CHAPTER 9

Brittle Materials: Principles

THE DISCUSSION in earlier chapters was confined to ductile materials. That is, to materials that, when deformed in bulk, plastically deform a significant amount before fracture occurs. Some materials, on the other hand, deform only elastically prior to fracture by the catastrophic propagation of a crack. They are then said to be brittle. Some materials that might become the subject of a metallographic examination are brittle in themselves. Examples include metallic carbides and nitrides; semimetals, such as silicon and germanium; ceramics; and glasses. In other instances, brittle materials may be present as the phases or constituents of an alloy or as a surface layer of a nonmetallic material. The behavior of these brittle materials or brittle phases may be different from the ductile materials that have been discussed to this point. In particular, abrasion may occur by a mechanism different from that by which polishing occurs.

Mechanisms of Abrasion

Chip-Fracture Mechanisms

Although in practice there are many variants, the general sequence of events followed when a sharp point is pressed into the surface of a brittle material under an increasing force and then unloaded is as follows (Ref 1):

1. A zone of irreversible deformation is produced beneath the indentation (Fig. 9.1a), and an impression remains in the surface after unloading. The mechanism by which this pseudoplastic deformation occurs is not known in most cases, but the fact that a permanent impression is left in the surface is a positive indication that it does occur.

2. At some critical indentation force, a crack is initiated below the point of contact where the stress concentration is greatest (Fig. 9.1b). This crack, commonly called a median vent crack, lies on a plane of symmetry in the applied stress field. The specific orientation of the plane depends on such factors as the geometrical configuration of the indenter and the structural anisotropy of the specimen material. The median vent crack closes but does not heal on unloading. Thus, an impression and several cracks oriented perpendicular to the surface are left in the surface after unloading.

3. The deformed zone and the median vent crack grow in a stable manner as the force is increased further, until, at a certain stage, sideways-extending cracks (termed lateral vent cracks) form during unloading. The lateral vent cracks begin to appear just before unloading of the indenter, because relaxation of the irreversibly deformed material superimposes intense residual stresses on the applied stress field. The lateral vent cracks continue to extend, eventually reaching the free surface, during further unloading (Fig. 9.1c).

Regardless of whether contact between the abrasive point and the specimen involves static indentation of the point into the specimen surface or translation of the point across the surface, material is removed from the specimen whenever a lateral vent crack extends to the free surface; in fact, vent cracks develop at smaller forces with sliding indenters (Ref 2). A considerable volume of material is thus removed—a much larger volume than that which is swept out of the surface by the indenting point. The material so removed can be called a fracture chip, as
distinct from the machining chip referred to in Chapters 3, “Machining with Abrasives: Principles,” and 7, “Polishing with Abrasives: Principles.” The formation of such fracture chips is the basic material removal mechanism for the abrasion of brittle materials.

The first implication of this mechanism is that rolling abrasive particles with sharp points (i.e., those operating in mode A, Fig. 3.6) may remove material each time that a point indents into the surface of the specimen. The second implication is that all contacting points, when translated while under a high enough force in two-body abrasion, remove material regardless of their rake angles. Because of this, and because a comparatively larger volume of material is removed by each contact point, the rate of material removal is potentially much larger for abrasion of brittle materials than for abrasion of metals. In general, it is an order of magnitude larger in practice.

The situation is a little different with blunt indenters (Ref 3). A spherical point, for example, can maintain perfectly elastic contact up to a certain applied force. Beyond this force, fracture is initiated just outside the contact circle, where the Hertzian elastic tensile stresses are at a maximum, and the crack propagates by running around the line of contact to produce a ring crack (Fig. 9.2). This crack is circular in an isotropic material, but its path may be partly modified to reflect the crystal symmetry in crystalline materials. The ring crack propagates downward on the surface of an expanding cone of maximum Hertzian stress, thus developing a cone crack (Fig. 9.2). The circular symmetry of the cone cracks is lost when the spherical point is slid across the surface, being replaced by a system of cracks that typically follow the trajectories illustrated in Fig. 9.3. Intersections of
crack systems from adjoining grooves could result in the removal of fracture chips, but this, at best, would be a minor mechanism of material removal.

However, just as in abrasion by sharp indenters, increasing the applied force eventually introduces additional systems of median and lateral vent cracks (Fig. 9.2). Material removal can then occur by the same mechanism as for sharp points, although only after the application of a larger force. Thus, with blunt points, the morphology of the crack systems is different, and the efficiency of material removal is smaller, but the major mechanism of material removal, when such removal occurs, is much the same.

These principles are illustrated in Fig. 9.4. In two-body abrasion (such as on abrasive papers), sharp abrasive points have removed chips along their tracks (Fig. 9.4a), whereas blunt points have produced tracks of partial ring cracks (Fig. 9.4b). In three-body abrasion, on the other hand, sharp rolling abrasive particles have produced large, randomly arranged pits (Fig. 9.4c), whereas blunt particles have produced randomly arranged sets of ring cracks (Fig. 9.4d). The sharp abrasive has removed considerable amounts of material in both modes, whereas the blunt abrasive has removed virtually none under these particular circumstances.

