

Wear and Life Characteristics of Microwave-Sintered Copper-Graphite Composite

K. Rajkumar, S. Aravindan, and M.S. Kulkarni

(Submitted March 17, 2011; in revised form January 12, 2012)

Copper-graphite composite is an important tribological material used in electrical sliding contact applications like electrical brushes in motors and generators. The electrical sliding contact experiences multiple stresses such as mechanical pressure and temperature. Traditional life tests under normal operating condition would be a time-consuming process due to the longer expected life of the composite. Accelerated wear testing was carried out to evaluate the life characteristics of the composite. This work focuses on evaluation of tribological performance of microwave-sintered copper-graphite composite using accelerated wear testing methodology using high temperature pin-on-disc tribometer. Microstructural studies of worn out surfaces were carried out using SEM with EDAX. Reliability and analysis on life characteristics were performed on the time-to-failure data using temperature-nonthermal-accelerated life-stress model. The obtained times-to-failure data from the accelerated wear testing was extrapolated to normal usage condition. Temperature and pressure are significantly affecting the wear performance. Self-lubricating action of graphite and improvement in wear resistance is helpful in extending the life of copper graphite composite. The life of the composite obtained through testing at mean and 99% reliability are 18,725 and 16,950 h, respectively.

Keywords microwave sintering, copper matrix, wear, times-to-failure, reliability

1. Introduction

Microwave processing of materials is a high potential alternative route to provide new approaches for enhancing material properties. Microwave processing offers economic advantages through energy savings and rapid product development. Microwave technology can be wisely employed to process materials, such as curing of polymers, sintering of ceramics, and powder metallurgy components (Ref 1-3). Copper-graphite composite is a promising candidate for applications in electrical sliding contacts due to its high electrical and thermal conductivity and good wear resistance. With graphite addition, a remarkable effect can be observed on wear resistance and coefficient of friction due to the formation of self-lubricating film.

Traditionally lead has been added to electrical sliding contact materials to improve their wear performance and durability (Ref 4, 5). Microwave-processed copper-graphite composite is a new generation sliding material and alternative to these conventionally used materials such as carbon and electro-graphite for electrical sliding applications. These conventional materials have only limited performance due to the low melting temperature of the lead binder, environmental hazardousness, and low current density (Ref 6, 7).

K. Rajkumar, S. Aravindan, and M.S. Kulkarni, Department of Mechanical Engineering, Indian Institute of Technology-Delhi, New Delhi 110016, India. Contact e-mail: aravindan@mech.iitd.ac.in.

Electrical sliding contact material wears out progressively due to the friction effect induced while sliding with the counter surface material. Electrical sliding contact wear limits the performance of the electrical machine. In order to introduce a newer material with enhanced properties for an industrial application, its performance, reliability, and life characteristics should be evaluated. Traditional life data analysis is carried out by analyzing time-to-failure data obtained through the tests conducted under normal operating conditions. For highly reliable products/components, the quantification of life characteristics under normal usage conditions will be a time-consuming process (Ref 8). In such case, time-to-failure data of the sliding contact material can be obtained by making this material fail more quickly under accelerated conditions than the

Nomenclature	
T'	$\ln T$
T	Time-to-failure
\bar{T}'	Mean of the natural logarithms of the times-to-failure
$\sigma_{T'}$	Standard deviation of the natural logarithms of the times-to-failure
L	Quantifiable life measure, such as mean life, $B(x)$ life, etc.
V	Temperature, °C
P	Pressure, kPa
E_A	Activation energy, eV
\bar{K}	Boltzman's constant (8.617385×10^{-5} eV K ⁻¹),
K	One of the model parameters of life-stress relationship ($K > 0$)
$B, C, \text{ and } n$	Model parameters

normal conditions (Ref 9). It is known as accelerated life testing (ALT) technique which is useful to find the life characteristics of products/components (Ref 10).

ALT are performed by applying a single stress or multiple stresses depending on the stress involved in the actual field application and by simplifying testing procedure (Ref 11). In actual field, a product/component usually fails under the combination of multiple stresses (Ref 12). Due to contact nature, electrical sliding component undergoes significant friction and wear (Ref 13-15). The wear rate of the electrical sliding contact is affected by many factors, such as applied pressure, temperature, sliding speed, and material properties (Ref 16).

ALT was designed, planned and the times-to-failure data were collected. Microwave-sintered copper-graphite composites were subjected to accelerated wear testing under multiple stress conditions. High temperature pin-on disc tribometer was used with various stresses such as temperature and pressure with different sliding velocities. Significance of stresses and their interactions are analyzed through Box-Behnken (BB) design of experiment method. Based on the time-to-failure data, a suitable acceleration model is selected. Reliability analysis of the new series of microwave-sintered copper-graphite composite was carried out through ALTO PRO 6 reliability software.

2. Material and Properties

From the previous studies carried out by the same authors (Ref 17), it is observed that copper-10%graphite particulate composites are the best suited ones for electrical sliding contact applications. Copper-10 vol.%graphite particulate composite was manufactured through the powder metallurgy route. Copper powder was chosen as a base for matrix material and its average particle size was 12 μm . Graphite particles having the average size of 50 μm and they were used as reinforcement. Electrical agate pestle mortar was used for mixing powders, correct volume percentage of powders were blended for 2 h with the speed of rotation being 20 rpm to ensure good mixing. Prior to compacting, the mixed powders were heated to a temperature of 150 $^{\circ}\text{C}$, to evaporate the volatile components. Cylindrical components of height 8 mm and diameter 14 mm were prepared using a steel die with the help of a single action hydraulic press. The specimens were sintered in industrial microwave furnace (2.45 GHz and 3.2 kW) at a temperature of

850 $^{\circ}\text{C}$. After a definite holding time, specimens were allowed to cool in the furnace itself. Fabricated composite have the following properties: density $\sim 7540 \text{ kg/m}^3$, porosity 8.75%, and hardness 98HV. Figure 1 shows the micrographs of microwave-sintered copper-graphite composite. Figure 1(a) shows that the graphite particles are evenly distributed with lower porosity content. Figure 1(b) shows strong interfacial bonding between copper matrix and graphite.

