LITHIC USE-WEAR ANALYSIS

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Mechanisms of Microcontact Fracture in Brittle Solids

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INTRODUCTION

The archaeologist studies stone tools as part of an attempt to reconstruct the cultural development of prehistoric man. It is his hope that the traces of manufacture and wear on such tools will provide him with some insight into ancient technologies and behavioral patterns. Microwear traces are of particular importance in this regard because they reflect most directly on the actual uses to which any given tool was put. There appear to be three main avenues open to the researcher in the investigation of stone artifacts: the oldest avenue is to invoke analogy with already well-documented technologies, either primitive or modern; the second is to try to simulate the original manufacture and/or use of the artifact by independent experimentation; finally, the researcher may try to interpret actual traces directly in terms of established mechanisms in the scientific theory of deformation and fracture. The largely empirical approach that has proved necessary in most use-wear and flintworking studies has not lent itself to a universally accepted basis for describing or classifying the wide variety of trace morphologies observed.

These, at least, are the impressions of the state of the art drawn from a number of review-type publications (Semenov 1964; Faulkner 1972; Keeley 1974; Odell 1975) by two total outsiders to the field of archaeology. We are involved in the "hard" science of brittle fracture (Lawn and Wilshaw 1975a), with a particular interest in microcontact ("indentation") fracture (Lawn and Wilshaw 1975b). Apart from affording an ideal means for investigating fundamental fracture processes in their own right, controlled indentation testing techniques bear on a wide range of current problems in materials science: strength evaluation of structural ceramic components, in which con-

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tact-induced cracks are used to provide an experimental base for predicting strength degradation in particle impact situations (e.g., automobile or aircraft windows); evaluation of material removal processes in brittle surfaces, where the cumulative damage effects of multicontact events may need to be either minimized, as in hostile erosion situations, or maximized, as in machining operations (grinding, abrading, polishing); ore drilling and comminution (fragmentation), where mineral breakup may again be viewed as the end result of a large number of small-scale contact events; etc. Applications in these areas have centered around basic studies on certain "model materials," such as silicate glass, quartz, diamond-structure crystals, and sapphire, although a limited amount of work has been done on more complex ceramics and minerals. Some striking similarities in the trace morphology on indentation test surfaces and on stone artifacts have already been investigated by a few workers (e.g., Kerkhof and Müller-Beck 1961; Speth 1972; Faulkner 1972) in admirable pioneering attempts to set their archaeological interpretations on a sound scientific footing.

In the present work it is our intention to outline the fundamental principles of indentation fracture, drawing on studies in our own laboratories for the bulk of the illustrative material. While most of the materials science applications cited above demand a rigorous mathematic description, we shall confine ourselves to qualitative features.[1] Microcracking results from an unavoidable tensile component in the indentation stress field. The fracture patterns are most conveniently classified according to whether the indenter is considered "blunt" (elastic contact) or "sharp" (plastic contact): "real" contact situations then fall somewhere between these two bounds. Further distinctions may be made between load rates (static or impact), load type (normal or tangential), original state of indented surface (smooth or rough), etc.

[1] A glossary of terms used in general fracture mechanics is included elsewhere in this volume.

In our discussion of the indentation patterns we shall resist the temptation to draw on any but the most obvious parallels with archaeological systems. Certain of the crack patterns will be seen to have a clear relevance to striation and manufacture traces on stone tools, particularly in the case of more brittle materials such as obsidian and quartz. While the relevance of other patterns may not be so clear, our main objective must be to paint the broadest possible picture of the field of indentation fracture, in the hope that the groundwork may be laid for future interdisciplinary research. At the same time, it is important that some of the gaps in our current knowledge be given due emphasis, in order that limitations in the application to lithic studies be appreciated.

PHYSICAL BACKGROUND TO THE INDENTATION FRACTURE PROBLEM

In order to be in a position to place a proper scientific interpretation on residual contact patterns in terms of specific deformation and fracture mechanisms it is necessary to have some appreciation of the basic mechanics involved. We need first to look at the way the stresses in the indented solid are distributed about the contact site: this distribution constitutes the "stress field." Then we must ask how the crack pattern evolves within this field: this is the realm of "fracture mechanics." The following brief outline of these two aspects of the problem summarizes a more extensive coverage given elsewhere (Lawn and Wilshaw 1975b).

Indentation Stress Fields

Although precise details will be determined by material and geometrical characteristics of both indenter and specimen, several features of the stress field are quite general. The stresses are highly concentrated about the contact, especially about any corners or edges of the indenter, and drop off very rapidly, ultimately in inverse-square fashion, as one proceeds radially outward from the indenter. It is this inhomogeneity in the field that accounts for the localization of the damage pattern. Although the indenter loading is ostensibly compressive, it is impossible to avoid components of shear and even tension, however small, in certain regions of the stress field (Lawn and Swain 1975). The presence of tensile stresses is of primary importance in any mechanical description of the fracture patterns, for failure in brittle solids almost invariably occurs via a tensile, or "opening," mode.[2] Shear and (hydrostatic) compressive components, while of secondary consideration, may nevertheless play a far from passive role in the overall damage process: the former may activate "plastic" (or even "viscous") flow mechanisms, and the latter may cause "compaction" (particularly in porous materials) thereby leaving some permanent deformation in the material. The relative activity of the fracture and these alternative modes can, for a given set of indentation conditions, be taken as an indicator of the material "brittleness."

The variability in indentation geometry and material response appears at first sight to give rise to a wide diversity of observable damage patterns. Indeed, it is this apparent diversity that has been largely responsible for the remarkably slow development of a suitable basis for a theory of indentation fracture: this despite a clear relevance to many practical problems in materials science, as mentioned earlier. The classification scheme that overcomes this difficulty, namely, the distinction between blunt and sharp indentations, is only recent (Lawn and Wilshaw 1975b). Essentially, the two categories depend on whether the immediate stress field about the contact is elastic or plastic (the term "plastic" now being used in its loose sense to indicate any of the alternative, irreversible deformation modes referred to above). If the indenter is blunt the contact area is relatively large, so the mean indentation pressure (defined as applied load divided by the contact area supporting this load) is not sufficient to cause the material to "yield" irreversibly. In this case the pressure builds up with loading, and similarly reverses on unloading to give complete elastic recovery (provided fracture has not occurred in the meantime). Such conditions are favored by rounder, softer indenters. On the other hand, if the indenter is sharp so the load is distributed over a relatively small contact area, the enhanced pressure induces local flow of the material, thereby leaving a residual impression upon indenter withdrawal. The indentation pressure now remains constant throughout the loading and provides a measure of the "hardness" of the material. In fact, this way of assessing hardness, using hard, pointed indenters, is not at all new, having been practiced extensively by engineers and metallurgist on relatively ductile (plastic) materials for the past century or so. It is seen that the hardness is simply a measure of resistance to deformation – more specifically, it is a measure of the "yield stress." Thus a harder material is one that, for specified indentation conditions, leaves a smaller residual impression. Because the plasticity is only local, the deformation zone that constitutes the hardness impression is surrounded by an elastic "matrix."

The contact pressure is an important parameter in indentation testing because it uniquely determines the "intensity" of the stress field. Another important parameter is the "characteristic diameter" of the contact area, which determines the "spatial extent" of the field. For blunt indenters these so-called field "scaling factors" relate to elastic properties of the material; for sharp indenters they relate to plastic properties.

Fracture Mechanics

Given the indentation stress field, we identify two important aspects of the ensuing fracture

[2] One notable exception is the case of subterranean rock, where very large confining pressures suppress all tensile stresses and promote failure via a shear mode.

evolution: (1) *initiation* – how and where do the cracks start? and (2) *propagation* – once started, what paths do the cracks follow, and what determines the extent of their growth? These were the fundamental questions addressed by Griffith (1920) in his classic work on brittle fracture (for a review, see Ch. 1 of Lawn and Wilshaw 1975a). Indentation fracture mechanics seeks to formulate the Griffith theory in terms of contact parameters.

