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Nature's Mechanisms for Tough, Self-healing Polymers and Polymer Adhesives¹

PAUL HANSMA, University of California

Spider silk² and the natural polymer adhesives in abalone shells³ and bone^{4,5} can give us insights into nature's mechanisms for tough, self-healing polymers and polymer adhesives. The natural polymer adhesives in biomaterials have been optimized by evolution. An optimized polymer adhesive has five characteristics. 1) It holds together the strong elements of the composite. 2) It yields just before the strong elements would otherwise break. 3) It dissipates large amounts of energy as it yields. 4) It self heals after it yields. 5) It takes just a few percent by weight. Both natural polymer adhesives and silk rely on sacrificial bonds and hidden length for toughness and self-healing.⁶ A relatively large energy, of order 100eV, is required to stretch a polymer molecule after a weak bond, a sacrificial bond, breaks and liberates hidden length, which was previously hidden, typically in a loop or folded domain, from whatever was stretching the polymer. The bond is called sacrificial if it breaks at forces well below the forces that could otherwise break the polymer backbone, typically greater than 1nN. In many biological cases, the breaking of sacrificial bonds has been found to be reversible, thereby also providing a "self-healing" property to the material.²⁻⁴ Individual polymer adhesive molecules based on sacrificial bonds and hidden length can supply forces of order 300pN over distances of 100s of nanometers. Model calculations show that a few percent by weight of adhesives based on these principles could be optimized adhesives for high performance composite materials including nanotube and graphene sheet composites.

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