

AN ABRASIVE WEAR MODEL FOR COMPOSITE MATERIALS

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Abstract: A simple physically-based model for the abrasive wear of composite materials is presented based on the mechanics and mechanisms associated with sliding wear in soft (ductile)-matrix composites containing hard (brittle) reinforcement particles. The model is based on the assumption that any portion of the reinforcement that is removed as wear debris cannot contribute to the wear resistance of the matrix material.

Keywords: Composites; Abrasive wear; Fracture toughness; Reinforcement size

1. INTRODUCTION

As advanced engineering materials, composites are used in many applications where high wear resistance is required, these include electrical contact brushes, cylinder liners, artificial joints, and helicopter blades. Indeed, compared to monolithic materials, wear resistance can generally be enhanced by introducing a secondary phase(s) into the matrix material. In this fashion, the wear properties can be varied substantially through changes in the microstructure, the morphology, volume fraction and mechanical properties of the reinforcing phase, and the nature of the interface between matrix and reinforcement.

In order to obtain optimal wear properties without compromising the beneficial properties of the matrix material, an accurate prediction of the wear of composites is essential. Unfortunately, for abrasive wear, existing models for composites are highly simplified and do not readily predict the role of the composite microstructure. In general, they are based on two simplified equations, the first of which, the inverse rule of mixtures, was introduced for two-phase composites by Khrushchov and Babichev [2]:

$$\frac{1}{W_C} = \frac{V_{M1}}{W_{M1}} + \frac{V_{M2}}{W_{M2}} \quad (1)$$

where W and V are, respectively, the wear rates and volume fractions of the matrix (designated by subscript m) and reinforcement (designated by R). Note that the wear resistance, R , in Khrushchov's original formulation is given by the reciprocal of the wear rate, $R = 1/W$. Eq. (1) for a two-phase composite is plotted in Fig. 1. Since the wear rate of the harder reinforcement is typically much smaller than that of the matrix, this relationship predicts that the abrasive wear behavior of a composite will be governed primarily by the reinforcement. The second wear equation for multiphase materials, introduced by Zum-Gahr to explain experimental data, is the linear rule of mixtures, here, the wear behavior of a composite is not dominated by a single phase [1]. Instead, the contribution from each component is linearly proportional to its volume fraction in the composite

$$W_C = V_{M1}W_{M1} + V_{M2}W_{M2} \quad (2)$$

and is also plotted in Fig. 1. In this model, the abrasive wear rate of the composite decreases linearly with increasing volume fraction of reinforcement.

While Eqs. (1) and (2) are presumed to provide upper and lower limits for abrasive wear rates in a composite, this is not confirmed by some experimental results due to the simplified, non-physically-based nature of the two models. Indeed, this can be appreciated in Fig. 1, which shows experimental results for composites that are reinforced with hard particles. Both models rely on the notion that all components in the composite wear in the same way as they would in a bulk material; consequently, the contribution of each component can depend only on its volume fraction and wear rate. The effects of other important factors, such as interfacial properties between the distinctive phases, relative sizes, and the fracture toughness of these phases, are not considered, even though it is clear that they have a significant influence on abrasion in composites. Specifically, the wear rates of composites can exceed the upper bound given by Eq. (2) in that they are higher than that of the pure matrix material [3,4]; this implies that the presence of reinforcement enhances the wear rate instead of reducing it—the negative reinforcement effect. Experimental data showing the negative reinforcement fall in the area denoted by region A in Fig. 1. The inability to predict such effects represents a major limitation of existing abrasive wear models for composite materials.

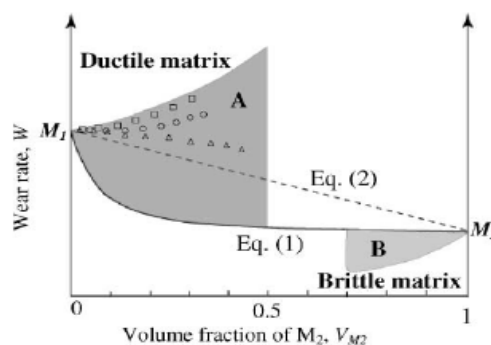


Fig. 1. Predicted abrasive wear rates of composites.