A key proposition in Griffith's theory is that cracks initiate from "flaws." These flaws are usually prepresent in abundance in typical brittle solids, either on the surfaces as minute handling damage (e.g., as a result of contacts with ubiquitous dust particles in the atmosphere) or within the bulk as microstructural defects (e.g., as weak boundaries between grains of like or unlike material): the former are more pertinent to homogeneous solids (e.g., glass, obsidian), the latter to inhomogeneous solids (e.g., rocks). Alternatively, the flaws may be deformation-induced; that is, the forces ultimately responsible for full-scale contact fracture may themselves nucleate flaws, via some particular stress-concentrating effect of local deformation below the indenter. Clearly, prepresent flaws are more pertinent to blunt indenters, deformation-induced flaws to sharp indenters. In typical brittle solids, flaws lie within the size range 1-100 μm. Some measure of control over crack initiation in routine fracture testing can be achieved either by introducing flaws (e.g., by surface abrasion with hard grit) or by removing them (e.g., by acid-etching the surfaces). Reference is made to Chapter 2 of Lawn and Wilshaw (1975a) for a survey of the various types of flaws that may be encountered.

Upon attaining some critical configuration, a "dominant" flaw, favorably located in a region of high local tension, develops into a well-defined propagating crack. According to the fundamental Griffith concept, this occurs when the driving force for extension of the crack just balances the resistance force associated with the intrinsic "toughness" of the material. In a perfectly brittle solid, the toughness arises solely from the energy absorbed in rupturing cohesive bonds in the atomic or molecular structure at the crack tip. However, in "real" solids additional work must be expended to overcome any number of subsidiary energy-absorbing processes operating in the region of high stress concentration about the crack tip, thereby elevating the toughness. For example, glasses derive their brittleness from their rigid (covalent) molecular structure, whereas rocks derive their toughness from their complex grain and phase microstructure; in the latter case cracks are continually held up as they search for a suitable path through or around individual grains (this is readily demonstrated by the comparative roughness of rock fractures). In isotropic solids (i.e., solids with direction-invariant properties, into which category fall glasses and fine-grained minerals) cracks tend to propagate so as to remain always closely normal to the greatest tensile stresses in the solid (Frank and Lawn 1967; Lawn and Wilshaw 1975a Ch. 3), thereby ensuring the continuance of an opening mode of failure. However, in anisotropic solids (e.g., single crystals, coarse-grained minerals) the tendency to preferred cleavage can modify the pattern to a greater or lesser extent. Real solids usually show evidence of some compromise between stress-controlled and cleavage-controlled fracture: indeed, departures from symmetry in the indentation crack patterns may be taken as a useful indicator of the degree of anisotropy present.

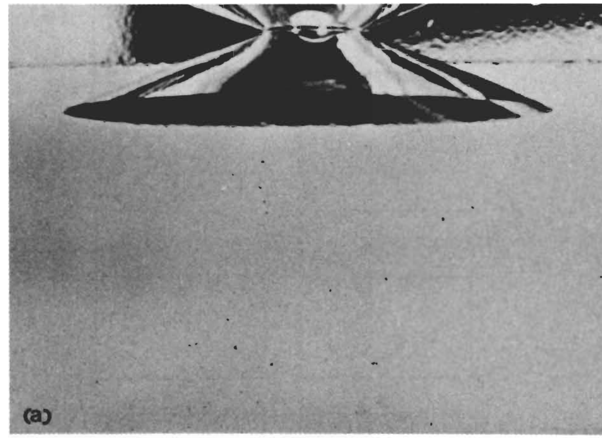
One factor in brittle fracture that warrants special attention is the time element: At what ***rate*** does the crack growth proceed? One may distinguish the following temporal categories: "controlled" growth, in which the crack grows incrementally in response to a corresponding increment in applied loading, so that the load rate determines the time to fracture; "slow" growth ($\lesssim$1 mm s^{-1}), in which chemical processes can activate bond-rupture at the crack tip in the presence of a "hostile" environment, and thereby advance the fracture even at constant applied load; "fast" growth ($\approx$1 km s^{-1}), in which the driving force for fracture increases as the crack extends, thus causing the front to accelerate to some fraction of the velocity of sound in order to dissipate the excess energy. Time-dependent effects in fracture are discussed in full elsewhere (see Chs. 5 and 8 of Lawn and Wilshaw 1975a): The special relevance of such effects to crack morphology is considered in this volume by Cotterell and Kamminga.

INDENTATION FRACTURE PATTERNS

We now survey the different categories of indentation fracture pattern. Reference is again made to the review article mentioned earlier (Lawn and Wilshaw 1975b) for more complete details.

Blunt Indenters

The eminent physicist H. Hertz (1881-1882) was the first to give a scientific description of the crack pattern produced when two curved bodies are brought into mutual contact. He studied the way in which the elastic contact circle expanded with applied loading until one of the bodies (indenter) caused the sudden development of a (truncated) cone-shaped crack, the so-called Hertzian cone crack, in the other body (specimen). Fracture was more easily induced with bodies of smaller radius, these generating more intense contact pressures at a prescribed loading. Figure 1 illustrates the classical morphology of the Hertzian crack for glass and quartz, two materials distinguished only by the nature of stacking of a common molecular unit (SiO_2): in glass the stacking is more or less random (amorphous) – the resultant structural isotropy is reflected in the near-circular symmetry of the cone crack in Fig. 1a; in quartz the stacking is ordered (crystalline) – the structure is now *an*isotropic, as is reflected in the cleavage-modified, crystallographic (trigonal) symmetry in Fig. 1b. Despite Hertz's pioneering studies, the cone crack remained little more than a curiosity for almost 80 years until its full potential in fracture testing, most notably in the convenient spherical-indenter/flat-specimen arrangement, began to be realized.



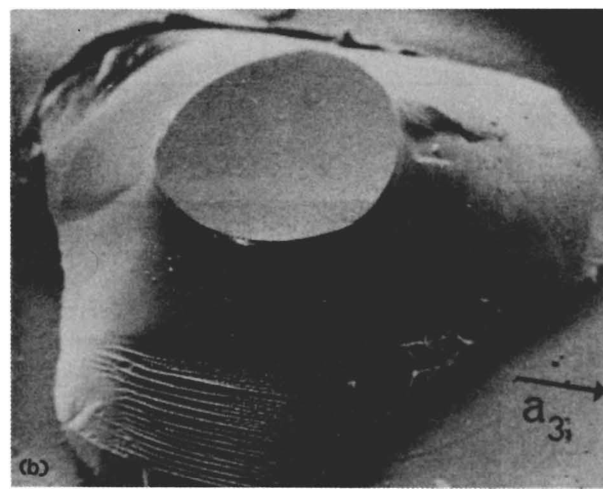


Fig. 1 Hertzian fractures. (a) Glass, showing classical cone morphology. (Optical photograph, width of field 45 mm, indenter load 40 kN; after Roesler 1956.) (b) Quartz, remnant cone punched through plate specimen, showing crystallographic effects in geometry. (Scanning electron micrograph, width of field 2.5 mm; after Hartley and Wilshaw 1973.)

The evolution of the cone crack is actually more complex than the preliminary observations

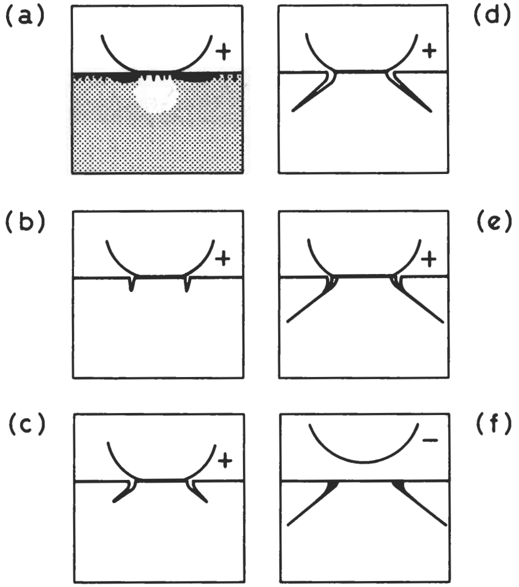


Fig. 2 Evolution of cone crack pattern during one complete loading (+) and unloading (-) cycle. Stress field indicated in (a).

of Hertz would indicate. Figure 2 depicts the sequence of events schematically for a complete indentation cycle in standard normal (perpendicular) loading. The tensile stress field, indicated as strong or weak by degree of shading in Fig. 2a, provides the driving force for the fracture. Directly below the indenter, in a tear-drop region, all stresses are compressive, as one might intuitively expect. However, on the free surface of the specimen outside the contact circle the stresses become strongly tensile: it is convenient to imagine this thin surface region as a highly tensile "skin" being drawn inward by the indenter like the membrane of a drum. Intermediate regions have a component of relatively weak tension. Thence we may describe the various stages in the evolution, as follows:

(a) The indenting sphere subjects prepresent surface flaws (indicated by the short dashed lines in the diagram) to an increasing tension outside the expanding contact circle.

