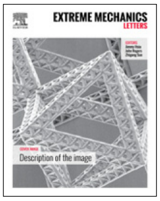
Extreme Mechanics Letters ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml



Carving 3D architectures within glass: Exploring new strategies to transform the mechanics and performance of materials

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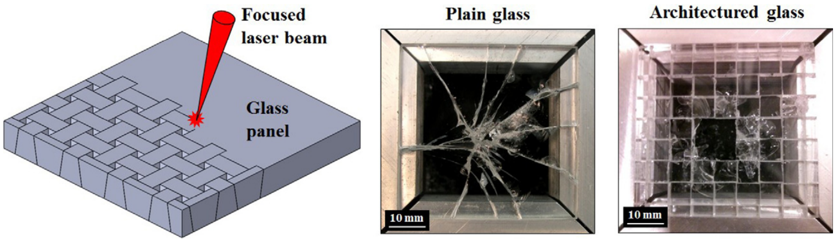
GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 November 2015
Received in revised form 9 February 2016
Available online xxxx

Keywords:
Architectured materials
Glass
Three-dimensional laser engraving
Topologically interlocked materials
Toughening mechanisms
Impact
Nonlinear deformations

ABSTRACT

Combining high strength, hardness and high toughness remains a tremendous challenge in materials engineering. Interestingly nature overcomes this limitation, with materials such as bone which display unusual combinations of these properties in spite of their weak constituents. In these materials, highly mineralized "building-blocks" provide stiffness and strength, while weak interfaces between the blocks channel non-linear deformation and trigger powerful toughening mechanisms. This strategy is also exploited in multilayered ceramics, fiber-reinforced composites, and more recently in topologically-interlocked materials. In this work we apply these concepts to the toughening of glass panels by incorporating internal architectures carved within the material using three-dimensional laser engraving. Glass is relatively stiff and hard but it has no microstructure, no inelastic deformation mechanism, low toughness and poor resistance to impacts. We demonstrate how introducing controlled architectures in glass completely changes how this material deforms and fails. In particular, our new architectured glass panels can resist about two to four times more impact energy than plain glass. Our architectured glass also displays non-linear deformation, progressive damage and failure contained within a few building blocks. This work demonstrates how micro-architecture, bio-inspiration and top-down fabrication strategies provide new pathways to transform the mechanics and performance of materials and structures.

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http://dx.doi.org/10.1016/j.eml.2016.02.016

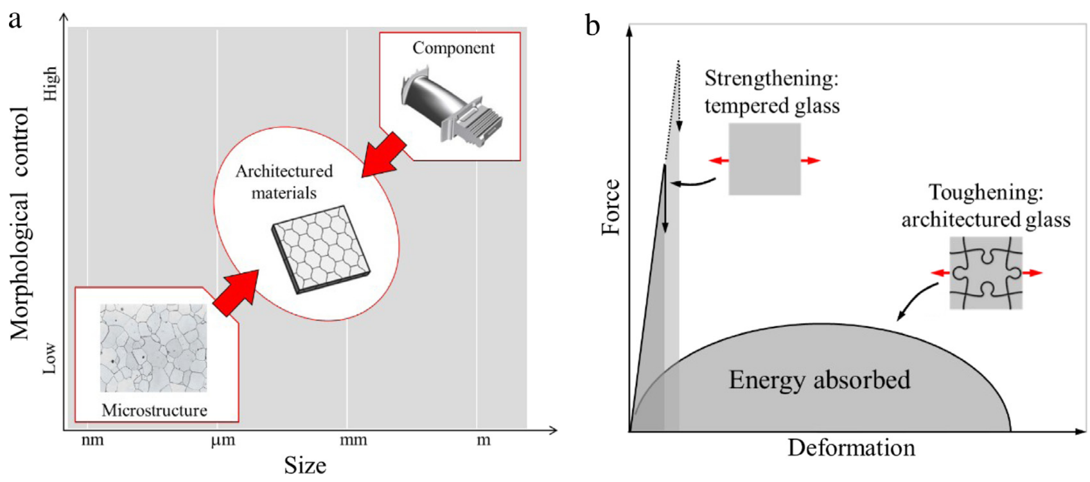

Fig. 1. General concept for dense architectured materials: (a) an "Architecture" is created within the material, and at lengths scales intermediate between the component size and the microstructure (adapted from [9,15]). (b) While methods such as tempering aim at increasing strength, introducing an architecture aims at increasing toughness and energy absorption, by for example enabling large deformations at weak interfaces.