3. Design of Multiple Accelerated Stresses

3.1 Testing Procedure and Planning

Figure 2(a) and (b) shows the photographs and schematic diagram, respectively, of a high temperature pin-on-disc tribometer. For high temperature experiments, the composite pin was inserted into cartridge heater assembly with thermocouple ("K" type)-based temperature controller. Specified temperature of the composite pin can be raised through the heat transferred by conduction from the cartridge heater. Good surface contact between the composite pin and cartridge heater and also good thermal conductivity of copper matrix reduced the energy loss between them. The temperature of composite was constantly maintained at the stated temperature till the end of the wear test through temperature controller. Experiments began when the pin temperature reached the stated temperature value. Linear variable differential transformer (LVDT) probe was used to continuously monitor the wear of pin (wear depth) during wear testing. EN30 steel disc having a hardness of 62 HRC was used as counter surface. Prior to the test, all the contacting surfaces were polished with 800 grade silicon carbide paper, then cleaned in acetone and dried.

Predominant stresses should be chosen to reflect the real degradation of component. Electrical sliding contacts in normal running conditions are subjected to mechanical and thermal stresses which make them to wear out/degrade or fail (Ref 6, 7, 16). While selecting the accelerated stress levels, care should be exercised so that the failure mechanism should be the same as that of normal usage conditions. The normal pressure acting on an electrical brush under normal usage conditions in DC motor (up to 1500 rpm) application is 27-34 kPa (0.26 N load). In the sliding application, copper-graphite brush starts to wear out at a mild rate beyond the applied load of 12 N (Ref 18). The failure mechanism of the copper-graphite composite was changed beyond the load of 200 N (Ref 19). Thus, accelerated load must

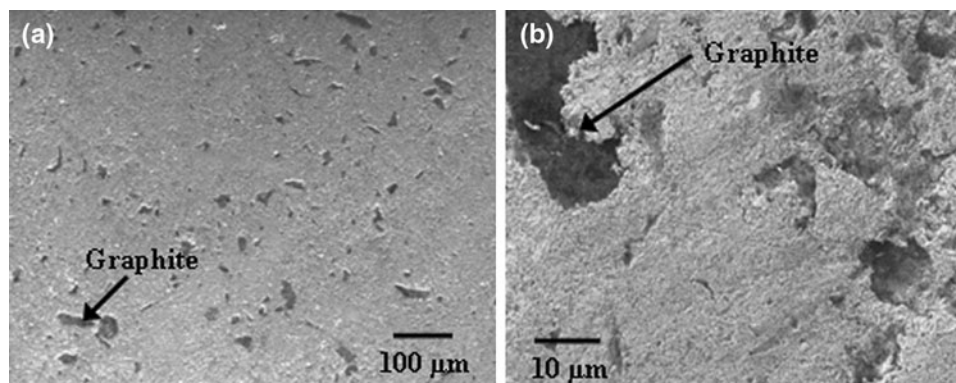


Fig. 1 SEM image of copper-graphite composite

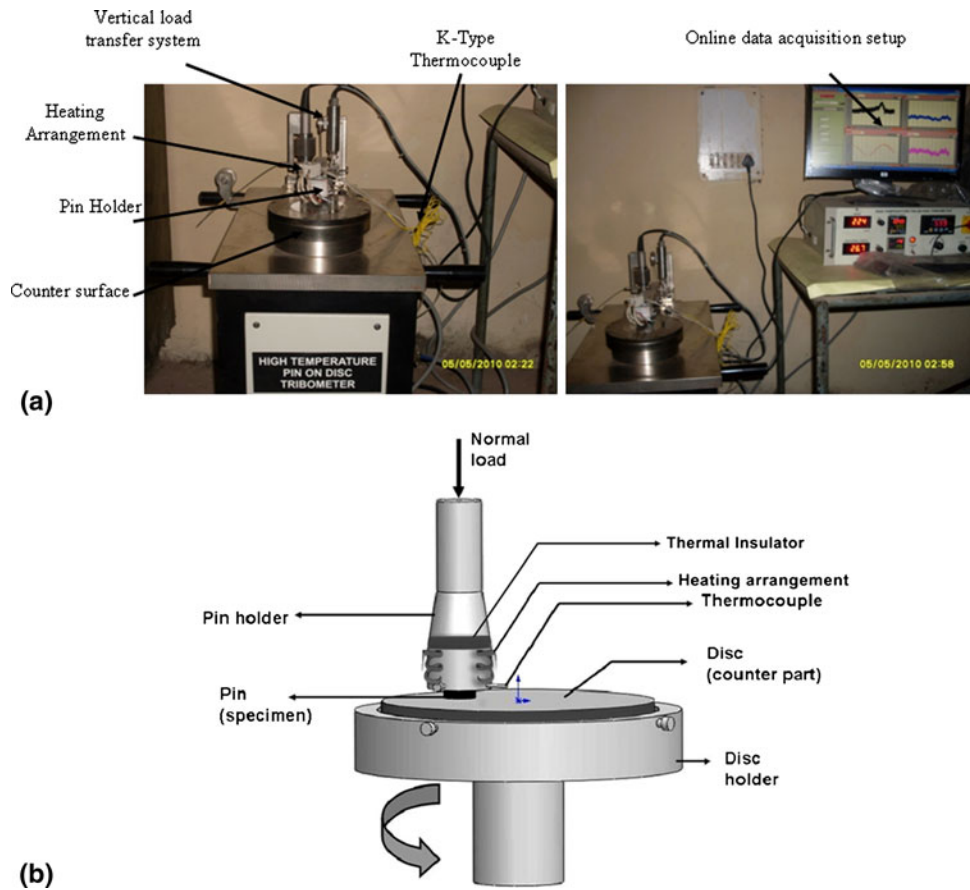


Fig. 2 (a) Photographs of accelerated wear testing setup and (b) schematic diagram of high temperature pin-on-disc tribometer

be chosen in the range of 12-200 N. Graphite retains its properties even at high temperature but the thermal softening temperature of copper is 190 °C (Ref 7). When the bulk temperature reaches around 190 °C, the strength of copper begins to decrease. At high temperature or beyond 190 °C, the failure mechanisms may not correlate well with that of normal operating conditions. When the bulk temperature reaches 60 °C, a beneficial effect would occur on the friction of copper-based electrical sliding contact owing to copper oxide film formation (Ref 20). Accordingly, the temperature must be selected from the range of 60-190 °C. Sliding velocity is one of the influencing parameters for tribological performance of materials under sliding condition. The lower range of sliding velocity has a modest effect on tribological performance of copper-based materials (Ref 21). Also, testing of this material at higher sliding velocities could possibly change the wear mechanism. Therefore, the experiments are conducted at moderate sliding velocities in the range 2.0-3.0 m/s.

