BIOINSPIRED CERAMICS: HARNESSING NATURE'S STRATEGIES FOR IMPROVING INTERFACIAL STRENGTH AND ENERGY ABSORPTION

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ABSTRACT

Ceramic materials, known for their strength, often lack the flexibility and energy absorption required for diverse applications. This study dives into the static and cyclic flexural properties, including energy absorption, stiffness, and strength, of bioinspired ceramic-polymer composites. Specifically, we explore how different micro-patterns influence these properties. Utilizing ultra-short pulsed picosecond lasers in a subtractive manufacturing process, we engrave an array of micro-patterns onto alumina tiles, mimicking the designs found in natural armors. These laser-engraved tiles are then layered with an interlayer of Surlyn®, a commercial monomer, to create the composites. Our findings highlight the intricate relationship between the composites' performance and the bioinspired surface patterns. Certain macro architectures result in significant improvements in energy absorption, with enhancements of up to 85%. These improvements are attributed to mechanisms such as crack deflection, interfacial friction, and plastic deformation of the soft phase. This research not only advances our understanding of natural armor structures but also lays the groundwork for a new era of ceramic composites with superior properties.

1. INTRODUCTION

Ceramics are vital materials across various industries, prized for their exceptional thermo-mechanical properties, hardness, durability, and low electrical conductivity. However, their inherent brittleness presents a significant challenge, limiting their damage tolerance. Despite efforts to enhance impact resistance and toughness through strategies like nano-material dispersion and microstructure control, significant improvements have been elusive [1-5].

In materials like nacre, significant energy dissipation occurs due to inelastic deformations around cracks, a primary toughening mechanism. Complex interfaces in natural materials lead to outstanding combinations of stiffness, strength, and toughness. For instance, the heterogeneous architecture of beetle cuticles initiates localized toughening mechanisms, enhancing mechanical performance while reducing weight [6-10].

Recent efforts have integrated bioinspired architectures with ceramics to achieve optimized stiffness, strength, and toughness balances. However, unlocking the full potential of bioinspired materials requires scalable manufacturing technologies capable of producing complex structures [11-15]. To address this, we've developed a digital manufacturing platform enabling precise control over 3D architecture, including micro-pattern cut depth. This platform fabricates multilayered ceramic composites with bioinspired hard building blocks and soft interlayers. Through experimental investigation, we compare the static and cyclic mechanical performance of these ceramics with and without patterns. This innovative approach yields a new class of ceramics offering predictable, high-performance responses, essential for advanced composite development [16-18].

2. MATERIALS AND METHODS

2.1. Material Fabrication

High-tolerance nonporous alumina ceramic tiles (96-99.8% Al_2O_3, 3875 kg/m^3 density, McMaster-Carr, No. 8462 K45) with a thickness of 635 µm serve as the rigid component. A 100 µm thick Surlyn® thermoplastic film acts as the soft polymer interface between the ceramic tiles. Four beams are created by circular diamond saw-cutting the ceramic tiles, each measuring 25 mm wide and 114 mm long. Laser machining is performed on the tiles before lamination, using established parameters for alumina laser machining. An Ytterbium picosecond fiber laser (YLPP-25-3-50-R, IPG Photonics, USA) with 50 W maximum average power, emitting 3 ps pulses at 1030 nm wavelength, is used. The laser can operate at up to 1.83 MHz repetition rate and generates a Gaussian beam profile.

A 45° oriented micro-pattern (Figure 1a) and a hexagonal pattern penetrating the entire ceramic thickness with 5 mm length (Figure 1b) are applied. The micro-patterns, designed for precise surface engraving, achieve a depth of 20 µm in a single pass with a 200 µm kerf width matching the spacing between patterns. Each beam consists of two ceramic tile layers with the same engraved hexagonal pattern and an intermediate Surlyn® layer. One group of beams includes micro-patterns, while the others do not. Components are assembled using vacuum bagging and subjected to a 5-hour heat treatment at 146 °C for proper bonding and desired properties.

