Morphology of Polycrystalline Alumina Brackets and its Relationship to Fracture Toughness and Strength

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Inherent defects seen in the morphology of polycrystalline ceramic brackets severely limit their fracture strength. Only by improving the surface characteristics can those mechanical properties which are necessary for sufficient strength and efficient orthodontic tooth movement be more fully realized.

KEY WORDS: • BRACKETS • CERAMICS • FRACTURE MORPHOLOGY • • FRACTURE TOUGHNESS • TENSILE STRENGTH •

Recently, SCOTT (1988) reported that the new ceramic brackets recently introduced for clinical use should not be evaluated with the same criteria that are applied to metal brackets. Although the tensile strength and hardness of ceramic brackets are substantially greater than those of metal brackets, he maintains that the crucial physical property of ceramic brackets is fracture toughness which is not a problem with metal brackets.

Already, the coefficients of friction of one polycrystalline bracket have oftentimes proved to be significantly greater than those of steel (Kusy et al., 1988), and the adhesive bond strengths have oftentimes exceeded the strength of tooth structure (JOHO, 1988; WEST, 1988). The clinician must now be apprised that the surface finish of ceramic brackets can drastically reduce the load threshold for catastrophic failure.

This paper documents the surface morphology of a typical ceramic bracket and evaluates its relationship to fracture toughness and strength.

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— Materials and Methods —

Both 0.018" and 0.022" slot *Transcend®** brackets were investigated in their as-received state. These brackets, which have been commercially available for some time now, are made of a fine translucent polycrystalline alumina.

After mounting some of these brackets in their as-received state on specimen studs, others were cleaved with a razor blade from the floor of the slot through the pad of the bracket. All were sputtered with a 2×10^{-2} micrometers (μm) coating of gold-palladium. Each sample was then observed using a scanning electron microscope (SEM), which was set in the gamma 1 mode at a 20kV accelerating voltage and 2.5A condenser current.

— Results —

The secondary electron images of a 0.022" *Transcend®* bracket (Figures 1-4) show a variation in roughness with location. From the overview (Fig. 1), the bracket appears rough like a concrete block rather than smooth like its stainless steel counterpart. The cleaved surface of the bracket (Fig. 2) highlights the polycrystalline structure of the alumina.

Although transgranular fracture and cleavage steps do appear, intergranular fracture predominates, and the equiaxed grains typically range from about 25 to 125μm. The external surfaces of the bracket (Fig. 3) contain many pores, which vary from irregular to polyhedral in form.

The diamond-machined slot (Fig. 4) also shows some corners of polycrystalline grains superposed on a somewhat smoother background.

The 0.018" brackets presented a similar appearance.

— Discussion —

Interpretation of Morphology

The intergranular fracture (Fig. 2) indicates that the interfaces between the particles are the weakest link. Although such features are not as prevalent on the undisturbed external surfaces (Fig. 3), grain fragments within the slot are sometimes plucked out by the shearing loads of the diamond abrasive disk (Fig. 4).

These grains are smaller than the scratches that Scott (1988) warned would seriously impair the strength of ceramics. Notwithstanding, these defects can have detrimental effects on bracket performance.

Evaluation Using the Fracture Toughness Expression

The surface roughness and the strength can be related to the fracture toughness by the expression,

$$K_{IC} = Y \cdot \sigma_F \cdot (\pi a)^{1/2} \qquad (1)$$

In equation (1), "kay-one-cee" is the critical stress-intensity factor necessary to produce fracture when a surface crack of length "a" is stressed to a failure value of "σ_F" and "Y" is a dimensionless geometry factor that equals approximately one. Assuming under the best reported conditions that $K_{IC} = 5.8 \times 10^6 Pa \cdot m^{1/2}$ and $\sigma_F = 1.4 \times 10^9 Pa$, the critical size of the surface crack that will lead to catastrophic failure is

$$a = \frac{K_{IC}^2}{\pi \cdot \sigma_F^2} = 5.5\mu m \qquad (2)$$

There is a great discrepancy between "a"

