American Mineralogist, Volume 58, pages 727–732, 1973

The Toughness of Jade

RICHARD C. BRADT,
Ceramic Science Section, Material Sciences Department

ROBERT E. NEWNHAM, AND J. V. BIGGERS
Materials Research Laboratory
The Pennsylvania State University, University Park, Pennsylvania 16802

Abstract

The mechanical properties related to the toughness of jade are measured for both jadeite and nephrite. Fracture surface energies are an order of magnitude greater than most commercial ceramics about 120,000 ergs/cm² for jadeite and 225,000 ergs/cm² for nephrite. Jadeite is the harder of the two minerals, but nephrite is the tougher and the stronger. Scanning electron microscopy of the fracture surfaces indicates that the exceptional toughness results from the fibrous texture of nephrite and extensive transgranular cleavage of the blocky microstructure of jadeite.

Introduction

Ornamental jades include two different minerals, jadeite and nephrite. Nephrite is an amphibole in the tremolite-actinolite series, $Ca_2(Mg,Fe)_5(Si_4O_{11})_2(OH)_2$, derived from alpine-type peridotite-dunite intrusives. The rarer jadeite is a pyroxene of composition $NaAlSi_2O_6$, found in Burma as stream-worn boulders. Jadeite is the harder of the two minerals, 7 on Mohs' scale compared to 6½, although nephrite, "the axe stone," is generally considered to be tougher and more resistant to fracture.

Beauty and durability are the essential attributes of a gemstone. Durability requires both hardness and toughness in order to withstand abrasion and impact. Hardness and toughness are physically irreversible properties, since their tests leave the material in a permanently altered condition. Although scientists and engineers generally describe these properties in a rather qualitative fashion, there are, in fact, specific quantitative methods of measurement. To the mineralogist, hardness means resistance to scratching and as such may be empirically defined by the Mohs' scale. Hardness may also be measured by indentation using the Vickers or Brinell tests. The three technqiues usually agree on the relative ranking of different materials, although the numerical scales appear quite different (Taylor, 1949).

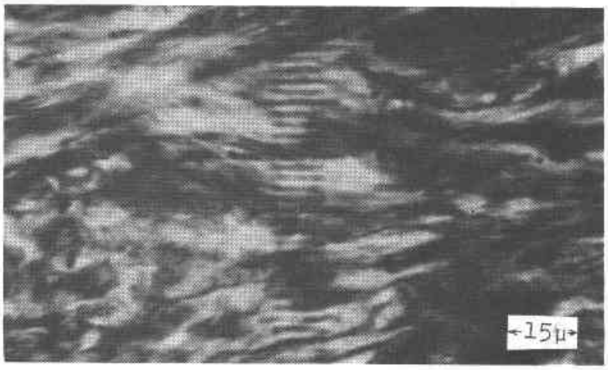
Qualitatively, toughness means the resistance to breakage. Quantitatively, it can be described by two related parameters, the work of fracture or fracture surface energy, and the fracture toughness (Tetelman and McEvily, 1967). Fracture surface energy is the amount of energy required to create a unit area of fracture surface. Fracture toughness, designated K_{Ic} for the opening mode of fracture common to brittle materials, is a measure of the resistance of the material to unstable crack propagation or fracture. Fracture toughness is derived by analyzing the stress distribution at a crack's tip and is equal to the square root of twice the product of the elastic modulus and the fracture surface energy of the material. Often, as is the case in this study, fracture toughness is reported as just K_c when the entire fracture process may not be an opening mode.

Among mineralogists there is no widely accepted scale of toughness, although some minerals such as jade are regarded as much tougher than others. Because of their exceptional toughness, jade boulders are often resistant to breakage with a hammer and may be frequently found in the nearly pure state, since weathering has worn away the surrounding minerals. Early man utilized jade extensively for making tools, finding it almost ideal to shape without fracture. This sentiment has been shared for centuries by Chinese craftsmen who have given the world many exquisite jade carvings, shaped to extremely delicate forms. It is the purpose of this study to quantitatively assess the toughness of several jades and to compare them with synthetic materials and with other minerals.

