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Designing functionally graded materials with superior load-bearing properties

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ABSTRACT

Ceramic prostheses often fail from fracture and wear. We hypothesize that these failures may be substantially mitigated by an appropriate grading of elastic modulus at the ceramic surface. In this study, we elucidate the effect of elastic modulus profile on the flexural damage resistance of functionally graded materials (FGMs), providing theoretical guidelines for designing FGMs with superior load-bearing property. The Young's modulus of the graded structure is assumed to vary in a power-law relation with a scaling exponent n; this is in accordance with experimental observations from our laboratory and elsewhere. Based on the theory for bending of graded beams, we examine the effect of n value and bulk-to-surface modulus ratio (E_b/E_s) on stress distribution through the graded layer. Theory predicts that a low exponent ($0.15 < n < 0.5$), coupled with a relatively small modulus ratio ($3 < E_b/E_s < 6$), is most desirable for reducing the maximum stress and transferring it into the interior, while keeping the surface stress low. Experimentally, we demonstrate that elastically graded materials with various n values and E_b/E_s ratios can be fabricated by infiltrating alumina and zirconia with a low-modulus glass. Flexural tests show that graded alumina and zirconia with suitable values of these parameters exhibit superior load-bearing capacity, 20–50% higher than their homogeneous counterparts. Improving load-bearing capacity of ceramic materials could have broad impacts on biomedical, civil, structural, and an array of other engineering applications.

1. Introduction

Ceramics are widely used in load-bearing biomedical applications due to their excellent biocompatibility, wear resistance and aesthetics [1–3]. Ceramic bearings for total hip and knee replacements are a notable case [4–8]. All-ceramic dental restorations are another excellent example [9–11]. However, ceramics are susceptible to flexural fracture, which accounts for millions of US dollars annually in replacement costs and can cause significant patient discomfort and reduced quality of life [12–15]. We propose to improve the resistance to flexural fracture of ceramics by grading ceramic surface with a low-modulus glass [16–18].

Traditionally, strengthening ceramics and improving their resistance to contact damage relies on the introduction of a compressive residual stress layer at the ceramic surfaces by tempering [19], chemical treatments (e.g. ion-exchange or partial leaching) [20], introduction of second-phase particles [21], or infiltrating glass with a lower coefficient of thermal expansion (CTE) [22,23]. However, surface compressive stresses are inevitably accompanied by tensile stresses in the bulk of ceramics, which can promote cracking [24]. More recently, Suresh, Padture and co-workers have introduced a new concept of improving the contact damage resistance of ceramics by infiltrating the ceramic surface with a low-modulus glass of matching CTE and Poisson's ratio, producing an elastically graded surface without any long-range residual thermal stresses [25–30]. Such modulus gradient can improve contact damage resistance of ceramic materials by diminishing tensile stresses at the outer surface of the diffuse layers. We have extended this concept to the flexural damage resistance of ceramics [17]. To date, only a few such studies have been published, all relating to biomedical applications [16,18,31] However, the effect of elastic modulus profile on the stress dissipation remains elusive.

A recent study conducted in our laboratory has shown that a low-modulus surface can effectively reduce the surface stress while diminishing and transferring the maximum stress from the surface to the interior of a bending beam or plate [18]. In that study, explicit flexure formulas have been derived to compute bending stress states across the section of a graded sandwich beam [18]. This was done by solving integrals of the moment–curvature relationship for a power-law modulus gradient – low modulus at the surface and high modulus within. Our analysis showed that such modulus gradients can effectively reduce surface tensile stresses and transfer them into the interior [16,18]. However, our

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stress analysis was based on a power-law modulus function with a given scaling exponent n value, determined from a model graded glass–zirconia system. The optimal condition for stress dissipation in relation to various modulus functions with different n values and bulk-to-surface modulus ratios has not been previously examined.

In this study, we elucidate the effects of modulus profile (power-law function with various n values) and ratio (bulk-to-surface Young's modulus ratio, E_b/E_s) on the stress dissipation in graded beams and plates. Experimentally, we demonstrate that graded structures with various modulus profiles can be fabricated by glass-infiltration of ceramic templates with various porosities. In addition, by infiltrating ceramics with marked differences in elastic modulus, we can alter the bulk-to-surface modulus ratio [17,32]. Flexural tests show significantly improved load-bearing properties imparted by the appropriate surface elastic grading of alumina and zirconia ceramics. In practice, such graded materials can also be fabricated using a robocasting technique, where structures consisting of thin layers with predetermined compositions and moduli can be printed [33–36]. Thus, our study provides a guideline for designing graded structures with appropriate modulus profiles for superior load-bearing capacities.

