# A mathematical model to evaluate wear depth of an aluminium alloy reinforced with a silicon carbide particle composite using finite element analysis

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**Abstract:** In the present study, an attempt is made to synthesize an aluminium alloy–silicon carbide (SiC) particle composite using a liquid metallurgy route and to characterize the composites in terms of sliding wear behaviour and numerical simulation by finite element analysis. The sliding wear behaviour was studied using a pin-on-disc apparatus with the composite pin sliding against an EN32 steel counter surface at different applied loads and sliding speed. The experimental results for the aluminium alloy–SiC particle composite were validated using a mathematical model. A wear equation was used to predict the steady-state wear rates. It is based on an exponential transient wear volume equation and Archard's equation. An algorithm for the finite element model to simulate wear tests was also developed. The predicted results were in good agreement with the experimental values.

**Keywords:** composite, mathematical model, finite element model, wear depth

## 1 INTRODUCTION

Aluminium matrix composites (AMCs) reinforced with hard ceramic particles have emerged as a potential material especially for wear-resistant and weight critical applications. In view of this, several attempts were made to examine the sliding wear behaviour of aluminium and AMCs [**1–4**]. In general, AMCs offer superior wear and seizure resistance as compared to the alloy irrespective of applied pressure and sliding speed. This is primarily due to the fact that the hard dispersoid makes the matrix alloy plastically constrained and improves the high-temperature strength of the virgin alloy [**5**]. Additionally, the hard dispersoids, present on the surface of the composite as protrusions, protect the matrix from the severe contact with the counter surfaces [**3**, **4**] and thus resulting in less wear, a lower coefficient friction, and a temperature rise in the composite as compared to that in the alloy [**6**, **7**]. In recent times, attention has been paid to the use of high-strength aluminium alloys for structural applications in aerospace.

On the other hand, a few investigators established knowledge about the effects of load and sliding distance on the wear rates, the wear coefficients, and the predominant mechanisms associated with each condition [**8**]. Wear maps have been developed showing transitions between different wear regimes. This extensive experimental work has been partially completed with a similar modelling effort [**9**, **10**]. However, the modelling requires the experimental values initially to predict the values. The models are accurate to some extent and need to be developed further. In that sense, the support of the finite element method may be valuable for understanding the mechanical state under the conditions of a wear test [**11**, **12**]. The wear behaviour of the composite can be simulated by calculating the wear depth of the material. The variation of stresses in the material can be calculated at various nodes and nodal elements at different points. This may be a valuable point for a complete understanding of the wear behaviour of metal matrix composites.

In view of the above, in this work, the results of pin-on-disc experiments on aluminium alloy reinforced with SiC particles for its wear behaviour were evaluated using a mathematical model. The

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experiment is conducted for different loads; fixed sliding speed and the wear characteristics are obtained for each load with varying sliding distance in steps. A finite elemental model is proposed to simulate the wear characteristics. The wear depth is calculated using Archard's wear equation [**13**].

## 2 EXPERIMENT

### 2.1 Material preparation

AlZnMg alloy and AlZnMg+10 wt% silicon carbide (SiC) particle composite have been used for the present study. The alloy has a chemical composition of Fe-0.29%, Cu-0.01%, Mg-1.63, Zn-5.85%, and Al-rest. The composite was synthesized by the solidification processing (stir-casting) route using SiC particles of size range 20–40 μm as reinforcement. The process involved melting the alloy, incorporation of preheated SiC particles in the melt by mechanically stirring, and casting of the composite melt in the preheated permanent cast iron mould. The alloy melt was also cast in the same permanent cast iron die in the form of a cylinder of 200 mm in length and 16 mm in diameter.

### 2.2 Sliding wear tests

The wear specimens were tested under dry (unlubricated) conditions using a pin-on-disc wear testing apparatus (model: TR20-LE, Wear and friction monitor, DUCOM make, Bangalore, India) under varying applied pressures at a fixed sliding speed of 3.35 m/s against an EN32 steel disc (in wt%: 0.45 C, 0.35 Si, 0.70 Mn, 1.40 Cr, 0.35 Mo, 1.80 Ni, 0.05 S, and 0.05 P) of hardness 500 HV. The pin samples were 27 mm in length and 8 mm in diameter. The surfaces of the pin sample and the steel disc were ground using emery paper (grit size 240) prior to each test. During sliding, the load is applied on the specimens through the cantilever mechanism and the specimens are brought in close contact with the rotating disc at a track radius of 100 mm. The samples were cleaned with acetone and weighed (up to an accuracy of 0.01 mg using a microbalance) prior to and after each test. The wear rate was calculated using the weight loss technique and expressed in terms of volume loss per unit sliding distance.

