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Technical Report

Accelerated wear testing for evaluating the life characteristics of copper–graphite tribological composite

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ABSTRACT

Sliding wear is a key determinant of the performance of electrical sliding contacts used in electrical machines. The behavior of the contact in sliding couple is controlled by the mutual metal transfer, friction and wear. Product life and reliability of sliding contacts are dictated by wear phenomenon. The present paper focuses on evaluation of tribological performance of copper–graphite composites using reliability theory. These composites are made up of a high electrical and thermal conductivity matrix with a solid lubricant reinforcement, making it most suitable for sliding contacts. Traditional life tests under normal operating condition would be a time consuming process due to a very long expected life of the composite. Hence, accelerated wear testing was carried out for evaluating the life characteristics. Analysis was then performed on the times-to-failure data and reliability models were developed. Life-stress relationship based on the inverse power law-Weibull model was used to make reliability predictions at normal usage level.

1. Introduction

The functioning of many mechanical and electromechanical components/systems gets affected by friction and wear. For such components/systems, the friction and wear mechanisms should be studied thoroughly in order to address the tribological issues. In electrical motor/generator industries, there is a high demand for electrical sliding contacts like electric brushes. Severe friction and wear conditions are experienced by the brushes since there is a relative movement between the brush and slip ring/commutator [1,2]. In electrical machines, the electrical sliding contact usually consists of carbon and electrographite brushes. These materials do not last long due to the generation of carbon dust when wear process commences [3]. As these brushes fall in the category of non-repairable components, they are expected to be replaced at regular intervals according to a preventive replacement schedule. Since this adds to the life cycle cost of the equipment, it is desirable to have a material with improved properties with respect to self lubrication, wear resistance, good conductivity and resistance to arcing [4,5].

It was found from the literature that microwave sintered copper–graphite composites possess the properties suitable for electrical sliding contact applications [6,7]. The present study proposes to use and evaluate the tribological performance of copper–graphite composite, processed through microwave sintering, as a potential material for electrical sliding contact. Due to a very long expected life of the composites, carrying out the traditional life tests under normal operating conditions would be time consuming. Hence, accelerated wear testing was carried out for evaluating the life characteristics, within a shorter duration. Reliability assessment was done based on life-stress relationship using inverse power law-Weibull model.

2. Accelerated life testing (ALT)

2.1. The concept

In conventional life data analysis, the life data of a test sample operating under normal (or usage) condition is analyzed in order to quantify the life characteristics of the product and make reliability predictions. However, due to time or budget constraints, it may be necessary to obtain test results more quickly than the normal operating condition. This can be achieved using quantitative accelerated life tests (QALT) to capture life data of the product under accelerated stress conditions. The QALT approach is to use life data obtained under accelerated conditions and estimate the probability density function (*pdf*) for the product under normal usage condition, which can then be further used to do a variety of reliability analysis [8,9].

To accelerate the time-to-failure for the products under test, two approaches viz. usage rate acceleration and operating stress acceleration can be employed [10,11]. Usage rate acceleration is appropriate for products that do not operate continuously under

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Nomenclature

Η	represents Weibull scale parameter	T	is time-to-failure
β	represents Weibull shape parameter (or slope)	$\bar{T}$	is mean time-to-failure
γ	represents Weibull location parameter	$f()$	is probability density function (*pdf*)
K	is one of the model parameters of life-stress relationship, ($K > 0$)	L	represents a quantifiable life measure
n	is model parameter of inverse power law	P	is the pressure level

normal conditions. Acceleration in such a case means operating the products under test at a greater rate than normal to simulate longer periods of operation under normal conditions. Once failure data is obtained, standard life data analysis techniques can be used. Employing stress acceleration means increasing the level of environmental factors, which cause the product to fail under normal conditions (like temperature, voltage, humidity, etc.), to stimulate product failures more quickly. For this type of tests, special accelerated life data analysis techniques are required. The objective is to develop a mathematical model that predicts the parameters of the time-to-failure *pdf* at normal usage condition from those at accelerated stress conditions. However, in order to do this, it is necessary to have a mechanism to relate stress levels with distribution parameters. In QALT terminology, these are called life-stress relationship models.

2.2. Life-stress relationship models

As mentioned above, life-stress relationship models allow the analyst to extrapolate a time-to-failure *pdf* at usage level from failure data obtained at accelerated stress levels [12,13]. These models describe the degradation path of the life characteristics from one stress level to another. The life characteristic can be expressed as a function of stress. It gives any life measure, like mean life and 90% reliability life etc.

A Weibull distribution has been used to model the time-to-failure distribution [14,15], where the scale parameter is stress-dependent. Developing a life-stress relationship model in this case would mean predicting the scale parameter as a function of stress, which in the present study is the pressure on the electrical contact.