2. DUCTILE-MATRIX AND BRITTLE-MATRIX COMPOSITES

The sliding of abrasives on a solid surface results in volume removal. The mechanism of wear depends on the mechanical properties of the solid [6]. In a ductile solid, the primary wear mechanism is related to plastic deformation, correspondingly, the hardness of the material is a key parameter in governing the amount of material removal. However, the dominant mechanism in a brittle solid depends on fracture at, or near, the surface such that the governing property is the toughness of the material.

To improve wear resistance, additional phase(s) can be introduced to either a ductile or a brittle-matrix material. However, the required mechanical properties of the reinforcement and the role of the reinforcement will be different in ductile versus brittle-matrices. For a ductile matrix, a hard secondary phase is needed to reduce wear, such that the presence of the hard reinforcement increases the effective hardness of the matrix, thereby reducing the penetration of the abrasive medium. Consequently, increasing the effective hardness acts to reduce the amount of material removed. Here, we term such a multiphase system composed of a ductile matrix and a hard reinforcement as a hard reinforcement or hardened composite. On the other hand, a tough reinforcement phase is needed for a brittle-matrix to increase wear resistance. The presence of a tough secondary phase reduces the tendency for fracture at, or near, the surface, and therefore tends to decrease the wear rate. In certain ceramic-matrix composites, i.e. brittle-matrix materials, the addition of a relatively ductile second phase can result in synergistically favorable wear behavior in which the composite wear rate can be less than the wear rates of the individual constituents. This behavior is denoted by region B in Fig. 1, and has been observed in ceramic composites [7]. A multiphase system composed of a brittle-matrix and a tough reinforcement may be termed a ductile-reinforcement or toughened composite.

3. ABRASIVE WEAR MODEL

A model is developed with simplified geometry in two dimensions, namely a triangular abrasive medium particle acting on a composite containing idealized rectangular reinforcements.

The model is based on the “equal wear rate assumption”, this postulates that the different components of a composite wear at steady state at an equal rate through the redistribution of the specific loads [2]. A general schematic drawing of a two-phase composite with a ductile matrix and a hard reinforcement in abrasion is shown in Fig. 2. The characteristic size of the reinforcement is represented by the parameter D_R .

If the fracture toughness of the matrix/reinforcement interface exceeds the minimum toughness of either constituent (a “strong” interface) and the fracture in the reinforcement is not favorable, then plowing will be the predominant wear mechanism, consequently, the resulting wear debris will be small in relation to the reinforcement size. With such a strong interfacial bonding and a tough reinforcing phase, the entire reinforcement particle will contribute to improving wear resistance. Both rules of mixtures, Eqs. (1) and (2), are commonly based on this assumption.

In practice, however, the reinforcement is removed due to failure at the matrix/reinforcement interface or in the reinforcement. The interfacial bonding between constituent materials may not be strong due to chemical incompatibility, mismatch in thermal expansion and elastic properties, e.g. stiffness, at the interface, and the presence of impurities and/or voids that arise during fabrication. In this case, the motion of the abrasive medium induces interfacial failure and debonding around the reinforcing particles. On the other hand, if the matrix/reinforcement interface provides a strong bond and the reinforcing phase has a low resistance to fracture, failure can occur in the reinforcement, which is often observed in composites under severe wear conditions.

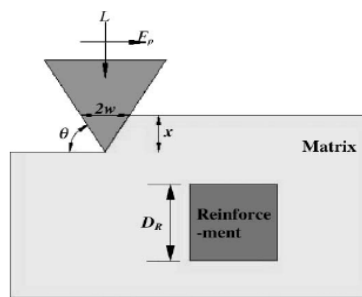


Fig. 2. General schematic drawing of a two-phase composite in abrasion with simplified geometry in two dimensions: a triangular abrasive medium and rectangular reinforcements.