2.2. Experimental Setup

All specimens undergo 3-point bending tests with an 80 mm fixed span length (Figure 1e). In static tests, a constant displacement control at 1.3 mm/min rate is applied until 12 mm deflection. For cyclic tests, a combined control strategy is used. Loading phase maintains a 6 mm/min rate for 1 mm/cycle over 12 cycles. The control mode transitions to load control during unloading to capture specimen behavior under cyclic loading, providing a comprehensive assessment of material response in static and cyclic conditions.

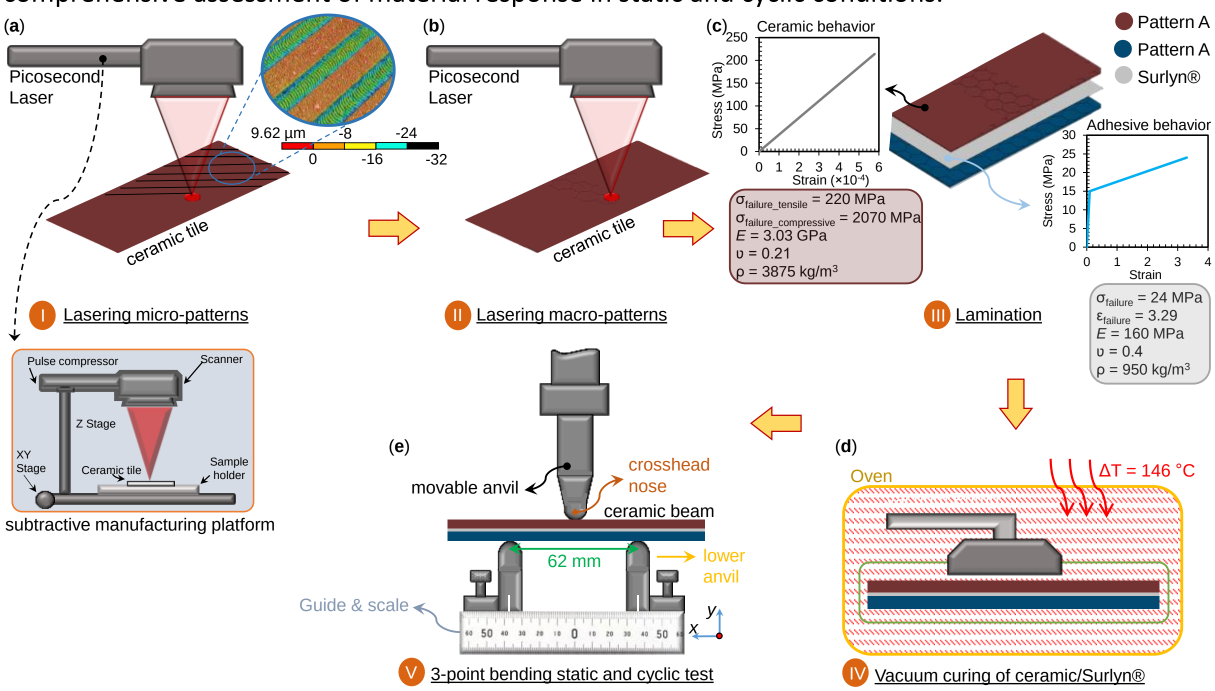

Figure 1. The manufacturing process of the bi-layer architectured ceramic beams: (**a**) Micro-patterning of ceramic tiles using the picosecond laser and subtractive manufacturing platform, (**b**) Macro-patterning of ceramic tiles using the picosecond laser, (**c**) Lamination of ceramic tiles and commercial monomer Surlyn, (**d**) Vacuum bagging and curing of ceramic composite beams, and (**e**) Configuration for static and cyclic 3-point bending tests.

3. RESULTS AND DISCUSSION

The architectured ceramic beams were subjected to 3-point bending static load testing to evaluate the impact of stacking sequences (Back-to-back (BB), Side-down (SD), Side-up (SU), and Face-to-face (FF)), along with micro-patterns, on their mechanical performance. The main parameters assessed included maximum load, flexural stiffness, and energy absorption. The energy absorbed by the structures in the static analysis was determined by the area under the force-displacement curves, while the cyclic analysis was represented by the loop area.

