Chapter 10

WEAR

Wear can be defined as the loss of material that occurs when two surfaces rub against each other. Two common forms of wear are:

- Adhesive Wear
- Abrasive Wear

Adhesive wear is also known as scouring, galling, or seizing. Deformation in shear is the main mechanism in adhesive wear. Generally, high contact stresses are involved which lead to local plastic deformation, resulting in the formation of adhesive bonds between the two surfaces, Fig. 10.1. Continuing the sliding motion increases the shear stress in the bonded region until the yield strength of the softer material is significantly exceeded.

Abrasive wear occurs when hard ceramic particles such as WC or SiC get trapped between the sliding surfaces, Fig. 10.2. The degree of material loss (volume or mass) is a function of the relative hardness of the ceramic particles and the sliding surface. Environment can be an additional factor in wear. It can lead to fretting, cavitation, erosion, etc. During abrasive wear, the surface asperities are worn down and the contact surfaces become mated. This reduces the local contact stress because of the increase in contact area. After this initial abrasive wear, the removal of oxidized particles occurs along the surface. This is generally a steady state process inasmuch as it requires reoxidation of the denuded surface in order to continue removing oxidized particles. The final stage of wear occurs in adhesive mode and occurs if the contact pressure increases to the point of shearing the particles. The result of shear is the formation of thin plate-like wear debris sheets. Depending upon the applied load, the sheets can result in significant material loss.

It is important to remember that, more often than not, wear is a system
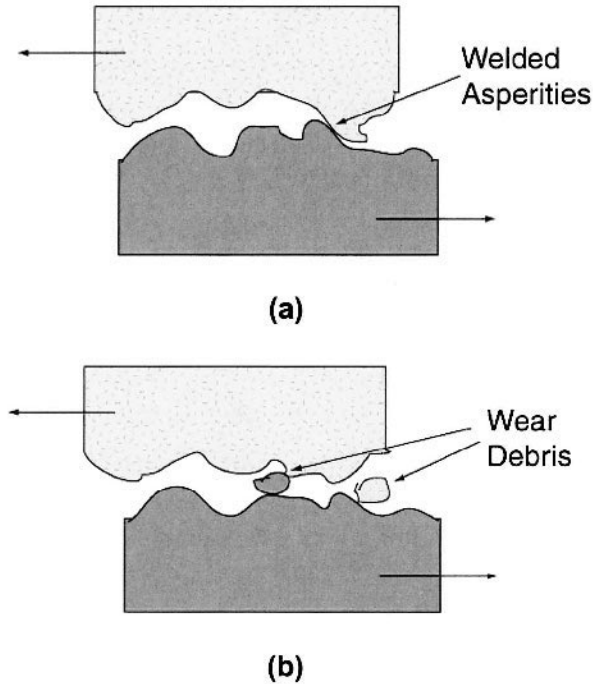
Fig. 10.1 Adhesive wear due to high contact stresses which lead to local plastic deformation, and (a) welded asperities and (b) wear debris between the two surfaces.

property. Consider the different types of variables involved: the matrix, reinforcement fibers or particles, orientation of fibers with respect to the wear direction, reinforcement/matrix interface, morphology, and size, and volume fraction of the phases in the composite. These are *intrinsic* microstructural variables. Testing or operational conditions can also affect the wear behavior. These include the type of counter surface or abrasive, force, speed, contact area, geometry, and environment (lubrication or dry). These are *extrinsic* variables. Two important wear testing techniques are described in the inset.

