced by 40 m/s sliding speed. As a result of the low interface heating at 10 m/s sliding speed, the low interface contact spot temperature prevents the brush from experiencing severe wear unless the bulk temperature is much higher than 156°C. The relationship between transition temperature, at which wear rate increases significantly, and sliding speed can be explained by the interface oxide film formation rate. As described earlier [4,5], the oxide thickness is critical in determining the effectiveness of the interface lubrication, and the film has to be thick enough to provide lubrication. The oxide thickness increases with surface temperature and also increases with time. For higher sliding speeds such as 40 m/s, there is less time for the oxide film to grow on the rotor surface before oxide removal during contact; therefore, transition occurs at a lower temperature.

It appears that the localized contact spot temperature at brush sliding interface plays an important role in the brush wear rate. Liu et al. [13] measured and predicted the interface contact spot temperatures of the HPC brush material without external heating. It is useful to examine the differences between the measured bulk temperatures and the predicted contact temperatures under the test conditions. Without external heating, the measured brush bulk temperatures range from 107°C to 130°C for tests with 40 m/s sliding speed and range from 62°C to 71°C for tests with 10 m/s sliding speed. For an apparent brush current density of 180 A/cm^2 and a brush downforce of 44.5 N, the predicted interface contact spot temperatures [13] at sliding speeds of 40 m/s and 10 m/s are 1,017°C and 467°C, respectively.

Examining figures 6 and 9, it can be found that, at a given brush bulk temperature, the brush wear rate increases by a factor of 2.4 to 3.2 due to the increase of sliding speed from 10 m/s to 40 m/s.

4. Conclusion

In sliding electrical contact, brush wear rate is one of the dominant factors in determining the success of a continuous duty electrical machine. The brush wear rate is affected by various factors, such as temperature, material properties, sliding speed, contact force, interface conditions, and environment. The effect of temperature on HPC brush wear rate was investigated in this research. From the HPC brush wear tests performed under the testing conditions of an apparent brush current density of 180 A/cm^2, a brush downforce of 44.5 N , and two different rotor surface sliding speeds, the major results can be summarized as follows:

1. In the case of 40 m/s sliding speed and testing brush bulk temperature range of 105°C to 150°C, the brush wear rate increases with increasing temperature due to brush material softening at high temperature. As the brush bulk temperature approaches 149°C, a stepwise rise in brush wear occurs.
2. In the case of 10 m/s sliding speed, wear rate data scatters but seems to increase with temperature in the brush bulk temperature range of 60°C to 80°C. The brush wear rate then drops steeply as the brush bulk temperature increases from 80°C to 103°C. As the brush temperature increases from 103°C to 160°C, the wear rate increases again. Under this sliding speed, the brush does not experience any significant wear rise even as the brush bulk temperature reaches 156°C.
3. The transition from mild wear to severe wear is probably caused by very high localized contact spot temperature due to the combination of high interface heat deposition and

high brush bulk heating from an external heat source. The temperature effect on brush wear cannot be determined by brush bulk temperature alone, and brush interface heat generation rate is also very important.

4. Under the sliding speed of 10 m/s and the brush bulk temperature range of 80°C to 103°C, the brush wear rate decreases with increasing temperature. This finding implies that, under certain sliding conditions, a minimum HPC brush wear rate can be achieved by externally heating the brush to an optimal temperature.
5. By increasing the sliding speed from 10 m/s to 40 m/s, at a given brush bulk temperature, the brush wear rate increases by a factor of 2.4 to 3.2.

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Table 1. Channel measurements for figures 3, 4, 7, and 8

CH	Measurement	Left End	Right End
01	Brush Bulk Temperature (°F)	0	400 (700) *
02	Motoring Pressure (V)	0	2
03	Voltage Drop at Interface (V)	0	2
04	Brush Downforce (V)	0	6
05	--	--	--
06	Rotor Speed (V)	0	50
07	Brush Wear (V)	0	20
08	--	--	--
09	--	--	--
10	Cable Temperature (°F)	0	200
11	Brush Holder Temperature (°F)	0	400 (700) *
12	Brush Current (mV)	0	10

*Values in parentheses are for figure 4 only

Figure Captions

Figure 1. Sliding electrical contact tester

Figure 2. Test brush and brush holder

Figure 3. Typical transient brush wear at 40 m/s rotor surface speed for the initial half hour sliding (without external heating)

Figure 4. Typical transient brush wear at 40 m/s rotor surface speed for the initial half hour sliding (with external heating)

Figure 5. Brush wear rate vs. brush bulk temperature (40 m/s rotor surface speed, 180 A/cm^2 brush current density, and 44.5 N brush downforce)

Figure 6. Brush wear rate vs. brush bulk temperature (40 m/s rotor surface speed, 180 A/cm^2 brush current density, and 44.5 N brush downforce). The wear data shown in figure 5 are replotted in this figure by dropping the high wear rate data.

Figure 7. Typical transient brush wear at 10 m/s rotor surface speed for the initial half hour sliding (without external heating)

Figure 8. Typical transient brush wear at 10 m/s rotor surface speed for the initial half hour sliding (with external heating)

Figure 9. Brush wear rate vs. brush bulk temperature (10 m/s rotor surface speed, 180 A/cm^2 brush current density, and 44.5 N brush downforce)

Additional information for typesetters or paste-up

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