Various types of life-stress relationships have been proposed in the literature and the appropriate one should be selected. One of the ways to do this is to look at similar experiments and the life-stress relationship used. Some of the available life-stress models most commonly used for accelerated life test (ALT) with single stress is the Arrhenius, Eyring, and inverse power law models [16,17]. Degradation of composite occurs with the increase in mechanical loading and thereby results in reduction of the life time. Inverse power law (IPL) life-stress relationship is well suited for such wear-out condition. Thus, IPL-Weibull model is applied here.

2.3. Designing accelerated tests

While designing an accelerated life test, appropriate stresses and stress levels should be chosen so that they accelerate the failure modes under consideration but do not introduce failure modes that would never occur under use conditions. One guideline is to use stress levels that fall outside the product specification limits but inside the design limits or below the destruct limits. However, if these stresses or limits are unknown, multiple tests with small sample sizes need to be performed to determine the appropriate accelerated stress levels. The normal pressure acting on an electrical brush in normal use condition in DC motor (up to 1500 rpm) application is 27–34 kPa. Wear rate increases with normal pressure which results in a reduction of the brush life. The predominant failure mechanism of DC motor is due to the worn-out brushes [18].

3. Material and its properties

Copper matrix composite specimens, reinforced with 10 vol.% of graphite particles were manufactured through microwave processing route. Centrifugal ball mill was used to mix copper (grain size 12 μm) and graphite (grain size 50 μm) powders too uniformly. The mixed powders were then cold pressed to fabricate a pin of 14 mm diameter and 10 mm height. The green specimens were sintered in an industrial microwave furnace (2.45 GHz) at 850 °C for 45 min excluding cooling time. The average values of mechanical properties such as density, porosity and hardness of the fabricated composite were 7.54 g/cc, 8.75% and 98 HV (±2%) respectively. The detailed discussion on the sintering process and the characteristics of composites are published elsewhere [7].

To obtain an understanding of distribution of graphite particles in the copper matrix, micro structural studies were carried out. Microwave sintered specimens were mirror polished using a standard metallographic technique and then scanning electron microscope (SEM) image was taken. SEM image of copper–graphite is presented in Fig. 1. The black areas in copper matrix are graphite particles. These graphite particles are uniformly distributed throughout the copper matrix due to adequate ratio of the surface areas of copper particles and graphite particles. Near equiaxed grain morphology and finer microstructure can be seen in Fig. 1. No cracks or fissures are seen in SEM micrographs which confirm the advantages of microwave sintering. It is also seen from the micrographs that the pores are of relatively smaller percentage.

4. Experimental procedure

4.1. Initial analysis

A pin-on-disc type wear testing machine was used to study the tribological performance of the composite [19]. Composite pins

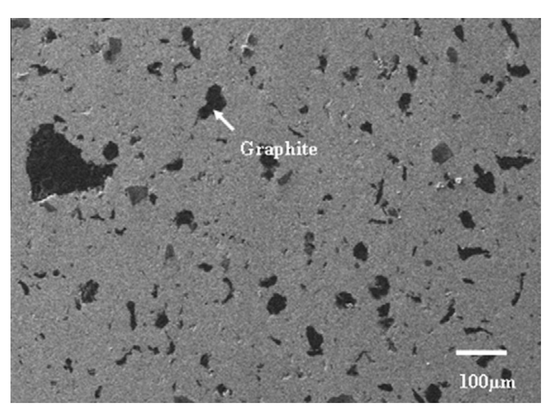

Fig. 1. Microstructure of copper–graphite composite.

were rubbed against an EN30 steel disc. This steel disc composition is similar to actual steel slip ring used in the DC motor electrical machine [20]. Prior to the test, all the contacting surfaces were polished with 800 grade silicon carbide paper, then cleaned in acetone and dried. In order to find out the accelerated pressure, the preliminary experimental trials were conducted on the copper–graphite samples in pin-on-disc machine with EN30 steel disc. The selected testing parameters are as follows: pressure 1250–5000 kPa, sliding velocity of 0.88, 1.88 and 2.88 m/s and a constant sliding distance of 13,000 m. The selected applied pressure here was higher than the usage pressure in order to accelerate the wear process. It was observed that the coefficient of friction increased to some extent above a sliding velocity of 1.88 m/s. Generally in sliding wear out process, coefficient of friction is recorded in a steady state condition. The wear test should be conducted at a longer sliding distance to minimize the fluctuation of coefficient of friction. The variation of wear rate with applied pressure is shown in Fig. 2. It was observed that the increase in applied pressure increases the wear rate of composites. As per Archard's wear theory [21], the increase of applied pressure or load the wear rate of the material is increased. In the case of copper–graphite composites, the increase in applied pressure causes the squeezing out of graphite particles from bulk towards the contact surface. This happens till 2500 kPa. It can also be seen that 2500 kPa is the transition point from low to mild wear rate. Beyond the transition pressure, though more graphite particles are squeezed out, localized stress is predominant to cause the worn out of copper matrix.

