Polishing Wear

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THE TERM "POLISHING WEAR" is used to describe interactions between two solids that remove material from, while at the same time producing a polished finish on, the surface of at least one of the two. This definition is not, however, a precise one because the surface condition known as a "polish" cannot be defined quantitatively. The term is, in fact, merely one of common usage describing a surface that reflects light brightly and that produces a clear image of distant objects in the manner expected of a mirror.

The light reflected from real surfaces, which inevitably are rough on a microscopic scale, consists of two components, one known as "specular" or "regular" reflection and the other as "diffuse" reflection. The specular component consists of rays reflected over a narrow range of angles, the same angle as the angle of incidence; these rays are required for the production of sharp reflected images. The diffuse component consists of rays reflected or scattered over a range of angles centered about the angle of specular reflection. Light does not just bounce off a reflecting surface. The incident beam is diffracted from many centers on the surface, and the emergent beam is the net result of the interactions between these diffracted rays. Specular reflection results when the diffracted rays reinforce one another at the appropriate angle and cancel one another at all other angles. For regular parallel grooves in an ideal flat surface, this phenomenon is possible only when the spacing of the centers at which diffraction occurs is less than the wavelength of the incident light (about 500 nm for visible light). The analysis of the reflectivity or activity of actual engineering surfaces, such as abrasive-machined surfaces, however, is complicated by the complex topography, with the spacing, depth, and contour of the roughnesses varying over a wide range. Theoretical and experimental studies (Ref 1) indicate that the variation in the intensity of specular reflection can be related to a probability distribution of the heights of these roughness grooves. On the other hand, the spread of the diffusely reflected light depends on the distribution of the slopes of the roughnesses.

A surface has to specularly reflect a large proportion of the incident light before it would be regarded as being "polished," but the degree of reflection and the angle of viewing are very subjective requirements. Thus, there can be no sharp distinction between polished and nonpolished surfaces, as defined by either their reflectivity or their topography. In general, the roughnesses in a reasonably well-polished surface prepared with abrasives consist of grooves spaced ~100 nm apart having a side slope of >100° and a length at least several orders of magnitude greater than the width of the grooves.

Because polished surfaces and unpolished surfaces differ only in degree, it may be concluded that polishing wear should only be considered as a special case of certain basic wear processes. This is true only to a degree, and thus this article will concentrate on the circumstances that can generate the required type of finish. Nevertheless, unique wear mechanisms are involved and will have to be considered. Unfortunately, polishing wear encountered in complex engineering systems has not been extensively studied; however, simple systems operated with the deliberate intent of producing a specific polish have been studied, but only to a limited extent. Consequently, the present discussion will necessarily have to be based on these limited studies of deliberate polishing processes, making adjustments as needed to recognize that the objective of these studies of deliberate polishing and of polishing wear have opposing goals: the objective of one is to maximize material removal rate (MRR), and the objective of the other is to minimize the material removal rate. Only materials with high intrinsic reflectivity, the majority of which are metals, need to be considered.

Property Requirements of an Abrasive

Typically, an abrasive is a hard material in the form of small particles (often called grits) bounded by irregularly shaped surfaces that meet at sharp edges and points (Fig 1). For commercial abrasives, the shape of the grits does not differ greatly, and it is the shape of their points and edges that is of primary importance; the diameter of the particles themselves is of secondary importance. This is demonstrated by the following example: An abrasive with a nominal particle diameter of, say, 10 μm (400 μin.) can be used to produce a good quality polish on many metals. The grooves produced on the workpiece surface with such an abrasive would certainly be <0.5 μm (<20 μin.) wide. Contacting grits can penetrate to only a small fraction of their diameter when producing such grooves (Fig 1), and the penetrating portion must comprise a point or, less likely, an edge. Thus, only the points and edges of abrasive grits actively contribute to a polishing process, and it is the shape of these points or edges that is the determining factor. The primary function of the rest of the individual grit is to support the con-

Fig 1 SEM micrograph of monocrystal diamond polishing abrasive that has a mean particle size of 5 μm (200 μin.). Grit shape is typical of that of most types and grades of abrasives on the market. Width of groove or scratch generated by abrasive is ~0.1 times the grit diameter. 750×