Experimental

The nephrite jades studied in this investigation were obtained from several American dealers and are thought to originate from Russia and Alaska, while the jadeite specimens were obtained from street shops in Hong Kong, and are probably Burmese in origin. The nephrites are a translucent mottled green with a specific gravity of 3.01, indicating appreciable iron content. X-ray diffraction patterns are in good agreement with the tremolite pattern (Stemple and Brindley, 1960). The texture (Fig. 1) of the matted fibers is characteristic of nephrite. The fibers vary widely in thickness and length, but are generally less than 10μm in diameter, with length-to-diameter aspect ratios from 10 to 50. In some regions, the fibers show a strong preferred orientation, being grouped into orderly bundles, while other regions exhibit a whirlpool-like appearance of a more random nature.

The jadeites vary in color from a pale green to icy white, with numerous glints of reflected light indicating the presence of large crystallites (Fig. 1). The individual crystallite size is much larger than the nephrite fibers, generally within the 50 to 100μm range. The grains exhibit a blocky morphology when compared to the nephrite fibers. Jadeite densities are about 10 percent greater than nephrite, generally about 3.33 gms/cm^3. The X-ray diffraction patterns are identical with those reported for $NaAlSi_2O_6$ (Yoder, 1950).



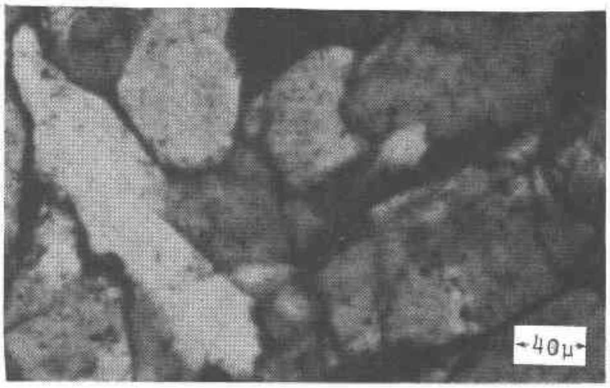


FIG. 1. Photomicrographs of nephrite (top) and jadeite. Note the matted fibrous texture of the nephrite, and compare it with the blocky grain texture of the jadeite.

To compare toughness on a quantitative basis, it is necessary to measure certain mechanical properties such as elastic modulus and fracture surface energy. Strengths are measured by breaking 1/8″ square bars in three point flexure over a 0.4 inch span with an Instron testing machine operated at 0.02 inches per minute cross-head speed. Fracture strength, σ_f, is calculated from the standard engineering-mechanics formula:

$$\sigma_f = \frac{3\,P\,L}{2\,b\,h^2}, \quad (1)$$

where P is the breaking load, and L, b, and h are the specimen's length, breadth, and height dimensions (Marin, 1962).

The elastc moduli are measured by a flexural resonance technique on ¼″ square by 3″ long bars employing a Nametre Model XII B acoustic spectrometer. This involves vibrating the sample in a flexural mode with an oscillator and observing the natural resonance of the specimen. The resonant frequencies depend on the sample dimensions and elastic modulus (Spinner and Teft, 1961), and are usually in the audio-frequency range. Damping capacities of the jades are determined from the resonance peaks by the bandwidth method (Kennedy, 1963).

