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Research Article

Strengthen Ceramics via Pre-Stressing Design

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Abstract

After the wide application of pre-stressing in the fields of concrete and glass, a pre-stressing design is interested in ceramics. A simple and economical technique via pre-stressing now solves a worldwide challenge — simultaneously improving the strength and damage tolerance of brittle ceramics.

Keywords: High rigidity; Ecological civilization; Pre-stressing; Sintering compatibility; Flexural strength

Body part

High strength and damage-tolerance, which could directly affect the service life and reliability of ceramic components, have long been the aspiration of manufacturing and engineering [1-3]. As structural materials, ceramics have excellent properties over metals including low density, high rigidity and hardness, corrosion and wear resistance, even at high temperature. However, ceramics are far more brittle than metals, seriously restricting the application of ceramic materials in many fields such as aerospace, machinery, combustion engines and so on. Similarly, enhancing the strength and damage tolerance of traditional ceramics will reduce the thickness of ceramics under the condition of constant carrying capacity, which could not only significantly lessen the consumption of raw materials, waste emissions as well as the cost of transport, but also dramatically improve the sustainable development of porcelain industry, construction of ecological civilization and protection of ecological environment. In general, high strength brittle materials are usually sensitive to surface damage and have low resistance to crack propagation. Therefore, simultaneously improving the strength and damage tolerance of ceramics is a worldwide challenge and a core issue in the progress of ceramic materials. It is well known that introducing a layer of compressive stress on the surface of brittle materials such as ceramics can remarkably improve the strength and inhibit crack initiation and growth from surface defects. While pre-stressing has been widely used to improve the strength of concrete and glass for over a century, many scholars prepared pre-stressed ceramics by simulating pre-stressed concrete [4] and tempered glass [5]. However, no significant progress has been made for ceramics. It is obvious that steel bars embedded in ceramics by simulating pre-stressed concrete cannot be sintered at high temperature.

Moreover, pre-stressed ceramics have been preliminarily prepared by simulated thermal (quenching) and chemical (ion exchange) treatments of tempered glass, but these treatments are not economical and are limited by thermal shock damage in larger and more complex shapes. As a consequence, due to the complexity of ceramic materials, how to use a simple fabrication technology to generate the effective residual stresses on ceramic surface available to large and complex components has been an important topic of research for many decades. Recently, a theoretical pre-stressing design and a simple fabrication technology to substantially improve the strength and damage tolerance of ceramic components was developed [6]. Particularly, in order to generate compressive stresses in the surface layer of a sintered ceramic component, the coating material is required to have a lower coefficient of thermal expansion (CTE) and a sintering temperature similar to that of the substrate. In any cross section of pre-stressed specimens, compressive stresses exist in the coating layer and tensile stresses exist in the substrate, and the stress integral over the cross section is zero due to force balance. To generate the maximum and effective surface compressive stress, the CTE of the surface material should be lower than that of the substrate, and the elastic modulus of the surface material should not be lower than that of the substrate. The residual stresses in the coating, σ_c, has the form as Eq.(1) [6],

$$\sigma_c = \left(\frac{S_s}{S_c}\right).\left\{1-\frac{\left[\frac{E_sS_s}{E_cS_c}+\frac{\alpha_c}{\alpha_s}\right]}{\left[1+\frac{E_sS_s}{E_cS_c}\right]}\right\}E_s.\alpha_s.\Delta T \quad (1)$$

In which α_c and α_s are the CTE of the coating and the substrate, respectively. S_c and S_s are the cross-sectional area of coating and substrates respectively. E_c and E_s are the elastic modulus of the coating and the substrate, respectively. ΔT is the difference between sintering temperature and service temperature. In order to obtain effective reinforcement, optimized conditions were given by:a) $S_s / S_c > 20$; b) E_s / E_c be as low as possible; c) $\alpha_s/\alpha_c > 1.2$. Good sintering compatibility between substrate material and coating material should be the precondition of the pre-stressing design [6]. Following the aforementioned pre-stressing principles, the flexural strength of pre-stressed domestic ceramics was drastically increased by 107%, from 53±3MPa to 110±5MPa, by sintering of a green bulk coated with a thin layer of low coefficient of thermal expansion (CTE) (Figure 1). In addition, we have successfully fabricated pre-stressed ZrO_2 ceramics and pre-stressed porcelain tiles. Detailed technological process for pre-stressed ZrO_2 ceramics and pre-stressed porcelain tiles are reported in [6]. In summary, the compressive residual stress in the surface layer will greatly improve the flexural strength and crack growth resistance of ceramic components. The strengthening method of the pre-stressed ceramics is simple and economical, and it can be used to improve the mechanical performance of large and complex ceramic components and could be broadly applicable for advanced ceramics, building ceramics and also refractories. Furthermore, it is worth noting that, similar to pre-stressed concrete and tempered glass, the pre-stressed ceramics is a kind of components, rather than a material because it is not machinable, otherwise the existence of pre-stressing force will be destroyed. Additionally, if the cost is not considered, it can be combined with other reinforcement mechanisms to achieve double reinforcement effects.

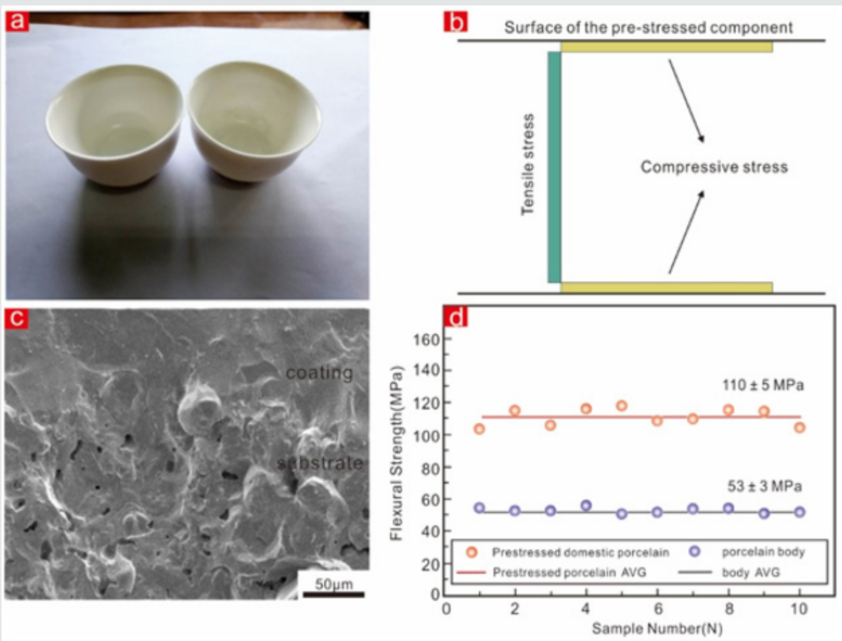

Figure 1: (a)Prototypes of pre-stressed domestic ceramics, (b)Schematic of stress distribution for the pre-stressed specimen, (c)SEM image showing the morphology of the interface between the porcelain body and the pre-stressed coating, (d)Flexural strength of pre-stressed ceramics by 3-point bend tests.

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