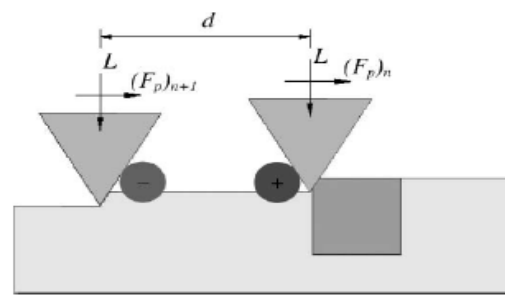


Fig. 3. Abrasive particles plow the matrix and reinforcement alternatively forming stress fields around them; compressive stresses are created in front and tensile stresses behind the abrasive particle.

Since the portion of the reinforcement that is removed due to failure at the interface or in the reinforcement cannot further contribute to improving wear properties of the matrix, its contribution to the wear resistance is inversely proportional to its relative size. The size of this non-contributing portion (NCP) can be estimated by modeling the three primary abrasive wear mechanisms, namely plowing, cracking at the interface or in the reinforcement, and particle removal. Based on this information, a new relationship for the abrasive wear rate of a composite is developed.

Plowing mechanism. The depth of penetration, x , of the abrasive medium depends on its geometry, the applied normal load, and the mechanical properties of a composite (relative to the abrasive medium). While the abrasive medium is moving, contact with the substrate occurs only over its half-front surface. Under an indentation load L , the depth of penetration of the abrasive particle can be written as

$$L = \frac{1}{2}(2wbH_C) \text{ and } \frac{x}{w} = \tan \theta, \quad x = \frac{L}{bH_C} \tan \theta \quad (3)$$

where b is the thickness of the substrate and abrasive medium, and H_C is the hardness of the composite. The magnitude of plowing load F_p required to plastically deform and remove material is proportional to the depth of penetration of the abrasive medium. The abrasive medium will plow the matrix and the reinforcement alternatively, and experience different plowing loads for the different phases (Fig. 3).

The expression for the plowing load on each phase can be expressed by employing the indentation load approximation

$$F_p = xbH_i \quad (4)$$

where H_i is the hardness of either the matrix or reinforcement material.

If the spacing, d , between individual abrasive particles is small compared to the extent of their respective stress fields, then an interaction between neighboring stress fields will occur (Fig. 3). Consequently, stresses around each abrasive particle will depend on the average distance between these particles and the magnitude of the plowing loads.

Cracking mechanisms. In a hardened composite composed of a ductile-(soft) matrix and a hard (brittle) reinforcement, a maximum load is applied on the system when the abrasive medium plows the reinforcing phase, $F_p = (F_p)_R$ in Eq. (4). Its magnitude depends on the depth of penetration, x , the average spacing between abrasive particles, d , and the hardness of the reinforcement, H_R . If the values of these parameters are very small compared to the size of the reinforcement, plowing is the dominant material removal mechanism. However, when their values become comparable or larger than that of the reinforcement, material may be removed due to the failure/cracking at the matrix/reinforcement interface or in the reinforcing phase (Fig. 4). The trajectory of the crack depends on the relative toughness of the interface to that of the reinforcing material.

