Supplementary Materials for

Stretchable Electronics for Extreme Environments: Ceramic Aerogel Metamaterials Enable High-temperature Sensing

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The PDF file includes:

Supplementary Notes

Supplementary Tables S1 to S2

Supplementary Movies S1 to S3

References (1–79)

Supplementary Notes

Supplementary Note 1: 2D Random Fiber Mechanical Model of CAMs

We constructed the randomly distributed ceramic fiber structure (Extended data fig.3) based on a modified Kagome/triangular lattice to replicate the microstructure of electrospun ceramic aerogel membranes. The initial base lattice consists of circumferentially arranged fibers with a fixed inter-fiber angle of 120°. Each fiber is randomly rotated within limits of $\pm\alpha$ where α takes selected values from 10° to 30°, where $\alpha = 30°$ implies no preferred orientation. The random distribution of electrospun nanofibers observed by SEM is characterized by $\alpha \geq 25°$.

A non-periodic square computational domain is adopted, with a side length 20 times the fiber spacing of the original Kagome lattice. This setup provides a sufficiently large representative volume element to capture the statistical randomness of the fiber network and avoid artificial stress artifacts induced by periodic boundary conditions. Our finite element model does not employ periodic unit cells; instead, the non-periodic representative volume element is used to faithfully reproduce the actual random distribution of electrospun fibers.

Euler–Bernoulli beam theory is adopted to describe the mechanical behavior of individual fibers, and the overall network is established as a 2D random fiber framework. The number of cross-over nodes on each fiber depends on the fiber density within the representative unit, and each fiber contains far more than two cross-over junctions. Notably, the fiber nodes on the boundary of the computational domain are not necessarily the physical free ends of fibers, and these boundary nodes are specially reserved for load application. Accordingly, it is inappropriate to simply treat these boundary fiber segments as unloaded free ends.

All parameters involved in the theoretical mechanical models are uniformly defined as follows: σ_{max} denotes the ultimate tensile stress of the fibrous membrane; K is the spring coupling coefficient related to force RF_1 and deformation U_1 at fiber cross-junctions, which characterizes the interfacial bonding strength and load-transfer capability of the network; E represents the intrinsic Young's modulus of the fiber matrix, and A refers to the cross-sectional area of a single fiber. d and L correspond to the average fiber diameter and length, and l defines the average internodal spacing between adjacent fiber intersection points. $\bar{\rho}$ is the relative density of the monolayer random fibrous network; E_{eff} and G_{eff} stand for the in-plane effective elastic and shear modulus of the fibrous network; B is a dimensionless constant determined by network topology; C and b are topology-dependent structural constants, where b gradually approaches 1 with the increase of fiber randomsness. $\varepsilon_{\mathrm{max}}$ defines the fracture strain of fiber-derived membrane materials. For serpentine architectures, $\varepsilon_{\mathrm{app}}$ is the macroscopic applied tensile strain; w is the structural width, R is the curvature radius of curved segments, α is the fiber random rotation angle ($0° \leq \alpha \leq 30°$), θ is the wrap angle of serpentine curved segments ($180° \leq \theta \leq 210°$), which determines the geometric deformation limit of the structure. g_1 and g_2 are configuration-related fitting parameters, G is a structural configuration-dependent combined coefficient, and t is the thickness of the fibrous membrane. $\varepsilon_{\mathrm{local}}$ represents the intrinsic local strain of the fiber matrix; $\varepsilon_{\mathrm{ribbon}}^{\mathrm{f}}$ and $\varepsilon_{\mathrm{mem}}^{\mathrm{f}}$ indicate the intrinsic ultimate tensile strain of narrow ribbon specimens and large-area intact membranes, respectively, while w_{cr} is the critical characteristic width governing the size-dependent mechanical behavior.

To precisely control the average fiber length L, a random breakpoint generation method was introduced: when the continuous length of a single fiber exceeded N times the average node spacing l (where l is the mean value of local node spacing l_{i}), random breakpoints were automatically generated along the fiber length. This strategy strictly controls the L/l (the ratio of fiber segment length to average node spacing) and simulates the random fiber segment morphology of actual ceramic aerogel membranes.

