International Association for Green Aviation

4th International Conference on Green Aviation

Rib-Reinforced Ultralight and Ultra-Strong Shell Lattices

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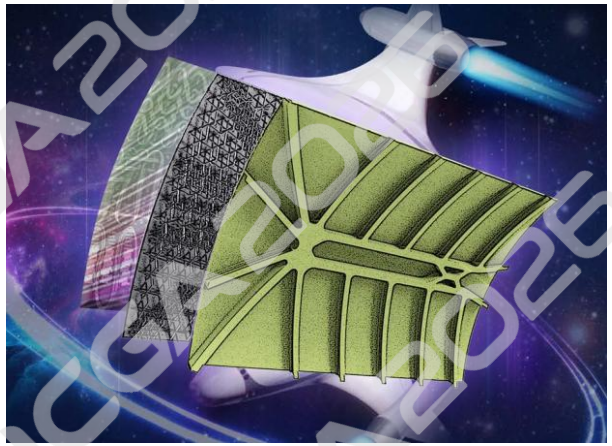
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Research Background

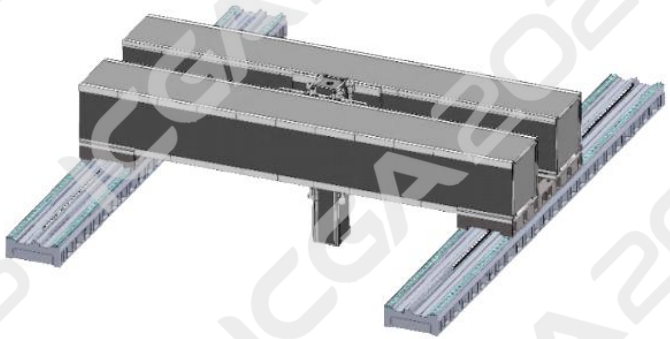
Next-generation aerospace and advanced manufacturing systems require extremely-high-performance and multifunctional materials/structures

Aerospace complex thin-walled structures



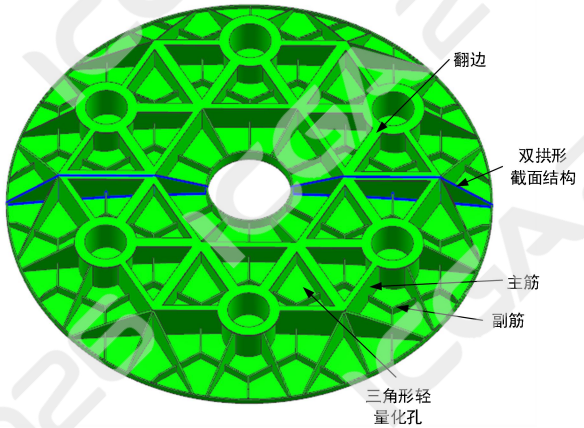
- Ultra-lightweight
- Ultra-high load-bearing capacity
- Extreme heat resistance
- Ultra-high precision

High-end machine tool moving components



- Ultra-lightweight
- Ultra-high stiffness
- Thermal stability
- Integrated load-bearing and thermal management

