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# Modelling the three-body abrasive wear of UHMWPE particle reinforced composites

A.A. Cenna [a,*], S. Allen [a], N.W. Page [a], P. Dastoor [b]

[a] *Department of Mechanical Engineering, University of Newcastle, Callaghan, NSW 2308, Australia*
[b] *Department of Physics, University of Newcastle, Callaghan, NSW 2308, Australia*

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**Abstract**

In this paper, some of the complexities in developing predictive models for polymer composite materials are discussed with particular reference to models based on surface deformation energy. Although there are models available for abrasive wear of metals, polymers and composite materials, models are suitable for a particular wear situation. Most of the cases, the wear models are based on traditional test methods, such as two-body abrasive wear test or tests in a controlled environment. Moreover models for polymer composite materials are very limited. This is due to the fact that the vast range of polymers and polymer composite materials present different wear behaviour in similar wear situations. This makes the modelling wear of polymer composite materials complicated.

This paper presents and discusses recent test results on ultra high molecular weight polyethylene (UHMWPE) particle reinforced composites with varying particle concentration from a unique test rig that exposes the wear surface to sliding bulk solids (granular materials). The wear phenomena of resin and UHMWPE particle reinforced resin surfaces abraded by bulk solids are discussed with respect to the interaction between the particles and the wear surfaces. The effects of elastic and plastic deformation energy of the surfaces on the abrasive wear resistance are also discussed in the context of an appropriate wear model for these surfaces and wear events. Finally a model is proposed to predict the wear of these polymer composites based on the deformation energy of the surfaces. Good qualitative agreement was obtained between the model and the experimental wear rates.


*Keywords:* Abrasive wear; UHMWPE; Composite

## 1. Introduction

Polymer matrix composites are being increasingly used in industry because of their unique combination of mechanical, electrical and thermal properties. Typically they have high specific strength and modulus, excellent fracture toughness and fatigue properties and good corrosion, thermal and electrical resistance properties. This combination of properties, particularly their high strength/stiffness to weight ratio, make them very attractive materials for transport applications where there is commercial advantage in minimising vehicle weight. One such application is in the transport and handling of bulk solids. However, their use in this application is limited by an incomplete understanding of their abrasive wear resistance and the means by which this can be controlled and improved.

In addition to transport applications, there has also been growing interest in their abrasive wear performance in applications such as chutes in mining and agricultural equipment [1]. A number of studies on polymer matrix composites subjected to sliding and abrasive wear indicate that wear resistance depends on the detailed properties of the material as well as the external wear conditions such as applied pressure and contact velocity [2–5]. Furthermore fibre addition to polymers does not necessarily improve their wear resistance [6].

In a previous work the authors have shown that the presence of ultra high molecular weight polyethylene (UHMWPE) reinforcement in particulate form can protect a polymer surface against abrasive wear. It was shown that the abrasive wear resistance of the UHMWPE particle reinforced polymer composite was improved compared with both unreinforced and glass fibre reinforced composites [7]. In more recent work [8], it has been shown that the wear rate decreases with the increase of volume fraction of UHMWPE particles in resin. It was also shown that the wear mechanism changes from three-body wear in resin only surface to two-body wear in surfaces with 20% or above volume fraction of UHMWPE particles.

* Corresponding author. Tel.: +61-49-217467; fax: +61-49-217468.
*E-mail address:* meaac@cc.newcastle.edu.au (A.A. Cenna).

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The aim of the work described in this paper was to provide a tool for predicting the wear of polymer matrix composite materials when subjected to abrasive wear from bulk solids.

## 2. Wear models

Theoretical understanding of abrasive wear is based on the physical processes distinguished as microploughing, microcutting, microfatigue and microcracking. Many of the present wear models are based on these physical processes that take place in any wear environment. The early wear model developed by Archard [9] correlates the wear rate with applied pressure and hardness of material. Rabinowicz [10] proposed another model incorporating operational parameter such as sliding distance and attack angle of the abrasive particles with the volume of material removed during two-body abrasion by conical abrasive particle as:

$$\frac{W_v}{s} = \frac{2\tan\alpha}{\pi}\frac{P}{H} \tag{1}$$

where $W_v$ is the volume loss due to wear, $s$ the sliding distance, $P$ the normal load on the conical particle, $H$ the hardness of the wearing surface, and $\alpha$ the attack angle of the abrasive particle.