A mathematical model of two-body abrasion by sharp abrasive points can be based on these concepts (Ref 4), with the following result:

$$ M = \eta \rho \frac{D}{L} (P \phi) $$

where $M$ is the mass removed, $\eta$ is a linear scaling factor relating the volume of material enclosed by lateral vent cracks to that of the plastic grooves, $\rho$ is the density of the specimen material, $D$ is the distance traversed, $L$ is the...
force applied, \( P \) is the indentation hardness of the specimen material, and \( \phi \) is a form factor for the indenter.

This equation is similar to that developed earlier for metals (Eq 2 in Chapter 3), except that the factor \( f \) (which generally is less than one) in the earlier equation is replaced by \( \eta \) (which generally is greater than one). Some implications associated with this model are that the mass (or volume) of material removed is independent of the apparent area of contact between the workpiece and the abrasive device, is independent of the diameter and number of contacting particles, and is dependent on the total force applied rather than the manner in which this force is distributed. The equation also implies that abrasion rate is dependent on the hardness of the specimen material, although it is to be noted that the apparent hardness of these materials can be influenced by both the rate of application of the indentering force and the environment. The abrasion rate would also be affected by other material parameters, if they influenced the development of vent cracks and consequently, the value of \( \eta \).

Quantitative data on the material removal rates obtained under these circumstances are not available. It is clear, however, that the removal rate would always be considerably higher than for ductile metals. Consequently, a brittle phase surrounded by a ductile matrix can be expected to abrade to a considerably lower level than the matrix under these circumstances. An example is illustrated in Fig. 9.5.

**Chip-Cutting Mechanisms**

Material is removed by a chip-cutting mechanism in the plastically deformed zone when the stress field beneath a contacting point is not high enough to drive lateral vent cracks to the surface. Ribbons of material that have all the physical characteristics of machining chips then separate, even from materials that are quite brittle in bulk (Fig. 9.6) (Ref 5). Moreover, the microstructure of the ribbons is closely similar to the structure of those that separate from ductile materials (Ref 5). This indicates that they have formed by some type of high-strain plastic instability, but the nature of this instability has not been established.

Thus, a transition from material removal by chip fracture to chip cutting can be expected to occur when the force applied to a contacting abrasive point falls below a critical value. For a given applied specimen pressure, the mean force applied to the contacting points of practical abrasive machining devices is determined by the number density of the contacting points, which in turn is determined principally by the diameter of the abrasive particles (the abrasive grade). Thus, material removal from a brittle material by the coarser grades of a particular type of abrasive device might occur by chip fracture but by chip cutting for grades finer than a certain value.

This transition can be illustrated by considering the finish obtained on the large, primary sil-
icon particles present in hypereutectic aluminum-silicon alloys. The surfaces produced on this phase by abrasion with silicon carbide paper ranging from 240 down to 600 grades are composed largely of fracture pits (Fig. 4.28a). This indicates that material removal occurs basically by chip fracture. However, a small number of grooves more characteristic of micromachining are present after abrasion with the finer grades in this range. Presumably, they are cut by contacting points where the applied force is smaller than average. The proportion of grooves is substantial after abrasion with a finer (P2400) grade of silicon carbide paper (Fig. 9.7a), indicating that material removal by a high proportion of the contacting points then occurs by micromachining. Virtually all contacting points machine grooves during abrasion with a 9 \( \mu \)m grade aluminum-oxide-coated polyester film (Fig. 9.7b), which has a higher number density of contacting points than coated papers. Similarly, all material removal occurs by chip cutting during abrasion with a 10 to 20 \( \mu \)m grade aluminum oxide wax lap, and narrower scratch grooves are formed (Fig. 9.7c). This is presumably because an even larger number density of contacting points is provided.

It is to be expected that the characteristics of other brittle materials and phases would be similar to those just described, although there may be quantitative differences in the abrasion conditions that are required to obtain the desirable chip-cutting mechanisms of material removal. Experience suggests that these differences, if any, are small.

**Mechanism of Polishing**

The transition from chip fracture to chip cutting invariably has occurred with any of the polishing processes considered in this book. That is, polishing, as defined here, always occurs by micromachining in the same way as it does with metals. There is, however, one possible exception. It is recalled that the polishing of metals occurs by a different, possibly delamination, mechanism when the finest grades of diamond abrasive (1.0 to 0.1 \( \mu \)m particle size) are used. It is not known whether this also applies to brittle materials.