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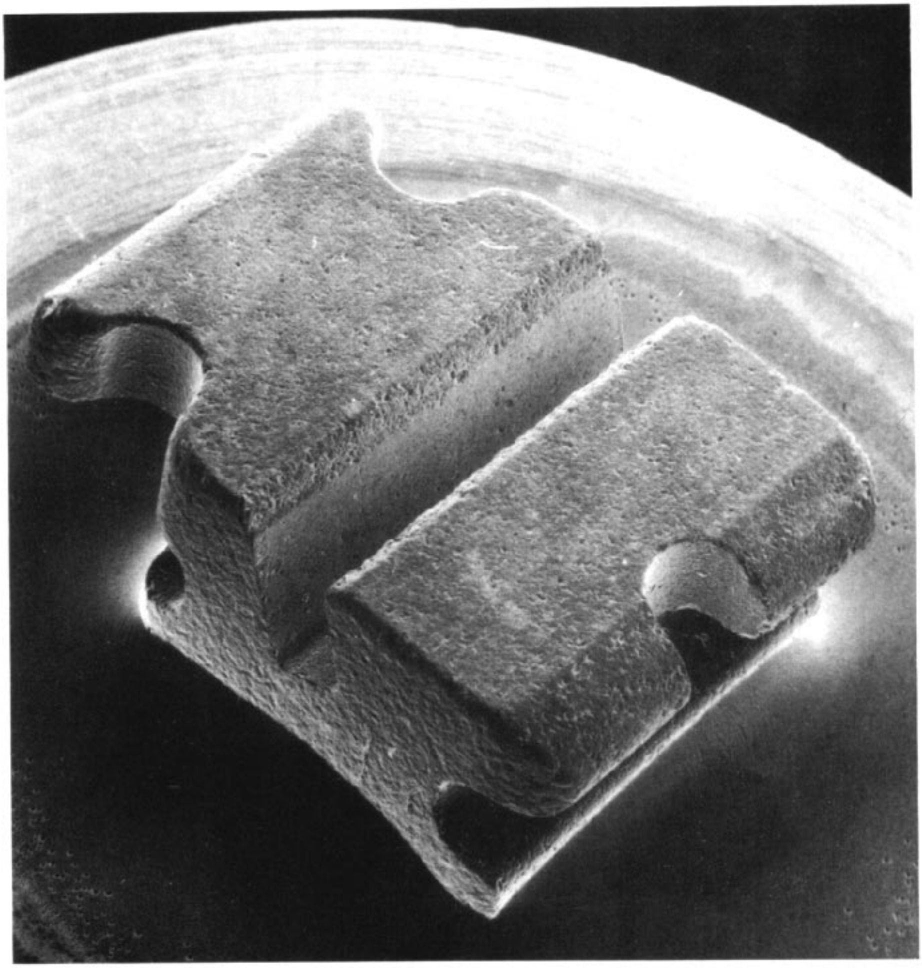

Figure 1
Overall view of a 0.022" Transcend® polycrystalline alumina bracket.
Figures 1–4 all show secondary electron images created with an accelerating voltage of 20kV at a condenser current of 2.5amp in the gamma 1 mode.

at only about 5μm, the overall measured optical surface roughness of 0.193μm (Kusy et al, 1988), and the missing polycrystalline alumina grain fragments that are routinely 50μm in length (Figures 3 and 4) and occasionally approach 100μm. Given the low reliability of ceramics (because there is a high probability of finding a critical combination of crack length and stress), these missing fragments indicate that failure could occur at a much lower stress than would be predicted from either "a" or surface roughness.