2. Generalized stress analysis in graded structures

A detailed derivation of closed-form flexure formulas for computing the bending stress distributions in simply supported graded sandwich beams subject to transverse center loads was presented in an earlier paper [18] and will not be repeated here. For readers' convenience, below we briefly summarize the key findings. But first we define the coordinates and parameters required for stress analysis (Fig. 1). The beam consists of a uniform core with graded layers at both top and bottom surfaces. h_2 and h_1 represent the half thicknesses of the beam and its homogeneous core, respectively, while $h\,(=h_2-h_1)$ is the thickness of each graded layer. b is the width of the beam. Assuming the elastic modulus changes with respect to the spatial coordinates according to a power-law relation, the stress distribution in the uniform core and graded layers can be expressed in Eq. (1a) and (1b), respectively [18]:

$$\sigma_{\rm xgu} = -\frac{ME_b}{E_bI_{gu} + E_sI_{gg1} + (E_b - E_s)I_{gg2}}y \quad (0 \le y < h_1) \tag{1a}$$

$$\sigma_{\rm xgg} = -\frac{M\left[E_s + (E_b - E_s)\left(\frac{h_2-y}{h}\right)^n\right]}{E_bI_{gu} + E_sI_{gg1} + (E_b - E_s)I_{gg2}}y \quad (h_1 \le y \le h_2) \tag{1b}$$

where E_b is the Young's modulus of the uniform core, E_s is the surface modulus of graded layers, y is the perpendicular distance to the neutral axis (NA), n is the scaling exponent of the modulus function, and $t = (h_2 - y)$ is the distance from the surface. The gradient of modulus may be described by a power-law relation [18]:

$$E = E_s + (E_b - E_s)\left(\frac{h_2 - y}{h}\right)^n \tag{2}$$

The bending moment, M, and moment of inertia, I_{gu}, I_{gg1} and I_{gg2}, are:

$$M = \frac{FL}{4} \tag{3}$$

$$I_{gu} = \frac{2bh_1^3}{3} \tag{4}$$

$$I_{gg1} = \frac{2b\left(h_2^3 - h_1^3\right)}{3} \tag{5}$$

$$I_{gg2} = \frac{2b(h_2 - h_1)^{(n+1)}\left(h_1^2n^2 + 2h_2h_1n + 3h_1^2n + 2h_2h_1 + 2h_2^2 + 2h_1^2\right)}{(n+3)(n+2)(n+1)h^n} \tag{6}$$

As can be seen from the above equations, three key factors govern the stress state in a graded structure: the total beam thickness to graded layers ratio ($2h_2/2h = h_2/h$); exponent n of the modulus function; and bulk-to-surface modulus ratio (E_b/E_s). Our previous study has examined the effect of total layer thickness to graded layers ratio on the stress distribution. It was found that a small thickness ratio ($h_2/h < 5$) is more likely to reduce the maximum stress. However, the previous study for a glass-infiltrated zirconia system was done using a fixed $n = 0.32$ (determined by nanoindentation) and $E_b/E_s = 3.2$ ($E_b = 240$ GPa for zirconia and $E_s = 75$ GPa for glass–zirconia graded surface). The effects of n value and modulus ratio on stress state have not been evaluated analytically, due mainly to the labor-intensive nature of such exercise. In the present study, we created a C++ code using the analytical Eqs. (1)–(6) to search for an optimal n value in reducing the maximum stress for any given h_2/h thickness ratio with constant $E_b/E_s = 3.2$. Once an optimal n value for a given thickness ratio was determined, we extended our study to investigate the effect of E_b/E_s ratio on the stress distribution.

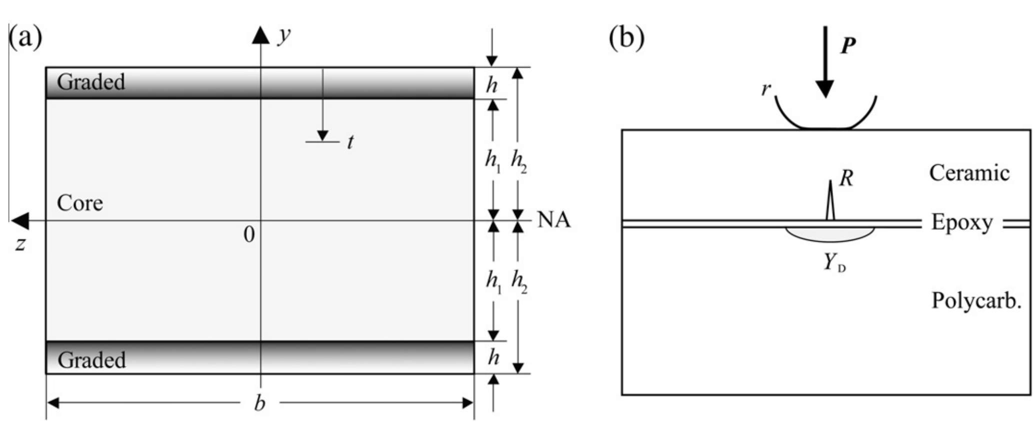

Fig. 1. Cross-section of graded sandwich structures. (a) A symmetrically graded sandwich beam of width b and thickness $2h_2$. h is the graded layer thickness, h_1 the distance from neutral axis (NA), z, to graded layer/core interface, and $t = (h_2 - y)$ the distance from surface. (b) A ball-on-ceramic/polymer bilayer test, which produces a through-thickness bending stress distribution in the ceramic plate, similar to that produced by a three-point bend or a biaxial test. P is the applied load; r is the radius of the indenter; R denotes the flexural radial cracks; and Y_D represents yield of polymer support.