Under appropriate conditions, the addition of ceramic particles to a metal matrix can lead to improved wear resistance. It should be recognized, however, that if the conditions are not suitable, the addition of ceramic particles may decrease wear resistance. For example, the ceramic particles may be removed from the matrix and lead to a wear process by three body abrasive wear, Fig. 10.2(b). Another point to keep in mind is that as the volume fraction or size of the reinforcement becomes large, the fracture
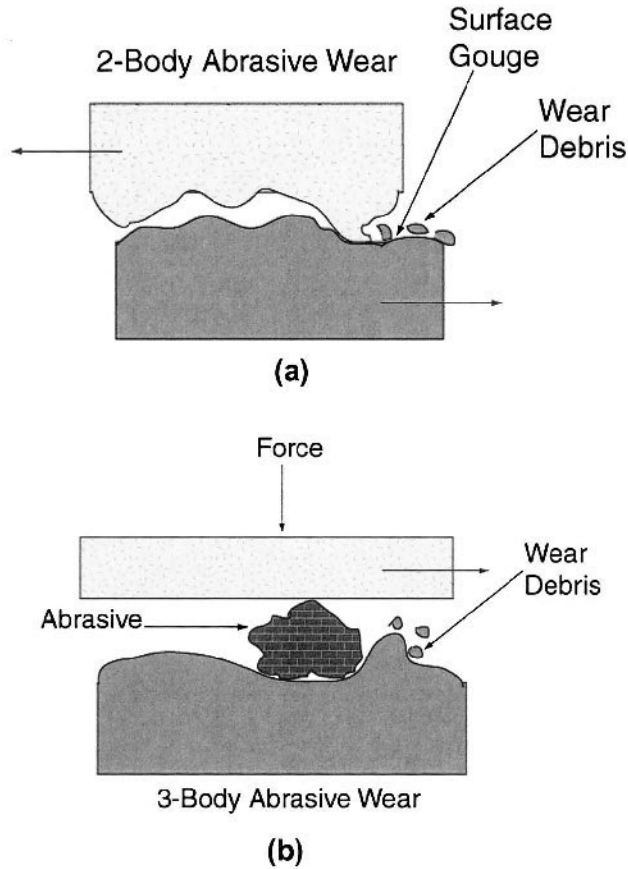
Fig. 10.2 Abrasive wear involving ceramic particles such as WC or SiC leading to debris trapped between the sliding surfaces: (a) two body wear and (c) three body wear.

toughness of the composite will be reduced significantly. If the fracture toughness is inadequate, the particles will fracture and contribute to the wear process. Increasing wear resistance without a penalty in toughness is a challenge.

Most of the work in the area of wear of MMCs has been on particle reinforced composites. Thus, in this chapter we focus mainly on the wear behavior of two important systems: silicon carbide/aluminum composites and tungsten carbide/cobalt. In the end we devote a short section on wear aspects in braking materials. A more comprehensive treatment on the applications of braking materials is given in chapter 11.

Wear Testing

Pin-on-disk wear testing (ASTM G99-95a)

In this test, a normal load is applied via pin onto a rotating disk. The sliding motion may be in one direction or reciprocating. The tests may be conducted in dry or in lubricated conditions. The coefficient of friction, μ, can be obtained from this test at any point in the test. Typically one measures the mass before and after the wear test by means of a sensitive microbalance. The wear rate is given by:

$$\text{wear rate} = \frac{\text{mass loss}}{\text{sliding distance}}$$

The wear rate may also be reported as:

$$\text{wear rate} = \frac{\text{volume loss}}{\text{sliding distance}}$$

High stress and low stress wear testing

In the high stress wear test (ASTM B611), a coarse alumina particle slurry ($\sim$590 μm) is used as an abrasive. A steel wheel is rotated at 100 rpm through the slurry bath. The test sample is pressed against the steel wheel with a known force. One measures the mass loss, after 1000 revolutions of the steel wheel, and obtains the wear number as:

$$\text{Wear number} = \frac{\text{Density}}{\text{Mass loss}}$$

Physically, the wear number gives the number of revolutions to remove a unit volume of the sample. The higher the wear number, the better the wear resistance.

In the low stress wear test (ASTM G65), dry quartz sand (200-300 μm) is used as the abrasive. It is softer than the alumina slurry used in the high stress wear test. Instead of a steel wheel, a rubber wheel is used. After 0.5 h at 200 rpm, we obtain the volume loss as:

$$\text{Volume loss} = \frac{\text{Mass loss}}{\text{Density}}$$

The lower the volume loss, the higher the wear resistance.