Polishing Wear with Abrasives

Abrasive action is one of the most common causes of polishing wear. It is one of the few types of wear processes that can easily occur on a fine enough scale to generate surfaces with the required topography. Polishing wear under these circumstances can be regarded as a special case of abrasive wear (see the article "Abrasive Wear" in this Section), which typically produces diffuse reflecting surfaces. Consequently, what needs to be discussed here are the conditions under which an abrasive wear system might be expected to generate a surface with a fine topography.
tacting regions in the same way that the shank of a lathe tool supports the cutting tool. Nevertheless, the dimensions of the particles can have a secondary influence if the maximum number of particles that can be packed together in a given area and, less obviously, the means by which the abrasive particles are held against the workpiece surface can be determined.

Abraives are typically considered to be hard materials (for example, silicon carbide, aluminum oxide, and diamond). Nevertheless, the hardnnesses of materials conventionally classified as abrasives vary over a considerable range (Table 1), from a value comparable to that of the harder metals (for example, silica, the abrasive most commonly present in natural wear systems) to that of diamond, the hardest material known. In fact, the only requirement of an abrasive from this point of view is that its yield strength be great enough relative to the workpiece to indent the workpiece without the abrasive deforming significantly itself. Strength (that is, hardnness) beyond this level of performance is of no benefit.

**Indentation hardness** values, as ordinarily determined, are valid indicators of the relative properties of the abrasive and the workpiece in this respect, and a sample theoretical analysis developed by Tabor (Ref 3) has indicated that the hardnness of the abrasive should be two to three times that of the workpiece if the abrasive is not to deform noticeably during indentation. However, an abrasive does not have to be quite that hard to indent the workpiece to some extent. Even if the abrasive itself is deformed a little in the process, it is still capable of removing material with at least a degree of effectiveness that would generate workpiece wear. In fact, one experimental investigation (Ref 4) has suggested that an abrasive need only be slightly harder than the workpiece itself to effect some abrasive wear. The material-removal efficiency was then found to increase rapidly with the increase in the hardnness ratio up to a value of 1.5 but leveled off at hardnness ratios >1.5. Unfortunately, neither the mechanisms by which the material was being removed nor the effect on surface finish was determined in this investigation. Therefore, these results cannot be precisely interpreted. Nevertheless, the general point has been established that a so-called abrasive does not necessarily require a high hardnness to effect wear but only that the hardnness of the abrasive must exceed the hardnness of workpiece material. Thus, particles of a hard metal could produce abrasive wear in many comparatively soft metals. Protruberances on the surface of a hard metal could also generate abrasive wear. However, hard materials such as the classical abrasives are required to produce wear in the harder alloys used in engineering practice.

A difficulty arises when applying to polishing wear those concepts that were developed with larger-scale processes such as abrasive wear and abrasive machining (grinding). Indentation hardnness tests, even the microindentation hardnness tests on which the concepts of abrasive wear have been based, are carried out on a much larger scale than the processes occurring during polishing wear. The question arises as to whether these abrasive processes are adequately represented under these circumstances. It was originally believed that the principle of similarity, on which hardnness comparisons rely, no longer applied to indentations smaller than a certain size. However, the best evidence currently available indicates that the principle does indeed apply down to the smallest conceivable indentations (Ref 5-7). The comparisons are still actually valid only if the workpiece material is fairly homogeneous over the entire range of indentation sizes specified. However, many metallic alloys are not homogeneous at the microscopic level at which polishing wear is produced. These metallic alloys can contain phases whose mechanical properties are considerably different from the matrix phase and whose size can vary over a wide range depending on the compositior of the material and thermal history of the alloy. It is quite possible for such a phase to be small enough relative to the scale of the grinding or abrasion process that it will not have a significant effect but be large enough on the scale of polishing wear to have a major effect on the performance of some types of abrasive grits. In this case, to act as an abrasive, a material would have to be matched to the characteristics of the second phase for polishing wear but not necessarily so for abrasive wear.

It has been recognized in other contexts (Ref 8) that it is convenient to divide abrasion-sensi- tive materials into two categories:

- All single-phase metals and alloys and those multiphase alloys in which either the properties of the additional phases do not differ significantly from the matrix phase or the particles of the additional phases are small relative to the grooves made by the abrasive particles
- Multiphase alloys in which one or more of the minor phases is much harder than the matrix phase and is large relative to the grooves made by the abrasive grits

As we have just seen, it is also convenient to categorize materials in the same way as for polishing wear. The difference is the presence of much smaller particles of a hard phase may require that an alloy be included in the second category.