(b) Upon attaining the critical "Griffith configuration" a favorably located flaw runs at high velocity around the contact to form a nearly symmetrical surface "ring crack," its simultaneous downward extension rapidly becoming retarded as it grows out of the skin region of strong tension (at this stage the ring crack is generally too small to be visible).

(c) On further loading of the indenter, the contact circle continues to expand and the ring crack is driven stably downward, in controlled fashion, at this stage deviating outward to avoid the compressive zone.

(d) Although now weak, the tension over the length of the growing crack cumulates in the net driving force until instability is once more attained, at which point the ring suddenly develops into a full cone crack (typically to a depth of the order of the contact dimension, this instability corresponding to the critical event observed in the conventional Hertzian test).

(e) On still further loading of the indenter, the crack continues in stable extension until the contact circle encompasses the surface trace of the cone, whereupon the primary crack closes up within the engulfing compressive zone and a secondary (and, ultimately, even a tertiary) concentric cone is similarly formed (this usually running into the primary crack, sometimes forming a detachable collar).

(f) Finally, on unloading the indenter the cracks try to close up in order to recover the elastic energy, but never completely do so because of mechanical obstruction at the interfaces due to fracture "debris" (e.g., chips from fracture steps, etc.), thus conveniently leaving residual traces for subsequent observation.

Now in this description the indentation field constitutes the sole driving force for the fracture. Accordingly, the approach to the threshold, as described in (c) and (d), should be fully controlled by the applied loading, independent of any time element. That is, the critical load to cone formation should be constant for any given indenter/

specimen system. This is in fact found to be so only if the tests are conducted in an inert atmosphere. For instance, tests on glass and quartz in vacuum (Swain, Williams, Lawn, and Beek 1973) indicate critical loads quite independent of load rate. However, the same tests carried out in the presence of water vapor (or indeed in ordinary atmosphere, in which water vapor is always present to some extent) show a marked reduction in critical load, this reduction becoming more pronounced with the duration of contact. The role of environmental effects in cone fracture has been studied in these laboratories by A.G. Mikosza, who devised a simple "section-and-etch" technique for observing crack profiles at various stages in the growth cycle. This involved making rows of indentations at prescribed loads and contact durations, sectioning through the rows of cracks and polishing down to the diameters, and acid-etching to reveal the profile traces. From air-environment sequences such as that shown in Fig. 3, in which one may piece together the pattern of crack evolution, chemically driven "slow" crack growth through the stable stages in Fig. 2c, e is readily adduced (Mikosza and Lawn 1971). The particularly potent effect of even minute traces of water in promoting

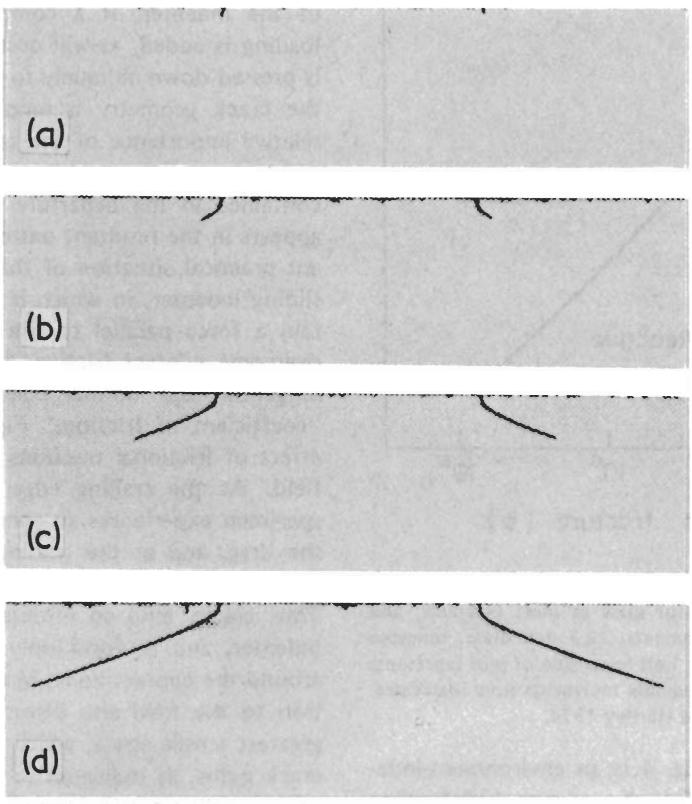


Fig. 3 Section-and-etch sequence of cone crack growth in glass in air, 12.3 mm diam. tungsten carbide sphere indenter, showing profiles after (a) 0.5, (b) 1.4, (c) 1.7, and (d) 100 s, at 65% vacuum value of critical load. (Optical micrographs in reflected light, width of field 2.3 mm; after Mikosza and Lawn 1971.)

crack growth in glass at subcritical loads is well understood in terms of chemical enhancement of bond rupture processes at the crack tip (Wiederhorn 1967).[3] As the load duration diminishes, the time available for external agents to enter the crack and penetrate to the reaction zone at the tip must also diminish. Consequently, one may anticipate a reduced influence of slow growth effects as the load rate increases, as reflected in the merging of curves for cone fracture in inert and reactive environments, Fig. 4.

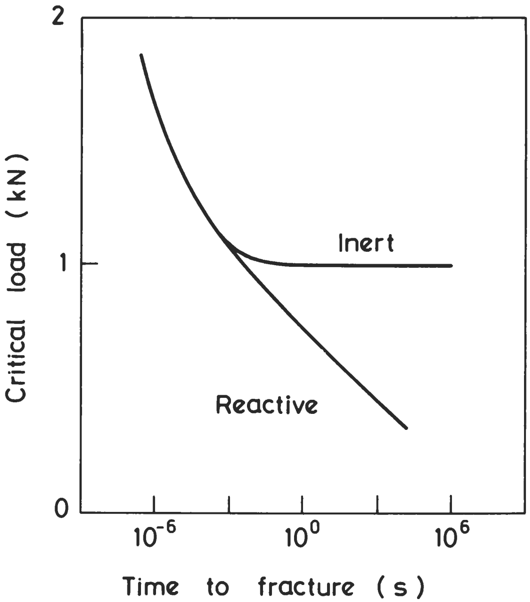


Fig. 4 Variation of critical load to Hertzian fracture with contact duration for glass in inert (vacuum) and reactive (water) environments, 12.3 mm diam. tungsten carbide sphere indenter. Left-hand side of plot represents fast load rates, right-hand side represents slow load rates. After Lawn, Wilshaw and Hartley 1974.

Also evident in Fig. 4 is an environment-independent temporal effect at extremely high loading rates. In this "dynamical" regime the time of contact becomes so small that the running crack can no longer maintain pace with the rapidly changing stress field (recall that cracks can run no faster than some fraction of the speed of sound). Higher loads are then necessary to achieve the instability condition for cone fracture. Secondary effects in the fracture, such as "stress-wave spalling" (see Ch. 5 of Lawn and Wilshaw 1975a), begin to assert themselves at these load rates. However, while such dynamical effects are important in supersonic or explosive impact situations, they are unlikely to be of any major significance in ordinary mechanical "percussion" situations (Cotterell and Kamminga, this volume).