10.1 PARTICLE REINFORCED ALUMINUM MATRIX COMPOSITES

In the abrasive stage of wear of MMCs, the degree of abrasion is a function of the applied load, speed, size and volume fraction of reinforcement, and interfacial bond strength between the reinforcement and matrix. Abrasive wear resistance of several Al alloys containing a range of ceramic particles and volume fractions have been examined by a number of researchers (Hosking et al., 1982; Wang and Rack, 1991; Chung and Hiang, 1994; Zhang et al., 1995; Garcia-Cordovilla et al., 1996). The addition of ceramic particles, such as alumina, to aluminum alloys result in substantial reduction of the wear rate (Hosking et al., 1982). The reduction in wear rate is influenced by the size of the reinforcement particle and the volume fraction of reinforcement. The greatest wear resistance is typically achieved with the alloy containing the largest volume fraction and the largest particle size, as shown in Fig. 10.3. Figure 10.4 shows an example of the effect of SiC particles on wear resistance (Venkataraman and Sundarajan, 1996a, 1996b). The improvement of the composite over the unreinforced alloy is greatest at higher loads.

After wear, the worn surface of the unreinforced aluminum alloys typically consists of long, continuous grooves, which are the result of abrasive particles plowing the surface. The surface of composites, on the other hand, exhibit substantially reduced surface plowing (Garcia-Cordovilla et al., 1996). The wear rate of the composites decreases as the volume fraction of reinforcement increases. The wear rate usually decreases as the particle size increases. This may be attributed to the particle strength being higher than the interface strength, for smaller particles. Thus, the smaller particles are pulled out before fracturing. The larger particles remain in the matrix longer and are able to carry the surface load until they fracture into smaller particles.

One should remember that, besides hardness, the fracture toughness of the reinforcement also has an important role to play. As the stress is increased, the fracture toughness of the reinforcement becomes an important parameter. The fracture toughness determines the extent of fracture of the reinforcement. Thus, the governing factor for wear with increased stress is the fracture toughness of the reinforcement particles.
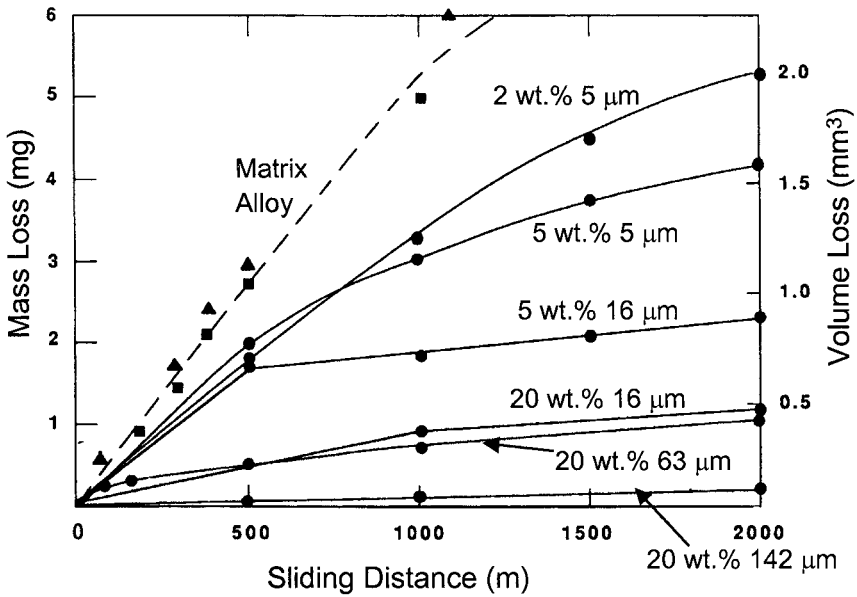
Fig. 10.3 Improved wear resistance of aluminum 2024 alloy matrix composites with increasing volume fraction and size of the alumina particles (after Hosking et al., 1982).
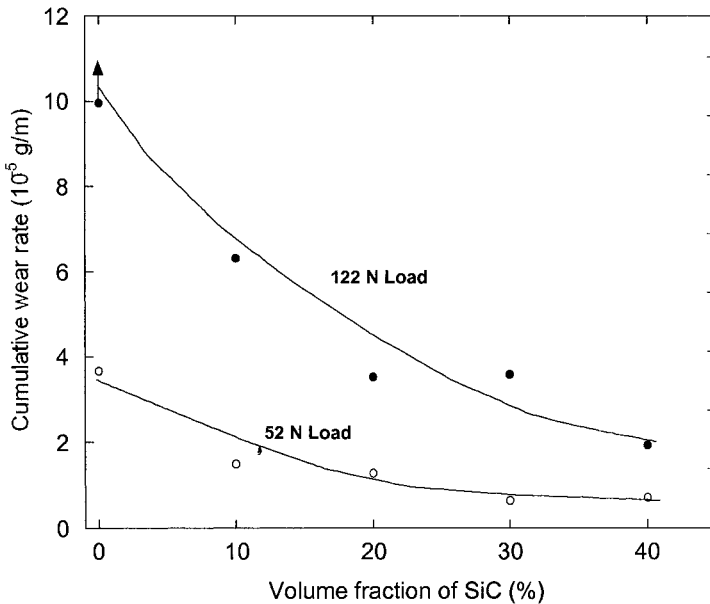