Fracture surface energies are evaluated by the work of fracture technique (Nakayama, 1965). The work required to propagate a stable crack over a specific area is measured using rectangular bars similar to those used in the strength measurements. The bars are notched at the midsection with a 0.010″ diamond blade, leaving a triangular cross section for the fracture area. After fracturing the bars in a non-catastrophic, stable fashion on the testing machine at a crosshead speed of 0.002 inches per minute, the work, or energy, of fracture is determined by integration of the force-displacement curve. Surface fracture energy is then calculated by dividing the work by twice the triangular cross-section area, since two surfaces are formed during the fracture process. A comparison of this technique with other methods has been given (Coppola and Bradt, 1972). The fracture surface energy and the strength results are reported as the averages with the 95 percent confidence limits as described by the "t" distribution. Thin-sections of jadeite and nephrite were also examined optically on a standard petrographic microscope and the fracture surfaces photographed with a scanning electron microscope after coating the samples with a thin layer of vapor-deposited gold to promote conductivity.

Results and Discussion

The mechanical properties of jadeite and nephrite are listed in Table 1. Although jadeite has the higher elastic modulus, nephrite is superior in strength, σ_f, fracture surface energy, γ_f, and fracture toughness, K_c, substantiating the general opinion that nephrite is tougher than jadeite. The confidence limits for the fracture surface energies and the toughnesses are comparable to that observed for most brittle materials, with the exception of the fracture surface energies of the nephrite. A wide range of scatter was observed on these specimens, with occasional values near 400,000 ergs/cm^2; however, no obvious correlations with place of origin or structural features were apparent. The jade fracture surface energies and calculated fracture toughnesses are compared with other polycrystalline and single crystal minerals in Table 2. It is apparent that jade is deserving of its reputation as a very tough material. Comparing these results with the fracture surface energies of other materials (Duga, 1969) indicates that jade is about an order of magnitude tougher than most ceramic materials.

Jade minerals are chain silicates, and the difference in their average fracture surface energies suggests that perhaps a network silicate, such as quartz or glass, might be even tougher. This concept proves quite erroneous, for the reported fracture surface energies of quartzite (see Table 2) and glass (Wiederhorn, 1969c) are only about 5,000 ergs/cm^2, or less. On the same scale of fracture toughness as Table 2, both glass and quartz are only about 7×10^7 dyne cm$^{-3/2}$. These comparisons suggest that the high fracture surface energy and fracture toughness of jade are not directly related to the atomic bonding *per se*, but are apparently related to texture and the restrictions which it imposes on crack propagation.

TABLE 1. Mechanical Properties of Jades

	Nephrite	Jadeite
Elastic Modulus, E (dynes/cm^2)	1.3×10^{12}	2.0×10^{12}
Damping	1×10^{-3}	1.5×10^{-3}
Fracture Strength, σ_f, (dynes/cm^2)	$2.12 \pm 0.55 \times 10^9$	$1.02 \pm 0.21 \times 10^9$
Fracture Surface Energy, γ_f, (ergs/cm^2)	226,000±155,000	121,000±32,000
Fracture Toughness, K_c, (dynes/cm$^{-3/2}$)	7.7×10^8	7.1×10^8

Scanning electron micrographs of the fracture surface of jadeite (Fig. 2) reveal a very high percentage of transgranular cleavage fractures. That is, when a crack propagates through jadeite, it does not proceed in an intergranular fashion following the boundaries between the grains, rather it proceeds directly through the grains in a transgranular fracture mode. Cleavage step patterns are especially obvious at the higher magnification, indicating that the fracture is almost wholly restricted to certain crystallographic planes. The elongated nature of some of these cleavage steps strongly suggests that the fracture is preferentially occurring parallel to the pyroxene chains, probably {110} planes. It is this extensive transgranular cleavage fracture mode that imparts high toughness to jadeite.