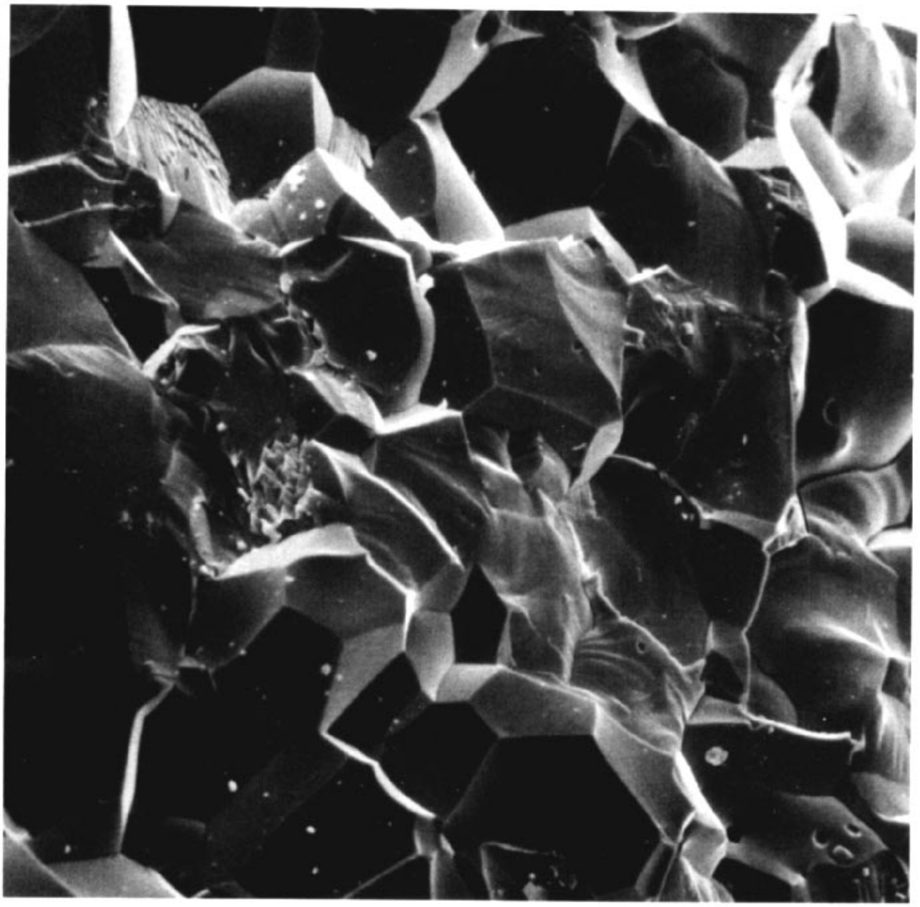

Figure 2
Morphology of the cleaved surface of a slot, showing predominantly intergranular fracture.

Assuming that the missing grain fragments approximate penny-shaped cracks and have crack-tip radii equal to the size of an atom, the strength may be reduced to one-third of the original σ_F, or

$$\sigma_F = \frac{K_{IC}}{(\pi a)^{1/2}} = 4.6 \times 10^8 \text{Pa} \qquad (3)$$

Although the tensile failure strength noted above is comparable to that of stainless steel brackets, the brittleness is not. Recognizing that the stress-strain diagram is linear up to failure, the corresponding critical strain (σ_F) can be calculated from Hooke's law,