Large space optical mirrors

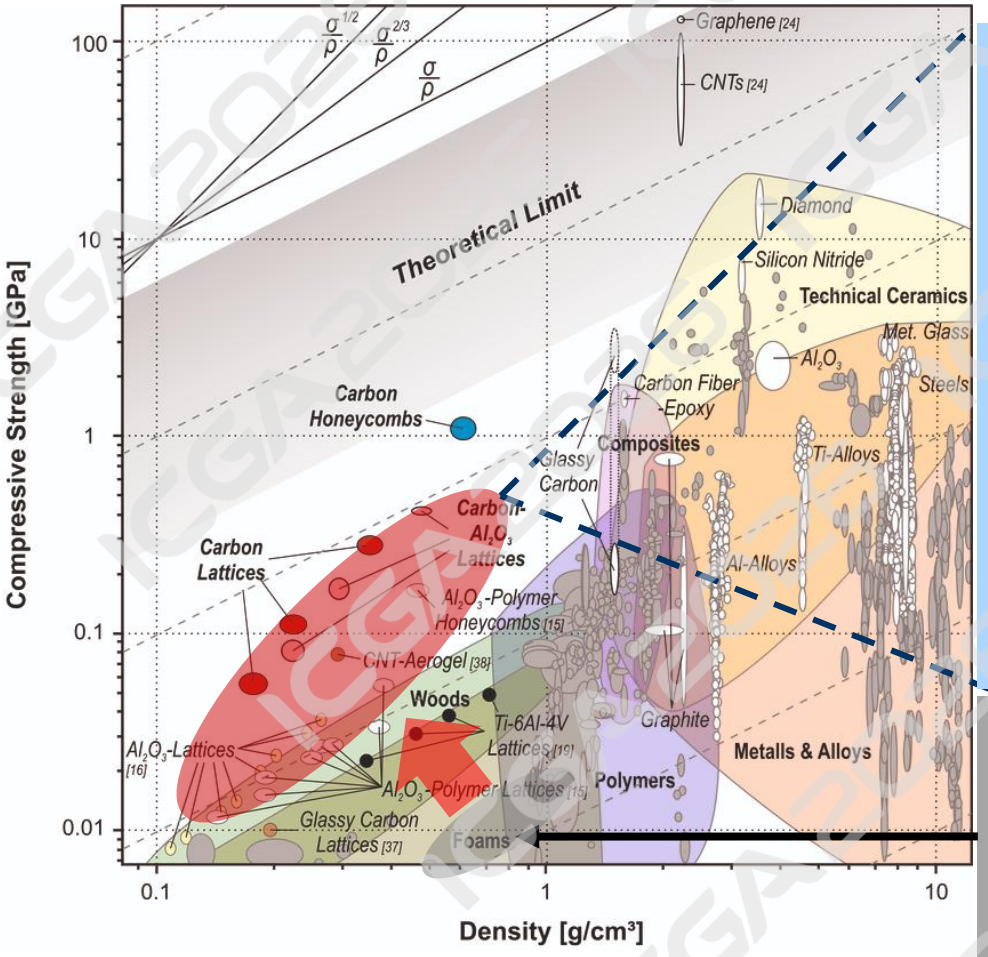


- Ultra-lightweight
- Ultra-high surface accuracy
- Ultra-high thermal stability

Integrated design and manufacturing of lightweight, high-performance, multifunctional materials and structures

New opportunities from lattice structures and additive manufacturing

Lightweight, high-strength, multifunctional lattices

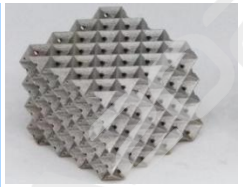


J. Bauer et al., Nature Materials (2016)

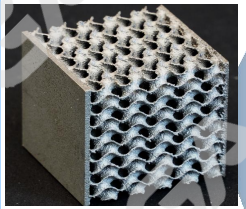
Additive manufacturing

Trad. Manuf.