We investigated the in-situ tensile deformation of ceramic nanofiber membranes via scanning electron microscopy (Extended data fig.3a-b). In-situ observations reveal that the fibers remain structurally stable without obvious sliding prior to reaching the maximum tensile strain, while pronounced fiber slippage—rather than intrinsic fiber fracture—occurs in the fractured regions after the peak stress is reached. This characteristic deformation behavior indicates that the tensile strength of the nanofiber membrane is dominated by the coupling strength at the fiber cross nodes. To quantify this nodal coupling effect, a spring coupling coefficient K is incorporated at the fiber cross nodes in our model to characterize the bonding strength and load-transfer efficiency between intersecting fibers. Thus, the corresponding effective stress could be expressed as:

$$\sigma_{\max} \propto Kl/EA \tag{S1}$$

where E denotes the fiber Young's modulus and A the fiber cross-sectional area. Surely, $\sigma_{\max}$ is the macroscopic strength of the lattice. It is a function of Kl/EA, approximately linear when the fiber length is less than the boundary length of the RVE and $Kl/EA < 0.01$ (Extended data fig.3g-i). By adjusting electrospinning parameters, we fabricate membranes with varied fiber diameters, node spacings, and areal densities, which show distinct tensile stress-strain responses. The relative density of single-layer random fibers can be expressed as[64]:

$$\bar{\rho} = \frac{Bd}{l} \tag{S2}$$

where d is the average fiber diameter, l is the average fiber internodes spacing and B is a constant based the network topology. Assuming that the fiber material exhibits linear elasticity and the fiber cross-points are rigidly connected ($Kl/EA = \infty$), the effective in-plane elastic modulus of the periodic Kagome two-dimensional network depends on the relative density and can be predicted as follows[65]:

$$E_{\mathrm{eff}} = CE\bar{\rho}^{b} \tag{S3}$$

where b and C are constants based the network topology. Therefore, the failure strain of aerogel membrane with the same fiber-node coupling coefficient can be expressed as:

$$\varepsilon_{\max} = \frac{\sigma_{\max}}{E_{\mathrm{eff}}} \propto \frac{l}{d} \tag{S4}$$

Systematic analysis of the stress-strain curves of KAGOME structures with different rotation angles and breakpoint settings identified core mechanical responses (Extended data fig.4a). The tensile stress of the fiber network increased with the rise of coupling coefficient Kl/EA. The pure KAGOME lattice at $\alpha = 25°$ exhibited a distinct buckling stress inflection point. This inflection point disappeared at $\alpha \geq 25°$ and the stress-strain curve became more linear, consistent with the mechanical behavior of actual random electrospun fiber membranes. Statistical analysis of the modulus ratio and areal density (Extended data fig.3i) showed the parameter b in Equation (S3) gradually approached 1 with increasing α. This trend indicates the fiber network evolved into an isotropic random structure.

The effect of length L and spacing l of fibers was investigated. In this model, fibers with a length greater than L are split into two segments by a randomly generated breakpoint. The tensile stress of the fiber network decreased with shortened fiber segments, enabling uniform strain dispersion and weakening the load-transfer path of single fiber segments. These results confirm the ductility and tensile strength of the fiber membrane can be regulated by adjusting the average fiber length L via breakpoint number and tuning the node coupling coefficient K. The proportion of fibers with true strain exceeding 0.5% increased with rising Kl/EA and L/l (Extended data fig.4i-k). The experimental tensile strain of the ceramic fiber membrane was approximately 2.5%. Simulation results with stress-strain curves matching experimental values were selected. The fiber network underwent macroscopic fracture when the proportion of fibers with true strain over 0.5% reached approximately 30%. This proportion was therefore defined as the fracture critical characteristic of the simulation. Critical stress-strain eigenvalues under different parameters were extracted (Extended data fig.4b-e). A smaller L/l led to superior membrane extensibility with fracture stress largely unchanged. In contrast, increasing Kl/EA strengthened the fiber-node coupling coefficient, significantly enhancing the fracture stress of the fibrous membrane with a slight reduction in fracture strain.