3.2 Design of Experiments and Experimental Results

To understand the influence of the factors affecting the wear performance of copper-graphite composite, BB method was chosen. Experiments were planned by varying temperature, load, and sliding velocity. Based on the wear depth data, wear criteria can be fixed. The preliminary wear test trials confirmed that there was a change in the wear mechanism with the increased wear depth large amount of wear fragments dislodged from the worn out surface could be observed, beyond the wear depth of 0.4 mm. Similar observations were also reported for copper-based sliding

Table 1 Factors and their levels chosen for full factorial design

Level	Temperature, °C	Pressure, kPa/load, N	Sliding velocity, m/s
-1	125	3125/30	2.0
0	150	4175/40	2.5
+1	175	5225/50	3.0

materials (Ref 22). The wear criterion hence was chosen as 0.4 mm and the same was maintained for all accelerated wear testing conditions. The time-to-failure signifies the duration of contact to reach the wear criterion for each wear test. The time-to-failure for each experiment was noted separately for each experiment. In this case, the time-to-failure data were used for analyzing the factors. Temperature, pressure, and sliding velocity were the process parameters chosen for the accelerated wear test. Calculation of pressure was carried out by assuming the perfect contact of the pin with the disc. Accordingly, the accelerated pressures for different loads were calculated. Accelerated temperatures selected for the experiments were 125, 150, and 175 °C. The levels selected for each factor in the design are shown in Table 1. The experimental run order and corresponding results of experiments are presented in Table 2.

3.3 ANOVA Analysis

The analysis of the time-to-failure obtained from the experiments was carried out using statistical analysis software

Table 2 Results of experiments

Std. order	Run order	A: applied accelerated temperature, °C	B: applied accelerated pressure, kPa	C: sliding velocity, m/s	Time-to-failure, min		
					First trial	Second trial	Third trial
4	1	150	4175	2.5	809	815	815
8	2	125	3125	2.5	1142	1149	1138
1	3	175	4175	2	698	692	695
15	4	150	3125	2	986	979	978
5	5	125	4175	3	1059	1058	1054
3	6	175	3125	2.5	922	917	918
2	7	150	4175	2.5	802	805	811
9	8	175	4175	3	677	684	682
13	9	150	4175	2.5	801	800	799
12	10	150	5225	2	764	771	766
7	11	150	3125	3	955	962	957
11	12	150	5225	3	736	744	743
6	13	175	5225	2.5	626	625	621
14	14	125	4175	2	1087	1080	1079
10	15	125	5225	2.5	1038	1033	1037

Table 3 ANOVA results

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F ratio	P value
Model	9	3.68E+05	4.09E+04	92.2618	5.09E-05
A: temperature	1	2.45E+05	2.45E+05	551.4071	2.61E-06
B: pressure	1	8.67E+04	8.67E+04	195.4911	3.36E-05
C: sliding velocity	1	968	968	2.1817	0.1997
AB	1	8.84E+03	8.84E+03	19.9151	0.0066
AC	1	30.25	30.25	0.0682	0.8044
BC	1	2.25	2.25	0.0051	0.946
AA	1	1.84E+04	1.84E+04	41.46	0.0013
BB	1	1.06E+04	1.06E+04	23.8937	0.0045
CC	1	12.4103	12.4103	0.028	0.8737
Residual	5	2218.417	443.6833		
Lack of fit	3	2133.75	711.25	16.8012	0.0567
Pure error	2	84.6667	42.3333		
Total	14	3.71E+05			

DOE++. The ANOVA results are presented in Table 3. A, B, and C denote the temperature, pressure, and sliding velocity, respectively. Pareto chart is used to graphically summarize the relative importance of the given factors. From Fig. 3, it can be seen that the sliding velocity has not affected the tribological performance of the composite when the same failure mechanism prevails. As the sliding velocity increases, the graphite reinforcements in the composites get squeezed out at the mating surfaces. It forms a thin adherent solid lubricating film which reduces the coefficient of friction. Thus, the composite does not show any significant variation in tribological performance up to certain sliding velocity. The temperature and pressure are the most significant parameters as observed in Pareto chart.

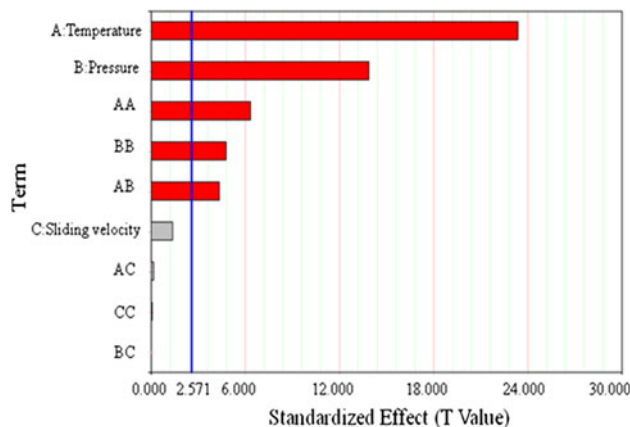


Fig. 3 Pareto chart of stress effect

4. Wear Characteristics

4.1 Effect of Temperature

From Table 2, it can be observed that the time-to-failure of the composite decreases with the rise in temperature (i.e., the wear rate of the composite increases). During sliding, the