This is the classic relationship for abrasive wear of metals—wear is inversely proportional to the hardness of the metal, the harder the metal, the lower the abrasion rate. It is evident that the first factor in the equation depends on the geometry of the abrasive particle and can be replaced by a wear coefficient $k$ leading formally to the Archard's wear law. It is important to note that the model applies to abrasives with fixed geometry relative to the direction of relative motion (two-body wear) and is not suitable for three-body wear, where the particles are free to rotate and change the cutting angles continually.

### 2.1. Models for polymer and polymer composites

A great deal of experimental work on the wear of polymers and polymer composite materials can be found in literature. Theoretical models for wear of polymer and polymer composites are few. This is primarily due to the fact that the wear models discussed earlier relied on material properties such as hardness and fracture toughness. The inherent problem with the polymer group of materials is that, there is no single plastic hardness scale is suitable for the wide range of plastics used in the industry today. Nonetheless, Shore D and recoil hardness tests were conducted by Budinski [11] on 21 high-performance plastics/elastomers to explore the possibility of a hardness–abrasion relationship. It was found that the hardest plastic, glass reinforced epoxy was harder than UHMWPE by a factor of 1.4, but their abrasion rate was higher by a factor of about 60. The scratch hardness, which correlates with the hardness of metals, does not correlate with the wear resistance of plastics. Spherical ended sabot was used to measure the rebound hardness of these materials by measuring the rebound velocity of the sabot. The rebound hardness also did not show any correlation with the abrasion volume losses of plastics. Wear phenomena with polymers and polymer composites are further complicated by the viscoelastic behaviour of many plastics.

Ratner et al. [12] developed a simple theory for the abrasive wear of polymers, based on the production of loose particles from the surface. They proposed that the production of loose wear particles involves three stages: (a) deformation of the surfaces to an area of contact determined by the indentation hardness, $H$; (b) relative motion opposed by the friction force, $\mu p$; and (c) disruption of material at the contact point involving an amount of work equal to the integral of the stress–strain relationship. An approximate measure of the later is the product of the breaking stress $s$, and the elongation to break $\varepsilon$. As these processes occur sequentially, the total wear can be regarded as being proportional to the probability of completion of each stage. Thus the volume worn per unit sliding distance can be expressed as:

$$V = c\frac{\mu p}{Hs\varepsilon} \tag{2}$$

where $c$ is an empirical constant. Although the relationship involves the indentation hardness, the dominant parameters are in fact $s$ and $\varepsilon$. The formulation was drawn without any detailed investigation of the mechanism of breakdown of the surface layer and separation of the particles.

Lancaster [13] reviewed the abrasive wear of polymers and identified the various physical processes involved. From an analysis of the experimental results of two-body abrasion it was concluded that with polymers, plastic deformation becomes predominant only when the indenter is very sharp. This is due to the fact that the elastic moduli of polymers are considerably lower than that of metals and therefore, elastic deformation will play a much more important part in the contact mechanics, and hence abrasive wear processes of polymers, than is the case with metals.

Budinski [11] performed tests on a wide range of plastics and elastomers to compare the applicability of the wear models available in the literature. The test specimens were indented with a 6 mm diameter spherical indenter to a fixed depth of 1.25 mm in a universal tension/compression tester. The area under the load–deflection curve was integrated and this was considered a measure of the energy required in deforming the materials plastically. Wear data were then plotted against the inverse of the energy term and a poor correlation was obtained. From the results it was observed that the model proposed by Ratner et al. was more promising than the others, but the correlation was still poor. Following on from this, Budinski defined a new deformation energy factor by multiplying the deformation energy, measured as described, by the coefficient of friction. The best correlation of wear was obtained using:

$$w \approx \mu(S_e) \tag{3}$$

where $w$ is the abrasion rate, $\mu$ the coefficient of friction and $S_e$ the area under the load–deflection curve from the ball indentation test.

### 2.2. Comparison of the Ratner and Budinski models

Ratner and Budinski models attempted to predict the abrasive wear of polymer and polymer composite materials well but fall short of doing so. Both the models compared the wear rates with deformation energy for fixed indentation depth, and deformation energy at rupture. Ratner's model was developed from a general consideration of the wear process, without detailed consideration of the wear surfaces and wear mechanisms involved. The main feature of this model is that there is a threshold surface deformation that must be exceeded before material is detached from the surface, and that this minimum energy threshold is proportional to the rupture energy for the material.

