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COMMENTARY

# Design achieving flexibility in ceramics through organic-inorganic hybrids and interfacial bond switching

**Bochao Xie[1,*] and Mengxi Zhao[2]**

[1]Department of Mechanical Engineering and Materials Science, Yale University, New Haven 06520, USA

[2]School of International Arts, Dalian University of Foreign Languages, Dalian 116044, China

*Correspondence: bochao.xie@yale.edu

Received: September 15, 2025; Accepted: October 24, 2025; Published Online: November 7, 2025; https://doi.org/10.59717/j.xinn-mater.2025.100167

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Citation: Xie B. and Zhao M. (2025). Design achieving flexibility in ceramics through organic-inorganic hybrids and interfacial bond switching. *The Innovation Materials* **3**:100167.



Ceramics have long been constrained by their inherent brittleness, a property that has prevented their integration into flexible and adaptive technologies despite their unrivaled thermal and chemical robustness. Recent breakthroughs have begun to dismantle this paradigm. People used distinct strategies, one hybrid and the other interfacial. This Commentary analyzes the mechanistic insights from these two seminal works, highlights their convergence toward a new conception of ceramics as flexible systems, and outlines the challenges that must be addressed to translate these discoveries into scalable and durable technologies.

## CERAMICS CHANGED

Ceramics represent one of the oldest classes of engineered materials, celebrated for millennia for their ability to withstand heat, corrosion, and wear. Their modern incarnations underpin aerospace, energy, biomedical implants, and protective coatings. Yet these advantages are bound to a fundamental flaw: brittleness. The inability to deform without fracture relegated ceramics to rigid domains and excluded them from flexible and conformal applications.

Attempts to overcome this brittleness traditionally relied on two approaches: designing composites where ceramics are embedded in ductile matrices or applying architectural strategies such as foams and lattices that mitigate fracture through geometry rather than intrinsic flexibility. Both methods, while useful, treat ceramics as unchangeably brittle and instead circumvent the problem externally.

The last two years have seen a striking departure from this mindset (Figure 1). Scientists showed that ceramics themselves can be made flexible through molecular or interfacial design.[1] People created "elastic ceramic plastics" by fusing organic and inorganic components at the molecular level, demonstrating elasticity in a material long considered incompatible with compliance.[2] discovered that coherent interfaces in silicon nitride could undergo bond switching, imparting plasticity without additives or secondary phases. These works signal not incremental advances but a conceptual rupture: brittleness is no longer inevitable, but a tunable property.

## INTERFACIAL PLASTICITY IN SILICON NITRIDE

Zhang and colleagues pursued a radically different approach, remaining within the realm of pure ceramics[1]. They investigated silicon nitride; a material long regarded as brittle despite its widespread industrial use and identified a hidden source of compliance: coherent interfaces between dual crystalline phases.

The mechanism centers on bond switching at these interfaces. Under applied stress, bonds at the coherent boundary do not fracture catastrophically but instead undergo reversible rearrangements. This process allows localized plastic flow within the ceramic lattice itself, dissipating energy without the propagation of cracks. Unlike external additives or organic linkers, this strategy relies on exploiting the intrinsic structural complexity of ceramics.

Mechanistically, the key lies in the reduced energy barriers at coherent interfaces. Atoms at these boundaries occupy configurations more amenable to bond exchange, creating pathways for deformation that are inaccessible in homogeneous crystalline phases. By tuning phase coexistence and interface density, the researchers achieved plasticity in a system previously assumed to be irredeemably brittle.

This discovery establishes that brittleness is not absolute but conditional. Ceramics can deform plastically if their interfaces are engineered to facilitate stress-induced bond reconfiguration. The advantage of this approach is its preservation of ceramic purity: no organic phases, no external modifiers, only crystallographic design. However, the limitations are equally clear. The effect depends critically on specific compositions and engineered dual-phase architectures. Extending this mechanism to other ceramics will demand precise control of processing, microstructure, and stress environments.

## MOLECULAR HYBRIDES AND ELASRTIC CERAMIC PLASTICS

Fang and colleagues approached brittleness at chemical bond. Traditional ceramics rely on dense networks of covalent and ionic bonds, which resist plastic flow but also prohibit reversible deformation.[2] introduced elasticity by embedding organic moieties into this rigid framework, creating covalentionic molecules that function simultaneously as ceramic backbones and elastic linkers.