$$E = \sigma_F / \varepsilon_F \qquad (4)$$

in which the ratio of σ_F/ε_F equals the modulus of elasticity (E). Using

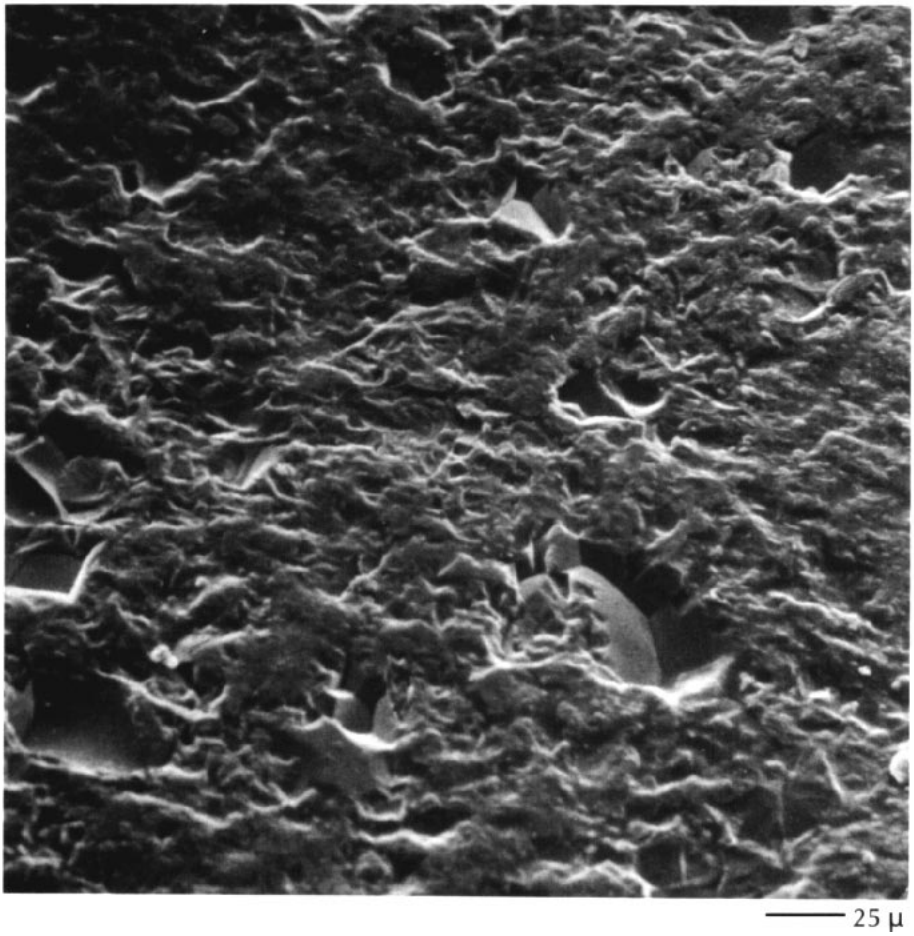

Figure 3
Morphology of the external facial surface of a bracket, *showing microcrystalline pull-outs.*

$E=2.8\times10^{11}$Pa and the recently calculated σ_F from equation (3),

$$\varepsilon_F = \sigma_F/E = 0.0016 \qquad (5)$$

In terms of elongation, this is less than 0.2%!

If static fatigue should occur within the aqueous oral environment at a prevailing ambient temperature of 34°C, then resulting chemical degradation could exacerbate the situation (SHACKELFORD, 1988).

Clinical Implications and Potential Remedies

The less conspicuous appearance of ceramic brackets is their only present advantage over stainless steel. From the electron micrographs of Figures 1–4 and

