Doctoral Dissertation Evaluation Review

Degree requested Doctor of Life Science Applicant's name CUI, WEI

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Title of Doctoral Dissertation

Design and Development of Soft Fiber-Reinforced Polymer Composites with Extraordinarily High Crack Resistance
(非常に高い亀裂耐性を示すソフト繊維強化ポリマー複合材料の設計と創製)

Results of Evaluation of the Doctoral Dissertation (Report)

Soft fiber-reinforced polymers (FRPs) are important in many industry applications, including high performance tires. One shortage of existing soft FRPs is the relatively low crack resistance (toughness). Designing soft FRPs with extremely high crack resistance is required.

In this study, the author aims to design and develop soft FRPs with extraordinarily high crack resistance using a novel design strategy, and the author also aims to acquire understanding on a general principle of highly crack-resistant soft FRPs. Thus, three important targets were focused on in the dissertation: 1) Selecting excellent matrices to fabricate extremely tough soft FRPs; 2) Understanding the energy dissipation mechanism of the resulting soft FRPs; 3) Proposing a universal design principle of extremely tough soft FRPs.

For target (1), the author introduced the design strategy of extraordinarily tough soft FRPs by selecting excellent matrices. Viscoelastic matrices that are adhesive, soft, and tough were utilized to combine with commercial fiber fabrics. The author clarified that three key properties of the matrices result in composites showing unique features that are totally different from traditional soft FRPs. The strong adhesion between fibers and matrices enables a strong interface, which ensures both fibers and matrices to dissipate energy over a large area; The softness of matrices gives extremely high fiber/matrix modulus ratio, leading to extraordinarily large energy dissipation zones that are on the order of centimeters; The tough matrices also show energy dissipation density comparable to fibers, contributing to the high energy dissipation density of composites in the dissipation zone.

For target (2), the author elucidated the energy dissipation mechanism of tough soft FRPs by relating their fracture toughness and behavior with sample width. The author found that the soft FRPs show a transition of failure behavior of fiber pullout (region I), to concurrent fiber pullout and fracture (region II), to fiber fracture (region III). In region I, where the sample width is below a characteristic width, w_1, the fracture toughness of the materials is determined by the matrix toughness, fiber geometry, and sample width based on a fiber pullout model. In region II, where the sample width is above w_1 but below another critical width, w_2, the fracture toughness of the materials is initially governed by fiber fracture but then by fiber pullout after a certain number of fibers are broken. In region III, where the sample width is above the w_2, the soft FRPs show an intrinsic size-independent fracture toughness. In this region, the intrinsic fracture energy (Γ) is decided by the force transfer length (l_T) as well as the energy dissipation density (W), as $\Gamma = W \cdot l_T$.

For target (3), the author proposed a universal design principle of extremely tough soft FRPs based on the understanding deduced in target (2), that is, maximizing force transfer length (l_T) and enhancing energy dissipation density (W) simultaneously. The author showed that the force transfer length (l_T) is related to the fiber/matrix modulus ratio while the energy dissipation density (W) results from the volume weighed average work of extension at fracture of the two components. Therefore, the force transfer length (l_T) can be maximized by maximizing the fiber/matrix modulus ratio and the energy dissipation density (*W*) can be maximized by using tough energy-dissipative components. By maximizing both l_T and *W*, the author successfully fabricated composites that showed fracture energy as high as 2500 kJ m^{-2}, exceeding any best-in-class tough materials including metals.

In conclusion, the author has made significant progresses not only in synthesizing, but also on understanding of the soft FRPs. The result will contribute to develop new tough composite materials. Therefore, we acknowledge that the author is qualified to be granted a Doctorate of Life Science from Hokkaido University.