On the other hand, Budinski's model is based on the assumption that the hysteresis in the load–deflection curve during indentation to a fixed depth is proportional to the plastic deformation energy. Another feature of this model is that it allows the comparison of materials deformation energy for equal indentation depth. The harder the material, the higher the load and hence the higher will be the deformation energy for equal depth of indentation. Such a result reflects the universal law of wear rate, which is inversely proportional to the hardness.

The wear models of Ratner and Budinski marked important progress in understanding the relationships between material properties and wear rates in polymer-based materials. However, correlations of measurements of wear rate against their energy parameters are still relatively poor.

In this study, we have proposed a model similar to Budinski's but instead of equal indentation depth, equal indentation load has been used. This choice has been made to test the hypothesis that those aspects of contact mechanics leading to wear are load controlled rather than deformation controlled. What is of interest is the comparative wear performance of different materials under the same environmental and load conditions. In order to study the load effects more explicitly, in our experiments to characterise material properties, indentation load has been reversed (unloaded) to determine the plastic and elastic energy of deformation for each indentation. We then compare the wear performance of a range of polymeric materials on the basis of this surface characterisation.

In this study we have a system of materials for which the surface characteristics are systematically altered by adding varying amounts of particulate reinforcement to a resin system. Previous work has shown such reinforcement can change the nature of wear mechanisms, for example, causing a switch from two-body to three-body abrasion when this is occurring by slip of granular materials along the surface [8]. Materials considered here includes vinylester resin, UHMWPE particle reinforced resin with volume fractions of 5, 10, 20, 25 and 30%. A systematic variation of the reinforcement allows us to look into the wear process and changes in wear mechanism with variation of the surface characteristics. At the same time it allows us to look into the wear models as discussed.

## 3. Experiments and discussions

### 3.1. Experimental details

The abrasive wear of different composite surfaces (ultra high molecular weight polyethylene particle reinforced resin of five different volume fractions, i.e. 5, 10, 20 25 and 30% UHMWPE) have been investigated. The abrasion was caused by the flow of a bulk solid across the material surface. This bulk solid consisted of irregular particles (with dimension 2–5 mm) of a relatively hard wear medium (ignimbrite). Ignimbrite was chosen as a representative abrasive wear medium due to its hardness and highly angular particle shape. Ignimbrite consists of vitric (glass) shards, variable proportions of pumice fragments and crystals, and a further variable proportion of lithic (stone) fragments. Another reason for choosing ignimbrite is that it retains its shape and angularity for a long duration of testing.

The UHMWPE particles (Shamrock Chemicals Corp., USA, and supplied by Plastral Fidene, Australia) consisted of crystalline polyolefin which could be easily dispersed in a solvent or water-based system. The resin used for manufacturing all the composites was Derakane 441-400 (Epoxy Vinyl Ester, Dow Plastics), which is a vinyl ester-based resin containing about 7.5 wt.% of a carboxyl-terminated butadiene acrylonitrile (CTBN) liquid polymer reacted into the resin base. Particle reinforced specimens were made by mixing the required amount of resin with the calculated amount of particles for the desired volume fraction of the particles. Details of the sample manufacturing process can be found in [8].

All of the abrasive wear testing was conducted using an open linear sliding abrasive wear tester for bulk materials that has been developed at the University of Newcastle [1]. This apparatus contains a bin and hopper arrangement that delivers the abrasive particles onto a conveyor belt which carries the material under the test specimen. Both the normal load on the specimen and the incident flux of abrasive particles can be varied. For the experiments described here, the average surface pressure was set to 5.4 kPa and the belt speed was set to be $0.54\,m\,s^{-1}$. Shear load cells attached to the carrier allow continuous monitoring of the friction force. After the wear medium passes beneath the test specimen, it is circulated back to the bin and then hopper via a bucket elevator. Previous experiments monitoring the particle degradation during testing [7] have shown that the ignimbrite does not show any significant degradation in particle size during testing. Optical micrographs of abrasive (ignimbrite) particles shown in Fig. 1 [8].

