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Tough and deformable glasses with bioinspired cross-ply architectures

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ABSTRACT

Glasses are optically transparent, hard materials that have been in sustained demand and usage in architectural windows, optical devices, electronics and solar panels. Despite their outstanding optical qualities and durability, their brittleness and low resistance to impact still limits wider applications. Here we present new laminated glass designs that contain toughening cross-ply architectures inspired from fish scales and arthropod cuticles. This seemingly minor enrichment completely transforms the way laminated glass deforms and fractures, and it turns a traditionally brittle material into a stretchy and tough material with little impact on surface hardness and optical quality. Large ply rotation propagates over large volumes, and localization is delayed in tension, even if a strain softening interlayer is used, in a remarkable mechanism which is generated by the kinematics of the plies and geometrical hardening. Compared to traditional laminated glass which degrades significantly in performance when damaged, our cross-ply architecture glass is damage-tolerant and 50 times tougher in energy terms.

Statement of Significance

Despite the outstanding optical qualities and durability of glass, its brittleness and low resistance to impact still limits its wider application. Here we present new laminated glass designs that contain toughening cross-ply architectures inspired from fish scales and arthropod cuticles. Enriching laminated designs with crossplies completely transforms the material deforms and fractures, and turns a traditionally brittle material into a stretchy and tough material – with little impact on surface hardness and optical quality. Large ply rotation propagates over large volumes and localization is delayed in tension because of a remarkable and unexpected geometrical hardening effect. Compared to traditional laminated glass which degrades significantly in performance when damaged, our cross-ply architecture glass is damage-tolerant and it is 50 times tougher in energy terms. Our glass-based, transparent material is highly innovative and it is the first of its kind. We believe it will have impact in broad range of applications in construction, coatings, chemical engineering, electronics, photovoltaics.

1. Introduction

With fast developments in the applications of glass in electronic devices, solar panels and windows for building and vehicles, there are increasing needs for tough and damage tolerant glass materials [1]. Toughness, which indicates the capability of a material to resist crack propagation and impacts, requires high strength and high deformability. However, strength and deformability are usually mutually exclusive in many traditional engineering materials [2]. Glass is a widely used material because of its hardness, optical properties, thermal and chemical stability, and durability. However, its range of applications is currently severely limited by its low fracture toughness (Fig. 1a). Currently, the main two methods used to improve the mechanical performance of glass are tempering and lamination [3]. Tempering consists of generating residual compressive stresses at the surface of glass components by either heat treatment or ion implantation, in order to offset tensile stresses arising from external loading. However, once a crack is initiated in tempered glass, the release of elastic energy produces catastrophic and "explosive" failures which destroy the entire component into small fragments. Laminating glass is another strategy which consists of intercalating glass layers with softer polymeric layers to keep glass fragments together in case of fracture. However, the impact resistance of laminated glass is not significantly higher than plain glass because the deformability and toughness of the polymer layers are not fully exploited [3]. Recent work has suggested new pathways to transform the mechanics and improve

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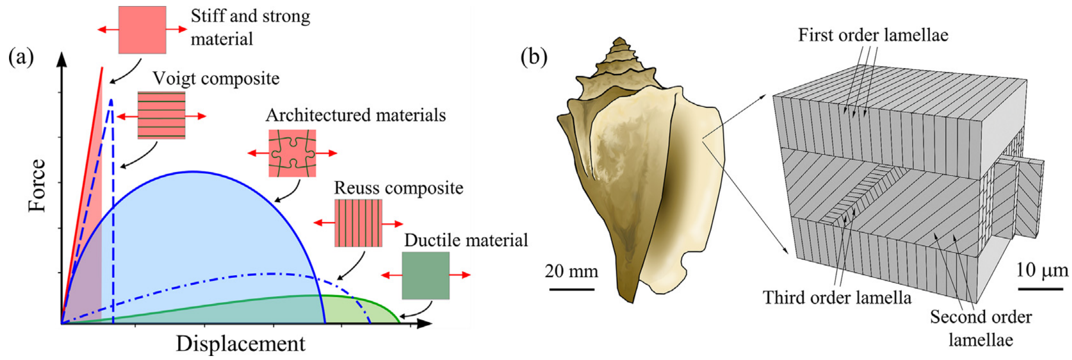

Fig. 1. (a) Generic force displacement curve for a stiff and strong (but brittle) material, a low-strength ductile material, and for three possible composites of these materials; (b) Cross-ply architectures in conch shell.

the properties of materials, by creating highly controlled material "architectures" at length scales intermediate between the micro-scale and the scale of the component.

