The thin ribbon silk of the brown recluse spider: structure, mechanical behavior, and biomimicry

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Abstract

Silk has enormous potential as a next-generation material: it is a biopolymer spun from protein at ambient temperature and pressure, and the best spider silks are as strong as steel and tougher than Kevlar. Because of its green production, mechanical robustness, and biocompatibility, silk has been studied for use in a range of engineering and biomedical applications. However, despite exciting recent advances in artificial silk fabrication via recombinant techniques, researchers remain unable to fully replicate the complex assembly and hierarchical structure of native silks. To better understand the fundamentals of natural silk assembly and morphology, we investigated a unique model: the 50 nm-thick, ribbon-like silk spun by the recluse genus of spiders (Loxosceles). The Loxosceles ribbon provided an ideal system for the study of silk structure and displayed surprising characteristics—including a looped metastructure that we found can enhance the toughness of any fiber. First, we characterized the Loxoscles ribbon using high-resolution atomic force microscopy (AFM) imaging and a custom AFM-based mechanical test, revealing a mechanical performance typical of other spider silks, a nanofibrillar substructure, and hitherto undescribed protrusions ("nanopapillae") on the surface. To complement these results, we investigated the flattened silk of the southern house spider, a relative of Loxosceles, and observed both nanofibrils and nanopapillae. We also studied native and redissolved silkworm silk protein that we assembled in vitro, and found nanofibrils only in the native samples. Beyond these studies of fundamental molecular-scale structure, we discovered that Loxosceles weaves its ribbon silk into sequential loops using specialized spinnerets and an intricate spinning mechanism. By performing mechanical tests of looped strands and designing a mechanical model of the system, we found that introducing sacrificial loops into a fiber can significantly enhance its toughness, and we identified which looping and fiber parameters optimize the effect. We then fabricated a proof of concept—a looped strand of tape—and found that it was far tougher than non-looped tape of equivalent length. Thus, our research of thin silk systems revealed both important aspects of silk's core structural constituents and surprising new insights, including the discovery of a looped ribbon metastructure that promises to advance the design of ultra-tough fibers.