SOFT MATERIALS

Nanostructured artificial-muscle fibres

Artificial-muscle fibres mimic the ordered nanostructures in natural-muscle fibres to achieve promising mechanical and actuation properties.

Shaoting Lin and Xuanhe Zhao

Randomly-distributed amorphous polymer chains endow conventional soft materials (including hydrogels and elastomers) with softness and deformability. However, amorphous polymer chains also lead to inferior mechanical properties such as low toughness, fatigue threshold, and tensile strength, which significantly limit the scope of soft materials' applications. An effective way to enhance the mechanical properties of soft materials is to design nanostructures such as nanocrystalline domains in soft materials. For example, introducing nanocrystalline domains into amorphous polyvinyl alcohol hydrogels can enhance their fatigue threshold from 10 to 1,000 J/m^2 refs. [1,2], and the interfacial fatigue threshold of polyvinyl alcohol hydrogels adhered on glass from 10 to 800 J/m^2 ref. [3]. The common methods for introducing nanocrystalline domains in soft materials include solvent evaporation, mechanical stretching, thermal drawing, and rapid quenching. One key challenge is to precisely engineer the size, density, and spatial distribution of nanocrystalline domains in soft materials. Writing in *Nature Nanotechnology*, Lang et al.[4] reported a critical step toward the design of nanostructures in soft-material fibres. The resultant nanostructured artificial-muscle fibres give simultaneously high actuation stress (up to 5.5 MPa), actuation strain (up to 80%), actuation efficiency (up to 75.5%), toughness (up to 121.2 MJ/m^3), and tensile strength (up to 150 MPa).

Mammalian skeletal muscle fibres harness ordered nanostructures such as the alternating I band and A band to achieve high actuation stress, actuation strain, and toughness. Lang and colleagues adopted a two-step strain-programmable crystallization method to achieve nanostructured fibres with well-controlled alternating nanocrystalline and amorphous domains, mimicking the alternating I band and A band in muscle fibres (Fig. 1a). The first step is to use the rapid-injection method to trigger the self-assembly of hydrophilic poly(ethylene oxide) (PEO) and hydrophobic poly(styrene) (PS), which forms a hydrogel fibre made of ABA-type triblock copolymers. The second step is to mechanically deform the hydrogel fibre at a specific elongation ratio followed by air drying, which further induces crystallization in PEO with controlled morphology of nanocrystalline domains. Through X-ray scattering characterizations, the authors demonstrated the capability of quantifying the crystallinity, spacing between nanocrystalline domains, and orientation of nanocrystalline domains in the fibres.

The nanocrystalline domains can effectively enhance the mechanical properties of the fibres such as toughness and tensile strength. More interestingly, the muscle-mimic ordered nanostructures further endow active properties to the fibres, including high actuation stress (up to 5.5 MPa), actuation strain (up to 80%), and actuation efficiency (up to 75.5%), superior to the corresponding properties of natural muscle fibres. The actuation of the fibres can be triggered by heat or water vapour. When subjected to heat, a strained fibre releases its internal stress due to the melting of the nanocrystalline domains of PEO, achieving a contraction actuation strain up to 80% (Fig. 1b). When exposed to water vapour, the strained fibre can expand over a short time (for example, seconds) due to swelling of the amorphous PEO domains (Fig. 1c), but contract over a long time (for example, fully hydrated) due to melting of the nanocrystalline domains of PEO.

Despite the promising actuation responses demonstrated by Lang and colleagues, several challenges remain before reaching the full potential of the nanostructured artificial-muscle fibres. 1)

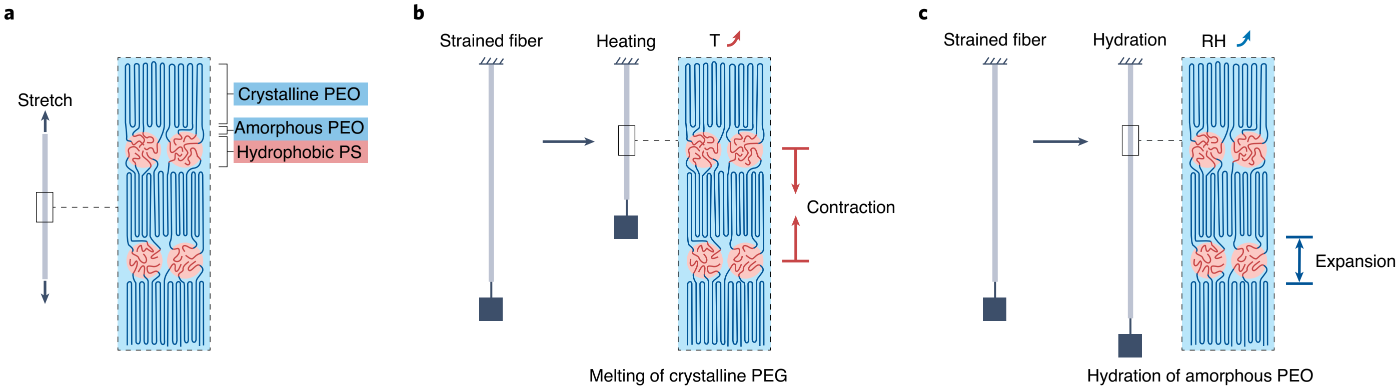

Fig. 1 | Nanostructured artificial-muscle fibres achieve extraordinary mechanical and actuation properties. a, The artificial-muscle fibres possess well-controlled alternating nanocrystalline and amorphous PEO domains and hydrophobic PS domains through strain-programmable crystallization. **b**, A strained fibre achieves a contraction strain up to 80% when subjected to heat. **c**, A strained fibre displays an expansion over a short time (e.g., seconds) when exposed to water vapour.

