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学 位 論 文 の 要 約

博士の専攻分野の名称　博士（ソフトマター科学）　氏　名　　魯 非雪　(Feixue Lu)

学 位 論 文 題 名

Study on Effects of Network Topology and Chemistry on Tensile Behaviors of Double Network Gels
（網目構造のトポロジーと化学構造がダブルネットワークゲルの引張力学特性に及ぼす影響に関する研究）

Understanding the factors that influence the mechanical performance of hydrogels is critical for optimizing their design and facilitating their application in biomedical devices, soft robotics, and structural materials. In this doctoral dissertation, I have systematically investigated how the topological and chemical structures of the first network and the extensibility of the second network affect the tensile and fracture behaviors of double network (DN) hydrogels. These studies provide valuable insights into the mechanics of DN hydrogels and introduce new strategies for their further enhancement.

In Chapter 3, the focus is on how the topology and chemical structure of the first network influence the tensile behavior of DN hydrogels. By varying the monomer and crosslinker concentration of the first network while keeping the second network constant, four distinct categories of tensile behaviors were observed: brittle, tough, optimized, and over-supported DN gels. These categories arise from the balance of strength between the two networks, quantified by the strand density ratio $\nu_{e,2}/\nu_{e,1}$. Additionally, universal scaling relationships were established between key tensile parameters (e.g., yield stress, yield stretch ratio, plateau stress, hardening stretch ratio, strain-hardening degree, and fracture stress) and the strand density of the first network. These findings indicate that mechanical behavior of DN gels is primarily governed by the topological structure, independent of chemical structure of the first network. While chemical structure influences monomer interactions, topology plays a more critical role in determining the overall integrity and the force distribution patterns of the material. These findings provide a theoretical framework for tailoring DN gels to achieve specific mechanical properties, from high toughness to controlled brittleness, by adjusting the relative strength of the two networks.

In Chapter 4, the effects of the extensibility and strand density of the second network on the fracture behavior and effective crack length of the first network were investigated by systematically altering the crosslinker concentration of the second network while keeping the first network constant. The introduction of the second network was found to significantly reduce the effective crack length c_{DN} of the first network by mitigating stress concentrations at crack tips, with c_{DN} being three orders of magnitude smaller than in single network gels. Microscopically, the second network redistributes stress within the first network, with molecular chains bridging crack sites and alleviating stress concentrations at crack tips. Additionally, it was found that as the second network becomes stiffer and less extensible, the fracture mode of the first network transitions from localized yielding-dominated fractures to macroscopically uniform deformation. The underlying mechanism lies in the ability of the stiffer second network to distribute stress more evenly throughout the material, preventing the accelerated fracture of the first network caused by local stress concentrations. However, reducing the extensibility of the second network also decreases the overall elongation of DN gels. These results highlight the crucial role of the second network in controlling the fracture behavior of the first network and optimizing the performance of DN gels.

This dissertation provides a comprehensive understanding of the complex mechanical mechanisms governing the tensile and fracture behavior of DN hydrogels. It elucidated how the topology and chemistry of the network affect the mechanical properties of DN gels. These insights not only advance the understanding of DN hydrogel mechanics but also offer new design strategies for developing functional hydrogels with high toughness, efficient energy dissipation, and controllable fracture behavior.

However, this dissertation primarily focuses on uniaxial tensile deformation, but the mechanical behavior of DN hydrogels may exhibit significant differences under various deformation modes, such as compression and biaxial stretching. These deformation modes could further elucidate the interactions between network structures under complex loading conditions. For instance, previous studies have observed distinct anisotropic damage characteristics and significant damage cross-effects in DN hydrogels through biaxial stretching

experiments. Future investigations into these deformation modes are expected to deepen the understanding of the mechanical responses in DN hydrogels, particularly with regard to their internal fracture mechanisms and anisotropic damage features.