Fig. 10.4 Increase in wear resistance with increased volume fraction of SiC (after Venkataraman and Sundarajan, 1996a).

Oxidation of surface debris during wear process is another phenomenon during wear of MMCs. Abrasion transforms to oxidative wear after a certain sliding distance. With increasing load, the wear behavior changes from mild, oxidative wear to severe wear by adhesion. Examination of the worn surface and debris indicates that debris formation is more influential on wear rate, within the abrasive regime, than deformation of the material (Ludema, 1996). After a certain sliding distance, the surface asperities wear down, which reduces the contact stress because of the increase in contact area for the same load. As a result, the wear rate and coefficient of friction also decrease during this period.

Suh (1973) proposed a delamination wear mechanism wherein voids and cracks nucleate at second phase particles in the subsurface region below the contact surface. This was attributed to the large hydrostatic pressure acting near the asperity contact. Cracks during wear typically propagate parallel to the contact surface (Suh, 1973, Jahanmir and Suh, 1977). During sliding wear the surface is plastically deformed, which introduces dislocations in the subsurface of the contacting materials. The dislocations lead to eventual formation of cracks and/or voids in the subsurface region. Fragmentation of the particles can also lead to decohesion of the particle/matrix interface, resulting in more void formation. With continued sliding, the cracks and void eventually coalesce and result in larger cracks. When the crack reaches a critical length, the material between the crack and the surface is removed from the surface in the form of wear debris. The severe wear by adhesion can occur by such a delamination process initiated by subsurface cracking. Three factors influence this phenomenon: Particle size, volume fraction, and type of reinforcement. Larger particles require larger loads to initiate subsurface cracking and eventual delamination. The work of Zhang and Alpas (1993) and Chung and Hiang (1994) supports Suh's delamination theory. They examined cross-sections of worn surfaces of aluminum alloys reinforced with SiC particles, which showed evidence of wear debris in the form of flakes. These flakes of debris were produced by subsurface delamination. Microscopic analysis showed cracks, which formed at the particle/matrix interface and propagated parallel to the surface. The cracks and resultant voids coalesced with eventual delamination of material from the surface. Depending upon the rate of wear debris formation, delamination may result in a reduction of wear by the formation of a debris layer between the contacting surfaces. This layer, also termed a mechanically mixed layer (MML) is comprised of the reinforcement, matrix material, and material from the counter surface (Venkataraman and Sundarajan, 1996a, 1996b).

Venkataraman and Sundarajan (1996b) found the hardness of the MML to

be approximately six times that of the bulk composite. They hypothesized that as the deformation increased, the reinforcement particles at the wearing surface fragmented and the number of voids began to increase. Once a critical void density was reached, shear instability was initiated at selected locations within the subsurface. The shear instability promoted turbulent plastic flow, which resulted in a mixture of material from both surfaces. The mixture of the material led to the formation of the MML, which appeared to have a direct influence on the wear rate. The rate of formation of the MML controlled the wear rate and was directly related to delamination wear.

Frequently, improved wear performance can also be obtained by adding a lubricant or by adding a reinforcement that provides lubricating characteristics. Rohatgi et al. (1992) observed that carbon, in the form of graphite particles, in aluminum can decrease the coefficient of friction against dry steel. Carbon in microcrystalline form, on the other hand, had practically no effect. This is understandable inasmuch as graphite flakes cleave easily and serve as lubricants. One should be cautioned that in addition to the parameters described above, the environment can also play a decisive role in the ultimate wear performance.