**Fracture Toughness.** An abrasive may easily meet the hardnness ratio criterion mentioned earlier and still not be applicable for a wear system because it fractures easily, either by crushing in compression or by fracturing in tension (due to the bending forces imposed on a contacting grit point as it plows across the workpiece surface). Fracture in bending is the more likely cause of point fracture because abrasives have poor fracture toughness. That is, abrasives are prone to catastrophic failure when stressed in tension in the presence of stress concentrators. Stress concentrators in the form of notches and cracks inevitably are present in abrasive grits. Fracture toughness can be quantified even in brittle materials. The fracture toughness values for all abrasives are low, but the values differ in a manner that is not necessarily related to hardnness. Silica, for example, is the least tough of the common abrasive materials even though it is the softest of them all; diamond, on the other hand, is the hardest of all abrasives and yet probably is the toughest. All common abrasives are significantly less tough than conventional engineering materials as judged by the values in Table 1, implying that common abrasives would fracture before the workpiece when the two are stressed in contact. The abrasive would then gradually be removed from the system, more so with some abrasives than others. The solution is less cut, however, when brittle phases are present in the workpiece material because the brittleness of some of these phases might approach that of the abrasives. A moderating factor, however, is that small particles of brittle phases are more ductile than expected when supported by a surrounding ductile matrix, but minimal detailed information is available on this phenomenon.

Nevertheless, these comparisons of fracture toughness predict a deterioration in the effectiveness of abrasives in wear systems. The comparison can be expected to be reasonably valid on a large-scale system typical of grinding machining, for example, but it may not be valid on the small-scale system in which polishing wear occurs. This is because small volumes of material are being deformed by an unusual and complex compressive stress system. The work of Bridgman (Ref 9) showed that materials that are brittle in bulk can react in a ductile manner under these circumstances. This certainly appears to be the case for the workpiece material but whether it is also the case for the contacting points of abrasive grits is a matter for conjecture.

Under such conditions, it would mean that certain abrasive materials might have a more serious effect on polishing wear than would be expected from their reaction in larger-scale processes.

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**Table 1 Typical values of hardness and toughness of selected abrasives and metals**

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness, HV</th>
<th>Fracture toughness, MPa·m²/()kis./in.²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>850</td>
<td>1.1</td>
</tr>
<tr>
<td>Zirconia (ZrO₂)</td>
<td>1150</td>
<td>(b)</td>
</tr>
<tr>
<td>Emery (Al₂O₃·Fe₂O₃)</td>
<td>1400</td>
<td>(b)</td>
</tr>
<tr>
<td>Alumina (Al₂O₃)</td>
<td>2000</td>
<td>2.2</td>
</tr>
<tr>
<td>Silicon carbide (SiC)</td>
<td>2100</td>
<td>2.5</td>
</tr>
<tr>
<td>Cubic boron nitride (CBN)</td>
<td>2750</td>
<td>5.7</td>
</tr>
<tr>
<td>Diamond (C)</td>
<td>8000</td>
<td>(b)</td>
</tr>
<tr>
<td>Metals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2% C, hardened</td>
<td>950</td>
<td>(b)</td>
</tr>
<tr>
<td>0.4% Hardened and tempered</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>Normalized</td>
<td>190</td>
<td>50</td>
</tr>
<tr>
<td>Ferrite phase</td>
<td>75</td>
<td>(b)</td>
</tr>
<tr>
<td>Cementite phase</td>
<td>1100</td>
<td>(b)</td>
</tr>
<tr>
<td>Aluminium alloy, age</td>
<td>135</td>
<td>30</td>
</tr>
<tr>
<td>hardened</td>
<td>27</td>
<td></td>
</tr>
</tbody>
</table>