## 3 NUMERICAL SIMULATION

The strength of finite element analysis (FEA) in making wear predictions is its ability to accurately consider both the variation of the contact pressure and the progressive change of the surface geometry caused by material removal in complex three-dimensional components. Thus, it is very important to identify how much material should be removed from the models. The basic approach to simulate wear is to:

(a) identify the important parameters affecting the material removal rate;
(b) determine appropriate wear rate from specimen-level tests;
(c) perform iterative FEA to progressively remove materials during simulation.

In this section, the wear coefficient and the wear rate are obtained from the pin-on-disc testing and are used to perform a series of FEAs to estimate the profile of the worn surface. Yang [**10**] has developed a model to simulate wear during the pin-on-disc tests. According to the well-established Archard's law, the wear coefficient is inversely proportional to the pressure $P$ applied. The formula for calculating the wear coefficient is

$$K_s = 3\,Hm_A d(1 - f_v) \times [1 - \exp(-g_3 f_v L)/d(1 - f_v)]/(Pg_3 f_v L) \qquad (1)$$

Similarly, for the wear rate, the wear rate (or pin height loss per unit time) is proportional to the applied pressure $P$ as follows

$$W = g_1 Pd(1 - f_v) \times [1 - \exp(-g_3 f_v L)/d(1 - f_v)]/(g_3 HLf_v) \qquad (2)$$

where $f_v$ is the particle volume fraction, $d$ is the average particle size, $H$ is the hardness number, $L$ is the sliding distance, and $g_1$ and $g_3$ are experimental constants determined by using the following formulae

$$g_1 = Hm_A/P \qquad (3)$$

$$g_3 = d(1 - f_v)(\ln m_A - \ln m_B)/f_v L_t \qquad (4)$$

where $m_A$ and $m_B$ are the constants determined by using the boundary conditions. Invoking the first boundary condition when the first derivative of wear volume is equal to $m_A$ and $L = 0$ and the secondary condition is at $L = L_t$, which is the onset of steady-state wear, where gradient of wear volume is $m_B$.

For the finite element modelling and analysis, a commercial program ANSYS is used to solve the contact problem so as to remove materials according to a differential equation, which for the linear case can be formulated as

$$\mathrm{d}h = (KP)\mathrm{d}s \qquad (5)$$

where $h$ is the depth of recession of the material normal to the surface, $s$ is the sliding distance, $K$ is the dimensional wear coefficient, and $P$ is the surface normal contact pressure.

A three-dimensional tetrahedral element with ten nodes was taken for the solution, and the cylindrical specimen was discretized with it. The algorithm for

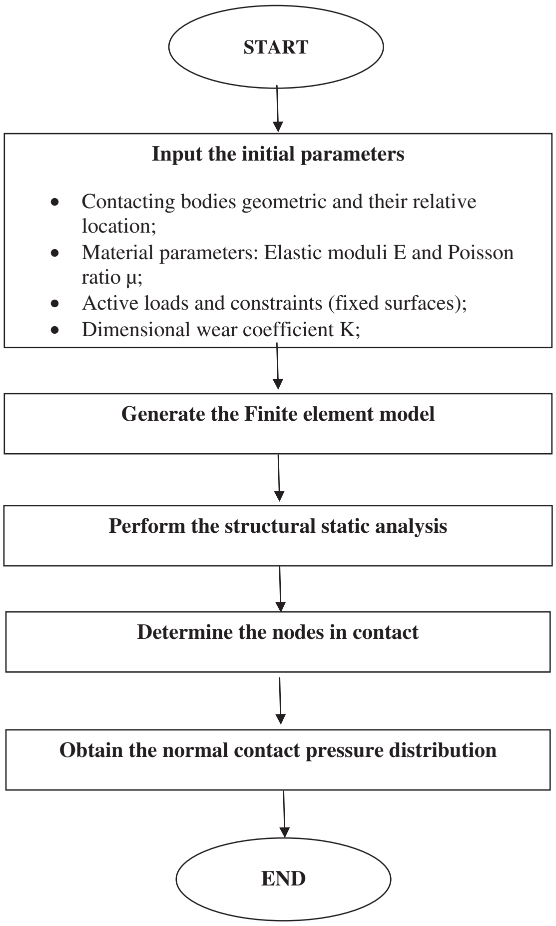


**Fig. 1** Algorithm for calculations for FEA

solving this is shown in Fig. 1. By using this algorithm, normal stresses were calculated at each node and then the wear depth was calculated by using equation (5). Figure 2 shows the ten-noded tetrahedral element distribution over the pin, normal load, and frictional load acting on the nodes with direction (represented by red colour arrows).