Thus far we have considered only normal loading of the indenter. If a component of tangential loading is added, as will occur when the indenter is pressed down obliquely to the specimen surface, the crack geometry is modified. A clue to the relative importance of the tangential and normal components in any oblique loading situations is contained in the departure from symmetry that appears in the resultant pattern. The most important practical situation of this type is that of the sliding indenter, in which it is necessary to maintain a force parallel to the specimen surface to overcome contact friction: then the ratio of the tangential and normal components defines the "coefficient of friction." Figure 5 illustrates the effect of frictional tractions on the tensile stress field. At the trailing edge of the contact the specimen experiences an enhanced tension due to the drag, and at the leading edge the specimen likewise experiences an enhanced compression. Thus cracks tend to initiate in the wake of the indenter, and to form only partial surface rings around the contact zone. Moreover, the modification to the field also distorts the trajectories of greatest tensile stress, which form the prospective crack paths, as indicated in Fig. 5. On formation of a so-called partial Hertzian crack (Lawn 1967) the stresses in the immediate vicinity of the contact zone relax somewhat, and so the subsequent formation of a second crack occurs only when the indenter has moved on sufficiently to allow the stress field to build up again. The net result is a

[3]Most brittle solids are susceptible to environmental enhancement of crack growth.

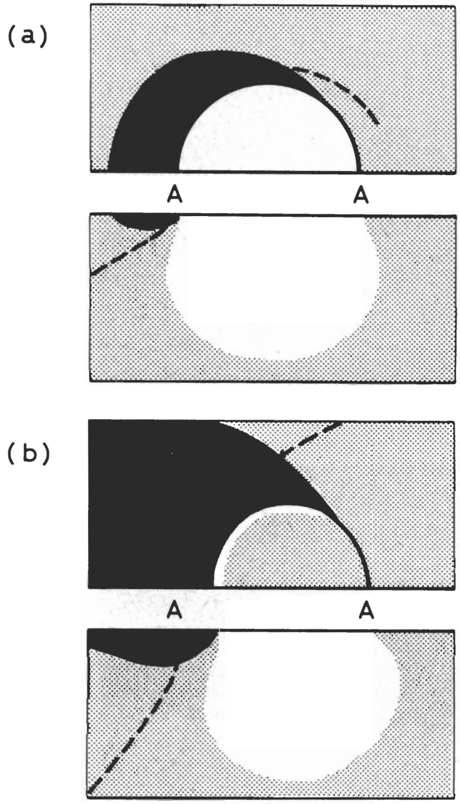


Fig. 5 Stress field beneath sliding sphere indenter (contact diam. AA), showing half-surface and side views, for coefficients of friction (a) 0.1 and (b) 0.5. Shading indicates tensile regions, dashed curves represent prospective crack paths. After Lawn 1967.

series of rather regularly spaced arcuate crack traces along the indentation track. Two examples are shown in the photographs of Fig. 6, the experimental conditions in these cases being chosen to produce friction forces commensurate with those represented in Fig. 5 (Crimes 1973). The greater tensile stresses and the more pronounced departure from circular symmetry generated by the higher friction are apparent in the photographs. It will be noted that the *direction* of sliding is easily deduced from the pattern asymmetry.

One aspect of all this work that imposes some limitation in applications to practical situations is that of "edge effects." As the contact zone approaches the edge of a block specimen, the free surface at the side must modify the Hertzian field. Theoretical calculations of such modified fields are lacking in the scientific literature, but Faulkner (1972) has empirically demonstrated the importance of edge effects on both the driving forces and the paths of the ensuing cracks, using a "photoelastic" technique. More work needs to be done in this area (Cotterell and Kamminga, this volume.

Sharp Indenters

As mentioned earlier, sharp indenters are used routinely in hardness testing. Most common are diamond pyramid indenters: the "Vickers" indenter, square-based with an angle of 136^{o} between opposite faces of the pyramid, is widely accepted for general applications, but the "Knoop" indenter, which produces an elongated impression with a ratio of 7:1 in the long to the short diagonal, is also used. Cone indenters are sometimes used in special applications. The science of hardness testing is a further area of recent intense research interest (Westbrook and Conrad 1973). Figure 7 illustrates the morphology of the cracks produced in glass and quartz by pyramid indenters: the patterns are clearly more complex than those obtained with blunt indenters (cf. Fig. 1). This crack system, even more so than the cone crack, has aroused mere token scientific interest: indeed, to the hardness-testing fraternity the appearance of any microcracking about an impression is generally taken to herald an unsuccessful experiment, and consequent rejection of data.

However, the upsurge in attention to general microfracture mechanisms prompted by materials science interests has changed all that. The evolution of the basic sharp-indenter crack pattern, depicted schematically in Fig. 8, takes place in two distinctive loading/unloading stages (Lawn and Swain 1975). During the loading half-cycle the tensile field, indicated by the shading in Fig. 8a, peaks

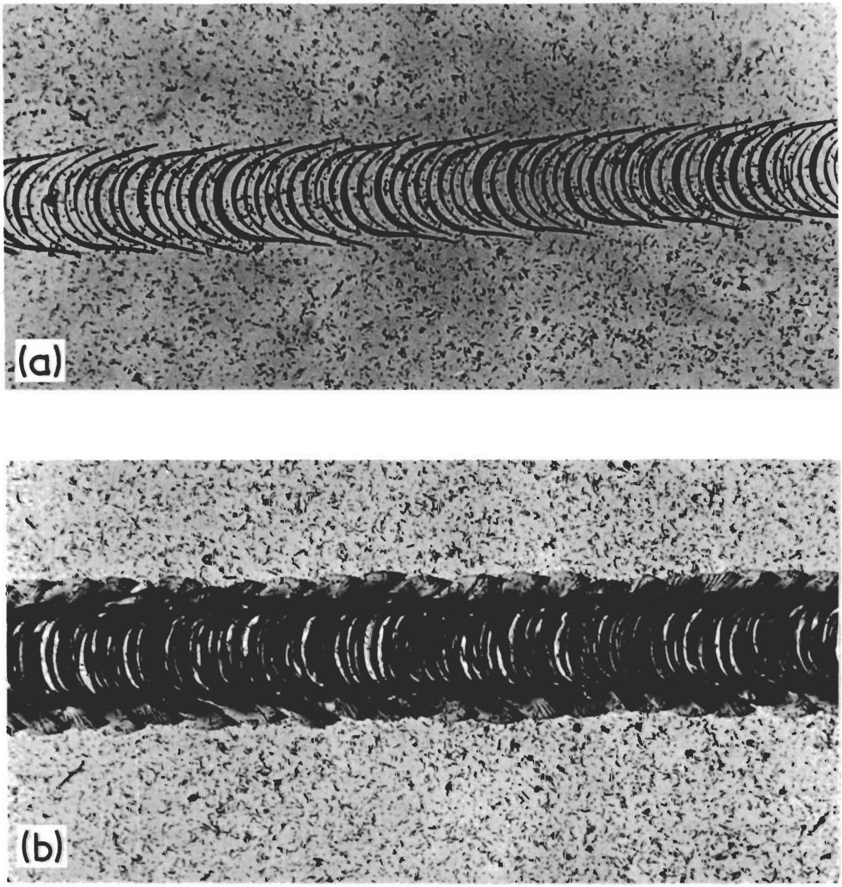


Fig. 6 Partial Hertzian cracks on glass surfaces, using 1.5 mm diam. tungsten carbide sphere, in (a) *n*-decanol, giving coefficient friction 0.12, and (b) water, giving coefficient friction 0.44. Surfaces etched; note flaws. Direction of sliding, left to right. (Optical micrographs in transmitted light, width of field 1.25 mm, normal load 10 N; after Crimes 1973.)