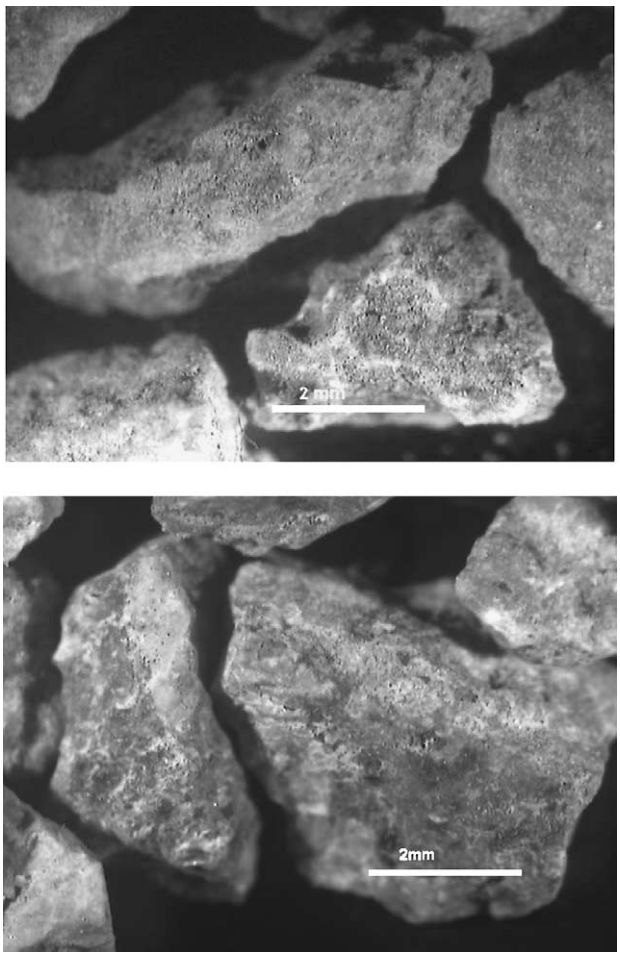


Fig. 1. Optical micrograph images of ignimbrite particles before abrasion (upper image) and after abrasion (lower image). The images show that there is no noticeable change in either particle size or angularity as a consequence of the abrasion process [13].

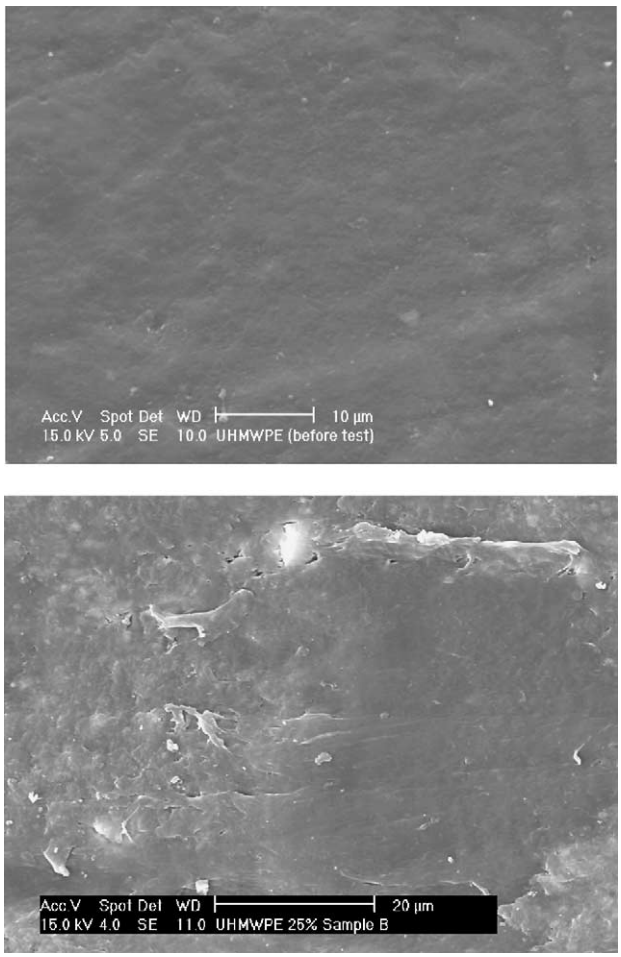


Fig. 2. (a) SEM image of the UHMWPE reinforced surface before the test. The UHMWPE is not visible in the surface layer indicating a pure resin skin. This skin is removed before the commencement of the actual testing. (b) High magnification SEM micrograph of surface with 25% volume fraction reinforced of UHMWPE particles abraded by ignimbrite abrasive material. Abrasive particle movement from right to left.