Nephrite has a vastly different appearing fracture topography (Fig. 3). Fibers and bundles of fibers can be seen protruding from the surface, even at low magnification. The random orientation of in-

TABLE 2. Comparison of Toughness

	Fracture Surface Energy, γ_f (ergs/cm^2)	Fracture Toughness, K_c (dyne cm$^{-3/2}$)
Polycrystalline Specimens		
Jadeite	121,000	71×10^7
Nephrite	226,000	77×10^7
Quartzite (Wiederhorn, 1969b)	4,320	7×10^7
Alumina (Gutshall & Gross, 1969)	15,000-50,000	$35\text{-}64 \times 10^7$
Magnesia (Clarke *et al.*, 1966)	20,000	35×10^7
Single Crystals		
Mica (001) (Bryant *et al.*, 1963)	450	4×10^7
Quartz (10$\bar{1}$0) (Brace and Walsh, 1962)	1,030	5×10^7
Corundum (10$\bar{1}$1) (Wiederhorn, 1969a)	600	7×10^7
Periclase (100) (Westwood and Goldheim, 1963)	1,200	9×10^7

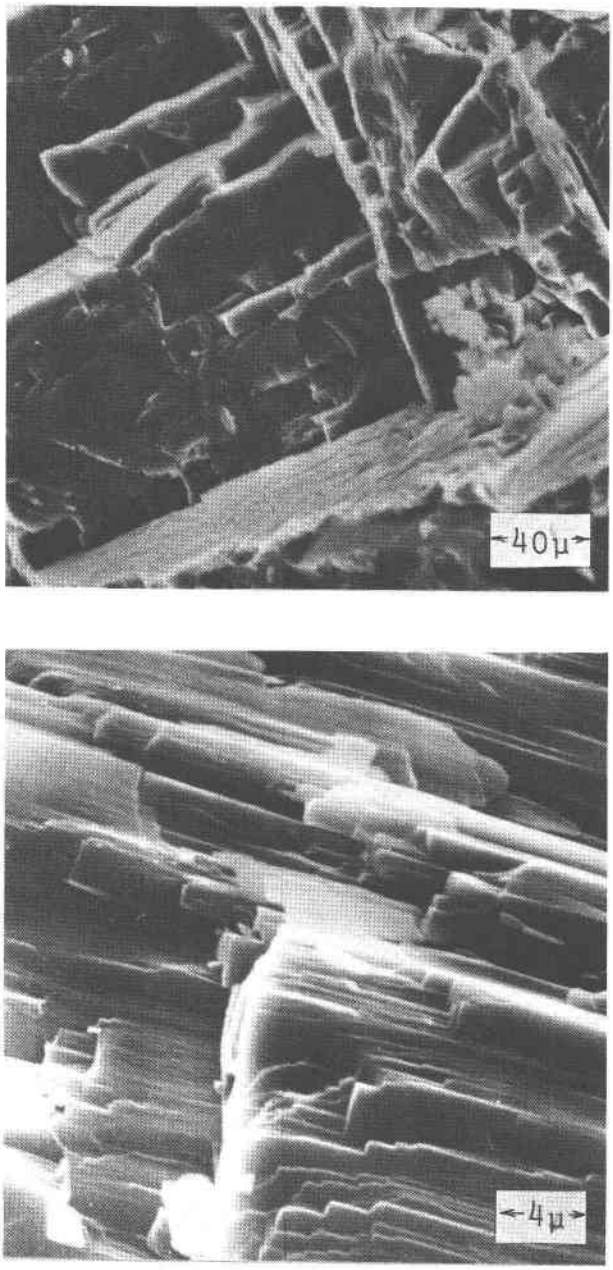


FIG. 2. Scanning electron micrographs of the fracture surfaces of jadeite. Note the extensive transgranular cleavage characteristics of the crack propagation.

dividual fibers and the wide distribution of fiber sizes becomes apparent at higher magnification. It is these variations in fiber and fiber bundle sizes and in orientations that are probably responsible for the variations in fracture energy reported in Table 1. No attempt was made to characterize the nephrites on the basis of fiber or fiber bundle size distributions; however, a correlation of these textural parameters with toughness undoubtedly exists, and is probably the main criterion by which jade carvers are able to select particularly "tough" jade specimens. While the exact contribution of a fibrous texture to increased toughness is not well understood, it has

FIG. 3. Scanning electron micrographs of the fracture surfaces of nephrite. Note the fibrous nature of the fracture surface, the difference in fiber sizes, the occasional bundles of fibers, and the regions of random orientation.

recently become a well documented phenomenon, having been reported in fiber composites (Lynch and Kershaw, 1972), in solidified eutectic alloys (Piekarski and Helmer, 1972), in silicon nitride (Lange, 1972) and in silicon carbide (Coppola and Bradt, 1972).