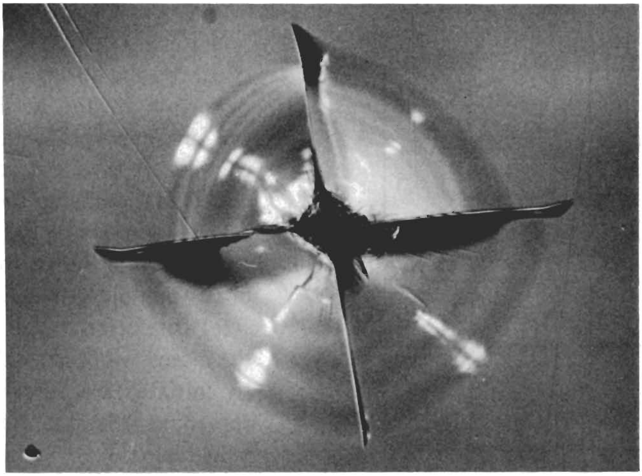
directly below the indenter point, where the irreversible deformation is greatest. The sequence of events is then as follows:

(a) The plasticity processes generate incipient flaw nuclei in the subsurface zone of maximum stress concentration (at the same time relieving the stress build-up on prepresent surface flaws).

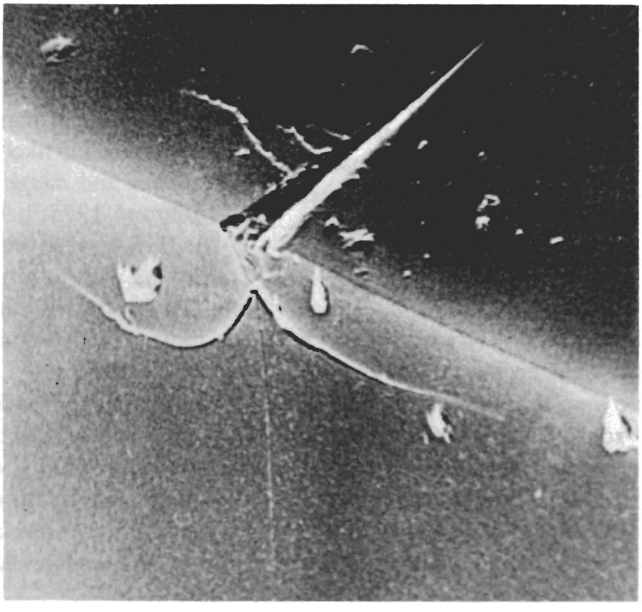
(b) On becoming critical (typically at some threshold load orders of magnitude less than that for cone cracks) one or more of the deformation-

Fig. 7 Median/lateral fracture system. (a) Glass, showing surface and side views of crack pattern produced by Vickers pyramid indenter. (Optical micrographs in transmitted light, width of field 1.8 mm, indenter load 100 N; courtesy B.J. Hockey.) (b) Quartz, showing surface and section views of crack pattern produced by Knoop pyramid indenter. (Scanning electron micrograph, width of field 100 μm, indenter load 2 N; after Lawn and Swain 1975.)

(a)



(b)



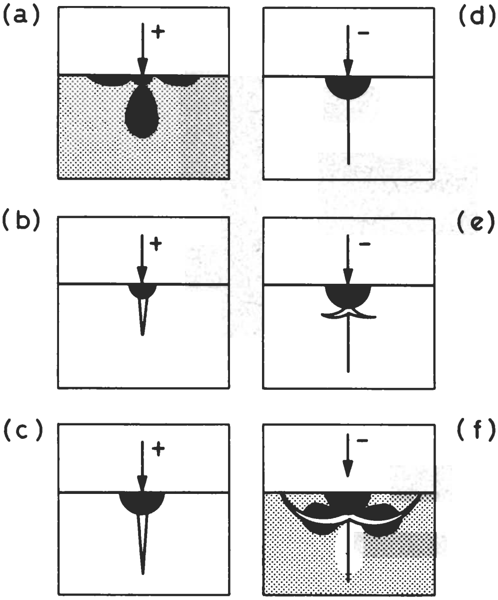


Fig. 8 Evolution of median/lateral crack pattern during one loading (+) and unloading (-) cycle. Dark region represents deformation zone. Point-loading and residual stress fields indicated in (a) and (f), respectively.

induced flaws grow suddenly into small, subsurface pennylike, so-called median cracks on symmetry planes that contain the load axis and the major impression diagonals.

(c) On further loading, the contact expands and drives the median cracks stably downward into the specimen and upward to intersection at the free surface, until the geometry is ultimately semicircular in profile with linear radial traces (leading to an alternative labeling, "radial cracks") extending from the corners of the impression on the specimen surface.

Now as the indenter cycle reverses, the entire nature of the tensile field begins to change in a strange and complex way. Because of its irreversibility, the plastic zone, unlike its surrounding elastic matrix, does not restore to its preindentation configuration. As a result of this incompatability in behavior across the elastic/plastic interface a considerable residual strain builds up around the contact zone during withdrawal, with an attendant distortion of the tensile maxima upward toward the specimen surface, as indicated in Fig. 8f. These changes in the field account for the sequence of events that make up the unloading half-cycle:

(d) As unloading begins, the walls of the median cracks try to move together, but fracture debris once again prevents complete closure.

(e) Just prior to full withdrawal of the indenter, the intensity of the residual field becomes sufficient to initiate an entirely new system of sideways-spreading, "lateral cracks" in the highly tensile wing regions.

(f) Finally, as the indenter leaves the surface, the lateral cracks continue to spread, in saucerlike fashion toward the specimen surface, and may even continue to grow long after the indentation cycle is complete if the environment is reactive.

An interesting feature of the sharp-indenter system is that, depending on the severity of the loading, both median and lateral cracks may or may not intersect the specimen surface (see Fig. 7). Thus a mere inspection of the contacted surface may not be sufficient to indicate the extent, or even the nature, of the damage incurred. In such instances it may be necessary to section and/or etch the specimen. The more penetrant median cracks (along with their blunt-indenter counterparts, the cone cracks) are particularly pertinent to the strength of materials, for it is these cracks that are ultimately likely to run through a structural component and cause failure (Lawn, Wiederhorn, and Johnson 1975; Lawn, Fuller, and Wiederhorn 1976; Lawn and Marshall 1977). The lateral cracks are more directly relevant to material removal processes, since they clearly constitute the most effective chipping mode (Lawn, Swain, and Phillips 1975).

Indentation tests with sharp pyramids are extremely valuable for the light they shed on the relative susceptibility of a given material to deformation and fracture, i.e., the brittleness. The Vickers test is especially useful in this regard. Thus in the well-developed pattern of Fig. 9 the

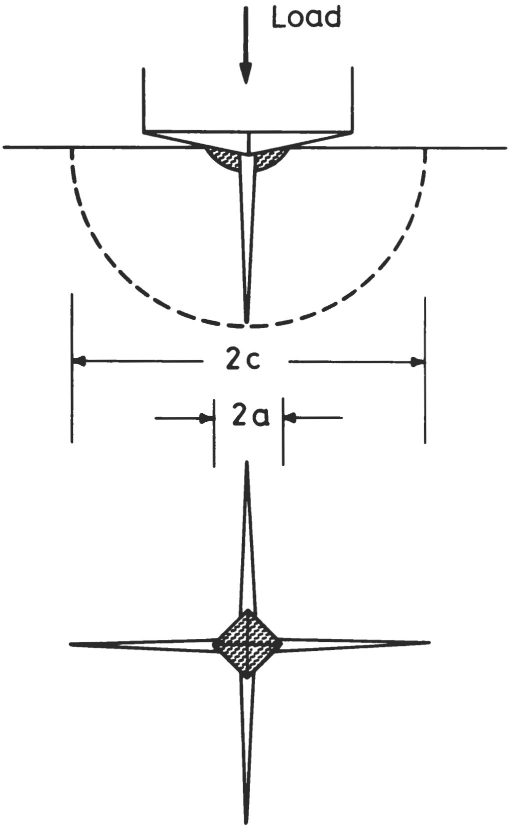


Fig. 9 Deformation/fracture pattern associated with Vickers pyramid indentation, showing section (top) and surface (bottom) views. Characteristic parameters *a* and *c*, respectively, quantify the hardness and the toughness of the specimen.