(a) Source: Ref 2. (b) No data available
**Melting Point.** It has been suggested in the past that the melting point is one physical property that has to be taken into consideration when assessing whether a particular material is likely to act as a polishing abrasive. It was believed that a material had the ability to polish only if its melting point was higher than that of the workpiece material (Ref 10). This conclusion was based on polishing trials with a reasonably wide range of abrasive-workpiece combinations, each of which initially supported this conclusion. However, trials subsequently carried out with a wider range of combinations (Ref 11) unearthed many systems that did not conform to the initial results (Fig 2). In the combinations investigated in the original experiments of Bowden and Hughes (Ref 10), black dots were found only above the line of equal melting points (Fig 2). Subsequent experiments by Rabinowicz (Ref 11) produced the combinations that are found below the line. Therefore, the concept of the significance of relative melting points can no longer be regarded as being valid. On the other hand, it is true that hard materials tend to have high melting points. Thus, a general if indirect correlation can be made between polishing ability and the melting point of an abrasive, although no reliance can be placed on the correlation in specific instances.

**Parameters Required to Generate Speculally Reflecting Topographies**

Experience indicates that the included angle of potential contacting points of abrasive grits is typically ≥100°, and indentations by points as obtuse as this can be taken to be directly analogous to those made by the Vickers-type or Knoop-type indenter, which has an included pyramidal angle of >100° (Ref 12). Consequently, the applied force required to produce a static indentation of a particular grit size can be calculated if the true surface hardness of the workpiece is known and the abrasive:workpiece hardness ratio criterion (see the section “Property Requirements of an Abrasive” in this article) has been complied with. The groove produced when an indented grit is then moved across the workpiece surface by a lateral force is known to be narrower than the static indentation but only by ~10% (Ref 13), a difference that can be ignored for the purposes of this discussion. On this basis, an approximate estimate can be made of the largest force that can be applied to contacting grits if they are to produce grooves that are narrow enough to generate a polished appearance (that is, if they are to produce grooves narrower than 50 to 100 nm). A limiting force of ~0.01 N (1 gf) is indicated for a workpiece hardness of 1000 HV and limiting force of 0.002 N (0.2 gf) for a hardness of 100 HV. The next step is to determine under what conditions the applied loads can be limited to this order of magnitude.

In the final analysis, the force applied to an abrasive particle is determined by the elastic constants of the entire system that holds the abrasive grits against the workpiece surface. This system consists of a number of units linked in a closed loop (namely, the grits; the cement, or any other device that holds the grits in place; the mechanical components that connect the workpiece and the abrasive; and the workpiece itself). Grinding machines of the type used in machine shop practice are representative of so-called hard elastic systems (that is, small changes in displacement between the grinding wheel and workpiece cause large changes in the force exerted between the two, principally because the mechanical components of the grinding machine simulate a very stiff spring). Consequently, such a machine can be expected to produce a polished surface if, and only if, the depth of indentation of the contacting grits can be kept appropriately low and if the whole system can be controlled precisely so that the penetration depth is maintained at the low value throughout the machining cycle. This can be done (Fig 3), but only under special conditions in precision machines (Ref 14). The grinding system required to produce such a highly polished finish must be very rigid and the depth of cut of the grinding passes has to be kept to an unusually small value to ensure that the surface grooves formed are shallow enough and closely spaced enough for specular reflectivity. Even then, a high polish can be obtained only on hard materials. These conditions are not likely to be achieved in an elastically-hard wear system but at least the principle is established that all which is required to produce a “polished” surface is to restrict the width and depth of the grooves generated on the surface. However, it also suggests that wear which yields polished surfaces is not likely to occur in elastically hard systems.

Cloth laps charged with a fine abrasive suspended in a liquid, such as those used in metallographic practice, are examples of soft elastic systems. The workpiece surface actually contacts the fibers of the cloth, either individual fibers or groups of fibers incorporated into a thread, and each fiber simulates an elastically soft cantilever spring (Fig 4). The fibers are typically ~20 μm (~800 μm) in diameter and made from materials with a low elastic modulus so that they can exert only a very small reactive force when distorted. Moreover, this reactive force would change little with variation in the distortion. Increasing the force applied to a workpiece causes it to sink into the cloth, thus increasing the number of fibers contacted but not markedly increasing the force applied by each component. The local force system is, in effect, self correcting, which permits comparatively easy control of surface finish. The dimensions of the cloth fibers, the method by which they are held or woven together, the elastic modulus of the fiber material, and the number of abrasive grits held in contact by each fiber are consequently the factors that determine surface finish as well as, but usually to a lesser extent than, the

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**Fig 2** Correlation between polishing ability and the relative melting points of the polishing powder and the workpiece solid. Solid dots indicate abrasive powder and solid combinations for which polishing does occur, whereas open dots indicate powdersolid combinations that do not generate a polished surface. Source: Ref 10, 11

**Fig 3** Hard steel cylinder whose surface was ground to a polish using precision toolroom practices. The cylindrical surface exhibits a high degree of specular reflectivity, as indicated by the clear and sharp reflections of the grid lines ruled on the plane on which the cylinder rests.