composite pin rubs against the disc (counter surface) and this result in the formation of copper oxide film (Ref 19) in addition to the smeared graphite film. This graphite lubricating film reduces the metal-to-metal contact and thereby reducing the

wear of composite. Figure 4(a) shows small white batches of oxide film and formed graphite layer with smaller wear scar on the worn out surface. Similar results on the formation of oxide film and graphite tribolayer on the worn surface of composite were also reported by researchers (Ref 19). Beyond 150 °C, besides oxide film formation, the composite undergoes extensive plastic deformation at the sliding contact zone due to the attainment of softening temperature. There is a reduction in the strength of the matrix with the increase in temperature (Ref 7). This high temperature leads to weakening of the microstructure of composite. Smaller volumes adjacent to the contact areas and the bond between matrix and graphite particles are weakened. When it rubs against hard counter surface asperities, the wear debris is formed. The phenomenon of plastic deformation plays a predominant role for increasing wear rate. The wear rate of composite increases with the temperature due to the deficiency in the self-lubricating action of graphite also. The combined effect of external and frictional heating at contact zone reduced the self-lubricating property of graphite significantly. The lubricating film of graphite is stable at the contact zone as long as the existence of moisture adsorbed by graphite. The de-adsorption of moisture by heating results in reduced lubrication effect. Similar observation is also reported for electrographite with copper counter surface material under thermal heating condition. The electrographite experiences higher friction due to the thermal heating. It reduces the amount of adsorbed water particles and that too partly covers the graphite surface (Ref 23). It leads to increased free surface energy at the contact surface which causes higher friction. It results in the high wear rate of electrographite sliding material. The cumulative effect of nonavailability of lubricating film at the contact zone further rises the temperature. This turns to increase the wear rate of the composite at high temperature. It is confirmed from the SEM of worn surfaces (Fig. 4b) exhibiting wide grooves and larger wear scar. The availability of self-lubricating carbon film at this surface is scarce. It reveals the high probability of formation of contact spots of metal-metal type during sliding. Due to this type of contacts, the friction zone temperature is relatively high and it leads to the marked change in the properties of material adjacent to the contact zone.

Figure 5(a) and (b) shows the typical EDAX profiles of the worn out surfaces tested under the conditions of 125 °C and 4175 kPa and 175 °C and 4175 kPa, respectively. EDAX results of worn surfaces at lower temperature and higher temperature were compared in the context of graphite film

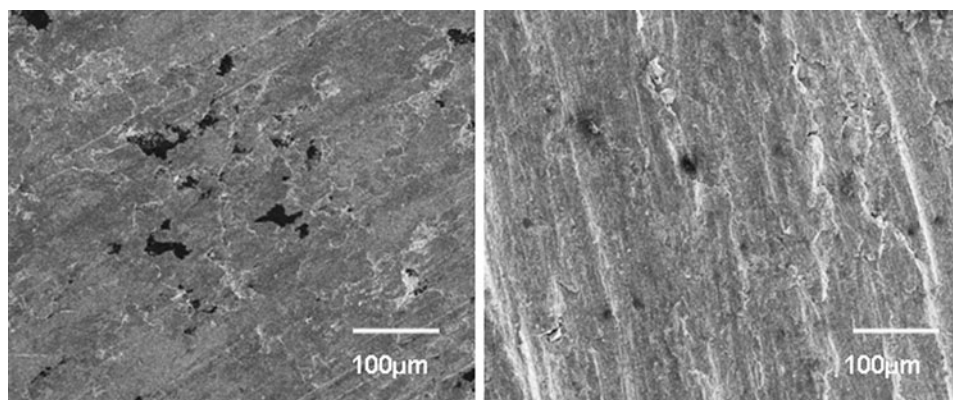


Fig. 4 SEM images of worn surfaces at (a) 125 °C and 4175 kPa and (b) 175 °C and 4175 kPa

formation. Figure 5(a) shows a very high intensity peak of C, low intensity oxygen peak, and very low intensity peak of Fe. The high intensity peak of carbon indicates the high order formation of a graphite film at the worn surface. As observed from Fig. 5(b), the reduction in the intensity of carbon peak when tested at high temperature reveals the depletion of carbon film at contact zone. Composition analysis (wt.%) of worn surfaces is embedded in respective figures to reveal the degree of self-lubrication effect at the contact zone. In all EDAX

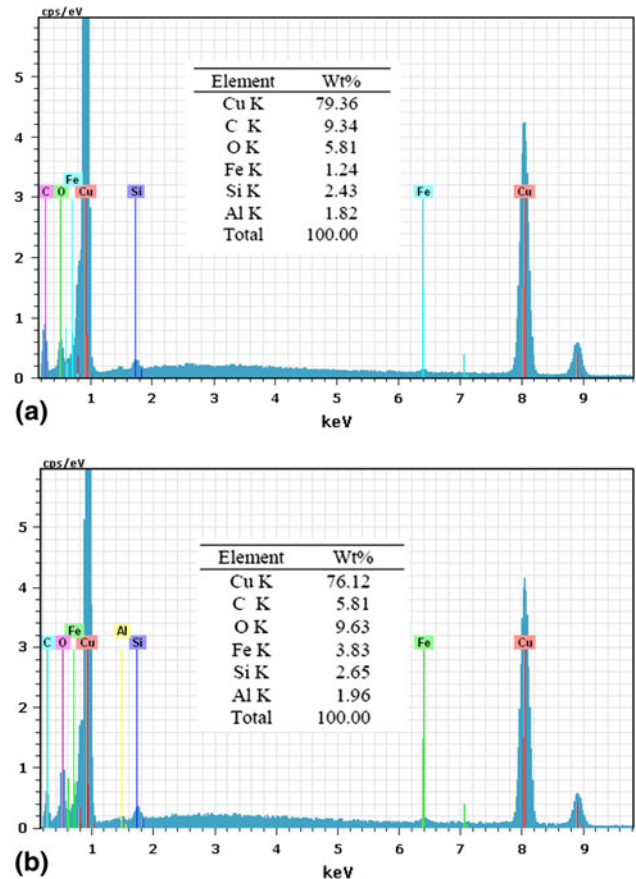


Fig. 5 Typical EDAX results of worn surface (a) 125 °C and 4175 kPa and (b) 175 °C and 4175 kPa

profiles of composite, the presence of oxygen peak indicates that there has been oxide formation at the worn out surface of the matting parts during wear test. The presence of silicon and aluminum peaks in Fig. 5(a) and (b) might have come from the steel disc counter surface material, as silicon and aluminum are the alloying elements of steel.

