Self-reinforced hydrogels toughen upon stretching

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In a recent work in *Science*, a team led by Mayumi and Ito at the University of Tokyo, Japan developed self-reinforced hydrogels upon deformation. These hydrogels showed high toughness, good stretchability, and high fatigue resistance after a hundred (un) loading cycles.

In the human body, tendons that connect muscles to bones need to remain tough, stretchable, and highly durable to sustain repetitive body movements.[1] Synthetic polymeric materials such as hydrogels have yet to match the mechanical features of biomaterials such as tendons in all dimensions. These hydrogels are often too weak or too brittle to persist against strong and repeated mechanical stress.

Scientists have been looking into this problem for decades, and they have synthesized new materials and developed different engineering methods to strengthen hydrogels. For example, a double polymer network design was introduced to increase the hydrogel toughness, in which a rigid polymer network is penetrated into a flexible network.[2] When the hydrogel is stretched or compressed, the rigid network is sacrificed to absorb the energy of the external force, but the toughness of the hydrogel decreases upon cycles of use. To address this problem, a noncovalently crosslinked network is introduced to replace the rigid covalent network in the double network design.[3] The noncovalent network deforms upon stretching and reforms when the force is removed, although the reformation process takes time and the network is not always fully recovered.

On the other hand, scientists have also invented new polymer materials with enhanced stretchability consisting of mobile slide-ring crosslinkers[4] and slidable coordination joints.[5] These materials can be stretched more than ten times their original size,[6] but they are considerably softer compared to those double network hydrogels. Among these stretchable hydrogels, the slide-ring polymers are unique; unlike conventional crosslinked polymers with fixed crosslinking points, the slide-ring polymers have highly mobile cross-linkages (Figure 1A). Therefore, slide-ring polymers can self-adjust their crosslinking density to the environmental change. For instance, when a slide-ring gel is swelled in water, the rings can move along the axle polymer to allow the network to expand to its maximum (Figure 1A, bottom).

The discovery of slide-ring network topology is exciting, but the first version of the slide-ring hydrogel has its limitations, which could be explained by knowing how they are made.[4] Slide-ring polymers use two key components: a ring-shaped molecule cyclodextrin, and a linear axle polyethylene glycol (PEG). When multiple cyclodextrins are threaded onto a PEG followed by an end group capping step, a polyrotaxane is formed (Figure 1A). Next, the cyclodextrins on the neighboring polyrotaxanes are linked to form the slide-ring polymer. Ideally, the number of cyclodextrins should be kept low, but it is synthetically challenging to do so. In addition, these threaded cyclodextrins are attractive to each other via hydrogen bonding interactions, limiting their mechanical performance in bulk.

Hydroxypropyl modifications of the cyclodextrin first addressed the ring aggregation problem,[6] and the control of cyclodextrin threading number was achieved recently through an enzymatic approach.[7] Very recently, Mayumi, Ito, and coworkers[8] reported a significant breakthrough to enhance the mechanical performance of slide-ring polymers, in which strain-induced PEG crystallization was discovered to reinforce slide-ring hydrogels upon stretching (Figure 1B).

In Mayumi and Ito's design, the coverage of threaded cyclodextrins is kept at only 2% to PEG to maximize the ring threading distances. A long PEG chain of 35 kDa is used as the axle. The cyclodextrin crosslinkers are randomly distributed along the PEG chain at a relaxed state, separating a long PEG into 6–7 segments of similar sizes. When stretched, the mobile cyclodextrin crosslinkers are pulled apart to expose a long PEG backbone. These high-molecular-weight PEGs are aligned to the direction of the force applied, triggering a fast PEG crystallization. The van der Waals interactions between the crystallized PEGs greatly enhance the mechanical toughness of the slide-ring hydrogel. When the force is removed, the crystallized PEGs return to their coiled state, which allowed the rings to move back. The research team confirmed the strain-induced crystallization through small- and wide-angle X-ray diffraction analyses. Impressively, after more than 100 cycles of mechanical loading and unloading, the hydrogel recovered instantly and showed almost no performance loss!

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https://doi.org/10.1016/j.matt.2021.06.048

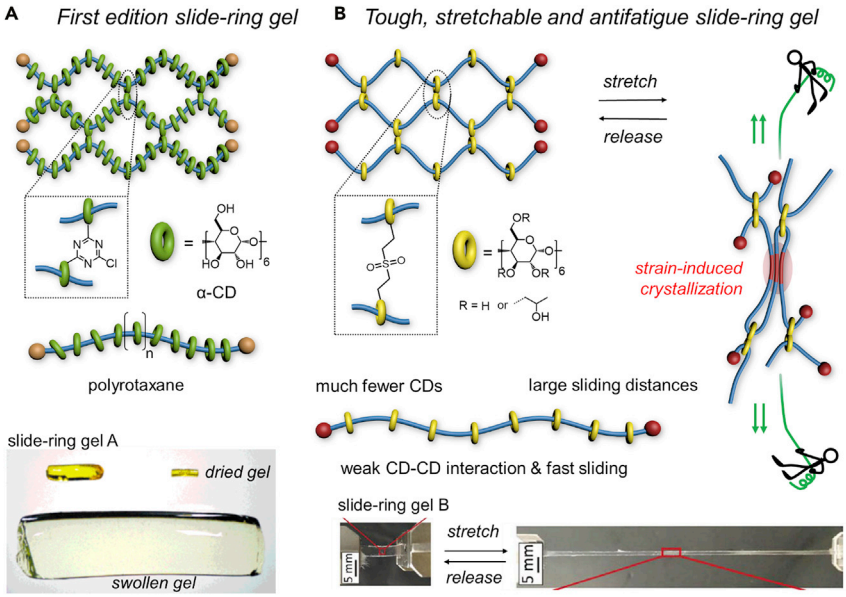

Figure 1. Strain-induced crystallization in toughening the slide-ring polymer

(A) First version of the slide-ring hydrogel and its large swellability in water. A large number of cyclodextrins (CDs) are threaded onto the PEG, which limited the extension of CD sliding motions. Photo reproduced with permission from reference.[4] Copyright 2001, John Wiley and Sons.

(B) The newly discovered slide-ring polymers with fewer CDs and a long PEG. When the hydrogel is stretched, the sliding of CDs exposes the long PEG segments, which crystallize rapidly to strengthen the hydrogel. Photo reproduced with permission from reference.[8] Copyright 2021, The American Association for the Advancement of Science.

The discovery of ring-sliding enabled polymer crystallization under mechanical stress opened up a new path to design hydrogels with outstanding mechanical properties. Future advancement of slide-ring polymers such as synthetic methods to control the cyclodextrin threading number (instead of using enzymes) and introducing repulsive macrocyclic molecules as ring components and other semi-crystalline polymers as axles will make the slide-ring polymers stronger and more cost-effective for a sustainable future.

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