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Editorial:Tackling the multiscale phenomena of soft materials for engineering innovations

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Editorial on the Research Topic
Tackling the multiscale phenomena of soft materials for engineering innovations

The study of soft materials is a cornerstone of materials science, playing a pivotal role in advancing the "Materials 4.0" era, which is expected to drive the fourth industrial revolution (Zhai et al., 2020). Globally, initiatives like the Materials Genome Initiative (MGI) in the United States (US) are at the forefront of addressing critical material challenges. Soft materials have diverse and complex properties—ranging from amorphous to hierarchical structures—and hold immense innovation potential (Shi et al., 2022). However, their full exploitation is hindered by an elusive process-structure-property relationship, which remains a significant barrier to their application across various engineering fields. Despite this, advancements in computational capabilities and experimental techniques are paving the way for breakthroughs.

1 The promise and challenges of soft materials

Soft materials and composites have garnered significant attention due to their intriguing properties and vast, yet complex, design space. These materials exhibit unique physical and mechanical properties that span multiple spatiotemporal scales—from nano- to macro-levels. However, the lack of a comprehensive understanding of these multiscale phenomena limits their potential to contribute to human society. The intrinsic complexity of soft materials arises from their ability to exhibit behaviors at different scales, which are often difficult to capture and model accurately. This complexity necessitates multiscale experiments and modeling and simulation techniques, which are now more feasible due to advancements in computational power and experimental methods.

2 The role of multiscale understanding

The process-structure-property relationship is central to materials science, yet soft materials remain poorly understood. This relationship governs how the processing of a material influences its structure, and how that structure, in turn, determines its properties.

For soft materials, this relationship is particularly elusive due to the interplay of phenomena across different scales. For instance, the behavior of a material at the nano-scale can significantly influence its macroscopic properties, but capturing this interplay requires sophisticated experimental and computational tools.

To address this, researchers are increasingly turning to multiscale modeling and simulation, which allows for the examination of material behaviors across different scales—nano-, micro-, meso-, and macro-scale. These techniques are complemented by artificial intelligence (AI) and machine learning (ML) methods, which are revolutionizing the discovery of new materials. AI and ML enable the efficient screening of material candidates, reducing the need for resource-intensive trial-and-error processes. This approach is particularly valuable in identifying materials with optimal properties for specific engineering applications, such as mechanical (Zhai et al., 2021), civil (Zhai et al., 2022d), chemical (Martin et al., 2021), biological (Lin et al., 2015; Yeo et al., 2018), thermal (Lin et al., 2019), or sports engineering (Li and Zhai).

3 Global initiatives and scientific projects

The challenges posed by soft materials are not unique to any single country. Recognizing the importance of materials science in driving technological advancements, many nations have launched scientific projects aimed at understanding the fundamental theories behind materials and solving practical engineering challenges. The MGI in the US is a prime example of such an effort. The MGI seeks to accelerate the discovery and deployment of advanced materials by integrating computational tools, experimental data, and collaborative research.

Similarly, other countries are investing in research to explore the potential of soft materials. These materials are particularly promising because they significantly expand the design space for engineering materials. Their multiscale structures—ranging from entirely amorphous to highly ordered, hierarchical arrangements—yield physical and mechanical properties that surpass those of conventional materials. Moreover, the study of soft materials is accelerating the discovery of bio-inspired materials, which mimic natural structures and processes to achieve superior performance.

4 The need for mechanistic studies

Despite the promise of soft materials, the lack of understanding of their process-structure-property relationship remains a significant impediment to their development. This gap in knowledge limits the ability to design new materials with tailored properties for specific applications. To overcome this, researchers are focusing on mechanistic studies that aim to elucidate the underlying principles governing the behavior of soft materials. These studies involve a combination of experimental techniques, computational modeling, and AI-driven approaches to uncover the fundamental mechanisms at play.

In this Research Topic, there are various endeavors on the above-mentioned topics. Li et al. simulate the viscoelastic natural plant fibers (Li et al.) with the Mori-Tanaka micromechanics model, viscoelasticity theory, and Zakian's inversion method and examine the impact of plant fiber microstructure on the viscoelastic behavior of multiscale structures. Liu et al. establish a multiscale mechanical model of a composite rocket motor case (CRMC) and enable data transfer among the microscale, mesoscale, and macroscale models with submodel techniques (Liu et al.); they predict the microscale material damage failure behavior under the internal pressure load of the composite shell by obtaining the material stress levels at macroscale, mesoscale, and microscale scales. Fu et al. prepare fluid solidified soil using ammonia alkali white mud, mineral powder, and fly ash (Fu et al.), revealing the structure-property relationship that can develop a good pore structure. Li and Zhai review various environment-friendly materials that can construct sports facilities, which offer sustainable alternatives to traditional construction materials (Li and Zhai). The mentioned materials in these studies are increasingly being used in polymer, and composite materials due to their sustainability and mechanical properties which are critical for mechanical (Zhai et al., 2022a), aerospace (Liu et al.), civil (Zhai et al., 2022c, 2022f; 2022b, 2022e), electrical (Zhai et al., 2018), and other applications.

5 Applications in engineering and beyond

The potential applications of soft materials are vast and span multiple engineering disciplines. In mechanical engineering, soft materials are being explored for use in flexible electronics, soft robotics, and wearable devices. In civil engineering, they are being used to develop environment-friendly materials for constructing sports facilities and other infrastructure. In chemical engineering, soft materials are being used to develop advanced coatings, adhesives, and membranes with tailored properties. Meanwhile, in sports engineering, the focus is on creating materials that enhance performance while minimizing environmental impact. The use of soft materials in these fields is driven by their unique properties, such as flexibility, durability, and the ability to be engineered at multiple scales.

6 The future of soft materials research

As we move closer to the fourth industrial revolution, the importance of soft materials in driving technological innovation cannot be overstated. The integration of multiscale modeling, AI-driven material discovery, and advanced experimental techniques is expected to unlock new possibilities for these materials. By gaining a deeper understanding of the process-structure-property relationship, researchers will be able to design materials with unprecedented properties, paving the way for breakthroughs in various engineering fields.

In conclusion, soft materials represent a Frontier in materials science with the potential to revolutionize multiple industries.

However, realizing this potential requires a concerted effort to overcome the challenges posed by their complex, multiscale nature. Through global initiatives like the MGI and the continued advancement of computational and experimental techniques, we are inching closer to a future where soft materials play a central role in shaping the technologies of tomorrow.

Author contributions

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