The wear mechanism operating in copper–graphite composite is analyzed by studying the worn out surfaces of tested pins. During sliding, the rubbing of composite pin against the counter surface leads to the formation of copper oxide film [4], besides the smeared graphite film. This graphite lubricating film reduces the metal to metal contact and thereby reduces the wear rate of composite. SEM images of worn surfaces of the composites are shown in Fig. 3. It can be observed from Fig. 3a and b that the worn out surfaces have considerable amount of grooves and scars. The worn out surfaces have exhibited a certain degree of roughness at lower and higher pressure. At 1250–2500 kPa, a considerable deformation of the worn surface structure is observed. It is observed from SEM (Fig. 3 a) that white batches (oxide film) is scarce and there is a smaller wear scar due to lower applied pressure and thereby wear rate of composite is reduced. The oxide film formation is observed to be increased with the increase in applied pressure. Due to increased applied pressure, the composite surface underwent plastic deformation in the sliding contact zone. Fig. 3b reveals the white batches (oxide film) with considerable wear scars. When composite pin is running against countersurface for a larger duration, there is an increase in temperature of bulk material. It results reduction in the strength of the matrix with increase in temperature rise. This temperature rise leads to weaken the microstructure of composite. Micro-volumes of composite material adjacent to the contact areas and the bond between matrix and graphite particles are weakened. With sliding, sub-surface deformation occurs which leads to peeling of tribo layer of the worn surface i.e., larger wear flakes are formed. This is similar to the delamination wear mechanism operating at low wear rates (Fig. 3a). Mild wear rate produces considerable deformation and fragmentation at tribo surface and sub-surface (Fig. 3b). This wear mechanism is also similar to delamination. Oxidative and sub-surface delamination wear mechanisms are predominant for copper–graphite composites at low and mild wear regimes. This has been also supported by the findings of Moustafa et al. [4].

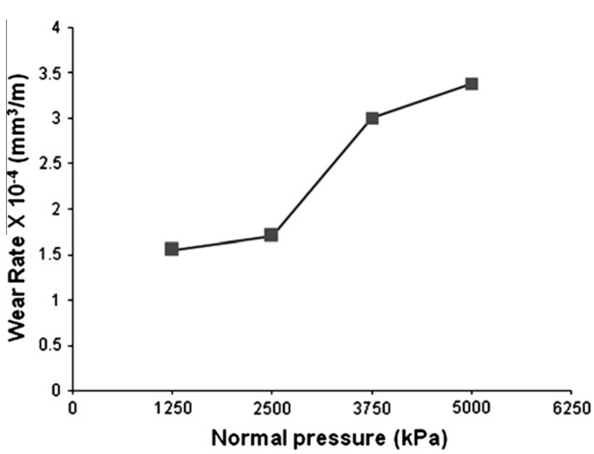

Fig. 2. Variation of wear rate with pressure for copper–graphite composite.

4.2. Accelerated wear life test

Pin-on-disc type wear testing machine was used to study the accelerated life testing of the composite. The wear tests were conducted at accelerated pressure in the range 1250–5000 kPa at a constant sliding velocity of 1.88 m/s. The times-to-failure of copper matrix composite reinforced with 10 vol.% of graphite particles for each pressure were noted separately. The failure occurs when the wear depth reaches a certain value in the substrate of sliding material [22]. Time-to-failure of composite is calculated on the basis of time at which wear depth reaches 0.4 mm. In the preliminary wear test trials, heavy fragments dislodged from the worn surface of composites was observed when the wear depth reached 0.4 mm at pressure 1250 kPa. This wear depth was kept constant for all applied accelerated pressure in ALT test.

4.3. Experimental data

Accelerated wear test was conducted for copper–graphite composite with different applied accelerated pressures. Pressure was selected in such a way that it could be extrapolated to normal usage condition where the same failure mechanism prevails. Four different accelerated pressures were selected in the range of 1250–5000 kPa. The times-to-failure data in ascending order for applied accelerated pressure is presented in Table 1. In this case, the times-to-failure data are used for selecting statistical distribution and reliability model. The wear depth was continuously monitored by the linear variable differential transformer (LVDT) probe that was incorporated in the wear tester. From the Table 1, it is observed that as the applied pressure increases, the time-to-failure of the composite decreases (i.e., the wear rate of the composite increases). The applied pressure increases the squeezing out of graphite particles more from the composite sub-surface to contact zone and simultaneously more composite pin deformation is occurred [23]. The smeared graphite particles form the graphite film at contact surface. At lower applied pressure, balancing actions of smeared graphitic film and modest deformation composite microstructure make composite to fail after a longer time. At increased pressure (5000 kPa), though more graphite squeezes out from the sub-surface to the contact surface the predominant action of deformation of microstructure results in. It weakens the formed graphite film during sliding. As a result of that the time-to-failure at higher pressure is short.

