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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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