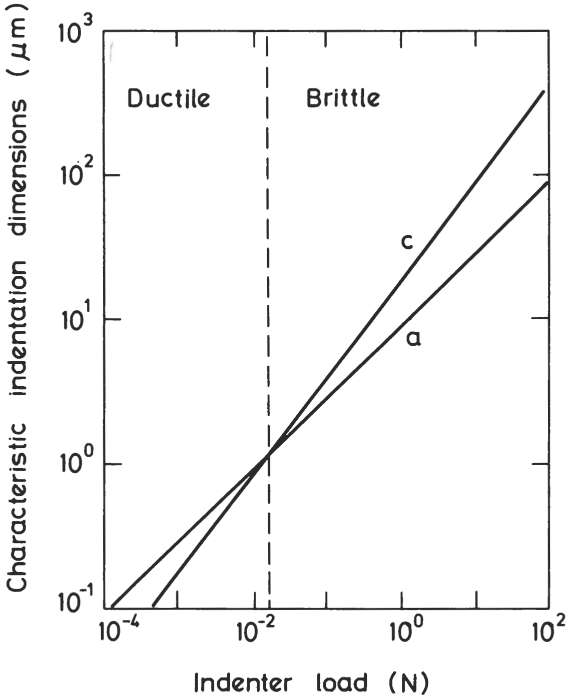


Fig. 10 Indentation data for Vickers pyramid tests on glass, showing transition from ductile to brittle response with increasing load; after Lawn, Jensen, and Arora 1976.

dimension *a* measures the extent of plasticity, and *c* similarly measures the extent of cracking at a prescribed load: more specifically, these two characteristic dimensions provide a relative (inverse) measure of the hardness and toughness (Lawn, Jensen, and Arora 1976). Now experimentally, both *a* and *c* are found to increase with indentation load, as intuitively expected, but at quite different rates, as shown in Fig. 10 for tests on glass. Then at low loads, corresponding to submicrometer scale impressions in Fig. 10, the indentation will appear to be predominantly plastic, while at high loads it will appear to be predominantly brittle. In other words, the damage exhibits a "ductile-brittle transition" as the scale of the indentation increases.[4]

In terms of a translating sharp indenter, this ductile-brittle effect takes on a special significance. We show in Fig. 11 a micrograph of a scratch

[4]Physically, this different response to increasing load arises because plasticity is a volume-controlled process, while fracture is an area-controlled process. Thus, say, to double the linear scale of the plastic zone the energy input from the indentation process would need to be increased by a factor of eight, since volume varies as the cube of linear dimension, whereas to double the scale of the fracture pattern the energy input would need to be increased by a factor of four, area varying only as the square of linear dimension. Hence for a given indentation energy input, the scale of fracture increases more rapidly than that of the deformation.

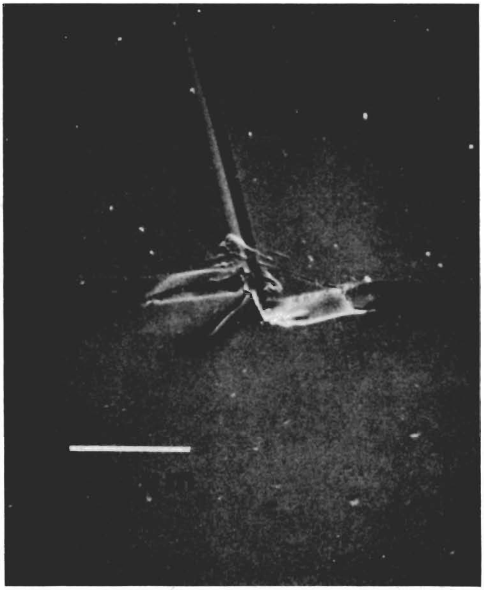


Fig. 11 Scratch on glass, with Vickers pyramid, showing surface and end views. (Scanning electron micrograph, normal indenter load 1.0 N; courtesy M.V. Swain.)

made on a glass surface using a modified Vickers arrangement, with one diagonal of the pyramid indenter aligned along the translational direction. On the surface the track is smooth and apparently fully plastic, but in the profile view there is clear evidence of both median and lateral cracking. At initial contact two median cracks form along the indentation diagonals, but only the one aligned along the prospective track ultimately survives: this favorably disposed crack simply translates along the indenter to produce a linear fissure, while the other crack remains immobile at the starting site. The lateral cracks form continuously in the wake of the indenter, and spread normally outward from the median plane.[5] Now if the scale of the indentation track is sufficiently small, the mechanics will be plasticity-controlled and the track will be smooth and crack free (even below the surface). In terms of a cumulation of a large number of such events the action, insofar as its surface-removal capacity is concerned, is termed (mechanical) "polishing" – a polishing operation is characterized by a relatively low removal rate, and a smooth, mirrorlike finish. On the other hand, if the scale of the indentation is comparatively large, the mechanics will be fracture-controlled and the track will be rough as a result of excessive chipping. In its cumulative manifestation this process is termed "abrasion" – abrasion is a rapid-removal operation, and leaves a rough surface. Thus it is that polishing operations in the glass and ceramics industry use very fine (submicrometer powders, while abrasion and grinding operations use coarse particles.

[5]It is precisely in the manner outlined here that the glass cutter produces his "linear score" for breaking window glass. Of course, the glass cutter's aim must be to promote median cracking at the expense of lateral cracking, in order that the cut be "clean." In this context the curious phenomenon of delayed chipping in the scored region, often several minutes after making the scratch and accompanied by an audible emission, is a too-familiar observation.

Real Indenters

In most practical situations, particles in contact with a brittle surface will not be ideally blunt or sharp as we have described them, but will represent some complex compromise between the two categories. Generally speaking, we would expect the average indenting particle to make contact at its sharpest protuberances: however, if we were able to look at these protuberances at ever-increasing magnification we would find a rounded tip, ultimately at the atomic level if not before. Hence there will be a tendency for the particle to behave as a blunt indenter on initial contact, and thereafter as a sharp indenter as penetration ensues.

This "blunt-sharp transition" in indentation response with increasing load has been neatly demonstrated by Phillips (1975), using the same section-and-etch technique described earlier (cf. Fig. 3). Figure 12 shows the sequential development of the crack pattern in a glass surface indented with a small sphere:

(a) At threshold the contact is elastic, and the classic Hertzian cone is formed.

