【Grant-in-Aid for Scientific Research (S)】

Creation of Functional Structures through Strategic Destruction

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Purpose and Background of the Research

●Outline of the Research

It is widely recognized that the elimination of microscopic defects is critical to achieving high performance in materials. In terms of mechanical properties, during deformation, stress is concentrated in the defective structure, resulting in fracture at a lower strength than originally expected. In polymeric materials, crazing, which forms when the polymer breaks, is a cause of reduced mechanical properties, and much research has been conducted to suppress crazing. However, the principal investigators have come up with the idea of adding functionality to materials by actively utilizing fractures, rather than pursuing higher performance by preventing them. By controlling the location and growth of fractures, they aim to obtain regular cracks and creases. In the chemical field, bottom-up material creation has been achieved by utilizing Self-Assembly. We propose a top-down approach of destructive assembly, in which new materials are created by inducing controlled fracture in materials.

Figure 1. Concept of Destructive Assembly

●Practicing Destructive Assembly: Solvent Fragility of Cross-Linked Polymers

Destructive assembly consists of two physical chemistry fusions: 'A: Design of mechanical strength at the nanoscale' and 'B: Active use of external stimuli'. Cross-linked polymer materials are used as a stage for the idea of material transformation by degradation and destruction according to intention. The research representatives have succeeded in generating a porous structure along the cross-linking by applying a solvent with a suitable solubility to a glassy polymer periodically cross-linked at intervals of several hundred nm (fig2). Since the characteristic feature is a fibrillar structure that bridges the cracks, it is named Organized Micro-fibrillation (OM) process. The destructive assembly in this OM process is established by 'A: Cross-linking according to light interference' and 'B: Swelling degradation by solvent', and it has been proven to be an optimal means of destruction control.

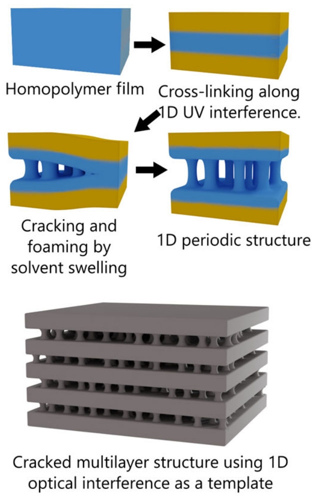

Figure 2. Designed crack-like porous structures in designed crosslinked polymers

●Background

The idea of controlling cracks and patterning them has been attracting a lot of attention in recent years. However, they are all primitive and mm-scale, far from the precision that self-assembly materials have achieved. The research leader and his colleagues are convinced that if they can freely control nm cracks in this project, they will have a great impact on the world. The OM process that uses destruction and degradation for structure fabrication was established by JST SAKIGAKE and its results were summarized in Nature (2019). Next, a project that aimed at the fine control of the structure was adopted by JSPS KAKENHI A. The result led to the precise control of crack structures and their application to microfluidic channels, and was published in Nature Communications (2022). However, we have only used the most basic polymers such as polystyrene, and their morphology was limited to forming parallel plate patterns in simple films. If we remove this limitation, we think that we can expand the theory of OM process not only to polymer materials but also to other metals, metal oxides, ceramics, etc., and establish a new methodology for material creation.

Expected Research Achievements

●Expansion of materials to apply OM process

The OM process was established with homopolymers that have crosslinkability as a single component. In addition, we have found in preliminary experiments that the OM process can also be applied to polymer blends that are mixed with non-crosslinking polymers and crosslinking polymers. That is, it is possible to add various sub-materials to the crosslinking polymer as a skeleton. Therefore, we apply the OM process to polymer blends and block copolymers (fig3). We add fillers such as carbon and clay, and analyze the effects of their volume, concentration and dispersion on the OM process.

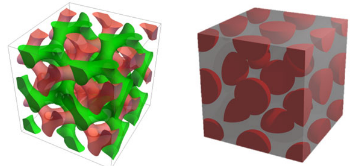

Figure 3. Diverse polymer materials such as block copolymers and polymer composites

●Diversification of morphology of OM process

We attempt to form cracks by cross-linking spherical materials such as polymer colloids, or by cross-linking fibrous materials ejected by electrospinning (fig4). We will form higher-order structures in crack-like materials by packing the colloids to form crystals and assembling the fibers.

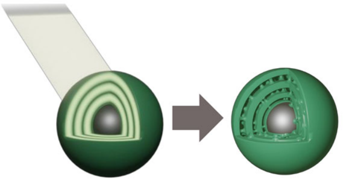

Figure 4. UV interference in morphologies other than thin films

●Exploration of new mechanisms of orderly destruction

Cracks occur in polymers due to rapid expansion and contraction by heat, or mechanical deformation beyond a threshold. We incorporate this mechanism into "designed destruction" and utilize it for structure formation (fig5). We give thermal shock by cooling rapidly after heating a polymer film with a pattern of strength formed by light crosslinking, and form cracks. Or we apply mechanical deformation such as stretching, shearing, bending, twisting, etc. to pattern-crosslinked polymers and try to form cracks. We consider the spatial heterogeneity of polymer materials and the growth of microcracks.

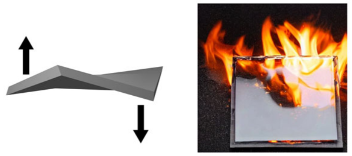

Figure 5: Exploration of fracture mechanisms

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