Simulation conclusions were verified with ceramic fiber membrane pretreatment experiments, further confirming the dual regulation mechanism of the membrane's mechanical performance (Extended data fig.2). Oxygen plasma treatment was applied to ceramic fiber membranes and effectively achieved fiber segment breakage, equivalent to reducing the L/l ratio in the simulation model. According to simulation-derived laws, a lower L/l significantly improved the fracture strain of the fiber membrane, thus enhancing the ductility of the ceramic aerogel membrane. A moisturizing treatment was also conducted and strengthened the bonding strength at fiber cross nodes, corresponding to an increased Kl/EA ratio in the simulation model (Extended data fig.4e). A higher Kl/EA led to a significant increase in membrane fracture stress with a slight, eventually stabilized reduction in ductility. This result improved the tensile strength of the ceramic aerogel membrane without obvious loss of deformability.

Supplementary Note 2: Stretchable Metamaterial Design and Size Effect of CAMs

To further enhance the stretchability of ceramic nanofiber membranes, we introduced a serpentine metamaterial architecture, which is widely utilized in stretchable electronics. In the case of the serpentine architecture considering in-plane deformation, the correlation between the actual strain and the loading strain is given by[48]:

$$\frac{\varepsilon_{\max}}{\varepsilon_{\mathrm{app}}}=\frac{\frac{w}{R}\left[\frac{12}{2-\frac{w}{R}}+\left(\frac{12}{2-\frac{w}{R}}-\frac{w}{R}\right)\left(\sin\alpha+\frac{l}{2R}\cos\alpha\right)\right]\left(\cos\alpha-\frac{l}{2R}\sin\alpha\right)}{\left[\begin{array}{l}\cos^2\alpha\left(\frac{l^3}{2R^3}+3\left(\frac{\pi}{2}+\alpha\right)\frac{l^2}{R^2}+12\frac{l}{R}-12\left(\frac{\pi}{2}+\alpha\right)\right)+\sin 2\alpha\left(6\left(\frac{\pi}{2}+\alpha\right)\frac{l}{R}+9\right)\\ +\frac{w^2}{R}\left[\left(\frac{\pi}{2}+\alpha\right)\left(\frac{l}{2R}\cos\alpha+\sin\alpha\right)^2+\frac{l}{2R}\left(\sin^2\alpha+\frac{3E_{\mathrm{eff}}}{2G_{\mathrm{eff}}}\cos^2\alpha\right)\right]+18\left(\frac{\pi}{2}+\alpha\right)\end{array}\right]} \quad (S5)$$

When out-of-plane deformation is considered, the correlation between the actual strain and the applied strain for the serpentine architecture is given as follows[47,66]:

$$\varepsilon_{\max}=g_1\sqrt{\varepsilon_{\mathrm{app}}}\frac{t}{2R}+g_2\varepsilon_{\mathrm{app}}^2\frac{w}{2R} \quad (S6)$$

The serpentine structure accounts for both in-plane and out-of-plane deformation, as described in equation (S6). We fitted this formula to experimental tensile data of samples with different widths, and found that the coefficient g_1 approaches 0. This allows us to simplify the strain correlation to:

$$\varepsilon_{\mathrm{app}}=\sqrt{\frac{\varepsilon_{\mathrm{local}}R}{Gw}} \quad (S7)$$

where G is a combined structure-dependent coefficient, explicitly highlighting the width-to-radius ratio (w/R) as a critical parameter governing the stretchability of the serpentine architecture.

We then investigated the size effect of the ceramic fiber membrane's intrinsic tensile capacity with respect to sample width, and found a strong dependence on the cutting method. Laser-cut fiber membranes preserve ductility at much smaller widths compared to blade-cut samples, which is beneficial for the design and fabrication of large-stretch structures. Based on experimental tensile results, we fitted the relationship between the intrinsic maximum tensile strain and sample width for both cutting methods:

$$\varepsilon_{\mathrm{ribbon}}^{\mathrm{f}}=\varepsilon_{\mathrm{mem}}^{\mathrm{f}}\left(1-e^{-\frac{w}{w_{\mathrm{cr}}}}\right) \quad (S8)$$

where $\varepsilon_{\mathrm{mem}}^{\mathrm{f}}$ is fitting parameters that differ between laser-cut and blade-cut samples, and w_{cr} is likely correlated with the average nanofiber length $\bar{L}$ or the average nodal spacing $\bar{l}$ between fiber cross-junctions. Thus, we propose the relational form $w_{\mathrm{cr}}=D\bar{l}$, where D is a cross-sectional topological factor related to the cutting technology (laser-cut samples exhibit a smaller D, indicating better ductility retention at narrow widths).