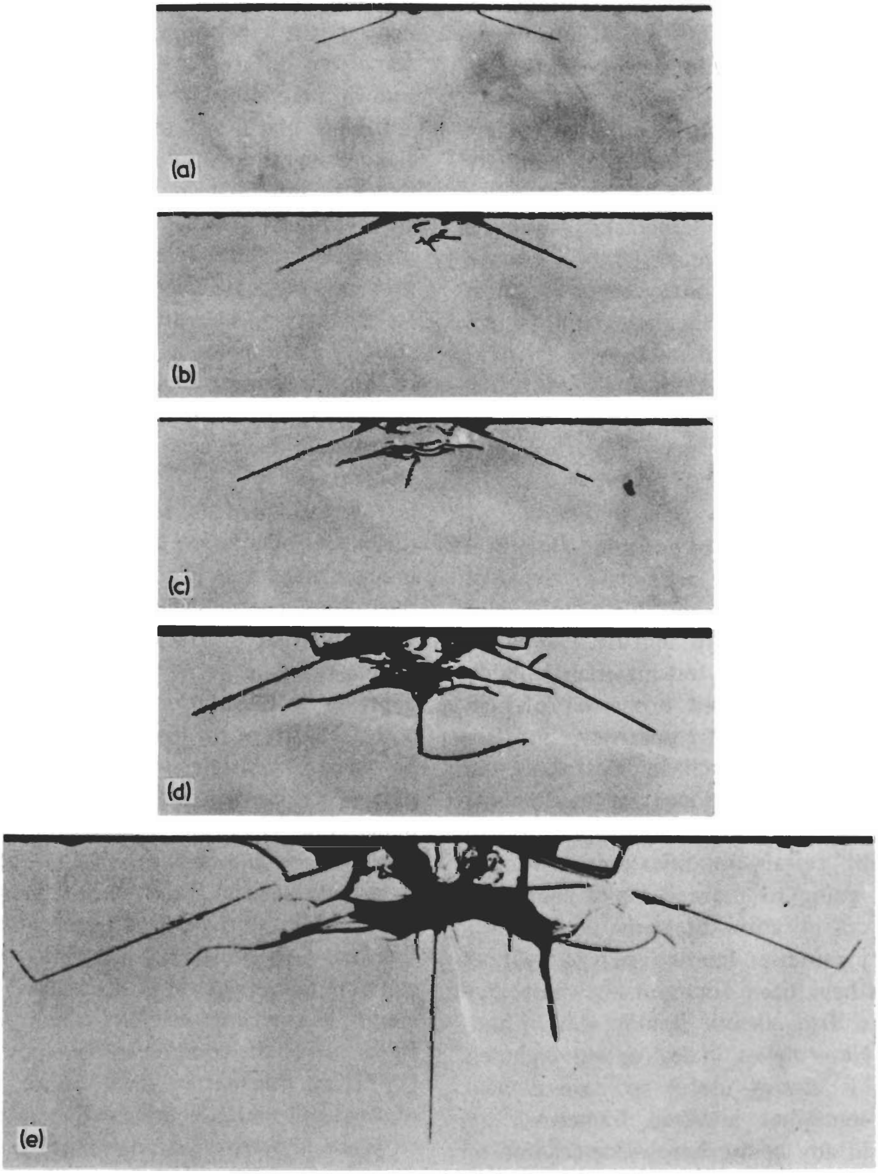


Fig. 12 Section-etch sequence of crack growth in glass indented by 1.0 mm diam. tungsten carbide sphere, showing profiles at loads (a) 100, (b) 140, (c) 180, (d) 266, and (e) 500 N. [Optical micrographs in reflected light, width of field in (a)-(d) 1.5 mm; courtesy K. Phillips.]

(b) On further loading, multiple-ring cracking occurs, and subsurface plastic flow, with attendant microcracking (due to residual stresses), begins to appear.

(c) The features just described continue to develop, and the first signs of a downward-extending median crack and sideways-extending lateral cracks are found.

(d) A hybrid cone/median/lateral crack system begins to take shape as the increasing plasticity allows the indenter to penetrate, the complex network of interlacing microcracks causing a "crush zone" around the contact site.

(e) At severe loading the contact becomes almost entirely plastic, and the median/lateral system accordingly starts to dominate.

IMPLICATIONS

In favorable cases it may be possible to interpret surface markings on stone artifacts in terms of specific mechanical actions, and thence to deduce information on manufacture and use. Our work has concentrated on model test materials, notably glass, having the convenient properties of high brittleness, homogeneity, transparency, and isotropy. In the context of archaeological tools, the above description of microcontact mechanisms might be expected to have ready application to obsidian, with certain modifications becoming necessary in going to more complex materials. Some of the complications that arise in extending the simplistic indentation fracture ideas to practical rock systems have been discussed elsewhere, but in little more than cursory fashion (Swain and Lawn 1977). Nevertheless, in dealing with complex situations it is always useful to have a well-defined, if somewhat idealized, framework on which to build any comprehensive description of aboriginal tool characteristics.

The basic fracture pattern produced by "blunt" indenters has already been shown to have a certain relevance to pressure or percussion cracking in tool manufacture (Kerkhof and Müller-Beck 1969; Faulkner 1972). Blunt flaking tools, particularly those made of soft materials like bone or wood, apparently effect removal of material by first initiating a cone (or partial cone) crack, and then driving this crack through to intersection with some free surface(s) of the stone core. The well-known practice of abrading or "scrubbing" the "striking platform" of the core prior to the flaking operation would certainly ensure an abundance of potential starting flaws for cone formation, although whether the abrasion was originally meant to facilitate ease of cracking or simply to provide "purchase" for the tool remains a point for discussion. The presence of moisture at the striking platform of an obsidian core would also reduce the loading required to produce cracking, as per Fig. 3, but it is more than doubtful that this would have been appreciated by the early toolmakers.[6]

It is well, perhaps, to emphasize here that the realm of indentation fracture, while surely embracing the question of crack *initiation* in flaking operations, certainly does not extend to the subsequent stages of crack *propagation* which lead to the ultimate detachment of the flake. In this context, it is useful to talk of the "near field" and "far field" of the loading, according to whether events are occurring on a scale comparable with that of the contact area or that of the specimen dimensions. Once the crack leaves the immediate contact zone and begins to feel the effects of the outer free surfaces, the system is more accurately described in terms of point-force loading in a specimen of prescribed geometry (cf. general contact field, described in terms of pressure loading in a specimen of effectively infinite extent). Reference to the comprehensive study of Faulkner (1972) on this matter, and to more current work of Cotterell and Kamminga (this volume), serves to place the Hertzian analysis in a proper perspective.

[6] The glass cutter is well aware of the beneficial effects of a "wet cut."

In turning to the relevance of indentation fracture to the interpretation of use-wear patterns, it would seem that the sharp indenter is deserving of special attention. One may appreciate that the presence of sharp indenters is unavoidable in everyday life — small quartz dust particles (∿1-100 μm in dimension) abound in the atmosphere and inevitably come into direct contact with exposed surfaces during the lifetime of any object. We have already alluded to the role of such contacts in producing strength-impairing flaws in brittle surfaces. Thus spectacle lenses and watch covers begin to show visible signs of cumulative surface scratching after prolonged use. The same is true of ancient artifacts, which may or may not, depending on the severity of the contact events, leave readily detectable traces indicative of their mechanical history. While the resultant markings may be readily discernible to the naked eye on heavily worked tools, an unequivocal interpretation may require recourse to a high-power optical microscope or even a scanning electron microscope (see Figs. 13-15). In certain cases microscopy may be necessary even to detect the telltale traces. On the other hand, high-power microscopy is a tool that must not be used without due consideration to the specific objectives of any given study: sometimes it may well be the relative disposition of the traces within the overall pattern, rather than the fine detail within any individual trace, that conveys the more pertinent information (Odell 1975).

In seeking to apply the present descriptions of sharp-indenter damage patterns to use-wear interpretations it is important to appreciate that the systems studied by the scientist, such as those in Figs. 7 and 11, correspond to highly idealized situations. We have made the distinction between "normally" and "tangentially" loaded indenters, and have invoked contrived experiments to demonstrate, with minimum complication, the contribution of both these components. In practical situations the conditions are far more complex, and it becomes necessary to introduce additional elements into the description. Thus, for instance,

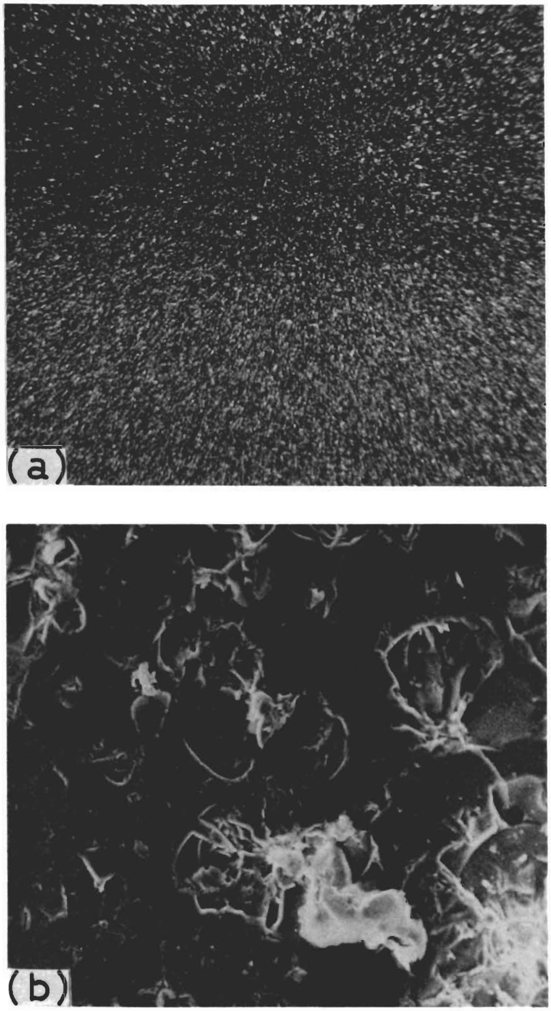


Fig. 13 Surface damage on glass surface, produced under "free" abrasion conditions using ∿ 5 μm carborundum grit. (a) Optical micrograph in reflected light, width of field 10 mm; (b) scanning-electron micrograph, width of field 100 μm; courtesy J. Kamminga.