5. Building a reliability model

5.1. Choice of distribution and assumptions

Since Weibull distribution provides a closer approximation to the probability laws of many natural phenomena [24,25], it is used

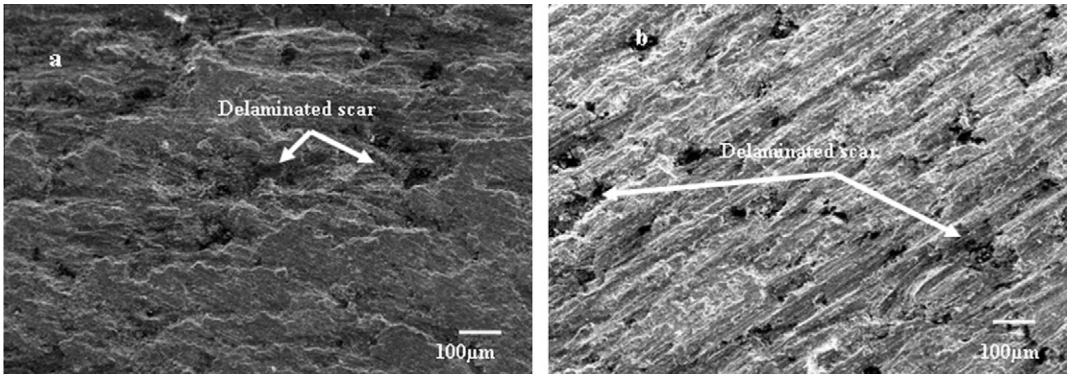

Fig. 3. SEM images of worn out surface of composite at: (a) 1250 kPa and (b) 3750 kPa.

Table 1
Times-to-failure with applied accelerated pressure.

Serial No.	Applied accelerated pressure (kPa)	Times-to-failure (min)	Serial No.	Applied accelerated pressure (kPa)	Times-to-failure (min)
1	1250	41,145	13	3750	19,315
2	1250	43,065	14	3750	21,205
3	1250	45,096	15	3750	23,134
4	1250	47,759	16	3750	25,051
5	1250	49,420	17	3750	26,984
6	1250	51,355	18	3750	28,765
7	2500	30,415	19	5000	10,235
8	2500	32,135	20	5000	11,765
9	2500	34,038	21	5000	13,357
10	2500	35,952	22	5000	14,953
11	2500	37,812	23	5000	16,468
12	2500	39,965	24	5000	17,986

as the underlying life distribution. In recent years a lot of attention is focused on the use of Weibull distribution due to its greater flexibility and simplicity. It can also give a good fit to experimental data [26–30]. The following assumptions were made prior to the reliability analysis and model building.

1. The underlying life distribution has a common shape parameter across different pressure levels.
2. The initial life parameters are constant over the life of the product.
3. The material property is isotropic and homogeneous.
4. Real contact area is equal to pin contact area.

Generally accepted practice is to assume a constant shape parameter across the different stress levels (independent of stress) when analyzing data of an accelerated life test [31]. It implies that the unit/component will fail in the same manner or with the same failure mode across different stress levels.

5.2. Life-stress model

The inverse power law (IPL) model is used to model the effect of stress levels on the characteristic life of the Weibull distribution. The model is widely used in reliability engineering for non-thermal accelerated stresses such as pressure and stress [16,32].

$$L(P) = \frac{1}{KP^n} \tag{1}$$

As the value of parameter 'K' increases, the life of the component decreases. The parameter 'n' is a measure of the effect of stress on life. Higher absolute value of 'n' indicates that stress has a significant effect on the life of the component.

5.3. Reliability model

The Weibull distribution function can be expressed mathematically as

$$f(T) = \frac{\beta}{\eta}\left(\frac{T-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \tag{2}$$

where η represents Weibull scale parameter, β represents Weibull shape parameter (or slope), γ represents Weibull location parameter, and T is time-to-failure.

Two parameter Weibull distribution is assumed by setting the location parameter γ, equal to zero. The above *pdf* can then be written as

$$f(T) = \frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1} e^{-\left(\frac{T}{\eta}\right)^{\beta}} \tag{3}$$

while, the Weibull reliability and mean life functions can be written as follows

$$R(T) = e^{-\left(\frac{T}{\eta}\right)^{\beta}} \tag{4}$$

$$\overline{T} = \eta \cdot \Gamma\left(\frac{1}{\beta}+1\right) \tag{5}$$

where β and η are the shape and scale parameters respectively.