**Fig 4** Schematic showing one method by which an abrasive grit can be held in a fixed position to ensure the application of a very small indenting force. This indenting force is determined by the elastic characteristics of a textile fiber that simulates a very soft cantilever spring. Source: Ref 15, 16
Mechanisms of Material Removal

The creation of a system of grooves may produce a specularly reflecting surface, but it does not follow that material is removed during the process (that is, that the workpiece actually wears). Little if any information is available on the subject of the material removal mechanisms involved in polishing wear systems. Consequently, it is necessary to make assumptions that are based on the knowledge of other systems, particularly deliberate polishing systems.

Chip Machining Mechanism. The most plausible explanation is that the contacting points of either abrasive-like grits or hard protruberances on another surface simulate tools that produce the grooves by machining out chips. This is the mechanism primarily responsible for the generation of surfaces in ductile materials by abrasive machining processes ranging from industrial grinding to polishing (Ref 15, 16, 18, 19). Evidence of the type illustrated in Fig 5(a) and Fig 8(a) indicates conclusively that chip machining is the dominant material removal mechanism in almost all polishing situations. Chip machining is even the dominant mechanism for many materials that are brittle in bulk form (Ref 20, 21). For reasons that are not clearly established and that need not be discussed at this point, these materials are more ductile during indentation when the depth of indentation is less than a critical value, where this critical value can be of the order of magnitude encountered in polishing. Therefore, hard brittle materials or phases may incur wear by the same type of mechanisms as ductile materials during polishing wear, but the materials or phases react quite differently during abrasion wear.

Not all of the contacting points machine out a chip in typical abrasive-machining processes. Some merely plow a groove in the surface, pushing a stem ahead (Ref 18). When viewed as a machining tool, whether a contacting point serves in a cutting mode or a plowing mode is determined by the rake angle of its leading face and the nature of the workpiece material. A point cuts a chip only when its rake angle is more positive than a critical value, a value that is a characteristic principally of the workpiece material (Ref 13, 18). Large numbers of points with a shape suitable for chip cutting are conducive to relatively high rates of material removal, which is desirable for deliberate polishing but clearly undesirable for wear applications. Although it is reasonable to assume that these principles would apply to abrasive polishing, there is no concrete evidence available to confirm this. No information is available on basic parameters (for example, the rake angles of contacting points and the

Fig 5 SEM micrographs of a track on a prepolished copper surface generated by a 1 μm (40 μm) diamond abrasive grit. (a) 7000x. (b) 5000x. The grit, moving in the direction of the arrow (b) relative to the specimen, first contacted the specimen surface at about point A and made an angular indentation at that location. The grit then tumbled across the specimen surface making additional angular indentations as the numerous edges and corners of the grit successively came into contact. At location B, the grit became fixed in position, perhaps by either one of the methods shown in (a) (b). Thereafter, it formed an extended groove, the end of which is shown in (a). A ribbon of metal that has all the characteristics of a machining chip is attached at the termination of the groove at location C. This groove was clearly machined out of the specimen surface.

Fig 6 SEM micrographs showing different methods of holding abrasive grits on a cloth in a fixed position and orientation. (a) Isolated grits (indicated by arrow) embedded in cloth fibers (210x). (b) Numerous grits (indicated by arrow) held to fibers by a pasty material (500x). (c) Isolated grits (indicated by arrow) entangled between the cloth fibers (250x). Grits must be held fixed to form an extended groove in a workpiece surface.
values of critical rake angles) that would be needed for the prediction of wear rates.