## 4 RESULTS AND DISCUSSIONS

In this study, the wear behaviour of the aluminium alloy reinforced with SiC particles was validated by using the Yang's equation, and also FEA was carried out on the specimen to know the stresses and the wear depth. The dimensions of the cylindrical specimen are 8 mm in diameter and 27 mm in length. The properties of the material are the following: Young's modulus $E$ is 106.9 GPa, Poisson's ratio $\sigma$ is 0.3 and friction coefficient $\mu$ is 0.64. The results were obtained by using Yang's mathematical model and Zhang's mathematical formula. These results were obtained by assuming the transient wear distance to be 2000 m for all loads, which was obtained from the experimental curve.

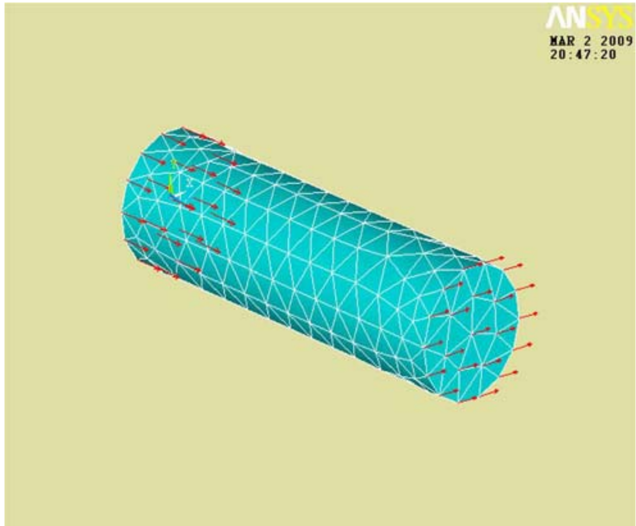


**Fig. 2** Elemental representation and load distribution on nodes

By using the above assumption, wear coefficient, wear rate and wear volume were studied at different normal loads with varying sliding distance. By using the FEA method, normal stresses were calculated at each node with the help of ANSYS software, and also wear depth was calculated by using those stresses. For validation of the method, wear depth was calculated by using wear coefficients from both the experimental model and the mathematical model. Wear depth was calculated without updating the geometry and assuming the shape to be circular for the whole sliding distance as well as the contact area to be constant.

Figure 3 shows the deformed shape of the pin due to the normal load and frictional force. The dotted line shows the original shape, whereas the blue colour solid line represents the deformed shape of the pin after the process (with the help of ANSYS software). It clearly

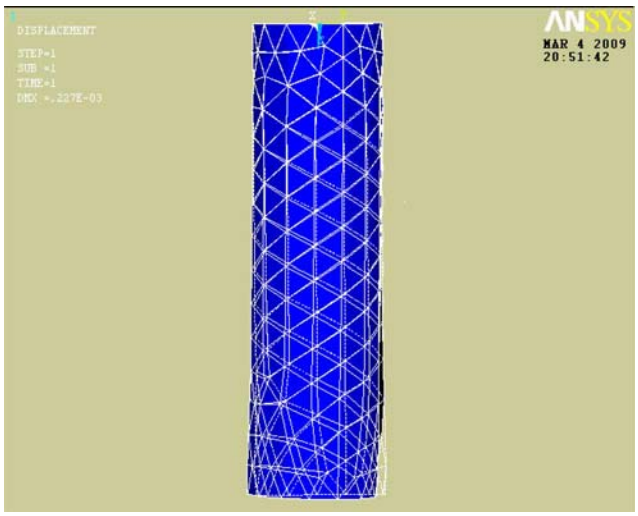


**Fig. 3** Original shape and deformed shape of the pin

shows that the pin bends in the direction of sliding velocity.

Sliding wear behaviour of the aluminium alloy and composite was studied by several investigators to improve the wear resistance of the materials. Subsurface deformation has been studies by Perrin and Rainforth [**14**] and reported that addition of reinforcement in the matrix alloy reduces the depth of the deformation zone when compared with the unreinforced alloy. However, the deformation zone increases linearly with increasing applied load. They further reported that because of the interaction of deformation and temperature rise, recrystallization of the matrix takes place. These are also responsible for inside precipitation and coarsening of precipitates. How and Baker [**6**] measured deformation zone size and the shear zone in the composites and noted that the plastic zone size in the composite is comparatively higher than in the alloy, but the reverse is true for the shear zone size. Nucleation of voids and cracks, and their subsequent growth occurs on the shear zone, which leads to delamination of the surface mixed layer. A smaller shear zone size may be a cause for better wear performance of the composite. Venkataraman and Sundararajan [**15**] reported that the mechanically mixed layer controls the sliding wear of the composite to a great extent. They identified this layer through elemental mapping in scanning electron microscope (SEM) and reported a flow line along the sliding direction just below the mixed layer. At the interface of the mixed layer and under-laying material, cracks are generated, which owing to growth cause delamination of the mixed layer. In fact, it is reported that a critical thickness of the mechanically mixed layer is beneficial to improve wear resistance. When the thickness of the mechanically mixed layer becomes greater than the critical value, it easily gets fractured and removed as wear debris, which results in higher wear rate. At higher applied load, the layer may be forming but the thickness of the layer is too high to be sustained on the specimen surface. It is also reported that the mechanically mixed layer thickness decreases with an increase in the reinforcement content.