in the scientific analysis of mechanical abrasion and polishing of brittle surfaces it is useful to distinguish between "free" and "fixed" indenting particles (Lawn and Wilshaw 1975a): with free particles the contact is nearly normal but intermittent, effectively producing a randomly dis-

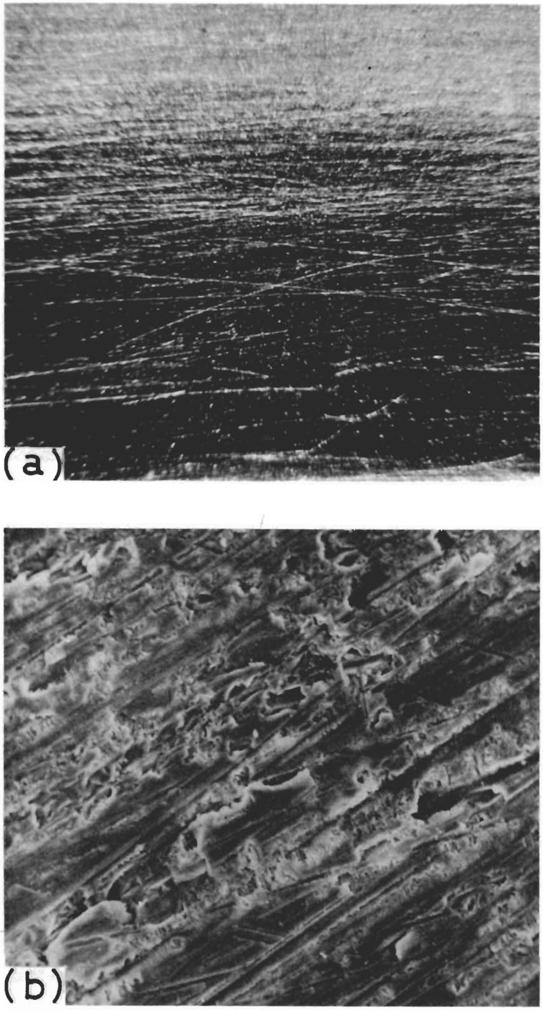


Fig. 14 Surface damage on glass surface, produced under "fixed" abrasion conditions using $\sim 5\ \mu m$ carborundum grit. (a) Optical micrograph in reflected light, width of field 10 mm; (b) scanning-electron micrograph, width of field 100 μm; courtesy J. Kamminga.

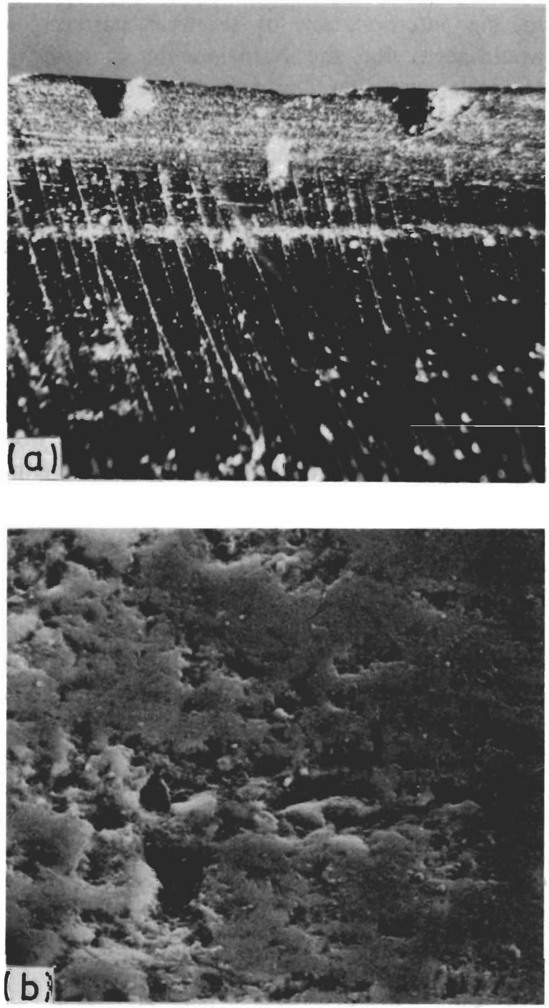


Fig. 15 Edge region of replicated wood saw, with striations (horizontal markings) produced by contact with deliberately added $\sim 150\ \mu m$ quartz grit. (Note nearly vertical fracture steps, traces of earlier manufacture, and fracture "debris.") (a) Optical micrograph in reflected light, widty of field 5 mm; (b) scanning-electron micrograph, width of field 30 μm. Courtesy J. Kamminga.

tributed array of discrete point-load indentations; with fixed particles the contact produces a continuous striation under a well-defined combination of normal and tangential loading, as with a sharp, sliding indenter. In the case of prehistoric tools, the nature of the contact would depend to a large extent on the material being worked (e.g., earth, wood, skin, food), in particular the capacity of this material to maintain any errant particles in direct contact with the tool. Most generally, one must expect the contact to vary between the two extremes, as particles first become wedged, then dislodged (possibly by particle breakup) and tumbled at the working interface.

To illustrate the potential link between indentation fracture analysis and interpretation of lithic use-wear patterns, we draw on some results from studies currently being carried out by Kamminga (1977) on the simulated use of aboriginal stone tools. Figures 13 and 14 show the surface damage patterns obtained in control abrasion tests, using sharp carborundum grit particles of median size $\sim$ 5 μm,[7] on glass microscope slides: in Fig. 13 the abrasive has been used under free conditions, in Fig. 14 under fixed conditions. The different abrasion conditions are clearly evident in the low-magnification optical micrographs, but it is only in the high-magnification scanning-electron micrographs that the true nature of the damage mechanisms begins to show. Figure 15 shows the surface damage incurred in an actual simulation experiment, in which a replicated obsidian tool was used in a wood sawing operation in the presence of a quartz grit environment, median particle size $\sim$ 150 μm.[8] In this figure the features of interest are the horizontal markings near the edge of the tool, identified unequivocally as use striations caused by contact with the quartz particles. (The nearly vertical markings in the optical micrograph are manufacture traces, so-called "fracture steps".) The high-magnification view in the scanning electron micrograph, when taken in comparison with Figs. 13b and 14b, indicate predominant, although not exclusive, fixed-abrasion conditions. One may reasonably conjure up a picture of quartz particles becoming fixed in the wood as the tool is drawn across, they themselves becoming fragmented (recalling that obsidian and quartz are based on the same molecular structure – SiO_2 – and are accordingly of similar mechanical properties) and thereby released from contact, giving rise to somewhat erratic linear traces. However, in making such interpretations from trace patterns one needs to be aware of the possibility of spurious effects from remnant "debris": thus, any particularly large surface chips adhering to the tool after manufacture might well be the cause of the most prominent striations in subsequent use, thereby enhancing the observed pattern; alternatively, softer matter from the substance being worked may enter and clog up the newly formed fracture crevices, obscuring all but the more gross details of the true pattern. Little systematic investigation has been made of any effects of this type.

It is tempting to finish this discourse on a note of optimism, and to suggest that the combined expertise of the archaeologist and the materials scientist must surely provide a much-needed scientific basis for analyzing manufacture and use traces on stone artifacts. This may be so, but it would be unwise not to sound a warning about drawing hasty comparisons between observations made under strictly controlled laboratory conditions and those made in the field. Moreover, one should not be under any illusion that our scientific understanding of deformation and fracture processes is a closed book – the materials scientist concerned with microcontact processes, no less than his archaeologist counterpart, has much to learn.

[7]Commercially available SiC grit, grade (mesh size) 320.

[8]Commercially available as "white glass sand," with spread over 100-600 μm particle size.

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