4.2 Effect of Pressure

From Table 2, it can be observed that increase in pressure increases the wear rate of the composite. The increased pressure from 3125 to 4175 kPa weakens the formed carbon film during sliding. It is observed from SEM image (Fig. 6a) that thin grooves are formed. The self-lubricating film is composed of a mixture of fine copper and graphite particles with no dominant amount of copper wear debris. When the test is carried out under high pressure (5125 kPa), the fracture of copper matrix is occurred at contact zone along with the ruptured of formed graphite film due to high local stress exerted by normal pressure. Similar observation was reported on the fragmentation of copper matrix and fast removal of formed graphite layer of copper-graphite composite at the higher load (Ref 19). This results the formation of wide grooves at the sliding surfaces of composite pin as shown in Fig. 6(b). This high local plastic deformation results in higher wear rate for a higher pressure. The plastic deformation is the operating wear mechanism for all the applied accelerated pressure.

The SEM image of wear debris obtained after testing the copper-graphite composite under a temperature of 125 °C and pressure of 3125 kPa is shown in Fig. 7. Most of the wear debris particles are observed to be small and equiaxed. This confirms that the composite has undergone plastic deformation.

The SEM image of wear debris obtained after testing the copper-graphite composite under a temperature of 125 °C and pressure of 5225 kPa is shown in Fig. 8. Most of the wear debris particles are seen to be large and equiaxed. This shows that the composite has undergone heavy plastic deformation, resulting in fracture of copper matrix and graphite particles.

It can be observed from worn out surfaces of copper-10%graphite composite the plastic deformation was predominant wear mechanism operating at all ranges of accelerated pressure and temperature. Since the wear mechanism prevails over the entire selected ranges of accelerated pressure and temperature, it is possible to evaluate the life characteristics of the copper-graphite composite through ALT.

5. Life Characteristics

5.1 Choice of Distribution and Assumptions

Accelerated life data analysis involves analyzing time-to-failure data of a component obtained. The data under

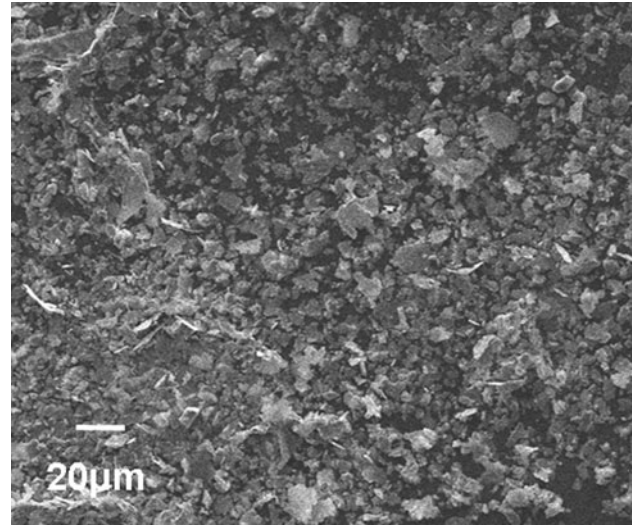


Fig. 7 SEM image of wear debris at 125 °C and 3125 kPa

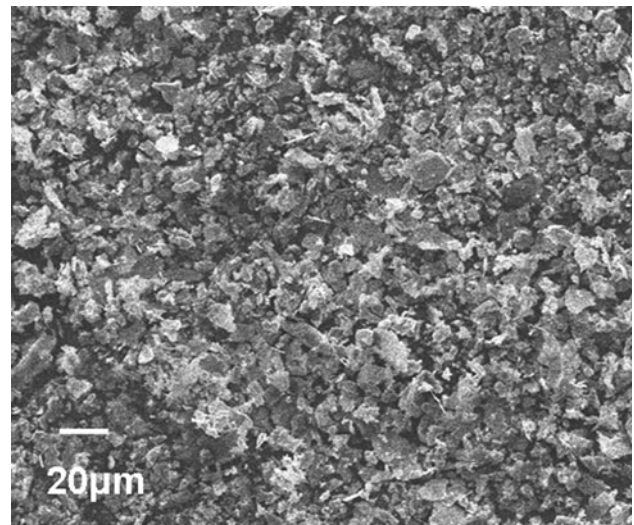


Fig. 8 SEM image of wear debris at 125 °C and 5225 kPa

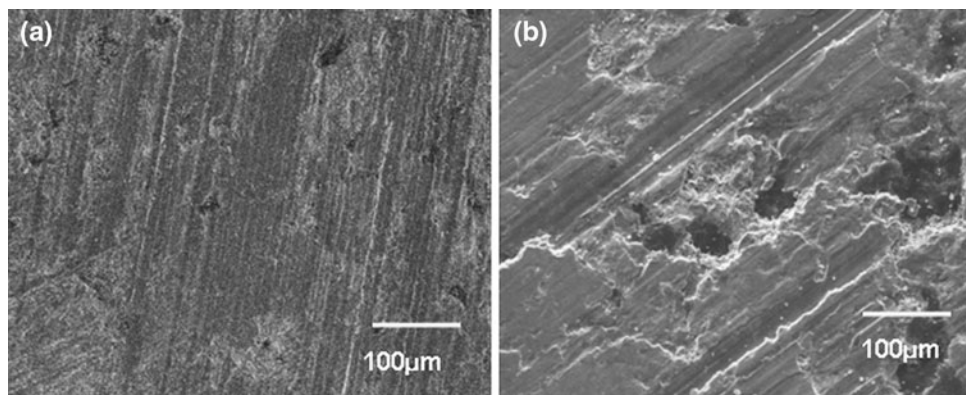


Fig. 6 SEM images of worn surface at (a) 125 °C and 3125 kPa and (b) 125 °C and 5225 kPa

accelerated condition is extrapolated to normal operating conditions to quantify the life characteristics of the component. Analysis of ALT data consists of an underlying life distribution that describes the component at different stress levels and a stress-life relationship model that quantifies the life characteristic of component across the stress levels. The tests are not censored, i.e., they are allowed to run till they attain wear criterion. Since lognormal distribution provides a closer approximation to the probability laws of many tribological phenomena (Ref 24), it is used as the underlying life distribution.