Moreover, there are some materials to which the generalizations do not apply, either in part or whole. Glass is one of these materials. A layer of hydrated material is always present on the surface of glass polished in the presence of water, and this hydration process is generally thought to have played a significant role in polishing processes (Ref 6). Certainly, the polishing rate is greatly influenced by the hydroxyl activity of the polishing fluid, the reactivity of the abrasive, and the reactivity of the glass (Ref 7). So, at the very least, micromachining, if it does occur, would have been modified in a major way by chemical processes. Presumably, similar modifications are also possible for other materials that can hydrate or react with the polishing environment. For example, aluminum oxide can hydrate, and single crystals of this material (sapphire) can be polished by rubbing them against a rotating disc of wood or graphite without abrasive, if this is done in an atmos-

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![Fig. 9.7](image) Comparison of the finishes obtained on particles of silicon phase in a hypereutectoid aluminum-silicon alloy by representative abrasion processes. (a) Abraded on P1200-grade silicon carbide paper; silicon removed partly by chip cutting but largely by chip fracture. (b) Abraded on polyester film coated with 9 \( \mu \)m grade aluminum oxide abrasive; silicon removed almost entirely by chip cutting (micromachining). (c) Abraded on 10 to 20 \( \mu \)m aluminum oxide wax lap; material removal entirely by chip cutting. Specimen pressure for all: \(-40 \text{ kPa (5.8 psi)}\). All, 250x
phere of steam at approximately 200 °C (390 °F) (Ref 8). Conversely, it may not be valid to extrapolate to metals the principles established for these materials.

The polishing of diamond is also an exception. Single crystals of diamond can only be polished by diamond abrasives, and the polishing rate then varies by several orders of magnitude, depending on the orientation of the face being polished and the direction on that face in which the abrasive moves (Ref 9). Variations of only a few degrees in this direction can have a significant effect. Polishing of diamond therefore can scarcely occur by micromachining. The process is not thermally controlled and thus cannot be due to an allotropic change, diamond to graphite, as was once proposed. The most likely mechanism appears to be one of chipping on cleavage planes on an extremely fine scale, with the highest polishing rate being obtained when the cleavage planes are most suitably oriented (Ref 9).

Surface Damage

The topography of the surface of a brittle material abraded under three-body conditions, when material removal occurs entirely by chip fracture, consists of a random array of pits. (The description that follows is based on observations made on single crystals of germanium and silicon, which can be taken to be representative of brittle crystalline materials.) The pits typically are bounded by conchoidal fracture surfaces (Fig. 9.8a), but some may be partly bounded by cleavage facets when the material has planes of easy cleavage. For two-body abrasion, on the other hand, mixtures of randomly arrayed pits and aligned grooves are present.

Fig. 9.8 Surfaces of a single crystal of germanium that have been abraded on 220-grade silicon carbide abrasive. (a) and (c) Three-body abrasion. 500x. (b) and (d) Two-body abrasion. 500x. The appearance of the surfaces is shown in (a) and (b). Taper sections of these surfaces are shown in (c) and (d). The sections have been etched lightly in a ferricyanide reagent. Taper ratio, approximately 10.
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(Fig. 9.8b). Small fracture pits tend to partly cover the surfaces of the grooves.

A damaged layer containing fine cracks is present beneath the fracture pits (Ref 10, 11). The cracks are randomly distributed after three-body abrasion (Fig. 9.8c) but tend to be grouped in arrays beneath the aligned grooves formed during two-body abrasion (Fig. 9.8d). The crack-containing layers extend to considerable depths, compared to the surface irregularities, and tend to be deeper after three-body than two-body abrasion. They are also deeper, as is to be expected, after abrasion with coarser grades of abrasive (Table 9.1). The ratio of the depth of the cracked layer to the depth of the surface irregularities is, however, approximately the same for all conditions of abrasion. The damaged layer may also contain a small density of dislocations associated with the cracks, but these features are not of importance in the present context. The damage cracks themselves are clearly residuals of lateral and median vent cracks. Presumably, they are vent cracks that have not intersected with other cracks in such a way that a fracture chip has been generated.

Damage cracks of this nature are not present in surfaces that are presumed to have been generated by micromachining. A plastically deformed layer can be expected to be present, but little information is available on this topic. However, dislocation arrays suggestive of the presence of plastically deformed bands have been detected by transmission electron microscopy in polished surfaces of silicon (Ref 11) and aluminum oxide (Fig. 9.9) (Ref 13).

Table 9.1 Maximum depth of the crack-containing surface layers produced by abrasion of a single crystal of germanium on a (111) surface

<table>
<thead>
<tr>
<th>Abrasive Type</th>
<th>Grade</th>
<th>Method of use</th>
<th>Depth of surface irregularities, µm</th>
<th>Depth of cracked layer(a), µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon carbide</td>
<td>220</td>
<td>Two-body</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>Two-body</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>Two-body</td>
<td>1.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>Three-body</td>
<td>23</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>Three-body</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>Three-body</td>
<td>3.5</td>
<td>11.5</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>320</td>
<td>Three-body</td>
<td>6</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>Three-body</td>
<td>2.5</td>
<td>9</td>
</tr>
</tbody>
</table>

(a) Depth beneath the root of the surface irregularities. Source: Ref 10

REFERENCES


![Fig. 9.9](image-url) Arrays of dislocations beneath scratches produced by polishing polycrystalline aluminum oxide on 0.25 µm diamond abrasive. Transmission electron micrograph, 20,000x. Source: Ref 13