Dimensionless wear rates were calculated according to Eq. (4) [14].

$$W = \frac{M_1 - M_2}{\rho A V t} \tag{4}$$

$M_1$ and $M_2$ are the specimen mass before and after test respectively, $\rho$ the density of composite, $A$ the apparent wear surface area, $V$ the belt speed and $t$ the running time.

Volume loss of material divided by the area gives the height reduction of the specimen. Hence Eq. (3) provides the reduction of height per unit length of distance the specimen has been under abrasive wear situation. Mass loss measurements were taken every 15 min to monitor the kinetics of the wear process by stopping the experiments at 15 min interval. This is done by temporary removal of the test tile from the wear apparatus followed by cleaning and weighing. From the loss of material and the experimental parameters, dimensionless wear rates are calculated by using Eq. (3). Tests were repeated at least three times to ensure the reproducibility of the data. SEM micrographs of unworn and worn UHMWPE reinforced resin samples are shown in Fig. 2 [8].

Indentation testing was performed to determine the deformation energy for different wear surfaces. Test specimens were prepared from the test samples prepared for wear testing so that the wear rates can be compared with the test results obtained in this test. Two series of indentation tests were conducted—one to constant depth to allow comparison with the Ratner and Budinski theories, and one to constant load, as discussed earlier. In the constant depth indentation tests, test specimens were indented with a 6 mm spherical steel ball with at constant speed (for equal indentation depth). The specimens were indented to a depth of 0.5 mm and slowly unloaded to determine the indentation deformation energy, elastic and the plastic deformation energy. The area under the load–deflection curve was integrated for each indentation. Elastic and plastic energy components for equal indentation load were determined by repeating

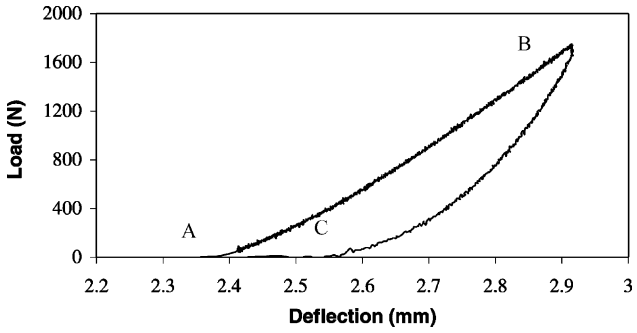


Fig. 3. Typical load–deflection curve for 6 mm ball indented to a depth of 0.5 mm and unloaded slowly to determine the indentation energy, and its elastic and plastic components.

the loading and unloading cycles of the same indenter on a Dynamight tester.

For the case of fixed indentation depth, a typical load–deflection curve for a 5% UHMWPE particle reinforced sample is shown in Fig. 3. The line AB is the loading and BC unloading. The area under the curve AB is the total energy of deformation whereas the area under the curve BC is the recovered energy. By subtracting these two quantities, the unrecovered (plastic) deformation energy is estimated. For polymer and polymer composite materials, which show considerable viscoelastic effect, the recovery can be slower than the load reversal time and the plastic deformation energy may be overestimated.

For the case of fixed maximum load, a set of load–deflection curves as obtained from Dynamight is plotted in Fig. 4. It was observed that the area between the loading and unloading curves, which represent the plastic deformation energy, were increased with increasing reinforcement volume fractions. This is clearly presented in Fig. 5, where the energy components are plotted against the volume fraction reinforcement of UHMWPE.

Elastic deformation energy seems to be insensitive with the volume fraction of UHMWPE particles and remains virtually constant. As a result the total deformation energy represents the trend observed in the plastic deformation energy. This shows the validity of the plastic deformation assumption made by Budinski [11] in his model and indentation energy calculations.

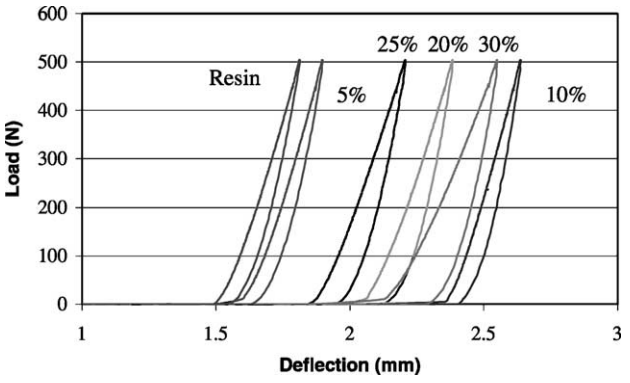


Fig. 4. Load–deflection curves for different materials for equal indentation load of 500 N. It is observed that the plastic deformation energy (area enclosed by the curve) is increased with increasing volume fraction of reinforcement.