10.2 TUNGSTEN CARBIDE/COBALT COMPOSITES

Tungsten carbide/cobalt (WC/Co) composites, commonly known as cemented carbides, are one of the most important metal matrix composites used for their excellent wear resistance (Upadhyaya, 1998). They were originally developed for drawing tungsten incandescent filament, where wear resistance is clearly important. Now they are also widely used for cutting, machining, and drilling purposes. Cemented carbides consist mainly of fine tungsten carbide particles and the binder metal cobalt.

The wear behavior of conventional WC/Co composites is characterized by plasticity of cobalt matrix and the high strength and hardness of the WC particles. In high speed machining, the temperature at the cutting edge can exceed 1000°C leading to phenomena such as diffusion and oxidation of the cutting tool, abrasion, and adhesion, e.g., the chip can adhere to the flank face. In general, the wear behavior is directly related to hardness, which in turn is a function of volume fraction and size of tungsten carbide particles.

10.2.1 Hardness and Strength of Cemented Carbides

Hardness is a critical property in determining the wear resistance of a material. WC/Co composites have been studied extensively and some useful

correlations have been obtained. Lee and Gurland (1978) proposed the following expression for the hardness of WC/Co composites:

$$H = H_{WC}CV_{WC} + H_{Co}(1 - CV_{WC})$$

where H is the hardness of the composite; H_{WC} and H_{Co} are the hardness of WC and Co, respectively; C is the contiguity of the WC particles, and V_{WC} is the volume fraction of WC in the composite. The parameter contiguity is defined as:

$$C = \frac{2S_{cc}}{2S_{cc} + S_{cm}}$$

where S_{cc} is the area between the carbide particles and S_{cm} is the area between the carbide particles and the matrix in a unit volume. The hardness of cobalt is related to the mean free path (λ) of the cobalt matrix in the composite by the following empirical relation:

$$H_{Co} = 304 + 12.7\lambda^{-0.5}$$

The important result in this case is that the hardness of cobalt matrix goes as the inverse square of the mean free path.

The homogeneous distribution of a high volume fraction of fine WC particles in a cobalt matrix, in conventional cemented carbides, enhances strength, wear resistance, thermal conductivity etc. of the composite, but at the expense of toughness. This has led to the development of a new type of composite which we describe in the next section.

10.2.2 Double Cemented Carbide (DCC)

A novel particulate composite metal matrix composite called Double Cemented Carbide has been developed (Fang and Albert, 1999; Fang et al., 1999; Deng at al., 2001). This material consists of granules of WC/Co composite embedded within Co or another metal matrix as shown in Fig. 10.5. Thus, it is a kind of "dual" composite with a "composite-within-a-composite" structure. This concept provides microstructural design variables not available in conventional particulate metal matrix composites. We describe some interesting relationships among the processing, microstructure and properties of this novel composite material. These additional degrees of freedom enable remarkably enhanced *combinations* of properties, such as
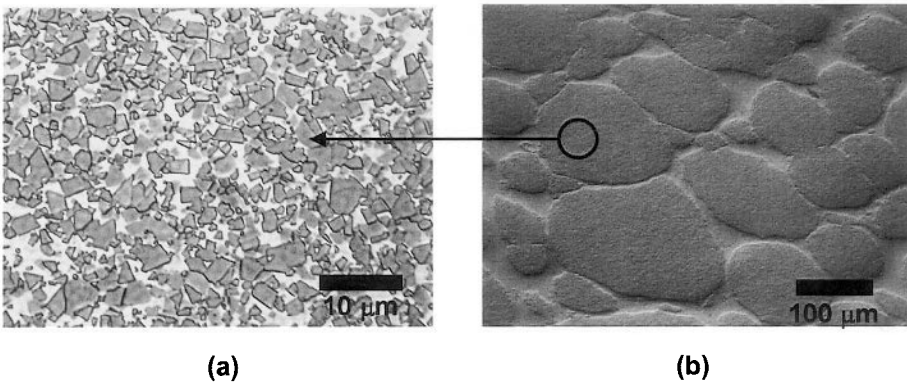
(a)   **(b)**

Fig. 10.5 Microstructures of cemented carbide (WC/Co) with (a) conventional and (b) DCC structure, containing the same *total* cobalt contents, 25 vol%. The coarse granules in (b) have a fine dispersed microstructure similar to that of (a).

high toughness and wear resistance.