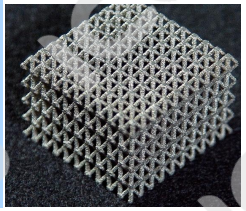
Plate lattice



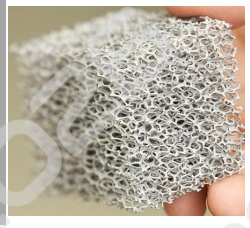
Shell lattice



Truss lattice



Metal Foam



Satellite antenna reflector



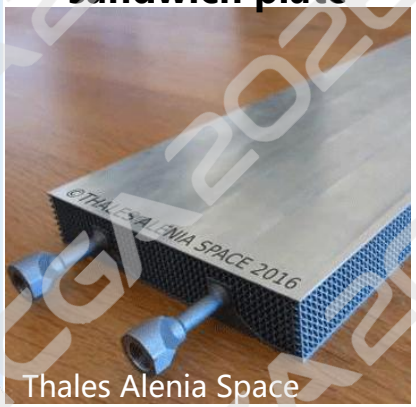
NASA

Heat exchange



nTop

Lattice core sandwich plate



Thales Alenia Space

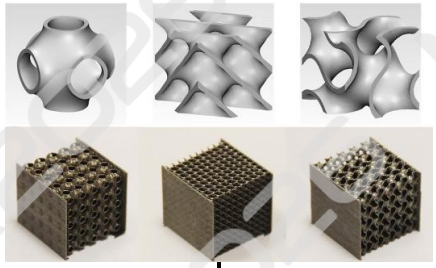
Lattice core sandwich wing structures



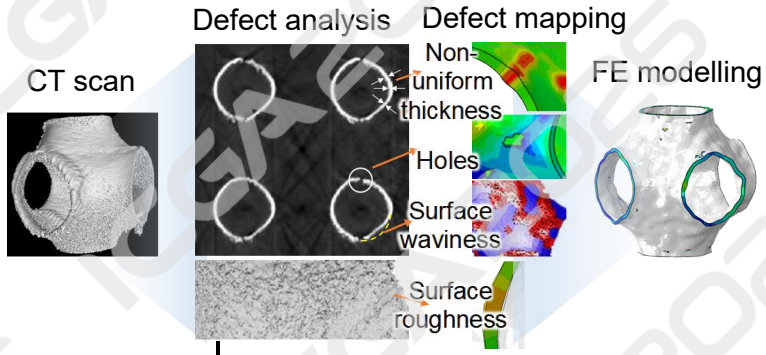
Farsoon

Integrated design and AM of TPMS shell lattices and applications

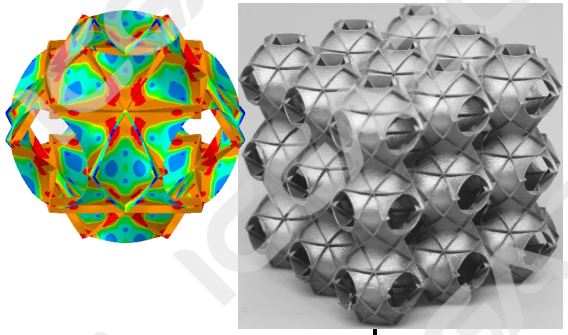
Design and metal AM of high-strength, high energy absorption **TPMS shell lattices**
ESI highly cited paper, citation: 1000+



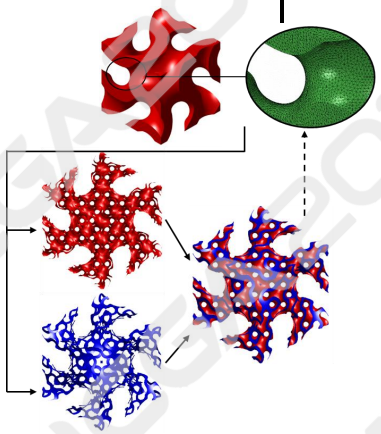
CT-based **high-fidelity and high-accuracy FE modelling** of considering AM defects



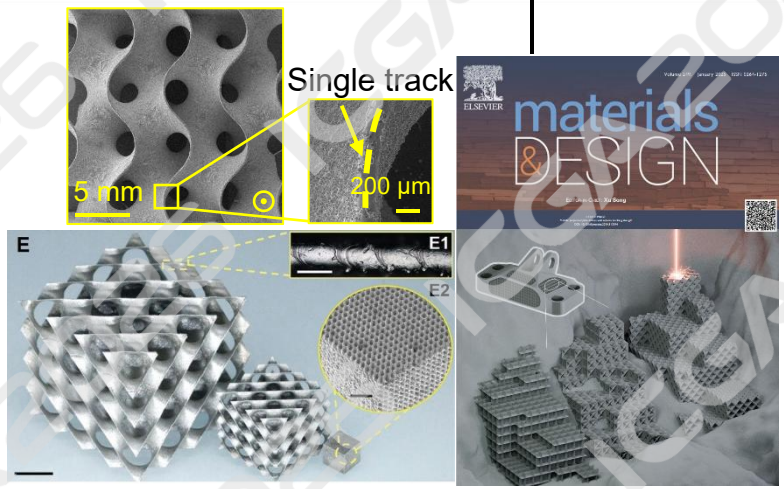
Design of ultralight and ultra-strong **ribbed shell lattices**



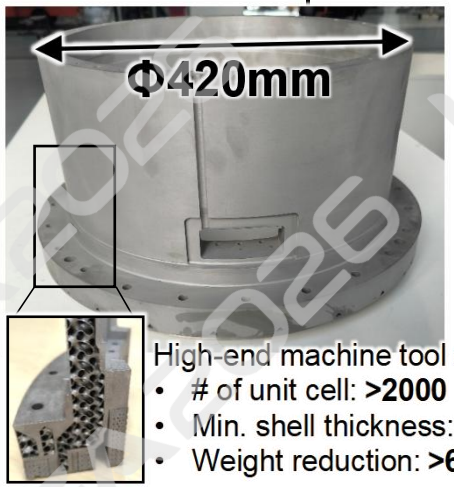
2018 2021 2022 2024-2025 2026



Design of buckling-resistant **hierarchical shell lattices**



Single track scanning strategy for laser powder bed fusion

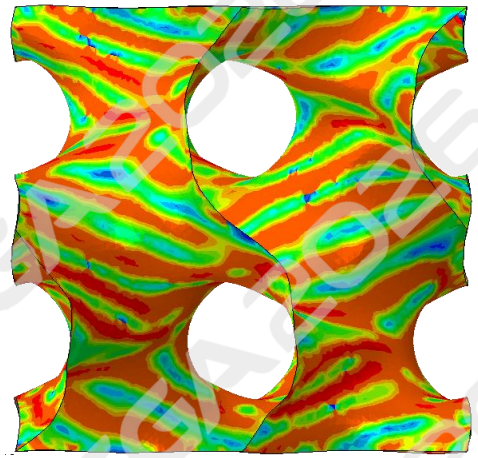


High-end machine tool component
- # of unit cell: **>2000**
- Min. shell thickness: **170μm**
- Weight reduction: **>60%**