3.1. Static Loading

Figure 2 shows how micro-patterns significantly enhance the ceramics' mechanical properties under static load. Micro-patterns improve energy absorption, with Ceramic FF increasing by up to 140%. Maximum load is also boosted, with Ceramics SD and FF increasing by up to 140% and 130%, respectively. Flexural stiffness sees notable improvements, particularly in Ceramics FF (up to 300%) and SD (up to 80%).
Enhancements stem from:

1. Enhanced interfacial bonding: Micro-patterns strengthen bonding between ceramic units, improving cohesion and robustness.
2. Optimized stress distribution: Specific micro-patterns disperse stresses more evenly, reducing localized failure risk and improving overall strength and stiffness.

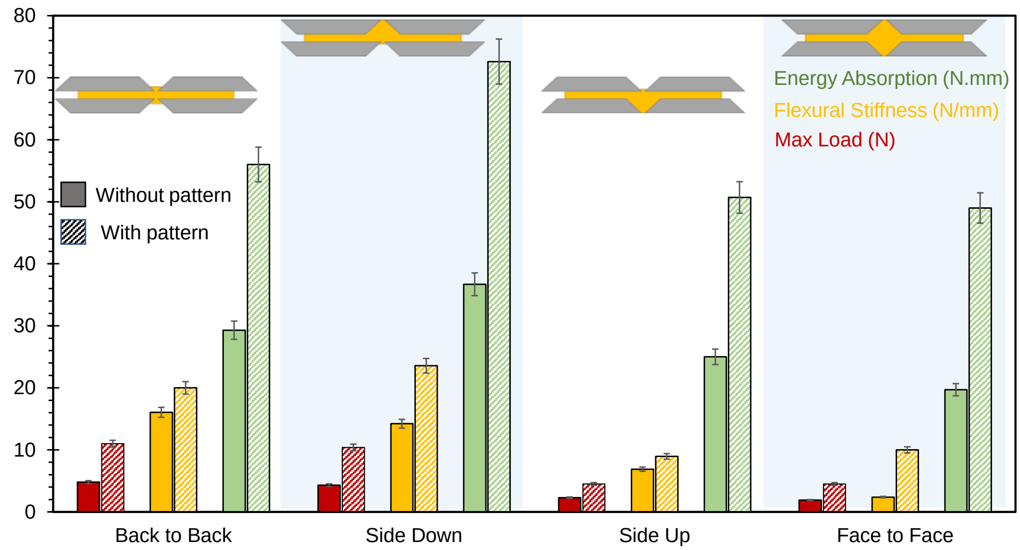

Figure 2. Static 3-point bending mechanical performance of the architectured ceramic beams with different stacking sequences (Back-to-back (BB), Side-down (SD), Side-up (SU), and Face-to-face (FF)) and micro-patterns: Maximum load, flexural stiffness, and energy absorption of the ceramics under static load with and without micro-patterns.

3.2. Cyclic Loading

Figure 3 illustrates the hysteresis force-deflection curves of architectured ceramic beams with varying stacking sequences (BB, SD, SU, and FF) and micro-patterns. Introducing micro-patterns on ceramic surfaces generally enhances the cyclic mechanical performance of the multilayered ceramic beams, improving both energy absorption and stiffness. However, the extent of this enhancement varies among the different stacking sequences. Notably, micro-patterns had a significant impact on Ceramics FF and SU, where Surlyn primarily influences the mechanical characteristics (controlled by shear force), emphasizing their role in these enhancements. For instance, the total cyclic energy absorption for Ceramic FF increased by up to 85%, whereas for Ceramic BB, this improvement was only 14%, as shown in Figure 3. Several factors contribute to the varying improvements in cyclic mechanical performance with the introduction of micro-patterns:

Interfacial bonding enhancement: Micro-patterns promote better bonding between ceramic units and the Surlyn matrix, improving load transfer and energy dissipation. This bonding is particularly beneficial for Ceramic FF, enhancing adhesion and interaction between layers.

