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Letter to the editor

Comments on "Measurement of the microstructural fracture toughness of cortical bone using indentation fracture"

A recently published communication (Mullins et al., 2007) presents results for indentation fracture toughness tests conducted on specimens of bovine cortical bone. Those authors report that by measuring the crack lengths emanating from the cube corner indentation impressions made with varying indentation forces, that the fracture resistance curve, or *R*-curve, may be determined over very small crack size ranges, specifically ~5–56 μm in that study. While we agree that determining the *R*-curve behavior at very small crack sizes is important for understanding the fracture behavior of bone, we wish to point out that there are some fundamental flaws in the methods used by those authors.

To evaluate the toughness, the authors use formulations developed in the early 1980s that were originally intended to determine the fracture toughness in ceramic materials by measuring cracks emanating from Vickers indents (Lawn et al., 1980; Anstis et al., 1981), and that were subsequently modified for use with the cube corner indent geometry (Pharr, 1998). This method utilizes the general equation:

$$K_c = \alpha\sqrt{\frac{E}{H}}\frac{P}{a^{3/2}}, \quad (1)$$

where P is the applied load, E is Young's modulus, H is the hardness, and a is the radial crack length measured from the center of the indent. α is an empirically determined "calibration" constant usually taken to be 0.016 ± 0.004 for Vickers indents, and which has been proposed to be closer to 0.040 for the corner cube geometry (Anstis et al., 1981; Pharr, 1998). There are many issues that have plagued the accuracy of this method over the years, including the large uncertainty in α ($\pm25\%$) and the fact that H generally decreases with increasing indentation load (Quinn and Quinn, 1997). The latter of these issues gives an erroneous, apparent rise in toughness for longer cracks even if the toughness is not actually higher. Furthermore, one of the more disturbing issues has been that the basic physics behind the above formulation, i.e., that cracks form upon unloading in response to the residual stress field around the indent, have rarely been found to be valid and that the details of the indentation cracking phenomena are extremely material dependent (Cook and Pharr, 1990).

Over the years there has been considerable evidence collected indicating the unreliability of this method for determining the fracture toughness of brittle materials, which has been recently reviewed along with new evidence by Quinn and Bradt (2007). Although many variants of Eq. (1) have been generated over the years, it has been found that while one equation might reasonably match the toughness for one material, it does not produce reliable results for other materials. Additionally, it has been shown that the apparent fracture toughness measured with the indentation method is generally a function of indentation load. This variation is sometimes increasing or decreasing with indentation force, so it cannot be attributed simply to variations in H. Thus, even if a well-correlated equation was used for a given material, it would not be possible to measure an *R*-curve by varying the indentation force. Accordingly, one must conclude that the indentation hardness test is unsuitable for measuring the toughness of brittle materials, and even more so for generating *R*-curves.

Additionally, another concern regarding the recent paper by Mullins et al. (2007) is the method for measuring cracks. This involved dehydrating the indented samples to make observations in a scanning electron microscope. Based on our experience, the dehydration of cortical bone specimens in the presence of a stress concentrator can often induce spontaneous cracking at the stress concentration. The authors do not report any procedures or verification methods to ensure that the cracks they observed were indeed produced during the indentation process and not during the dehydration process. The cube corner indent is a very sharp stress concentrator, much higher than the other indents used by the authors, and cracking may have occurred during the dehydration process rather than during the actual indentation.

In conclusion, we caution readers from deducing conclusions from the results presented by Mullins et al. (2007) on the fracture behavior of cortical bone as determined by indentation tests. Based on nearly three decades of work in this area, the indentation toughness method has proven to be unreliable for measuring toughness of brittle materials, and is even more unsuitable for the evaluation *R*-curves.

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References

Anstis, G.R., Chantikul, P., Lawn, B.R., Marshall, D.B., 1981. A critical evaluation of indentation techniques for measuring fracture toughness. I. Direct crack measurements. Journal of the American Ceramic Society 64 (9), 533–538.

Cook, R.F., Pharr, G.M., 1990. Direct observation and analysis of indentation cracking in glasses and ceramics. Journal of the American Ceramic Society 73 (4), 787–817.

Lawn, B.R., Evans, A.G., Marshall, D.B., 1980. Elastic/plastic indentation damage in ceramics: the median/radial crack system. Journal of the American Ceramic Society 63 (9–10), 574–581.

Mullins, L.P., Bruzzi, M.S., McHugh, P.E., 2007. Measurement of the microstructural fracture toughness of cortical bone using indentation fracture. Journal of Biomechanics 40 (14), 3285–3288.

Pharr, G.M., 1998. Measurement of mechanical properties by ultra-low load indentation. Materials Science and Engineering A 253 (1–2), 151–159.

Quinn, G.D., Bradt, R.C., 2007. On the Vickers indentation fracture toughness test. Journal of the American Ceramic Society 90 (3), 673–680.

Quinn, J.B., Quinn, G.D., 1997. Indentation brittleness of ceramics: a fresh approach. Journal of Materials Science 32, 4331–4346.

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