The probability density function (pdf) of the lognormal distribution is given by,

$$f(T) = \frac{1}{\sigma_{T'}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{T' - \bar{T}'}{\sigma_{T'}}\right)^2}, \quad (\text{Eq 1})$$

where T' is the $\ln(T)$, T is the time-to-failure, and \bar{T}' is the mean of the natural logarithms of the times-to-failure, $\sigma_{T'}$ is the standard deviation of the natural logarithm of the time-to-failure or shape parameter of distribution or shape parameter.

The following assumptions are made prior to the model building and analysis.

1. The underlying life distribution has a common shape parameter across different stress levels. This assumption is valid when similar failure modes are at accelerated and normal condition.
2. The sample is uniformly heated.
3. The initial life parameters are constant over at least most of the life of the component.
4. The material property is isotropic and homogeneous.
5. Contact area with disc is equal to pin area.

It is a generally accepted practice to assume a constant shape parameter across the different stress levels when analyzing the data of an ALT (Ref 25). It implies that the unit/component will fail in the same manner or with the same failure mode across different stress levels. In this case, the copper-graphite composite exhibited same wear mechanism under all the selected stress levels. Similar observation is also reported in conventionally fabricated copper-graphite composite (Ref 19) for

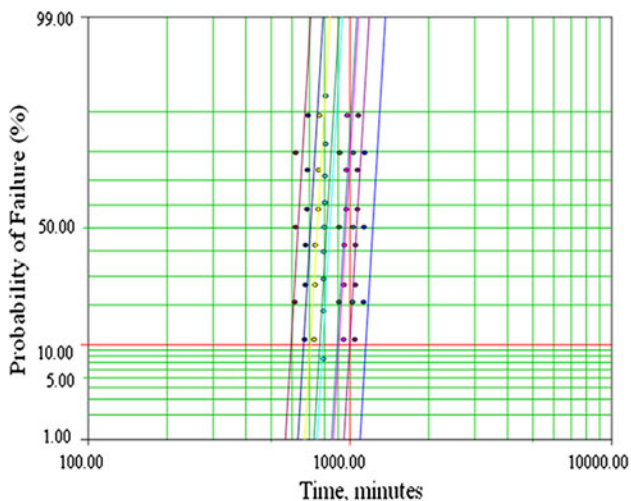


Fig. 9 Lognormal probability plot

different stress levels. However, it is necessary to validate the assumption of constant shape parameter across different stress levels. The time-to-failure data given in Table 2 is used for validation of assumptions as well as model building.

For the calculation of distribution parameters, separating the time-to-failure data of the each stress level and assumed that lognormal distribution as underlying distribution for the time-to-failure data. The results are shown in lognormal probability plot (Fig. 9). The linearity of the data supports the use of the lognormal distribution. In addition, the data appear parallel on this plot, this reinforces the assumption of a common shape parameter. The maximum likelihood value (-231.0627) for the lognormal distribution is higher than that (-240.0112) of the Weibull distribution. This validates the assumption of fitting the time-to-failure data given in Table 2 to the lognormal distribution. The computation of maximum likelihood value is performed using ALTA 6 PRO software package imbedded with standard computational algorithms.

5.2 Life-Stress Relationship

The Arrhenius life-stress relationship is one of the most common life-stress relationships utilized in ALT. It has been widely used when the stimulus or acceleration stress is thermal (i.e., temperature) (Ref 26). The inverse power law (IPL) life-stress relationship is widely used in reliability engineering for nonthermal accelerated stresses such as pressure (Ref 27). Arrhenius and the IPL models can be combined to yield the temperature-nonthermal (T-NT) model. This model is given by,

$$L(P, V) = \frac{C}{P^n e^{-\frac{B}{V}}}. \quad (\text{Eq 2})$$

where L represents a quantifiable life measure; P represents pressure (kPa); V represents temperature ($^{\circ}\text{C}$); B , C , and n are model parameters.

5.3 T-NT Lognormal Model

For the T-NT Lognormal model, the reliability for a mission of time T for the T-NT Lognormal model is determined by

$$R(T, P, V) = \int_{T'}^{\infty} \frac{1}{\sigma_{T'}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t - \ln(C) + n \ln(P) - \frac{B}{V}}{\sigma_{T'}}\right)^2} dt. \quad (\text{Eq 3})$$

The T-NT Lognormal mean life function can be written as

$$\bar{T} = e^{\ln(C) - n \ln(P) + \frac{B}{V} + \frac{1}{2}\sigma_{T'}^2}. \quad (\text{Eq 4})$$

The estimation of parameters such as B , C , and n are obtained using maximum likelihood estimation (MLE) through ALTO PRO 6 tools, as follows: $\sigma_{T'} = 4.7817E - 02$, $B = 177.4474$, $C = 15219.6871$, and $n = 0.4898$. B is a measure of the effect that the temperature has on the life. Larger values of B indicate that the life is highly affected by temperature. n is model parameter which indicates the effect of pressure on the life of the composite. The standard computational algorithm for estimation of above-mentioned parameters is imbedded with ALTA 6 PRO software package. The validation of assumed T-NT Lognormal model can be carried out using graphical method. The graphical method is performed through lognormal probability paper. This method is used to estimate the standard deviation of the natural logarithms of the time-to-failure data of Table 2. The estimated standard deviation of the natural logarithms of the time-to-failure or shape

parameter from the graphical method is $4.6978E-02$. Shape parameter calculated by MLE method is very small difference with graphical method. Hence, the obtained time-to-failure data is well fitted to assumed model to predict the life of accelerated wear tested composites.