In order to use a model based on accelerated test data, the scale parameter η of the Weibull distribution has to be replaced by $L(P)$ of the inverse power law (IPL) model. Accordingly, the modified Weibull *pdf*, reliability and mean life functions can be written as

$$f(T,P) = \beta KP^n (KP^nT)^{\beta-1} e^{-(KP^nT)^{\beta}} \tag{6}$$

$$R(T,P) = e^{-(KP^nT)^{\beta}} \tag{7}$$

$$\overline{T} = \frac{1}{KP^n} \cdot \Gamma\left(\frac{1}{\beta}+1\right) \tag{8}$$

The approach involved separation of the data set on each stress level and calculating the distribution parameters for each data set assuming Weibull distribution. Kececioglu Dimitri [33] reported the procedure of estimating the correlation coefficient, Accordingly the correlation coefficient is estimated and it confirms the fitness of life data in probability plot for Weibull distribution. The absolute value of the correlation coefficient for the Weibull distribution is 0.99, almost equal to 1. Correlation coefficient for lognormal distribution is 0.92 which is less than the Weibull correlation coefficient. This validates the assumption of fitting the times-to-failure data to the Weibull distribution.

The parameters of the model were obtained using the test data in Table 1, through maximum likelihood parameter estimation method. Obtaining numeric values for the model parameters using maximum likelihood estimator requires the use of a computational algorithm imbedded in a software package like ALTA 6 PRO. The obtained parameters are $\beta = 5.917$, $K = 9.748 \times 10^{-08}$ and $n = 0.737$.

The obtained times-to-failure for different applied pressure were used to construct the Weibull probability failure plot. The Weibull probability failure plot for different applied pressure is shown in Fig. 4. The constant shape parameter (β) at each applied pressure and zero location parameter (γ) were used for each distribution so that the distributions of times-to-failure data were separated along the abscissa. Similar usage of constant shape parameter for accelerated wear testing of an induction motor bearing was reported [34]. The plotted points for each applied pressure tend to follow straight line, and thus the Weibull distribution can be assumed to describe the times–to-failure data adequately. In addition, the fitted straight lines appear to be almost parallel. The parallelism of all fitted lines indicates the same failure mechanism and it also reveals that the Weibull distribution at different pressure has a common value for the shape parameter, since the wear mechanism remains unchanged for different applied pressure. It clearly indicates that degrading path was not changed due to the unchanged shape parameter for any time and any accelerated pressure.

The validation of assumed model can be carried out either through likelihood ratio test or by graphical method (Weibull probability paper). The graphical method is used to estimate the shape parameter from the times-to-failure data of Table 1. The estimated shape parameter (β) from the graphical method is 5.92. The shape parameter calculated by the maximum likelihood parameter estimation method is 5.91, which is used for the parameters estimation in this study. It is confirmed that the assumed model is well fitted with the times-to-failure analysis of accelerated wear test data. Similar graphical method is reported for validating the assumed Weibull-inverse power law model for the life prediction of mylar-polyurethane laminated high voltage insulating structure [35].

The estimation of shape parameter is biased, even though the maximum likelihood method produces a closer value of model parameters due to the smaller sized samples. The unbiased estimator of β can be obtained by using the formula [36].

$$\beta_u = \frac{\beta_b}{1.0115 + \frac{1.278}{r} + \frac{2.001}{r^2} + \frac{20.35}{r^3} - \frac{49.68}{r^4}} \tag{9}$$

where β_u is the unbiased estimator of β, β_b is the biased estimator of β, r is the number of times-to-failure.

The other parameters were recalculated by using the value of unbiased β_u. The unbiased parameters are $\beta_u = \beta = 5.532$, $K = 9.492 \times 10^{-08}$ and $n = 0.741$. The value of β is greater than one, and this confirms that the material fails due to a degradation based failure mode. Using the above the unbiased shape parameter and model parameter, the life of the composite at accelerated pressure level can be extrapolated to the usage pressure level. The life vs. pressure plot for the copper–graphite composite is shown in Fig. 5. The three lines in the Fig. 5 correspond to the component life at 1%, 50% and 99% reliability for the usage level pressure of 27–34 kPa. The 99% reliable life of the composite at the usage pressure condition of 27–34 kPa is 6149 h. Similar ALTA 6 PRO software package imbedded with maximum likelihood estimator was reported for predicting the life of optical products and thin film transistor gate line interconnects [37,38].

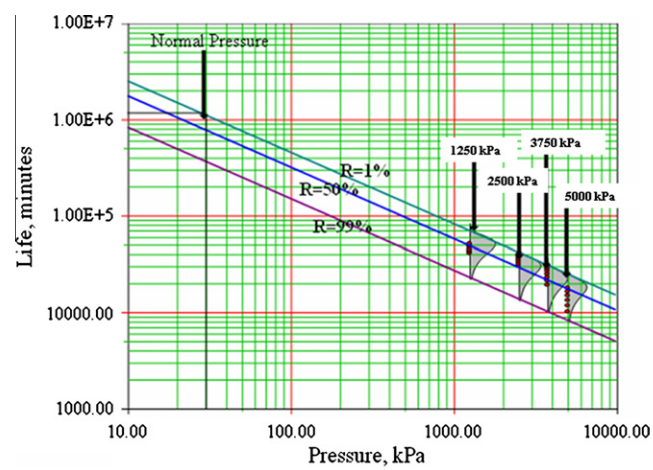

Fig. 5. Variation of life of composite with applied accelerated pressure.