The actuation time of the fibres is sensitive to specific stimuli. For example, when subjected to heat, the actuation time is determined by the thermal conductivity of the fibres; when exposed to water vapour, the actuation time is determined by the diffusivity of water in the fibres. 2) No quantitative model has been developed to optimize actuation performances of the fibres; the design of the fibres follows the Edisonian approach. 3) Fabrication of the artificial-muscle fibres relies on extremely large mechanical deformation of the fibres, significantly limiting the fabrication in confined spaces.

In addition to Lang and colleagues' efforts, engineers and scientists have described several other types of fibre-shaped artificial muscles[5–7] that exploit advantages derived from the twisted and coiled geometries of the fibres. All these efforts together with the development by Lang and colleagues are moving this nascent field forward.

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https://doi.org/10.1038/s41565-022-01149-6

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Competing interests

The authors declare no competing interests.

HETEROGENEOUS CATALYSIS

Zeolite facilitates selective olefins production

The addition of nanoscale zeolite to Na–FeC_x unlocks the potential of catalysts for selective olefins production in a fixed-bed reactor.

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In a future without utilizing crude oil resources, integrated petrochemical complexes may continue to operate using more circular drop-in petrochemical building blocks, such as synthetic olefins. Olefins are indispensable for the manufacture of plastics, detergents, lubricants, etc., and may be produced from carbon monoxide (CO) and hydrogen (H_2) (known as 'synthesis gas'). Synthesis gas provides the platform for the production of synthetic fuels and chemicals from more sustainable, alternative carbon-containing feedstocks, including carbon dioxide (CO_2), waste gas streams, natural gas, municipal waste, and biomass[1].

The industrial process to convert synthesis gas to lower olefins, namely ethene, propene and butenes (C_2-C_4 olefins), is indirect and proceeds via methanol. The methanol synthesis reaction is thermodynamically limited and has a low conversion per pass, meaning recycling of reactants is needed. While the conversion of methanol to hydrocarbons does not face the same challenge, coking resulting in rapid catalyst deactivation is common[2]. A direct process combining the two reactions in a single fixed-bed reactor is able to overcome the thermodynamic limitation of methanol synthesis and increase catalyst lifetime[3]. However, conversion remains low due to incompatibility of reaction conditions for each reaction. In contrast, the Fischer-Tropsch to olefins (FTO) technology offers a direct process and flexibility in reaction conditions to improve catalytic performance. However, the hydrocarbon product distribution is broad because the FTO reaction is a surface polymerization reaction governed by the Anderson-Schulz-Flory (ASF) distribution. This statistical distribution of hydrocarbon products means the maximum selectivity towards lower olefins is around 60% with a corresponding methane selectivity of almost 30% (ref. 4). To suppress methane selectivity, a deviation from the ASF distribution is needed or the higher hydrocarbons should be targeted[5].

Writing in *Nature Nanotechnology*, Wang et al. report on the use of zeolite nanosheets to promote the activity and selectivity of iron-based catalysts for the low-temperature FTO reaction[6]. At 260 °C, 20 bar and $H_2/CO = 1$, the combination of sodium-promoted iron carbide (FeC_x) catalysts and MFI zeolite nanosheets resulted in more than 70% C_2-C_{10} olefins selectivity (excluding ~50% CO_2 selectivity) at around 70% CO conversion. While the catalytic performance of the combination increased olefins productivity 30-fold in comparison to the sole FeC_x catalyst, the proposed role of the zeolite nanosheets with an emphasis on the short b-axis of 90–110 nm, is more intriguing. The zeolite pores (4.7 Å × 4.46 Å × 4.46 Å) are hypothesized to act as nanochannels to facilitate the desorption from the FeC_x surface and prevent the re-adsorption of olefinic products on the FeC_x surface (Fig. 1). The short b-axis of the zeolite was further suggested to improve the diffusion of the olefins, which amplified the promoting role of the zeolite component. This is conceptually different from similar state-of-art Fischer-Tropsch synthesis catalytic systems, in which the acidic sites of the zeolite component catalyse oligomerization, isomerization and aromatization[7–10].

To demonstrate that the acidic sites of the aluminosilicate zeolite nanosheets were indeed not catalytically active, Wang et al. synthesized and tested a pure silicate nanosheet material with the same MFI-type framework but without acidic sites, and similar improvement in catalytic performance was achieved. In addition, the co-feeding of α-olefins over the porous aluminosilicate alone showed high isomerization activity leading to high iso-/α-olefins ratios, but negligible