Depending on the application (and where the stress is exclusively thermal), the parameter B can be replaced by,

$$B = \frac{E_A}{\bar{K}} \quad (\text{Eq 5})$$

where E_A is the activation energy, \bar{K} is the Boltzman's constant, B has the same properties as the activation energy.

Life of composites can be predicted at normal usage pressure level from the life versus stress plot, as shown in Fig. 10. Also life versus stress plots can be very useful in assessing the effect of each stress to a component's failure. In this case, since the life is a function of two stresses, two different plots should be created. Such plots are created by holding one of the stresses as constant at the desired use level, and varying the second. Figure 10 is generated by holding the pressure constant at normal usage level, and plotting life as a function of temperature. The three lines in the Fig. 10 correspond to the component life at 1, 50, and 99% reliability at room temperature 30°C .

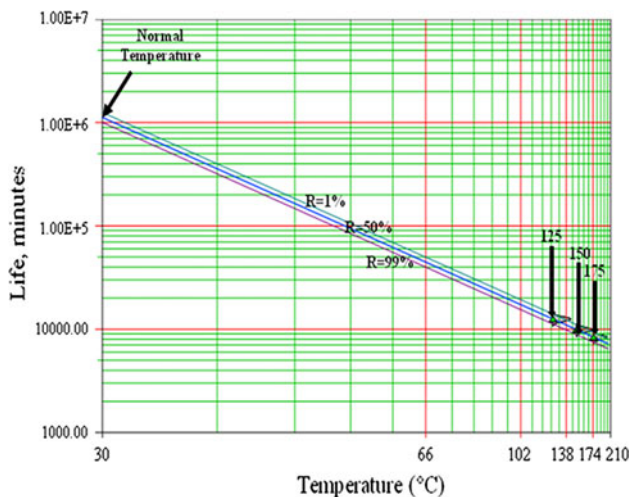


Fig. 10 Life versus temperature at use level

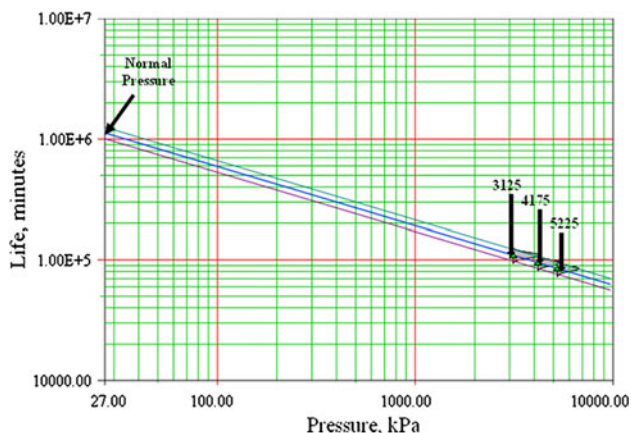


Fig. 11 Life versus pressure at use level

The life of the composite is 12,000 min (200 h) at temperature 125°C and it decreases to 8000 min (133.33 h) at temperature 175°C as shown in Fig. 10. This large value of reduction in the life of the composite indicates the impact of temperature on the life of the composite. At higher temperatures the copper matrix begins to soften which leads to weaker interfaces between the copper matrix and the reinforcement. It results in fracture of graphite particles from the copper matrix.

Similarly, by holding the constant temperature at normal usage level, and plotting life as a function of pressure is shown in Fig. 11. Three lines in Fig. 11 correspond to the component life at 1, 50, and 99% reliability level for an usage level pressure of 27-34 kPa which normally acting over the electrical sliding contact (Ref 20).

From Fig. 11, it is observed that the life of the composite at 3125 kPa is 105,000 min (1750 h) and it decreases to 8100 min (135 h) at 5225 kPa. Thus, the pressure has also significant effect on the life of the composite. Any increase in pressure tries to weaken the self-lubricating carbon film and consequent reduction of area covered by the film resulting in increased wear. Figures 10 and 11 can be used as an assessment of the effect of each stress on the life of the component extrapolated to normal usage condition. It shows that the mean life of the composite at normal usage level in both cases is 1,123,500 min (i.e., 18,725 h). The 99% reliable life of the composite at the usage pressure level (27-34 kPa) and room temperature can be calculated using Eq 3, the predicted value of 99% reliable life is expressed in 16,735 h. The expected life of the conventional contact brushes made of graphite is 2000-5000 h (Ref 20). As can be seen, this is much less than the mean life of the composite. Under normal temperature and pressure, the graphite possessing poor thermal conductivity compared to copper could not dissipate the generated heat. As a result, graphite particles will easily break away from of the contact surface causing higher wear rate. Thus, the conventional contact made of graphite could not survive for a longer time. On the other hand, copper-graphite is an excellent tribological composite, exhibiting longer service life since it has copper to have good thermal conductivity and graphite for self-lubrication.

Copper-graphite composite exhibits good performance and life for electrical sliding contact applications. A strong dependency is shown between the pressure and the temperature influencing the wear rate of the composite. The graphite brush material exhibit lower life for this type of operation. Thus, this high efficient copper-graphite composite can be successfully applied to new generation motors and sliding contact applications.

6. Conclusions

Microwave sintering technology is successfully applied to fabricate the copper-graphite composite. The developed composites are subjected to the state-of-the-art multiple stress accelerated wear test. Temperature and applied pressure are found to be significantly affecting the wear characteristics of the developed composite. Self-lubricating carbon and oxide film formations are helpful to extend the life of copper graphite composite during wear test, as confirmed through SEM with EDAX studies. T-NT lognormal model is suitable to estimating the life characteristics and reliability of the composite under sliding wear condition. The microwave-sintered copper-

graphite composite exhibited three and half times higher mean life than electrographite sliding contact material. T-NT Lognormal life-stress model predicted the mean life and 99% reliability of 18,725 and 16,735 h, respectively for the developed composite.

