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# Knotted synthetic polymer or carbon nanotube microfibres with enhanced toughness, up to 1400 J/g

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## ABSTRACT

In the past 50 years, a number of synthetic polymer microfibres, such as para-aramid or ultra-high-molecular-weight polyethylene, have been developed, exhibiting remarkable strength. However, their toughness is considerably smaller than that of some natural fibres such as spider silk, thus limiting their performance in applications ranging from surgical devices to vehicle parts. Here, we implement a recently proposed strategy, using micro-knots as frictional energy dissipators, to achieve record toughness values of up to 1400 J/g in synthetic microfibres, while maintaining their strength virtually unchanged. The same strategy is also applied to carbon nanotube microfibres, exploiting their superior ideal mechanical strength compared to any other existing fibre at the nanoscale, and toughness improvements of more than an order of magnitude are observed. We also show how knotted nanotube fibre configurations can be optimized for maximum toughness by modifying fibre diameter and twist angle, and how frictional and wear levels can be tuned by varying tightening and number of coils in the micro-knots. The results demonstrate the potential to design and produce fibres and textiles with unprecedented simultaneous strength and toughness for a variety of technological applications.

## 1. Introduction

It is known that many biological structural materials can effectively combine properties that are apparently mutually exclusive, or at least in strong competition, such as high stiffness and low density [1], or strength and toughness [2,3]. Teeth [4], mollusc shells [5] or crustaceans [6] display exceptional combinations of stiffness, strength, flaw tolerance and toughness, at present unrivalled by engineering materials. Spider or silkworm silk is another prime example of this, with a tensile strength comparable to that of high-grade alloy steels, and a toughness three times higher than even high energy-absorbing polymers such as Kevlar® [7,8]. This means that silk fibres are able to dissipate a huge (e.g. kinetic) energy before breaking. In Ref. [8], the toughest known biomaterial is discussed, namely the silk spun by a giant riverine orb spider, reaching energy-to-break values of 520 MJ/m$^3$, which is 10 times that of para-aramid synthetic fibres such as Kevlar®. In the case of artificial materials, Carbon NanoTubes (CNTs) provide excellent candidates to achieve superior mechanical properties [9,10], since their ideal mechanical strength is an order of magnitude greater than most commonly used industrial materials. The exceptional mechanical strength and low density of CNTs [11,12], similar to that of Graphene [13–15], evoke the possibility of futuristic projects such as the so-called "Space Elevator" [16,17]. However, the prospect of achieving these mechanical properties with the corresponding macroscopic fibres still presents a considerable challenge [18–20].

There is great interest in manufacturing fibre and film assemblies that attain on a macroscopic level the mechanical strength of individual CNTs. The ability to assemble CNTs into continuous fibres or threads (terms used indistinctly in CNT literature) has progressed considerably. Perhaps the most advanced methods to date

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