1. Introduction

Despite large efforts in material development and mechanics, some combinations of mechanical properties remain inaccessible to engineering materials [1,2]. For example materials which are simultaneously hard and tough are highly desirable for many applications, yet these properties remain mutually exclusive in engineering materials [1,3]. Interestingly, nature has overcome these limitations by incorporating intricate microstructures which are associated with powerful deformation and fracture mechanisms. For example, natural nacre [4,5], conch shell [6], tooth enamel [7], or bone [8] display unusual and attractive combinations of stiffness, hardness and toughness. The construction of these materials follows a "Universal" strategy where highly mineralized building blocks provide stiffness and hardness (platelets in nacre, mineralized fibrils and osteons in bone), and much weaker interfaces provide non-linear deformations, crack deflection and other powerful toughening mechanisms [9]. The idea of introducing weak interfaces to increase the mechanical performance of materials is counterintuitive, yet it is a common strategy in nature [9–12]. This strategy is also used in engineering materials such as multilayered ceramics and fiber reinforced composites, to generate crack deflection and controlled fiber pullout [13,14]. More recently, materials with more sophisticated three-dimensional architectures have emerged [15,16]. These materials introduce specific structural features at a length scale which is intermediate between the microstructure and the size of the component (Fig. 1(a)). Because the length scale associated with this architecture is larger than traditional microstructures, higher level of morphological control can be achieved with existing fabrication technologies, which is a requirement for a tight control of the deformation and fracture mechanisms. In dense architectured materials, stiff building blocks are assembled in larger structures, and the interfaces between the blocks are weak so they can generate a wealth of non-linear deformation mechanisms and crack deflection, which echo the concepts found in natural materials (Fig. 1(b)). In topologically interlocked materials (TIMs) the blocks have specific shapes which interlock to form architectured materials with combined strength and toughness under transverse static [17,18] or impact loading [19]. These materials also display quasi-ductile behavior [20], localized damage [18], and re-manufacturability [21]. Different shapes of building blocks such as regular tetrahedral [19], osteomorphic [18], regular cubes [22,23], and buckyballs [20] have been used so far for TIMs. Building blocks have been made of materials such as polyvinyl chloride (PVC) [17,22], polyester [18], alloys of magnesium, titanium and aluminum [17,22], steel [17], ABS P400 polymer [16,21], alumina [23] or ice [24]. The blocks are fabricated first, and then assembled to fabricate materials and structures from the bottom-up.

In this work we present a new fabrication technique based on a top-down strategy, where weak interfaces are carved within a hard but brittle material. We use glass as a base material, and three-dimensional laser engraving to generate weak interfaces within the bulk of the material [25,26]. Glass is not only an ideal model material to explore the laser engraving approach, it is also a material which is used for its optical properties, hardness, durability, thermal and chemical stability in countless applications. Glass has however relatively poor fracture toughness and impact resistance, which restricts its potentially broader range of applications. Glass can be strengthen by tempering, which consists of generating residual compressive stress state within a thin layer of material at the surface, by either heat treatment or ion implantation. Once a crack is initiated, tempered glass has however no resistance to crack propagation, which results in catastrophic fracture and complete destruction of the component. Laminating glass is another strategy which consists of intercalating glass layers with softer polymeric layers to keep glass fragments together in case of fracture. Tempering and laminating can be used simultaneously, but none of these methods truly increases the fracture toughness of glass (Fig. 1(b)). The idea of introducing an

Please cite this article in press as: M. Mirkhalaf, et al., Carving 3D architectures within glass: Exploring new strategies to transform the mechanics and performance of materials, Extreme Mechanics Letters (2016), http://dx.doi.org/10.1016/j.eml.2016.02.016