References

1. E.T. Thostenson and T.W. Chou, Microwave Processing: Fundamentals and Applications in Composites, *Appl. Sci. Manuf.*, 1999, **30**, p 1055–1071
2. K. Venkateswarlu, Suman Saurabh, V. Rajinikanth, Ranjan Kumar Sahu, and Ajoy Kumar Ray, Synthesis of TiN Reinforced Aluminium Metal Matrix Composites Through Microwave Sintering, *J. Mater. Eng. Perform.*, 2010, **19**, p 231–236
3. S.M.L. Nai, J.V.M. Kuma, M.E. Alam, X.L. Zhong, P. Babaghorbani, and M. Gupta, Using Microwave-Assisted Powder Metallurgy Route and Nano-size Reinforcements to Develop High-Strength Solder Composites, *J. Mater. Eng. Perform.*, 2010, **19**, p 335–341
4. A. Uecker, Lead-Free Carbon Brushes for Automotive Starters, *Wear*, 2003, **255**, p 1286–1290
5. R. Honbo, H. Wakabayashi, Y. Murakami, N. Inayoshi, K. Inukai, T. Shimoyama, et al. Development of the Lead-Free Brush Material for the High-Load Starter, *Proceedings of the Fifty-First IEEE Holm Conference on Electrical Contacts*, 2005, September 26–28, 2005, p 298–303
6. J.K. Lancaster, The Influence of the Conditions of Sliding on the Wear of Electro Graphitic Brushes, *Br. J. Appl. Phys.*, 1962, **13**, p 29–41
7. M. Bravunovic, V.V. Konchits, and N.K. Myshkin, *Electrical Contacts: Fundamentals, Applications and Technology*, 1st ed., CRC press, New York, 2007
8. J.R.V. Dorp and T.A. Mazzuchi, A General Bayes Weibull Inference Model for Accelerated Life Testing, *Reliab. Eng. Syst. Saf.*, 2005, **90**, p 140–147
9. B.X. Wang, Testing for the Validity of the Assumptions in the Exponential Step-Stress Accelerated Life-Testing Model, *Comput. Stat. Data Anal.*, 2009, **53**, p 2702–2709
10. F. Pascual, Accelerated Life Test Planning with Independent Weibull Competing Risks, *IEEE Trans. Reliab.*, 2008, **57**, p 435–444
11. A. Mettas, Modeling & Analysis for Multiple Stress-Type Accelerated Life Data, *IEEE Proceedings of Annual Reliability and Maintainability Symposium*, Los Angeles, California, USA, January 24–27, 2000, p 138–143
12. L.M. Klyatis and E.L. Klyatis, *Accelerated Quality and Reliability Solutions*, 1st ed., Elsevier, Amsterdam, 2006
13. Y. Maozhong, Tribological Behavior of a Novel C/C-Cu Sliding Electrical Contact Material, *Tribology*, 2009, **29**, p 458–463
14. D. Betz, Relationship between Contact Resistance and Wear in sliding Contacts, *IEEE Trans. Parts Hybrid Packag.*, 1974, **10**, p 32–37
15. Y. Watanabe, Composite Materials Containing Solid Lubricants as the New Sliding Contact Materials, *IEICE Trans. Electron*, E82-C, 1999, p 19–24
16. H.P. Liu, R.W. Carnes, and J.H. Gully, Effect of Temperature on Wear Rate of Homopolar Pulse Consolidated Electrical Brushes, *Wear*, 1993, **167**, p 41–47
17. K. Rajkumar and S. Aravindan, Microwave Sintering of Copper-Graphite Composites, *J. Mater. Process. Technol.*, 2009, **209**, p 5601–5605
18. I. Yasar, A. Canakci, and F. Arslan, The Effect of Brush Spring Pressure on the Wear Behaviour of Copper-Graphite Brushes with Electrical Current, *Tribol. Int.*, 2007, **40**, p 1381–1386
19. S.F. Moustafa, S.A. El-Badry, A.M. Sanad, and B. Kieback, Friction and Wear of Copper-Graphite Composite Made with Cu-Coated and Uncoated Graphite Powders, *Wear*, 2002, **253**, p 699–710
20. R.J. Hamilton, DC Motor Brush Life, *IEEE Trans. Ind. Appl.*, 2000, **36**, p 682–687
21. A. Emge, S. Karthikeyan, H.J. Kim, and D.A. Rigney, The Effect of Sliding Velocity on the Tribological Behavior of Copper, *Wear*, 2007, **263**, p 614–618
22. H. Kato, M. Takama, Y. Iwai, K. Washida, and Y. Sasaki, Wear and Mechanical Properties of Sintered Copper-Tin Composites Containing Graphite, *Wear*, 2003, **255**, p 573–578
23. Z.L. Hu, Z.H. Chen, and J.T. Xia, Study on Surface Film in the Wear of Electrographite Brushes Against Copper Commutators for Variable Current and Humidity, *Wear*, 2008, **264**, p 11–17
24. C. Steele, Use of the Lognormal Distribution for the Coefficients of Friction and Wear, *Reliab. Eng. Syst. Saf.*, 2008, **93**, p 1574–1576
25. A. Mettas and P. Vassiliou, Modeling and Analysis of Time-Dependent Stress Accelerated Life Data, *IEEE Proceedings of the Annual Reliability and Maintainability Symposium*, Seattle, Washington, USA, January 28–31, 2002, p 343–348
26. D.J. Groebel, A. Mettas, and F.B. Sun, Determination and Interpretation of Activation Energy Using Accelerated Test Data, *IEEE Proceedings of the Annual Reliability and Maintainability Symposium*, Philadelphia, Pennsylvania, USA, January 22–25, 2001, p 58–63
27. W. Shin and S. Lee, A Development of Accelerated Life Test Method for Blower Motor for Automobile Using Inverse Power Law Model, *Int. J. Mod. Phys. B*, 2008, **22**, p 1074–1080