Figures 10.5(a) and (b) show composites containing 75 vol% WC particles in a cobalt matrix but with the two different types of structure: (a) conventional particulate composite structure with homogeneously distributed particles and (b) DCC structure. The DCC material has twice the toughness and six times the high-stress abrasive wear resistance than the conventional material, at the same total particle volume fraction. These improvements in properties result from the partitioning of the matrix to produce particle-free matrix regions separating the granular regions, which have higher particle volume fractions than the overall average. These ductile intergranular regions enhance fracture resistance with little detriment to abrasive wear resistance. Wide ranges of combinations are achievable by fine tuning of granule composition and properties, granule size, matrix composition and heat treatment.

Figure 10.6 shows a plot of fracture toughness vs. wear number in terms of kilo revolutions per unit cm^3. It illustrates the difference in toughness/wear resistance behavior between conventional and DCC composites. Recall that the higher the number of revolutions, the better the wear resistance. The thicker line represents the relationship for essentially all grades of conventional cemented carbide, i.e., with wide variations in cobalt matrix fraction and WC particle size. As with most conventional particulate composites, improvement in either property comes at the expense of the other. Thus, enhanced toughness means poor wear resistance and vice versa. This restricted relationship results from the limited degrees of freedom in
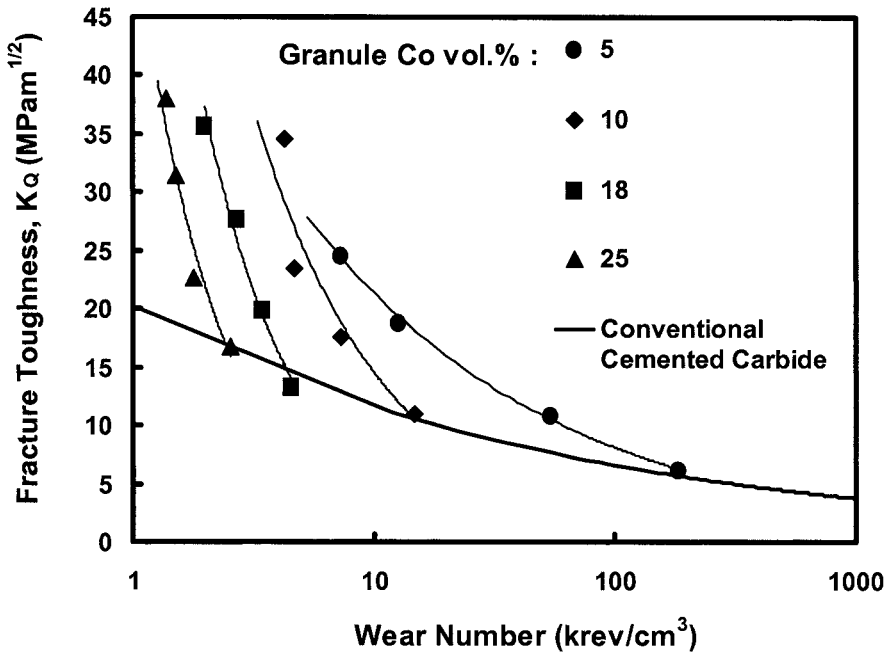
Fig. 10.6 Superior combination of toughness and wear resistance of DC Carbide vs. conventional cemented carbide (after Deng et al., 2001).

microstructural design and restricts the balance of properties in essentially all particulate MMCs. The curves for different DCCs with different granule properties (decreased cobalt yields harder granules with increased wear resistance and decreased toughness) and different volume fractions of intergranular matrix, show that at comparable wear resistance the DC structure has higher toughness than the conventional structure and at comparable toughness DC has higher wear resistance (Deng et al. 2001).