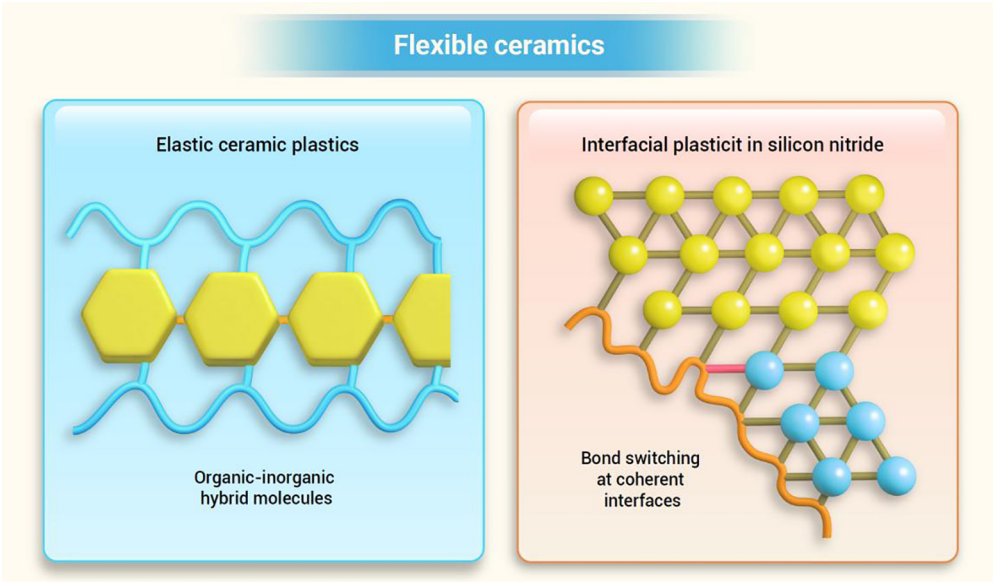


**Figure 1. Comparison of two major approaches toward achieving flexibility in ceramics.**

The mechanism hinges on the rotational and translational degrees of freedom provided by organic bonds. While ceramic covalent–ionic linkages anchor the structure with mechanical robustness and thermal stability, the organic segments act as hinges, dissipating stress through bond rotation rather than fracture. This bond-level design transforms brittle fracture into elastic recovery. Unlike composites where organic and inorganic phases are simply blended, these materials are unified at the molecular scale, ensuring intimate mechanical coupling and homogeneous response.

The implications extend beyond flexibility. By retaining significant ceramic content, these elastic plastics inherit chemical inertness and heat resistance unavailable to polymers alone. At the same time, the processability of the hybrids resembles that of organic materials: they can be cast, molded, or shaped into thin films. The study demonstrates that ceramics need not be excluded from flexibility but can be rewritten at the level of chemical architecture to express elasticity as an encoded property.

Still, this pathway reveals its own boundary conditions.[3,4] The flexibility originates in the organic fraction, raising questions about stability under extreme temperatures or corrosive environments. The ceramic phase ensures structural integrity, but the long-term endurance of hybridized bonds remains untested. Furthermore, while the materials achieve compliance, they do so by redefining ceramic as a hybrid entity, inviting debate over whether they constitute ceramics in the traditional sense.

## CHALLENGES AND FUTURE DIRECTIONS

Together, their studies mark a redefinition of ceramics, but their implications raise urgent questions. The first concerns durability. Elastic ceramic plastics rely on hybrid molecular linkages whose long-term thermal and chemical resilience remains uncertain. Interfacial plasticity, while intrinsic, must demonstrate endurance under cyclic loading, fatigue, and environmental extremes. Both approaches must prove that flexibility is not transient but stable across lifetimes relevant to devices.

A second challenge is functional integration. Ceramics are prized not only for mechanical strength but also for properties such as electrical insulation, ionic conductivity, or catalytic activity. Introducing organic components or manipulating porosity and interfaces may compromise these functions. Balancing flexibility with functionality requires predictive models capable of mapping the multi-dimensional performance space of ceramics.

Scalability presents another obstacle. Hybrid ceramics must be synthesized with molecular precision at industrial volumes, while interface-driven ceramics require tight control over phase composition and microstructural uniformity. Translating these laboratory successes into manufacturing processes will test the limits of existing ceramic processing technologies.

Perhaps the most profound challenge is theoretical. The mechanics of flexible ceramics cannot be captured by classical brittle fracture models. Neither the hybrid bond-rotation mechanisms of elastic plastics nor the interfacial bond-switching processes of silicon nitride conform to established constitutive frameworks. A new theory is needed—one that unifies chemistry, crystallography, and microstructure into a coherent description of ceramics that are neither brittle nor ductile but flexibly adaptive.

These questions are not merely technical but conceptual. If ceramics can bend, their role in technology must be reconsidered. They could underpin wearable electronics capable of withstanding sweat and heat, sensors embedded in turbines that conform to curved surfaces under vibration, or robotic systems operating in environments lethal to polymers.

## CONCLUSION

The path toward flexible ceramics has begun with two milestones. Both converge on insight that brittleness is not immutable but designable. For centuries, ceramics were defined by rigidity. These studies prove otherwise. The challenge now is not to ask whether ceramics can flex but to determine how their flexibility can be stabilized, scaled, and integrated. The future of ceramics lies not in abandoning their identity but in expanding it, allowing rigidity and flexibility to coexist. In this reimagined landscape, ceramics are no longer confined to brittle service but become active materials for adaptive, intelligent systems.

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## FUNDING AND ACKNOWLEDGMENTS

There is no funding needed to report.

## AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no conflicts of interest.