The optimum condition from the standpoint of minimizing wear rate is one in which all of the contacting points are operating in a plow mode. Nevertheless, it is still possible that the points would remove material by mechanisms that are of minor importance in abrasive machining but that could be significant in terms of wear. One of these conditions occurs with contacting points that have negative side clearances when serving as machining tools. Contacting points with negative side clearances are commonly encountered in machining practice. Some of the material flowing into the prow established ahead of the contacting point tends to flow towards one side of the groove being produced, thus forming a thin fin at the edge of the groove (Fig 9). This fin is sure to break off sooner or later. Another potential condition is that the prows themselves sometimes detach by shear fracture at their base (Ref 19). Prows are also likely to detach, partly if not completely, when they reach an external edge of the workpiece. Finally, a prow sometimes may behave as the equivalent of a built-up edge (BUE) on a tool and cause the separation of a small secondary chip when the contacting point itself would not do so (Ref 19). Although each one of these phenomena can be assumed to occur in polishing wear, no information is available about the conditions under which they are likely to occur and, hence, their likely contribution to material removal cannot be quantified.

**Delamination Mechanism.** An entirely different material removal mechanism from that just described has been observed to occur during certain conditions of deliberate polishing. These conditions involve the use of very fine abrasives (<1 μm, or 40 μm, particle size) and produce surfaces that are brilliantly specular but still composed of systems of parallel grooves. Material removal in this case occurs via the very small slabs of material being lifted out of the surface (Fig 8b), presumably by some form of delamination. Moreover, it seems that this delamination phenomenon is typical, occurring in varying degrees in all abrasive-machining processes from grinding (Ref 22) to polishing (Ref 16); however, this phenomenon is overwhelmed by the chip-cutting mechanisms in the
courser processes. Yet for some as yet unknown reason, the chip-cutting mechanism begins to be phased out at a certain stage of the process as the finish flatness is increased. It eventually ceases, and the delamination mechanism is then left as the sole material removal process. The amount of material removed by the delamination mechanism is likely to be much less than that removed by chip cutting. An adequate explanation for this phenomenon has not yet been developed (Ref 22, 23).

**Multiple-Pass Mechanisms.** All of the mechanisms discussed to this point assume that the active contacting point is harder than the workpiece (that is, it meets the Tabor criterion); moreover, they assume only a single pass of the contacting point. We have already noted that some commonly occurring abrasive materials cause wear even though they are considered to be comparatively soft by these standards. In addition multiple passes are likely in wear, particularly when material is being removed at a low rate. Kosel and his colleagues (Ref 8, 24, 25) have shown that abrasives can wear harder materials and phases after multiple passes and that material removal can then occur by several mechanisms (for example, delamination and the removal of fragments by fracture). The resultant wear rate is small. The conditions necessary to
induce these mechanisms, however, seem to be too severe to be conducive to the generation of speculatively reflecting surfaces. Nevertheless, it is expected that multiple passes could enhance the significance of delamination and other secondary processes.

**Erosion Mechanisms.** It was mentioned in the section "Parameters Required to Generate Specularly Reflecting Topographies" that polishing wear can be caused by an abrasive suspended in a liquid that circulates past the workpiece surface. Normal erosion wear mechanisms can then be expected to operate. The mechanism most likely to occur depends on the momentum of individual grits perhaps being sufficient for the grits to indent into the workpiece surface when they strike the surface and then to sweep across the surface, producing an arc-shaped groove. The grits would either plow or machine out a chip, depending on the shape of their contacting point, typically the same process encountered for fixed abrasives. Small grits and low flow velocities would tend to produce shallow grooves conducive to the generation of a polished finish and comparatively low wear rates. However, it appears that highly reflecting surfaces are likely to be produced by this method only on harder phases; poorly reflecting indented surfaces tend to be produced on soft phases (Fig 7b). A further consequence is that adjoining particles or phases of an alloy with differing polishing characteristics are more likely to polish to different levels than when the abrasives operate in a chip-cutting mode. The difference in relief between phases may even be discernible to the naked eye. Moreover, for reasons that are not clear, preferential erosion tends to occur locally at the interface between phases that have markedly different polishing characteristics (Ref 15).