This approach provides a promising way to exploit the synergies between constituents in a composite material and to achieve new combinations of properties [4]. Since morphological control is high, the shape, size and arrangement of the building blocks can be tailored to maximize overall material properties and generate new and useful combinations of strength and deformability (Fig. 1a). Interestingly, nature is well ahead of engineers in making use of architectured materials [4]. Materials such as bone, teeth or mollusk shells are also made of stiff building blocks of well-defined sizes and shapes, bonded by deformable organic interfaces. The interplay between the building blocks and the non-linear behaviors at the interfaces generate powerful combinations of stiffness, strength and toughness not yet found in synthetic materials [4,5]. For example, Fig. 1b shows the architecture of conch shells, a remarkable material made of >95% vol. of brittle biominerals with a toughness three orders of magnitude higher than that mineral [6]. The architecture of conch shell consists of a series of cross-plies at different length scales [7,8], where mineral lamellae are separated and adhered by thin organic interfaces. Propagating cracks are deflected and guided by the weaker organic interfaces, which triggers powerful toughening mechanisms such as crack bridging [9,10]. Cross-ply architecture with similar toughening mechanisms can also be observed in the decussation zone of enamel [11]. The organic content in enamel only represents 1–5 wt% content but it contributes substantially to overall toughness [12]. Removing the protein interfaces in enamel can reduce the toughness by 40% [13]. Cross-ply architectures are also found in fish scales [14,15] and arthropod cuticles [16], generating powerful crack resisting mechanisms such as crack deflection, crack twisting, crack bridging, and process zone toughening [14,15,17]. In addition, the interfaces between the fibers in these materials can undergo large deformations [12], so that fibers can rotate and align with the pulling direction, strengthening the material along that direction. While nature presents spectacular examples of cross-ply architectures, attempts to systematically incorporate these bio-inspired designs in synthetic materials have been so far limited [18–20]. Here we combine the concepts of lamination in glass [3], highly controlled material architecture [4], laser-induced weak interfaces [21], highly deformable interlayers [12], and bioinspiration [9,11,22] to generate new types of glass with a superior combination of toughness, deformability and damage tolerance. We examine the effect of the architecture on micromechanics of deformation, overall performance, and fracture mechanics by using combinations of experiments and models.

2. Fabrication protocol

In this study, we used 0.22 mm thick standard borosilicate glass (Fisher Scientific, PA, USA) as the base material, combined with a continuous, 0.15 mm thick adhesive layer. A critical requirement for the adhesive is to be highly deformable at moderate stress in order to promote interlayer shearing over the fracture of the glass layers. To explore possible adhesives, we conducted single lap shear tests on a selection of adhesives using 1 mm thick borosilicate glass substrates. The adhesives were an ethylene-vinyl acetate (EVA, Caida, Tianjin, China), an ionomer (DuPont Surlyn, DE, USA), a cyanoacrylate (Adhesive System, IL, USA) and an epoxy (BMB Solutions Composites, QC, Canada). Force and displacement were converted to shear stress and shear strain using the surface area and thickness of the adhesive layer (Fig. 2). As expected, Cyanoacrylate and epoxy have high shear strength but very low deformability, making them unsuitable for our material. Surlyn show a combination of high shear strength (>10 MPa) and high shear strain at failure (>300%). However, preliminary experiments on the thinner glass slides used in our architectured laminated glass showed extensive damage in glass because Surlyn is too strong. EVA was the most suitable for our material: it is optically transparent, it has strong adhesion on glass, and can undergo large inelastic deformations with energy dissipation. The shear strength of EVA is sufficiently low to promote yielding at the interlayer over brittle fracture of the glass substrates. Fig. 3 shows the fabrication protocol. A pair of plain glass plates was first covered with a heat resistant polyimide (PI) tape (McMaster-carr, IL, USA) to facilitate

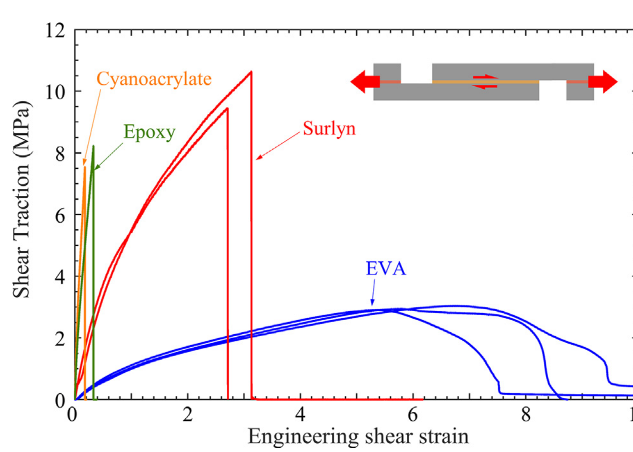

Fig. 2. The shear stress-strain curves from the single lap shear tests on EVA, Surlyn, cyanoacrylate and epoxy. The glass substrates failed in the tests of cyanoacrylate, epoxy and Surlyn.

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