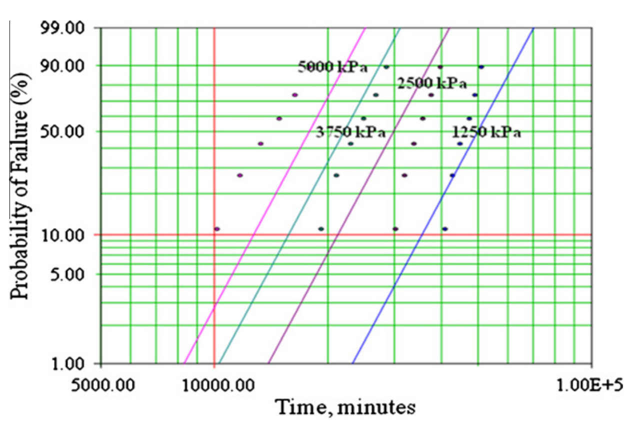

Fig. 4. Weibull probability plot.

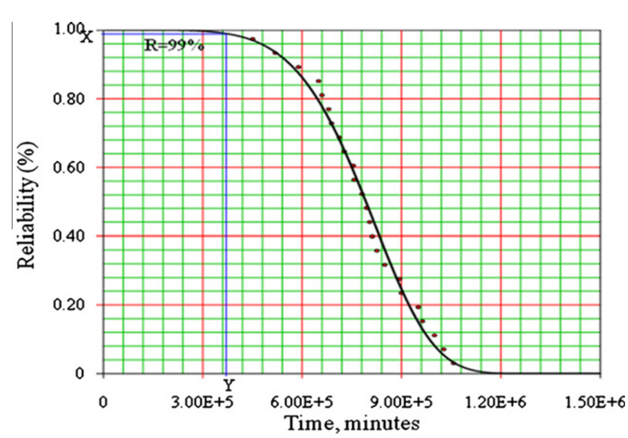

Fig. 6. Variation of reliability of composite with time.

Table 2
Variation in Sensitivity Index with model parameter.

Parameters of IPL-Weibull model	Variation (%)	Model parameter value	Mean Life (h)	Sensitivity Index
β	2	5.643	13,058	0.06
	−2	5.421	13,028	
K	2	9.682×10^{-08}	12,776	1.02
	−2	9.302×10^{-08}	13,310	
n	2	0.756	12,394	2.49
	−2	0.726	13,692	

Fig. 6 shows the reliability vs. time plot at the normal usage condition. Initially the wear rate of composite pin with time is higher due to direct metal to metal contact established between the sliding surfaces [5]. With the continuation of sliding, the graphite from the composite pin surface is exposed to the contact zone, and then the contact between them is changed to mixed contact which includes direct metal to metal and contacts separated by smeared graphite film. This condition exists up to certain duration till the contact zone is covered with complete graphite film. The complete coverage of graphitic film in the contact zone is termed as steady state which can be understood from the constant slope of reliability vs time plot (Fig. 6). It is usually known as useful life period. During this period of time, the lowest wear rate occurs. The reliability prediction is made from this useful life period. The mean life of composite under usage condition also lies within this useful life period. After the longer duration of operation, delamination of formed graphite film occurs [4]. This leads to more rapid wear rate with time, as seen from tail end of the plot. Similarly, the mean life can be calculated from the Eq. (8), the mean life of the copper–graphite composite at normal usage condition will be 13,043 h.

The expected life of the conventional contact brushes made of graphite is 2000–5000 h [3], which is at lower order when compared to the mean life of developed composites. The high reliability of the copper–graphite sliding material avoids frequent down time and unscheduled interruptions. Thus it can be consistently used for a longer time. Under normal temperature and applied pressure, the graphite possessing poor thermal conductivity compared to copper. It could not dissipate the generated heat. As a result, graphite particles will easily comes out of the contact surface causing higher wear rate and carbon dusting problems [3,39]. On the other hand, copper being a good thermal conductor which dissipates the heat quickly and when it is reinforced with graphite particles, it produces an excellent tribological composites having longer life.

6. Sensitivity analysis

Life characteristics can be varied due to variation in material quality and inherent testing error. It would affect the estimation of the parameters of a given distribution. Under such circumstances there is a possibility of variation in estimated parameter values [40]. Moreover, β, K and n are point estimates [41]. Thus, it is important to investigate the sensitivity of the reliability estimates to the variations of the estimated changes in parameters. The variation of estimated parameters value is considered as ±2%.