There appear to be several mechanisms by which transgranular cleavage, such as evidenced in the jadeite, and the fibrous texture, such as that of the nephrite, might increase fracture surface energy and enhance toughness. It almost seems contradictory to consider cleavage as a tough process, particularly with reference to mica. However, mica is a single crystal where the cleavage planes traverse the entire specimen, whereas the cleavage planes in polycrystalline jadeite traverse only a single grain. A propagating crack in polycrystalline jadeite must change direction to a differently oriented cleavage plane each time it crosses a grain boundary. This directional change can be up to 47° in jadeite and very likely causes secondary cracks or fractures which consume additional energy. (Friedman *et al*, 1972) These directional changes also result in a zig-zag fracture path that yields a roughened fracture surface, so that the real fracture surface area is greater than the apparent fracture surface area. (Hoagland *et al*, 1971) This increase of surface area, probably only about 50 percent, does not appear to be as important as secondary cracking or crack-branching in jadeites.

Nephrite fractures in accordance with its fibrous texture, a structural feature that has already been cited to enhance toughness. Several factors may be responsible for this high fracture surface energy, one of which is undoubtedly the high ratio of real-to-apparent fracture-surface area. This contribution is most certainly greater in nephrite than in jadeite. However, probably more important are the frictional effects when individual fibers or bundles of fibers are extracted during fracture. Furthermore, there is little doubt that the propagating cracks in nephrite are often forced to make drastic directional changes to permit the fiber pullouts, so secondary crack branching almost certainly occurs. Presently it is not possible to define clearly which process contributes most to the jade's high fracture surface energies, but it is clear that jade fully deserves its reputation as a very tough mineral.

In regard to the other mechanical properties of jade, the lower elastic modulus of nephrite is almost certainly a result of its lower density; however, its magnitude is still comparable to commercial ceramics and about twice that of common glass. It appears (Fig. 1) that the jadeite-bearing rock has a secondary phase between the jadeite grains, acting as a bond between crystallites; however, no secondary phases were identified in the X-ray patterns or thin sections, and the relatively high modulus and low damping suggest that any secondary phase is a strong, coherent one. The relatively low damping suggests good structural integrity in both jades, with relatively little porosity.

The strengths of the two jades exceed most comerically available ceramics; however, they are not comparable to the ultra high strength of hot-pressed oxides and nitrides used for cutting tools and turbine vanes. The Griffith relation, $\sigma_f = k\sqrt{E\gamma_f/c}$, offers an explanation of the strengths. This equation relates the fracture strength σ_f, to the elastic modulus E, the fracture surface energy γ_f, and the flaw size c, through a proportionality constant k. (Kingery, 1960). From the data in Table 1, it is apparent that nephrite has the higher fracture surface energy and strength, even though the modulus is lower. However, the quantity $\sqrt{E\gamma_f}$ in the Griffith equation accounts for only about 10 percent of the observed differences in the jade fracture strengths. The remainder may be attributed to the smaller flaw size in the nephrite. Flaw size is generally related to the size of microtextural features, and in this case the nephrite fiber diameter is considerably smaller than the jadeite grain size.

Acknowledgment

The authors would like to acknowledge the contributions of G. Gardopee, T. Cline, R. Wolfe, and J. Lebiedzik of the Pennsylvania State University for assistance in the experimental work, and Hok Shing Liu of Chung Hing Mining, Hong Kong, and the Cheng-Kung University, Tainan, Taiwan, ROC, and N. Lambert for assistance in obtaining the jades.