Figures 4 to 7 represent the stress distribution in the direction of sliding velocity for the normal loads of 1, 3, 5, and 7 kg, respectively. As the normal loads increase, the stresses on each element also increase marginally, further increasing wear volume loss and also the deformation of the pin. It is noted from the figures that the stress in each element and each node is different for each load.

Figure 8 shows the validation of the FEA method for wear depth (wear volume loss) to the sliding distance by varying normal loads. The fixed parameters such as modulus of elasticity, 106.9 GPa, Poisson's ratio, 0.30, and frictional coefficient, 0.64, are used and the experimental calculated values are noted. It is observed from the figure that it consists of eight observations

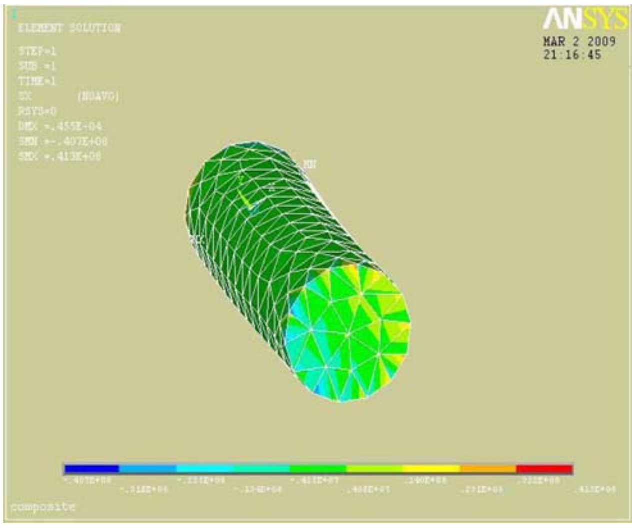


**Fig. 4** Stress distribution for load $P = 1$ kg

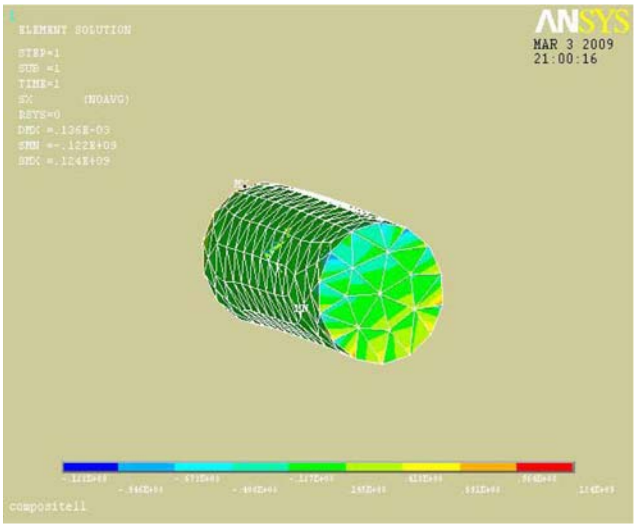


**Fig. 5** Stress distribution for load $P = 3$ kg

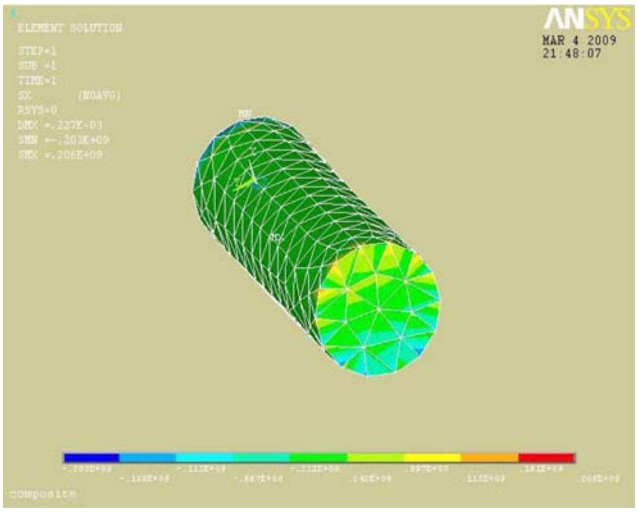


**Fig. 6** Stress distribution for load $P = 5$ kg

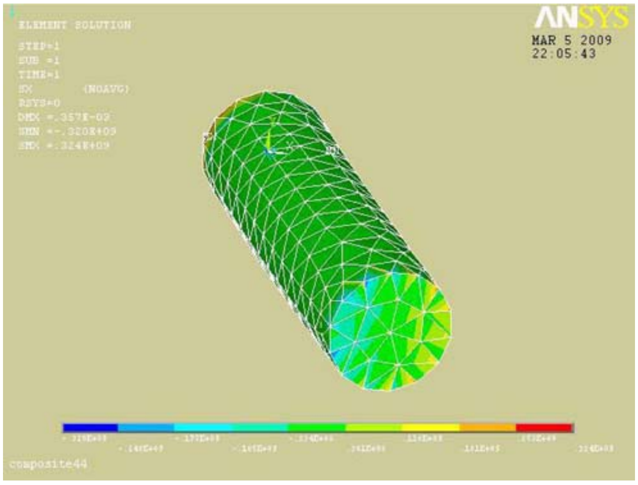


**Fig. 7** Stress distribution for load $P = 7$ kg

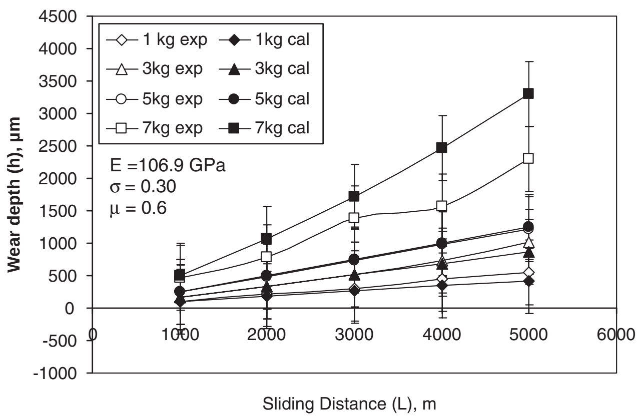


**Fig. 8** Validation of the FEA method for wear depth as a function of sliding distance (exp: experimental; cal: calculated)

out of which four are for experimental values, and remaining four are for calculated values by using FEA with the help of ANSYS software. It was also interestingly observed that in Fig. 8, the error increases as the normal load on the pin increases from 1 to 7 kg in steps of 2 kg and also as sliding distance increases from 1000 to 5000 m. The error increases from 1 per cent to 25 per cent as the distance travelled from 1000 to 5000 m at an applied load of 1 kg. Furthermore, the error also increases from 1 per cent to 7 per cent as the normal load changes from 1 to 7 kg for a sliding distance of 1000 m. The trend of wear depth varying with sliding distance at higher loads is different from that at lower loads; this is because of the fact that after a critical load there is a transition from smooth