The improved toughness of the DCC composite is a function of the increased mean free path through the intergranular matrix (~20 µm vs. < 1 µm in conventional cemented carbide). The improved abrasive wear resistance of the double composite is due to a different wear resistance mechanism than with conventional particulate MMCs. Protrusion of the large, hard composite granules from the wear surface can be seen after wear, Fig. 10.7. The best wear resistance/toughness combination results from a high volume fraction of relatively large, hard granules, since increased granule size increases the intergranular mean free path, which enhances toughness. Larger granules exhibit the greatest protrusion for wear resistance and are the most difficult to remove via matrix erosion.
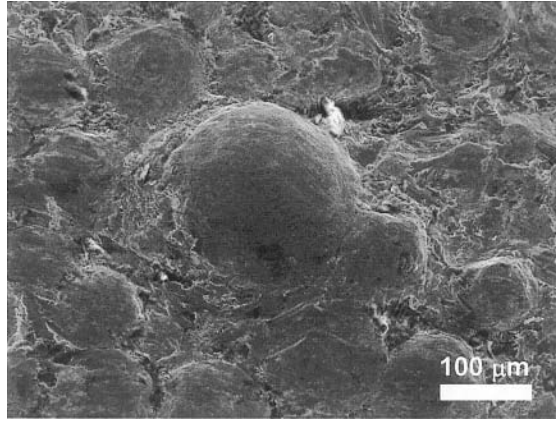
Fig. 10.7 Wear surface of DC carbide after high stress abrasive wear testing, showing protrusions (after Deng at al., 2001).

10.3 Wear in Braking Materials

Wear and frictional characteristics are very important in materials used for braking applications. In addition, one must consider physical properties such as thermal conductivity. Every time we apply a brake to stop a moving vehicle, the kinetic energy of the rotating elements of the vehicle must be absorbed by the brake. This energy is dissipated in the form of heat within the brake. The rise in temperature because of energy dissipated as heat can be simply written as:

$$E = mC\Delta T$$

where m is the mass of the device, C is the specific heat, and ΔT is the temperature rise. Conventionally, we use steel, cast iron (trains), and asbestos. The latter has been mostly replaced because of its carcinogenic nature. A material used in a braking system must be able to generate the torque sufficient for stopping the vehicle, must absorb and dissipate the heat produced during the slippage process, and withstand the high temperatures reached during stopping. It should also have superior structural properties for transferring the torque to the tires, without adding extra weight to the vehicle to make it inefficient (Chawla, 1998). MMCs with appropriate frictional characteristics such as wear, durability and ability to withstand higher temperatures are excellent candidates for braking materials. Heat resistance capability of aluminum alloys can be increased substantially by adding 30% by volume of SiC particles. Such a composite was used to make

a brake rotor (Nakanishi et al., 2002).The composite brake rotor had a higher heat resistance than those than a conventional cast iron rotor, especially a more stable coefficient of friction.

Zeuner et al. (1997) developed a MMC disc brake for high-speed trains that resulted to be not only mechanically superior to conventional cast irons, but also cost effective in terms of manufacturing braking system of a train is composed by four brake discs and the necessary calipers, hand brake, and electromagnetic track brakes. The higher thermal conductivity and lower modulus of elasticity of aluminum result relatively low thermal stresses during the braking operation, which is a great advantage for Al-MMC discs over cast iron. For the same braking load, the cast iron discs showed higher thermal stresses and non uniform temperature distribution than the Al-MMC disc, resulting in cracks due to thermal stresses in cast iron brakes but not in composite, see chapter 11.

In summary, metal matrix composites, especially the particulate variety, can provide significant improvements in applications involving friction and wear. The ability to tailor their properties such as stiffness, hardness, and toughness are the main keys to such improvements. The material properties, reinforcement size and volume fraction have a profound influence on wear resistance. Increased volume fraction increases the stiffness but generally lowers the fracture toughness. Thus, increased volume fraction of ceramic particles will result in greater wear resistance at lower loads, but the fracture toughness becomes an important issue with increased load. For a given volume fraction, increased particle size provides the best wear resistance, but larger particles are also more susceptible to fracture. Fine particles are less likely to experience fracture, but are more likely to be buried in matrix and removed by delamination. The loading conditions, matrix and reinforcement properties, and reinforcement size and volume fraction influence the creation of a mechanically mixed layer between the contacting surfaces, which will help to protect the surfaces and slow the wear rate. Thus, in designing for wear resistance, it is important to select the proper combinations of matrix, reinforcement, and reinforcement size and volume fraction.

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