**Summary.** Assuming that the abrasive material has adequate mechanical properties to withstand undamaged its interaction with the workpiece, it is the shape of the points of the grits and the orientation of the grits as they encounter the workpiece surface that determine their potential to cause wear. The term "shape" refers to the details of the configuration of the small portion of the point that actually contacts the workpiece surface. A perfectly smooth spherical point, for example, might generate a groove in the surface, but it typically would not remove material by machining out a chip because it would present only a highly negative rake angle as a machining tool. On the other hand, a point that contains numerous fracture facets, even if it has a generally spherical form, might be able to do so because some of the fracture facets might have a shape that enables it to act as a machining tool. These facets could be original or they could be the result of fracture in use (Ref 25). However, these cases are contingent on the grit being held in a fixed position in space for a sufficient time to machine a lengthy groove.

**Wear Rates**

It is a widely accepted belief that polishing wear rates are inversely proportional to workpiece hardness. This view has been implied throughout this article. However, the presumed relationship actually is based on little more than intuition because it has never been supported by quantitative experimental evidence. In addition, theoretical analyses, even the very generalized ones given above, indicate that a simple relationship of this nature is not to be expected.

The width (and hence the volume) of the grooves generated on a polished surface can indeed be expected to be inversely proportional to the local surface hardness of the workpiece. Even if this is not necessarily identical to the bulk hardness of the material because it usually would have to be adjusted to account for the effects of surface layer deformation during previous machining and wear and to account for the hardness of individual phases of the microstructure. Even then, a correlation with workpiece hardness would be obtained only if all of the volume of the surface grooves were removed from the surface (that is, if the theoretical limiting wear rate was obtained). An alternative possibility would be that a constant fraction of the grooves was removed for all materials, which is a highly unlikely event. In reality, only a fraction, x, of the groove volume is removed, and this fraction varies considerably (0 < x < 1) with different materials. In fact, the fraction depends on a multitude of factors, many of which are in no way related to workpiece hardness. The fraction cannot be predicted, although experimental determination is sometimes possible. The variation in this fraction is sufficient to negate the possibility of a correlation between wear rate and hardness.

Experimental evidence on the effects of the properties of the workpiece material on polishing rate is scant and confined to metallographic polishing processes. Nevertheless, the evidence that is available confirms the complexity of the matter. Figure 10 explores the possibility of a relationship with workpiece hardness. Figure 10 indicates the existence of an upper boundary for results in which the polishing rate decreases with hardness. Within this boundary, however, the relationship is highly random. A particularly anomalous feature is that the polishing rates of the alloys considered are, with only one exception, higher for their softer base metals.

The above considerations are concerned with the efficiency of the wear process. The absolute value of the wear rate depends also on the rate at which the surface grooves are formed; that is, the rate at which abrasive grits contact the wearing surface and become active. A very large quantity of grits is usually present in the general vicinity of a wearing surface, but very few of the particles are actually in contact with the workpiece surface. The fraction of contacting points will vary considerably with different types of systems, and this fraction is difficult to determine. Nevertheless, some qualitative indication of the importance of the factor can be obtained. For example, the wear rates obtained in deliberate polishing operations on cloths charged with an abrasive such that a comparatively high proportion of grits contact the polishing surface (as in Fig 6b) are an order of magnitude higher than those obtained when few grits contact the polishing surface (as in Fig 6a), even though the grits available per unit surface area of cloth are the same (Ref 15).

The fraction of contacting points available also contributes to the effect of abrasive particle size on the polishing wear rate because, for equal weights, the number per unit area of grits decreases rapidly with the increase in grit diameter. Figure 11 shows that the wear rate decreases markedly when the particle size is >3 μm (>120 μm). This condition can be at least partially attributed to a decrease in the number of

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**Figure 10** Variation of polishing wear rate with workpiece hardness. Circled symbols indicate alloys of the base metal, whereas uncircled symbols indicate commercially pure metals. Wear rates were determined under comparable stringent conditions; the abrasive was under conditions that ensured the grits were held to the fibers of a polishing cloth by the method shown in Fig 6b. Source: Ref 15

**Figure 11** Variation of the polishing wear rate with the particle size of a diamond abrasive used to machine 30% Zn brass.
grits present per unit area of the polishing cloth. In this instance probable contributory cause is the fact that the fraction of the grits held in a workpiece-contacting position has also changed because it becomes more difficult to hold grits in a contacting position when the grit diameter approaches or exceeds the diameter of the cloth fibers (Fig 5c). Under these conditions, the rapid decrease in wear rate when the grit diameter falls to \(<3\ \mu m\ (<120\ \mu m\ )\) (Fig 11) might seem to be paradoxical. However, the decrease in wear rate occurred and added a further complication because the predominant cutting mechanism began to be phased out, leaving only the inefficient delamination mechanism to provide the material removal process (see the section "Mechanisms of Material Removal" in this article).