Finally, by substituting the intrinsic size effect formula (S8) into the simplified serpentine structure stretchability formula (S7), we derived the overall maximum applicable tensile strain of the structure:

$$\varepsilon_{\mathrm{app}} \leq \min\left(\sqrt{\frac{\varepsilon_{\mathrm{mem}}^{f} R}{G w}}\left(1 - e^{-\frac{w}{w_{\mathrm{cr}}}}\right), \frac{\theta}{1-\cos\theta} - 1\right) \tag{S9}$$

This formula quantitatively links the fiber membrane's width-dependent intrinsic stretchability to the macroscopic deformability of the serpentine architecture, providing a predictive framework for designing high-performance stretchable ceramic devices.

Supplementary Table S1.

Recent advances in high-temperature sensors of diverse materials

Sensor type	**Working temperature**	**Max strain**	**Sensing parameters**	**References**
PDC based sensors	< 600 °C	< 2%	Single	10,23,67
Polymer sensors	< 300 °C	> 50%	Multi-parameter	19-22,27,68-71
Alloy/Ceramic sensors	> 800 °C	< 0.5%	Single	15-18,72-75
Ceramic aerogels sensors	> 800 °C	< 2%	Single	24-26,31
SCAME	**> 900 °C**	**> 50%**	**4-parameters**	**This work**

Supplementary Table S2.

Recent advances in high-temperature mechanical properties of thermal isolate aerogels.

Materials		Form	Compressive strain	Tensile strain	Temp.	References
SiC-based Ceramic Aerogels	3C-SiC nanowires	bulk	76%	N/A	~1500 °C	30
	SiC-SiO_X bicrystal	film~bulk	80%	20%	−196 °C ~1200 °C	35
	SiC@SiO_2 nanowire aerogel	bulk	80%	N/A	~1200 °C	76
Carbon-based Aerogels	Super-aligned carbon nanotubes	2 mm	N/A	N/A	~2600 °C in vacuum	33
	Carbide aerogels	bulk	99%	N/A	1300 °C in air −269 ~ 2000 °C in vacuum	32
	CNT Aerogel	N/A	N/A	220%	~1344 °C	29
	Graphene aerogels	~2 mm	90%	5% LE; 5400% (patterned)	~300 °C	28
Nitride Aerogels	Si_3N_4 Nanofibrous AGs	bulk	80%	N/A	−196 °C ~ 1200 °C	77
	hBN AGs	bulk	95%	N/A	900 °C in air 1400 °C in vacuum	39
Oxide Ceramic Aerogels	SiO_2 AGs	bulk	80%	N/A	−196 °C ~ 1100 °C	78
	ZrO_2−Al_2O_3 aerogels	bulk	60%	N/A	~1300 °C	49
	Al/Si aerogels	bulk	60%	40%	−196 °C ~ 1400 °C	36
	$Y_2Zr_2O_7$ fibrous membrane	50 µm	60%	Foldable	~1200 °C	50
	ZrO_2-Al_2O_3 nanofiber	10 ~ 700 µm	N/A	2%	~1400 °C	79
Structurally Engineered Ceramic Aerogels	Zig-zag architecture	bulk	90%	20%	~1300 °C	37
	Highly-buckled nanofibrous	bulk	N/A	80%	~1000 °C	34

Supplementary Video 1. Infrared imaging videos of the SCAME on the flame of an alcohol lamp.

The stretchable network of platinum-coated ceramic fibers reaches a maximum temperature of 793 °C under an alcohol lamp flame, while retaining its flexibility without fracture or fusion failure.

Supplementary Video 2. Video demonstrating the bidirectional SCAMs under cyclic tensile strain tests from 30% to 80%.

The stretchable ceramic fiber network was subjected to cyclic tensile tests at strain from 30% to 80% with an interval of 10% on a cyclic tensile testing machine. Fracture occurred only when the strain exceeded 80%.

Supplementary Video 3. Optical and infrared imaging videos of the engine exhaust nozzle test integrated with SCAME.

Heat flux sensor arrays are mounted on the nozzle inner and outer walls. Tests were recorded by an infrared thermal imager and an optical camera. Sensors acquired heat flux data during startup, preheating, ignition, acceleration, steady operation and shutdown. Reduced-size infrared footage and engine speed are presented on the right.

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