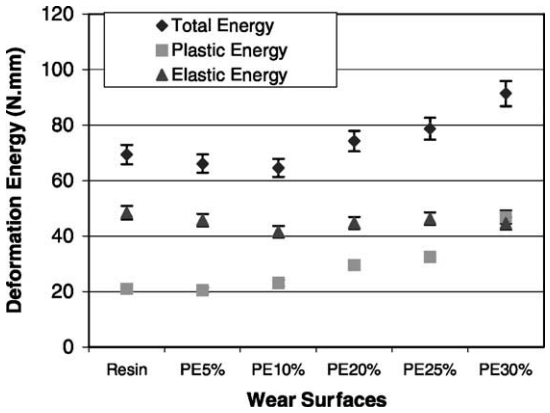


Fig. 5. Variation of deformation energy, elastic and plastic energy for pure resin and UHMWPE particle reinforced samples with 5, 10, 20, 25 and 30% reinforcement indented by equal indentation load of 500 N.

Fig. 6 shows the variation of the deformation energy with the respect to the volume fraction of particle reinforcement indented to equal depth of 0.5 mm. It is evident that the deformation energy decreases with increasing volume fraction of the UHMWPE particles.

Previous work has shown the variation of wear rate with volume fraction of UHMWPE particle reinforced surfaces [8]. The results are reproduced in Fig. 7. It can be seen that wear rate decreases for volume fraction of reinforcement greater than about 5% and that it approaches a plateau for volume fraction of reinforcement 25–30%.

The deformation energy determined by the two methods as described (equal indentation depth and equal indentation load), show trends which mirror the wear behaviour shown in Fig. 7. For the case of constant deformation load shown in Fig. 5, both plastic and total deformation energy can be seen to increase for particle reinforcement levels higher

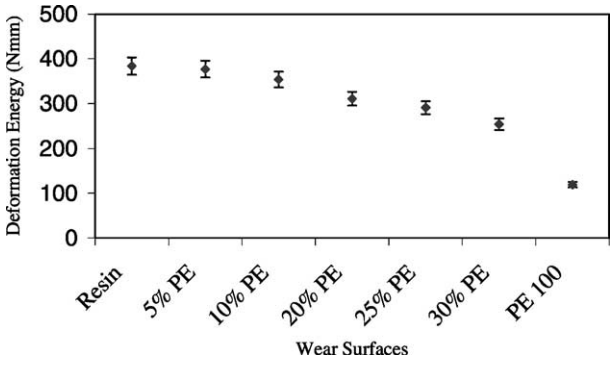


Fig. 6. Deformation energy (area under the deflection curve) measured for different wear surfaces with 6 mm spherical indenter to a depth of 0.5 mm.

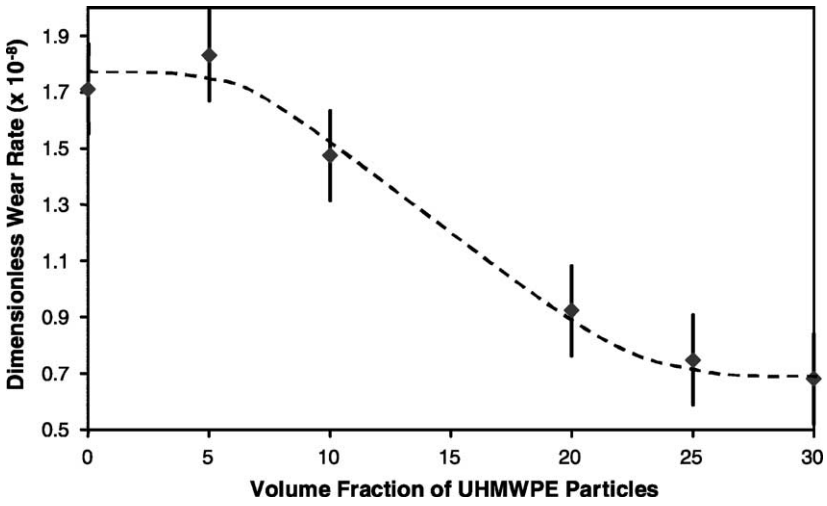


Fig. 7. Variation of dimensionless wear rate as a function of volume fraction of reinforcing UHMWPE particles in the polymer resin for surfaces abraded by ignimbrite particles [7,8].

than about 10%. For the case of constant deformation depth shown in Fig. 6, the deformation energy starts decreasing after 10% volume fraction particle reinforcement.