linear increase wear rate to sudden increase in wear rate. Because of the greater degree of softening of the pin surface and considerable higher amount of material transfer between the counter surfaces, the surfaces become smoother. This fact leads to greater degree of sliding action and spreading of softer material on the specimen surface. As a result, the wear rate after transition load remains unchanged up to certain applied pressure. However, at the point of seizure, the temperature increases significantly, so that the pin surface material becomes partially melted and this highly viscous material becomes completely adhered with the counter surface and subsequently removed readily from the specimen surface in the form of flash. This leads to a sudden increase in wear rate to a significantly higher value, and is identified as seizure of the specimen.

## 5 CONCLUSIONS

The experimental results for the aluminium alloy–SiC particle composite were validated using Yang's mathematical model and Zhang's mathematical formula. The predicted results were in good agreement with the experimental values. The results obtained from these models were in agreement with the experimental values initially. However, due to the assumptions in deriving the equation, the errors induced became larger with sliding distance. These errors can be minimized to some extent by using the actual hardness value, which varies with temperature. As the load increases, the errors also increase. Understanding the normal contact pressure distribution on the original shape and the deformed shape of the pin by various applied loads gives an idea of developing an algorithm. The finite element method has become a tool for the numerical solution for deformation and stress analysis. By using the FEA method, normal stresses were calculated at each node with the help of ANSYS software, and wear depth was calculated by using those stresses. For validation of the method, wear depth was calculated by Archard's law using wear coefficients from both the experimental model and the mathematical model.



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