Crack deflection and propagation: Certain micro-patterns, like grooves or ridges, act as crack arrestors, deflecting cracks and preventing propagation. Ceramic FF may benefit more from crack deflection mechanisms due to its configurations.

Stress redistribution: Micro-patterns redistribute stress concentrations, preventing localized high-stress areas that could lead to failure. Ceramics FF, SU, and SD with intricate micro-patterns may show more significant improvements in stress redistribution compared to Ceramic BB.

Energy dissipation pathways: Micro-patterns create additional pathways for energy dissipation, allowing the material to absorb more energy before failure. Unique patterns on Ceramic FF offer effective pathways for energy dissipation.

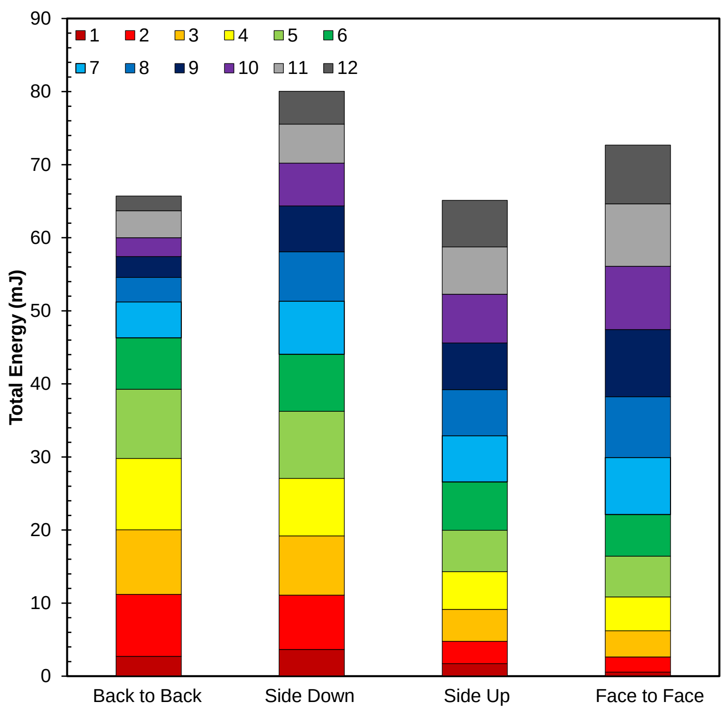

Figure 3. Cyclic 3-point bending mechanical performance of the architectured ceramic beams with different stacking sequences (BB, SD, SU, and FF) with micro-patterns: Total energy absorption as well as energy absorption, flexural stiffness, and plastic deformation of each cycle.

After cyclic 3-point bending tests, each ceramic system exhibited plastic deformation, evident in the increase in residual deflection with each cycle. Up to the third cycle, all ceramic groups, micro-patterned or not, showed similar levels of plastic deformation. Beyond this point, Ceramics BB and SD underwent significantly greater plastic deformation, indicating enhanced energy dissipation mechanisms and damage accumulation. Conversely, Ceramics FF and SU displayed higher durability and resistance to plastic deformation but lower energy dissipation capabilities under cyclic bending. Micro-patterned specimens exhibited comparable plastic deformation levels but at higher load capacities, suggesting improved interfacial strength and stress distribution.

4. CONCLUSION

In this study, we investigated bioinspired ceramic-polymer composites' static and cyclic flexural properties using an advanced subtractive manufacturing platform. Alumina tiles were engraved with micro patterns and stacked with Surlyn® interlayers to create the composites. Micro-patterns significantly improved properties, enhancing energy absorption, maximum load, and flexural stiffness. Ceramic FF showed up to 85% more cyclic energy absorption due to crack deflection, better bonding, stress distribution, and energy dissipation. Cyclic behavior insights showed FF's stability, SD and BB's higher energy dissipation potential, and BB's initial energy absorption loss. In summary, micro-patterns further improved properties, particularly in energy absorption and bonding. This study highlights tailoring ceramic properties for various applications by choosing stacking sequences and micro-patterns carefully.

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