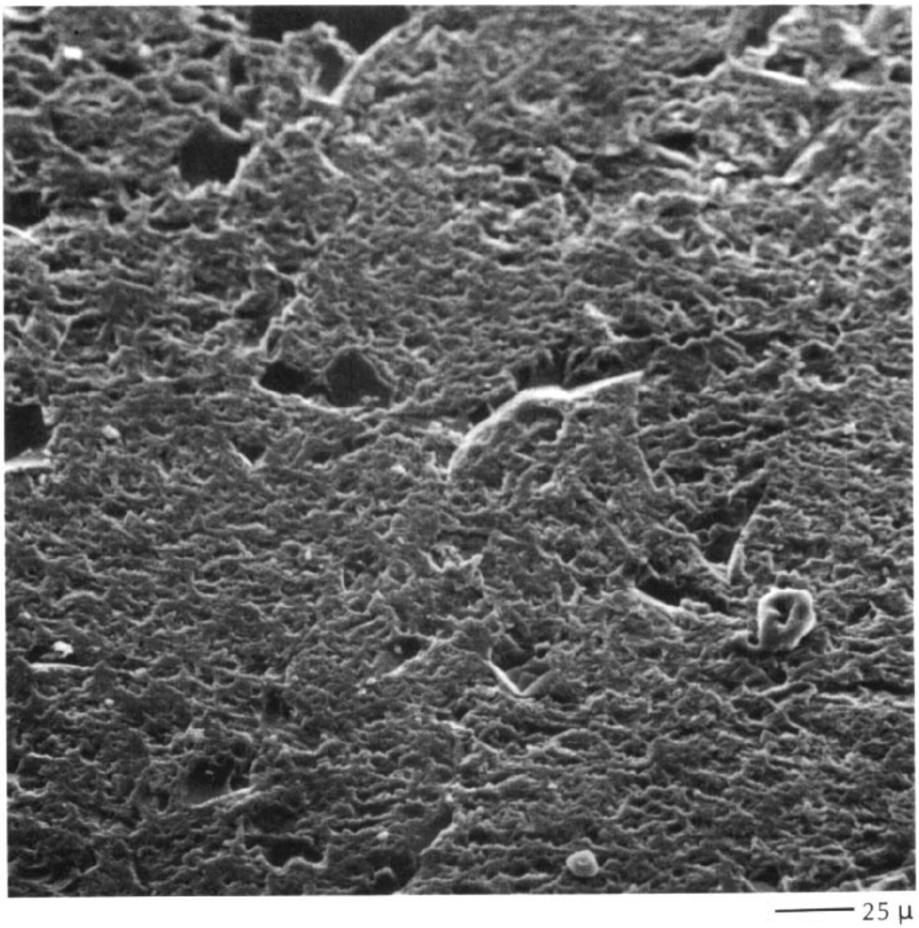

Figure 4
Morphology of the internal surface of a slot.

the calculations of equations (1)–(5), neither the stress nor the strain at fracture are outstanding. When considered along with the inherent roughness and higher coefficients of friction (KUSY AND WHITLEY, 1988) and their excessive bond strengths (JOHO, 1988; WEST, 1988), both clinician and patient may be getting much less than they anticipated.

To merely bemoan the deficiencies of alumina brackets would be improper. Developmental crises are common in all products, including those that are innovative (PETROSKI, 1985). Moreover, competition and the demand by both patients and clinicians for less noticeable appliances have perhaps nurtured a somewhat premature product introduction. This suspicion is fueled in part by the inconsistent supply of brackets in the marketplace and the rumors of drums of rejects accumulating at manufacturing plants. Nevertheless, progress toward a more aesthetic appliance may be realized if some of the present problems can be circumvented or, at least, ameliorated.

The likelihood that either polycrystalline alumina or single-crystal alumina sapphire brackets will be fabricated into a ductile product is not an immediate prospect. Fracture toughness measurements of the best ceramics fall short of the most brittle metals (SHACKELFORD, 1988). Based on equation (1) then, efforts at modifications must address some combination of the failure strength (ςF) and the surface crack length (a).

Here are three potential remedies:

(1) Reduce the dimensions of the alumina particles to decrease the size and possibly the number of grain fragment pullouts.

(2) Produce a glazed surface on the bracket to reduce the overall surface roughness, the inherent defect size, and perhaps the coefficients of friction.

(3) Treat the surface of the bracket either thermally or chemically to place it in compression, thereby increasing the applied tensile stress required for fracture.

Improvement may not come quickly, since the structural problems of these brittle brackets are common throughout ceramic engineering. Manufacturers recognize the importance of surface conditions and must compensate within the constraints of size. Practicing orthodontists must also continue to be involved; their insight and daily contact can be invaluable in the ongoing development of brackets that work well.

In time, worthwhile improvements will materialize. Until then, clinicians should seek bonding agents that optimize the chair time required for bonding, replacement, and debonding. If the highest magnitude of fracture toughness is necessary, however, clinicians should still select stainless steel brackets over alumina.

I would like to thank Dr. G. E. Scott for stimulating the writing of this manuscript, after reading his most recent publication in this Journal, and Mr. J. Q. Whitley for critically reading the manuscript.

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