The sensitivity analysis identifies the sensitive parameters which need to be estimated with much attention for the purpose of minimizing the risk of obtaining an erroneous solution [42]. A numerical value of sensitivity of mean life of the composite to each parameter was calculated, using a sensitivity index, as mentioned below

$$\text{Sensitivity Index} = \frac{\frac{\Delta\overline{T}}{\overline{T}}}{\frac{\Delta p}{p}}. \tag{10}$$

where $\overline{T}$ represents the mean life of the composite obtained by using the estimated parameters, $\Delta\overline{T}$ represents the variation in the mean life of the composite, p represents one of the estimated parameters, Δp represents the variation in the estimated parameter.

Table 2 presents the mean life of the composite. The mean life of the composite was calculated by varying one parameter with ±2% variation while keeping the other parameters as constant. The mean life of the copper–graphite composite under accelerated pressure condition appears to be the most sensitive one to the changes of the parameter 'n'. The sensitivity of 'n' depends on applied accelerated pressure on the composite pin. The parameter 'n' in the inverse power relationship (Eq. (1)) is a measure of the effect of the stress on the life. The applied pressure can invariably influence the wear rate of composite and the wear mechanism. With the increase in applied pressure increases the wear rate of composite increases. The wear mechanism depends on the applied pressure and formation of self lubricating film and copper oxide film. However the wear mechanism is not changed for the entire range of applied pressure. It can be understood from above discussion that the selection of accelerated pressure is very crucial for extrapolation of life from accelerated level to usage level. Variation in the value of β does not affect the mean life of the composite due to the constant shape parameter for any applied pressure and time. Variation in the values of K causes insignificant variation. The model is robust to changes in the parameters β and K. But variation in the values of 'n' causes significant variation in the mean life of the composite. So the estimate of the parameter 'n' should be accurate to reduce the error in the life estimation.

7. Conclusion

Life testing of components having high reliability under normal usage condition requires a longer time. Hence ALT is a highly useful method to estimate the life characteristics and reliability aspects of the component in a shorter period of time. The life prediction of microwave sintered copper–graphite composite for electrical sliding contact application under accelerated pressure condition was performed through accelerated wear testing methodology. The reliability analysis was performed, based on complete failure time data. Times-to-failure data were well fitted by a Weibull distribution as confirmed by a high value of correlation coefficient. The life-pressure relationship is established using IPL-Weibull model to demonstrate the ALT methodology for life prediction. The Weibull probability plot is in agreement with the assumption of a common shape parameter for all accelerated pressures to extrapolate to usage condition. The life of the copper–graphite composite at normal usage condition at 99% reliability is up to 6149 h. The mean life of the composite at normal usage condition is 13,043 h which is much higher than that of the traditional materials.

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References

[1] He DH, Manory R. A novel electrical contact material with improved self lubrication for railway current collectors. Wear 2001;249:626–36.
[2] He DH, Manory R, Grady N. Wear of railway contact wires against current collector materials. Wear 1998;215:146–55.
[3] Hamilton RJ. DC motor brush life. IEEE Trans Ind Appl 2000;36:1682–7.
[4] Moustafa SF, El-Badry SA, Sanad AM, Kieback B. Friction and wear of copper–graphite composite made with Cu-coated and uncoated graphite powders. Wear 2002;253:699–710.
[5] Kestursatya M, Kim JK, Rohatgi PK. Wear performance of copper–graphite composite and a leaded copper alloy. Mater Sci Eng A 2003;339:150–8.
[6] Rajkumar K, Aravindan S. Tribological performance of microwave-heat-treated copper–graphite composites. Tribol Lett 2010;37:131–9.
[7] Rajkumar K, Aravindan S. Microwave sintering of copper–graphite composites. J Mater Process Technol 2009;209:5601–5.