The trend in deformation energy in both the cases can be explained by considering the deformation energy in relation to material strength and stiffness (which scale with hardness). For fixed depth of indentation, the harder the material, the more energy is required to deform the same volume of material. As a result, with increasing volume fraction of UHMWPE particles in the specimen, less indentation energy is required for the same volume of indentation. On the other hand, for fixed load of indentation, the harder the material the smaller is the indentation depth. With smaller indentations, the contribution of the elastic deformation is a more significant fraction of the total deformation. This can be seen in Fig. 5, where the elastic and plastic deformation energy for 500 N indentation load is presented for all the specimens. For resin samples, the elastic energy forms a larger fraction of the total than the plastic energy. As the deformation increases with increasing volume fraction of UHMWPE particles, the total energy of deformation also increases, and the relative plastic contribution also increases.

The deformation energy measured with fixed indentation depth and fixed indentation load are plotted against the dimensionless wear rate in Figs. 8 and 9, respectively. Fig. 8 shows that the dimensionless wear rate increases with increasing deformation energy (fixed depth) whereas Fig. 9 shows the wear rate decreases with increasing the deformation energy (fixed load).

One of the important findings here is the correlation of deformation energy (measured with either method) and wear resistance as a function of volume fraction UHMWPE particle reinforced samples. It is seen that the wear rate varies with the particle reinforcement, is for the most part monotonically except for a small discontinuity between resin and 5% particle reinforcement. This correlation is now analysed

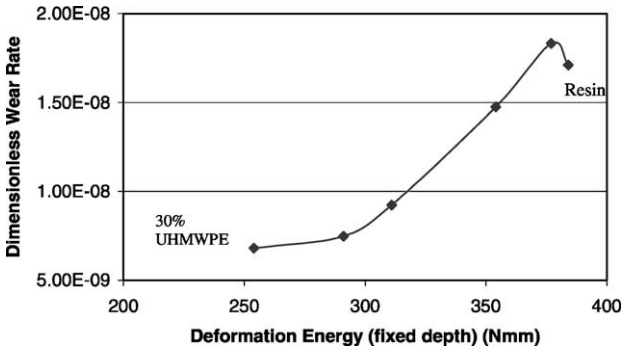


Fig. 8. Relation between the dimensionless wear rate and deformation energy measured from the fixed indentation depth tests.

considering the deformation energy factor as described in the Budinski [11] and Ratner et al. [12] models for wear resistance of materials.

The deformation factor was calculated by multiplying the deformation energy by the coefficient of friction for both fixed depth method of calculation. In Ratner model (Eq. (2)) wear rate as expressed as inversely proportional

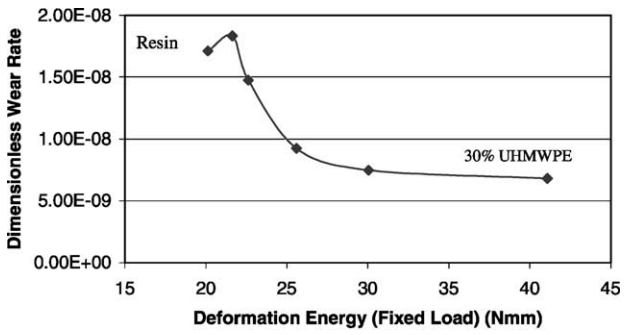


Fig. 9. Relation between the dimensionless wear rate and deformation energy measured from the fixed indentation load tests.

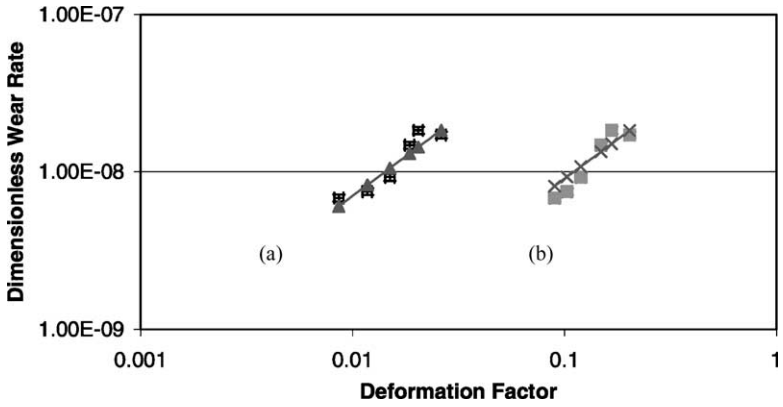


Fig. 10. Relation between the dimensionless wear rate and the deformation factor. (a) Represents the Ratner model, where the deformation factor is defined as: coefficient of friction/plastic deformation energy for a fixed load, (b) represents the Budinski model, where the deformation factor is defined by: the coefficient of friction × total deformation energy measured with fixed indentation depth.