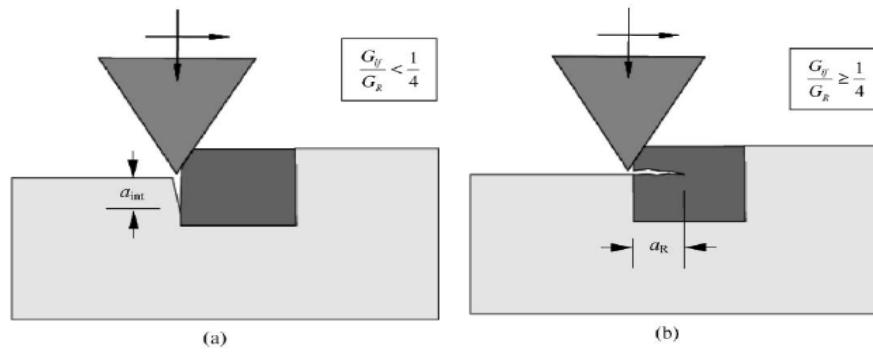


Fig. 4. With a “weak” interface between the matrix and the reinforcement, the motion of abrasive medium leads the crack propagation along the interface (a); when the matrix/reinforcement interface is relatively “strong” in that the ratio of the fracture toughness between interface and reinforcement is larger than ~0.25 for this geometry, the crack penetrates into the reinforcement (b).

Cracking at the matrix/reinforcement interface. When the ratio of the fracture toughness of the interface, G_{if} , and the reinforcing material, G_R , is less than approximately 0.25 for this geometry (this ratio does vary with the orientation of the crack), plowing by the abrasive medium can lead to the propagation of a crack in the “weak” interface. Fig. 4 (a), i.e. when:

$$\frac{G_{if}}{G_R} < \frac{1}{4} \quad (5)$$

Cracking in the reinforcement. On the other hand, if the interfacial bonding between the matrix and the reinforcement is good (a “strong” interface), the crack will propagate into the reinforcing phase (Fig. 4(b)). In this case, the ratio of the interfacial fracture toughness to that of the reinforcing phase must be higher than 0.25 (for a crack normal to the interface):

$$\frac{G_{if}}{G_R} \geq \frac{1}{4} \quad (6)$$

The lengths of the interfacial crack, a_{int} , and the crack in the reinforcement, a_R , depend on the fracture toughness and parameters such as the average distance, d , between abrasive medium and the plowing loads, viz:

$$\text{crack size} = f \{G_i, (F_p)_R, d, (F_p)_{n+1}\} \quad (7)$$

where G_i represents either the interfacial fracture toughness, G_{if} , for the case of an interfacial crack of length a_{int} , or the fracture toughness of the reinforcing material, G_R , for a crack of length a_R in the reinforcement.

Particle removal. In a hardened composite system with a weak interface, continuous plowing of the abrasive medium reduces the level of the wear surface until the tip of the interfacial crack finally reaches the bottom of the reinforcement. The plowing of the next abrasive medium will cause further propagation of the interfacial crack around the reinforcing particle (Fig. 5(a)). The continuous motion of the abrasive medium can result in complete removal of the remaining portion of the reinforcement leaving a void of the same size on the surface. As a portion of reinforcement is now removed as a large mass (due to interfacial failure), it cannot contribute to the wear resistance. It is assumed that the size of the crack, a_{int} at the interface or a_R in the reinforcement, of a composite under given wear conditions is constant. The fraction of this “NCP” (non-contributing portion) is large mass (due to interfacial failure), it cannot contribute to the wear resistance. It is assumed that the size of the crack, a_{int} at the interface or a_R in the reinforcement, of a composite under given wear conditions is constant. The fraction of this “NCP” is

$$NCP = \frac{x + a_{int}}{D_R} \text{ (crack at interface)} \quad (8)$$

where x is the depth of penetration of the abrasive medium, a_{int} the size of the interfacial crack, and D_R is the size of the reinforcement (Fig. 5(b)). However, with a relatively strong interface, plowing of the abrasive medium will lead to crack growth in the reinforcement (Fig. 4(b)). It is assumed that the crack, a_R , propagates parallel to the wear surface.