[8] Mettas A, Vassiliou P. Application of quantitative accelerated life models on load sharing redundancy. In: Proceedings of the annual reliability and maintainability symposium. Los Angeles, California, USA; January 26–29 2004.
[9] Mohammadian SH, Ait-Kadi D. Design stage confirmation of life time improvement for newly-modified products through accelerated life testing. Reliab Eng Syst Saf 2010;95:897–905.
[10] Yang G. Accelerated life tests at higher usage rates. IEEE Trans Reliab 2005;54:53–7.
[11] Mohammadian SH, Aït-Kadi D, Routhier F. Quantitative accelerated degradation testing: practical approaches. Reliab Eng Syst Saf 2010;95:149–59.
[12] Groebel DJ, Mettas A, Sun FB. Determination and interpretation of activation energy using accelerated-test data. In: Proceedings of the annual reliability and maintainability symposium. Philadelphia, Pennsylvania, USA; January 22–25 2001.
[13] Oman S, Fajdiga M, Nagode M. Estimation of air-spring life based on accelerated experiments. Mater Design 2010;31:3859–68.
[14] Cattell MK, Kibble KA. Determination of the relationship between strength and test method for glass fibre epoxy composite coupons using Weibull analysis. Mater Design 2001;22:245–50.
[15] Kimber AC. A Weibull-based score test for heterogeneity. Lifetime Data Anal 1996;2:63–71.
[16] Kececioglu D, Jacks JA. The Arrhenius, Eyring, inverse power law and combination models in accelerated life testing. Reliab Eng 1984;8:1–9.
[17] Bai DS, Chung SW. An accelerated life test model with the inverse Power law. Reliab Eng Syst Saf 1989;24:223–30.
[18] Shin W, Lee S. A development of accelerated life test method for blower motor for automobile using inverse power law model. Int J Mod Phys B 2008;22:1074–80.
[19] Rao RN, Das S. Wear coefficient and reliability of sliding wear test procedure for high strength aluminium alloy and composite. Mater Design 2010;31:3227–33.
[20] Yasar I, Canakci A, Arslan F. The effect of brush spring pressure on the wear behaviour of copper–graphite brushes with electrical current. Tribol Int 2007;40:1381–6.
[21] Ramalho A. A reliability model for friction and wear experimental data. Wear 2010;269:213–23.
[22] Wang KS, Chen CS, Huang JJ. Dynamic reliability behavior for sliding wear of carburized steel. Reliab Eng Syst Saf 1997;58:31–41.
[23] Ma W, Lu J, Wang B. Sliding friction and wear of Cu-graphite against 2024, AZ91D, and Ti6A14V at different speeds. Wear 2009;266:1072–81.
[24] Al-Garni AZ, Sahin AZ, Al-Farayedhi AA. A reliability study of Fokker F-27 airplane brakes. Reliab Eng Syst Saf 1997;56:143–50.
[25] Sivapragash M, Lakshminarayanan PR, Karthikeyan R, Raghukandan K, Hanumantha M. Fatigue life prediction of ZE41A magnesium alloy using Weibull distribution. Mater Design 2008;29:1549–53.
[26] Amaral PM, Fernandes JC, Rosa LG. Weibull statistical analysis of granite bending strength. Rock Mech Rock Eng 2008;41:917–28.
[27] Tang LC, Goh CJ, Lim SC. On the reliability of components subject to sliding wear. Scripta Metall Mater 1988;22:1177–81.
[28] Elgueta M, Diaz G, Zamorano S, Kittl P. On the use of the Weibull and the normal cumulative probability models in structural design. Mater Design 2007;28:2496–9.
[29] Andreasen JH. Reliability-based design of ceramics. Mater Design 1994;15:3–13.
[30] Sakin R, Ay I. Statistical analysis of bending fatigue life data using Weibull distribution in glass–fiber reinforced polyester composites. Mater Design 2008;29:1170–81.
[31] Mettas A, Vassiliou P. Modeling and analysis of time-dependent stress accelerated life data. In: Proceedings of the annual reliability and maintainability symposium. Washington, USA: Seattle; January 28–31 2002.
[32] Allegri G, Zhang X. On the inverse power laws for accelerated random fatigue testing. Int J Fatigue 2008;30:967–77.
[33] Kececioglu Dimitri B. Reliability and life testing handbook, vol. 1. Pennsylvania: DEStech Publication; 2002.
[34] Wang W. Reliability quantification of induction motors-Accelerated degradation testing approach. In: Proceedings of the annual reliability and maintainability symposium. Washington, USA: Seattle; January 28–31 2002.
[35] Kalkanis G, Rosso E. The inverse power law model for the lifetime of a Mylar-polyurethane laminated DC HV insulating structure. Nucl Instrum Method Phys Res 1989;A281:489–96.
[36] Zhang LF, Xie M, Tang LC. Bias correction for the least squares estimator of Weibull shape parameter with complete and censored data. Reliab Eng Syst Saf 2006;91:930–9.
[37] Lam CF, Huairui Guo, Larson L. Time-varying multi-stress ALT for modeling life of outdoor optical products. Reliability and maintainability symposium. Orlando, FL: RAMS '07; January 22–25 2007. p. 265–70.
[38] Thomas Martin, Aris Christou. Life-stress relationship for thin film transistor gate line interconnects on flexible substrates. In: IEEE CFP09RPS-CDR 47th annual international reliability, physics symposium. Montreal; 2009. p. 117–21.
[39] Holm E. Specific friction force in a graphite brush contact as a function of the temperature in the contact spots. J Appl Phys 1962;33:156–63.
[40] Nasser Fard, Chenhua Li. Optimal simple step stress accelerated life test design for reliability prediction. J Stat Plan Infer 2009;139:1799–808.
[41] Charruau S, Guerin F, Hernández Dominguez J, Berthon J. Reliability estimation of aeronautic component by accelerated tests. Microelectron Reliab 2006;46:1451–7.
[42] Monroe Eric M, Pan Rong, Anderson-Cook Christine M, Montgomery Douglas C, Borror Connie M. Sensitivity analysis of optimal designs for accelerated life testing. J Qual Technol 2010;42:121–35.