to the fracture energy ($s\varepsilon$) and proportional to friction. The Ratner model has been modified by replacing the fracture energy with the plastic energy of deformation determined from the fixed load indentation tests and the deformation factor was calculated as (coefficient of friction/deformation energy). The fixed load of indentation method was adopted as the reference method of determination for the deformation energy in order to compare the wear resistance of materials in a similar wear load conditions where, in fact, the materials would be subjected to a fixed load rather than a fixed depth of deformation.

Dimensionless wear rate is shown plotted against deformation factor in Fig. 10. It is evident that the simple indentation tests provide measures of material properties which correlate with wear performance. The log–log axes were used for model parameter estimation purposes.

The experimental wear equation can be represented in the form:

$$\dot{w} = k(fE_{\text{def}})^{\alpha}$$

$k$ and $\alpha$ can be estimated from the experimental data from the graph.

Using parametric estimation the values of $k$ and $\alpha$ are estimated as $k = 1 \times 10^{-7}$ and $\alpha = 1$, and finally the wear equation of Budinski form can be represented as:

$$\dot{w} = 1 \times 10^{-7}(fE_{\text{def}})$$

where $f$ is the coefficient of friction and $E_{\text{def}}$ the deformation energy of the material for a 6 mm spherical indenter and indentation depth of 0.5 mm.

Using the similar approach, the parameters are also determined for the Ratner model, where the rupture energy is replaced by the plastic deformation energy for equal load conditions. The final equation for wear rate for this condition is given by:

$$\dot{w} = 7 \times 10^{-7}\left(\frac{f}{E_{\text{def}}}\right)$$

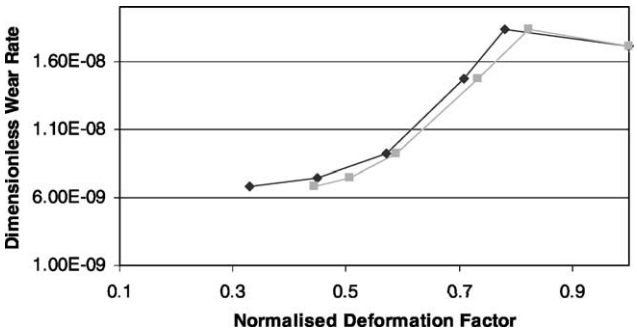


Fig. 11. Relation between the dimensionless wear rate and the normalised deformation factor measured by both the fixed indentation load and indentation depth showing marginal difference.

Experimental wear rate and the predicted wear rate from the models are presented in Fig. 10. It is evident from the figures that the model developed by the present approach, using energy measures based on constant indenter load, gives marginally better correlation with the experimental results (86% compared with 83%).

This is further evidenced from Fig. 11, where the normalised deformation factors are plotted against the dimensionless wear rate.

## 4. Conclusions

A simple approach for predicting the wear rate of polymer composites has been considered in this work. It is demonstrated that the wear resistance of polymer materials having similar mechanical properties can be predicted by determining their deformation characteristics using an indenter loaded to constant maximum load. When incorporated with previously published Ratner model for wear, this material characterisation leads to higher correlations coefficient with measured wear data than obtained using either of the published models by Ratner or Budinski.

The model used here has been adapted from that originally proposed by Ratner based on the general considerations without detailed information about the wear mechanism(s). In the present work, the model was applied to abrasive wear caused by bulk solid flow across the wear surface and where the variations in wear mechanisms have been identified. Yet the model successfully predicted the wear rate for the materials under consideration.

The use of plastic deformation energy instead of the fracture energy simplifies the Ratner model and gives better correlation with the experimental wear rate. Further studies using this approach including a wider range of polymer and polymer matrix composite may lead to a generalised predictive model for wear resistance of polymer composite materials.

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