The polishing systems used in Fig 10 and Fig 11 can be regarded only as highly idealized and simplified models of wear systems that are typically encountered in engineering practice. These models certainly indicate, however, that the diagnosis and treatment of practical systems should be logically determined using a step-by-step procedure. The mechanisms of material removal certainly have to be established before rational analysis can commence. Subsequent comparisons with more idealized systems may indicate which methods of controlling the wear rate are feasible.

**Polishing Wear without Abrasives**

There are several possible mechanisms of polishing wear that do not depend primarily on the physical removal of material by the machining or scraping action of abrasives. Two such methods are discussed in this section:

- **Surface flow**
- **Chemical-mechanical mechanisms**

**Surface Flow.** It was once hypothesized that polishing was a thermally activated process in which a small volume at the crest of an asperity on a solid is heated to a high temperature for a brief period when an asperity on another solid contacts it and is traditionally believed that the flash temperature reached the melting point of the solid of the pair that had the lower melting point and that some portion of this solid melted (Ref 26, 27). It was then proposed that the molten material is transported from the asperity crest into an adjoining trough, thus gradually leveling the surface. The realization that the flash temperature might not always quite reach the melting point again altered the proposal for this process to suggest this crest material would be transported by plastic shear at high temperature. In either case, however, it was anticipated that the surface would gradually be made smooth and eventually become specularly reflecting (Ref 26, 27). In the strictest sense, the theory implies that small changes would occur in the dimensions of the surface being polished but that no material would be removed unless the process were supplemented by a more conventional wear process. (This process would necessarily have to be one that does not destroy the specular reflectivity.) This theory became known as the Beilby theory of polishing; however, there is no need to elaborate on it further because conclusive evidence is now available that confirms it is invalid (Ref 15).

Nevertheless, it is still possible that the asperities on a moderately rough finished surface could be flattened by compression when rubbed by another stronger solid. Even modest localized heating of the workpiece surface during rubbing would increase this possibility. A specularly reflecting finish might then be obtained if the surface finish on the rubbing solid was conformed to specifications. This technique has been applied by jewelers, for example, to burnish precious metals by using tools of a polished hard material such as agate. However, wear in terms of material removal would again occur only if a subsidiary material removal mechanism did not destroy specular reflectivity during the machining process.

**Chemical-Mechanical Mechanisms.** Valid, if indirect, evidence exists that polishing can generate mechanisms which involve both chemical and mechanical elements in a symbiotic relationship (Ref 15, 28). The general concept is that the corrosion-protective film that normally covers a metal surface is removed from asperities by the rubbing solid. The protective layer is then reformed, consuming a thin layer of workpiece in the process. Repetition of the process gradually removes the crests of surface asperities, and the workpiece surface is leveled (Fig 12). Only a small wear rate is expected, but a high polish is typically produced.

The rubbing should be, and indeed usually has to be, of a very gentle nature, but the contacting solid can consist of a range of types, including those with well-rounded contacting asperities. For example, rolling abrasives could be effective as could abrasives with well-rounded grits. This is in contrast to mechanisms that depend on abrasive machining. The presence of a medium that is only mildly corrosive would also be adequate. The process could theoretically occur, for example, in air because oxidation takes place the moment the protective film is removed. Nevertheless, the process is more likely to occur when a liquid (water being adequate in most cases) is present. More reactive liquids can, of course, accelerate the process. It is anticipated that metals whose apparent corrosion resistance depends on being covered by a self-healing surface film (that is, the more electronegative metals) would be most responsive to polishing wear by this mechanism, and that truly noble metals would be the least responsive. However, the production of a polish is in all cases dependent on a balance being achieved between the chemical and mechanical elements of the process. Even then, the development of some differences in the level of grains and constituents of the microstructure of the workpiece material is likely.

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