While the abrasive medium is moving through the reinforcing phase, the crack, a_R , stays in front of it. When the tip of the crack reaches the reinforcement/matrix interface, further motion of the abrasive medium will cause removal of a portion of the reinforcement as a wear particle (Fig. 6(a)). As the size of this NCP with respect to the path of abrasive medium is the product of the depth of penetration, x , and the size of crack, a_R , as shown in

Fig. 6(b), the fraction of the NCP of the reinforcement can be estimated by

$$NCP = \frac{xa_R}{D_R^2} = \frac{a_R}{D_R} \text{ (crack in reinforcement)} \quad (9)$$

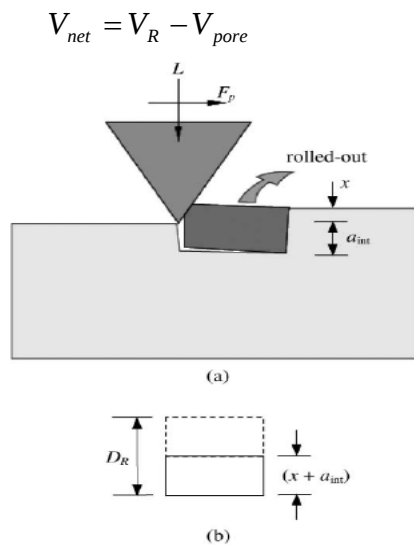
where a_R is the size of the crack in the reinforcement, x the depth of penetration of the abrasive medium, and D_R is the size of the reinforcement.

Thus, the net volume fraction of the reinforcement, which contributes to the wear resistance, can be written as follows:

The wear rate of the three-phase composite can again be obtained based on the “equal wear rate assumption”:

$$\frac{1}{W_C} = \frac{V_m}{W_m} + C \frac{V_R}{W_R} + (1 - C) \frac{V_{pore}}{W_{pore}}, \quad V_R \leq 0,5 \quad (12)$$

where W_C , W_m , W_R and W_{pore} are the wear rates of composite, matrix, reinforcement and pores, V_m and V_R are the volume fractions of the matrix and the reinforcement, and C is a new parameter, which we term the contribution coefficient of the reinforcement. This parameter describes the relative contribution of each of the primary wear mechanisms and is defined as



(11)

Fig. 5. (a) The tip of the interfacial crack reaches the bottom of the reinforcing particle and continues to propagate around the particle; (b) the size of the NCP of reinforcement due to the failure at the matrix/reinforcement interface is $(x + a_{int})$.

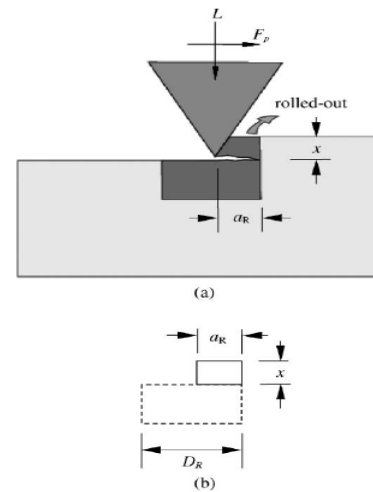


Fig. 6. (a) When the tip of the crack reaches the reinforcement/matrix interface, continuous motion of abrasive medium causes removal of a portion of the reinforcement as a large mass; (b) the size of the NCP of the reinforcement per path of each abrasive medium is $(a_R x)/\text{path}$.

$$C = \left(1 - \frac{x + a_{int}}{D_R}\right) (\text{crack at interface})$$

$$C = \left(1 - \frac{a_R}{D_R}\right) (\text{crack in reinforcement})$$
(13)

Since the third term on the right side of Eq. (12) will vanish because the wear resistance of pores is equal to 0, $1/W_{pore} = 0$, we can obtain a final expression for the abrasive wear rate of a composite from this physically-based mechanistic model as

$$\frac{1}{W_C} = \frac{V_m}{W_m} + C \frac{V_R}{W_R}$$
(14)

The contribution coefficient parameter, C , represents the effects of critical factors, including the fracture toughness and the relative size of the reinforcement; its magnitude varies from zero to unity.

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