References

Brace, W. F., and J. B. Walsh (1962) Some direct measurements of the surface energy of quartz and orthoclase. *Amer. Mineral.* **47,** 1111–1122.

Bryant, P. J., L. H. Taylor, and P. L. Gutshall (1963) Cleavage studies of lamellar solids in various gaseous environments. *Trans. 10th Annu. Nat. Vacuum Symposium*, American Vacuum Society, pp. 21–26.

Clarke, F. J. P., H. C. Tattersall, and G. Tappin (1966) Toughness of ceramics and their work of fracture. *Proc. Brit. Ceram. Soc.* **6,** 163–172.

Coppola, J. A., and R. C. Bradt (1972) Measurement of fracture surface energy of SiC. *J. Amer. Ceram. Soc.* **55,** 455–460.

Duga, J. J. (1969) Surface energy of ceramic materials. *Defense Ceram. Inform. Center Rep.* **69–2** (June).

Friedman, M., J. Handin, and G. Alani (1972) Fracture surface energy of rocks. *Int. J. Rock Mech. and Mineral. Sci.* **9**, 757–766.

Gutshall, P. L., and G. E. Gross. Observations and mechanisms of fracture of polycrystalline alumina. *Eng. Fract. Mech.* **1**, 463–471.

Hoagland, R. G., G. T. Halm, and A. R. Rosenfield (1971) Influence of microstructure on fracture propagation in rocks. *Batelle Columbus, ARPA Contract Number Ho 210006 Semiannual Res. Rep.*

Kennedy, A. J. (1963) *Processes of creep and fatigue in metals.* J. Wiley and Sons, New York.

Kingery, W. D. (1960) *Introduction to ceramics.* Wiley.

Lange, F. F. (1972) Relationships between strength, fracture energy, and microstructure in hot pressed silicon nitride. *Bull. Amer. Ceram. Soc.* **51**, 429.

Lynch, C. T., and J. P. Kershaw (1972) *Metal matrix composites.* CRC Press.

Marin, J. (1962) *Mechanical behavior of engineering materials.* Prentice Hall.

Nakayama, Junn (1965) Direct measurement of fracture energies of brittle heterogeneous materials. *J. Amer. Ceram. Soc.* **48**, 583–87.

Piekarski, K., and M. Helmer (1972) Fracture energy of lamellar eutectic. *Eng. Fract. Mech.* **4**, 129–131.

Spinner, S., and W. E. Teft (1961) A method for determining mechanical resonant frequencies and for calculating elastic moduli from these frequencies. *Proc. Amer. Soc. Testing Mat.* **61**, 1221–1238.

Stemple, I. S., and G. W. Brindley (1960) A structural study of talc and talc-tremolite relations. *J. Amer. Ceram. Soc.* **43**, 34–43.

Taylor, E. W. (1949) Correlation of Mohs' scale of hardness with Vicker's hardness numbers. *Mineral. Mag.* **28**, 718–721.

Tetelman, A. S., and A. J. McEvily (1967) *Fracture of Structural Materials.* John Wiley and Sons, New York.

Westwood, A. R. C., and D. L. Goldheim (1963) Cleavage surface energy of (100) magnesium oxide. *J. App. Phys.* **34**, 3336–3339.

Wiederhorn, S. M. (1969a) Fracture of sapphire. *J. Amer. Ceram. Soc.* **52**, 485–491.

——— (1969b) Fracture of ceramics. *In, Mechanical and thermal properties of ceramics, N.B.S. Spec. Publ.* **303**, 217–241.

——— (1969c) Fracture surface energy of glass. *J. Amer. Ceram. Soc.* **52**, 99–105.

Yoder, H. S. (1950) The jadeite problem. *Amer. J. Sci.* **248**, 225–248.

Manuscript received, October 2, 1972;
accepted for publication, February 27, 1973.