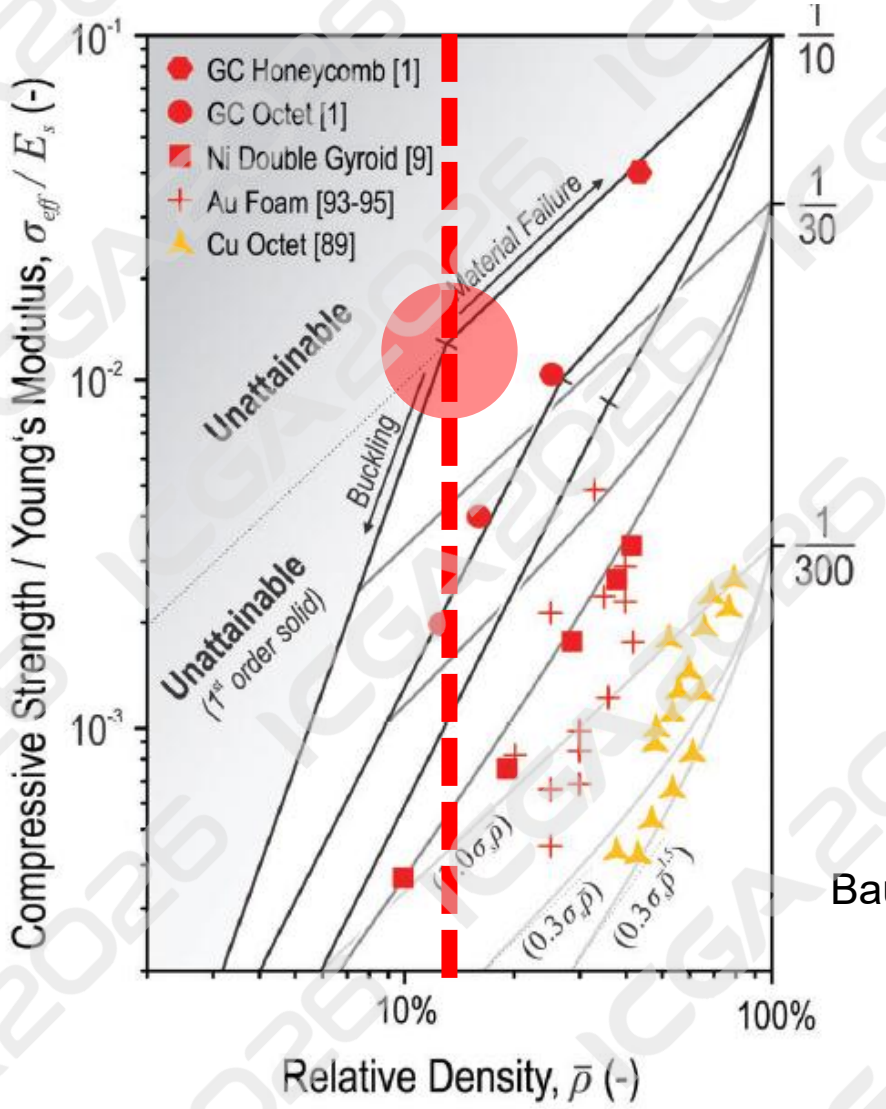
Direct slicing software of large-scale and ultra-thin shell lattices and applications

Challenge: how to design ultralight and ultra-strong lattice?

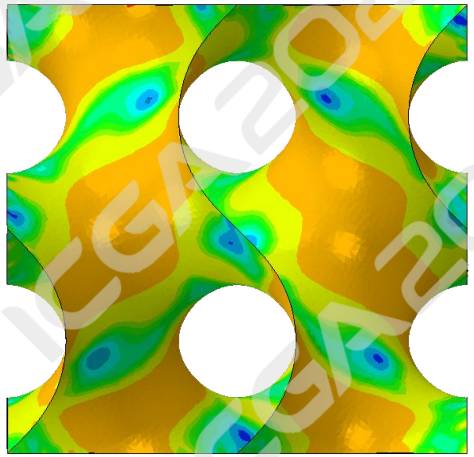
Ultralow density: Buckling failure



- Aspect ratio >50
- Rapid decease of strength w.r.t density



Low density: Material yield failure

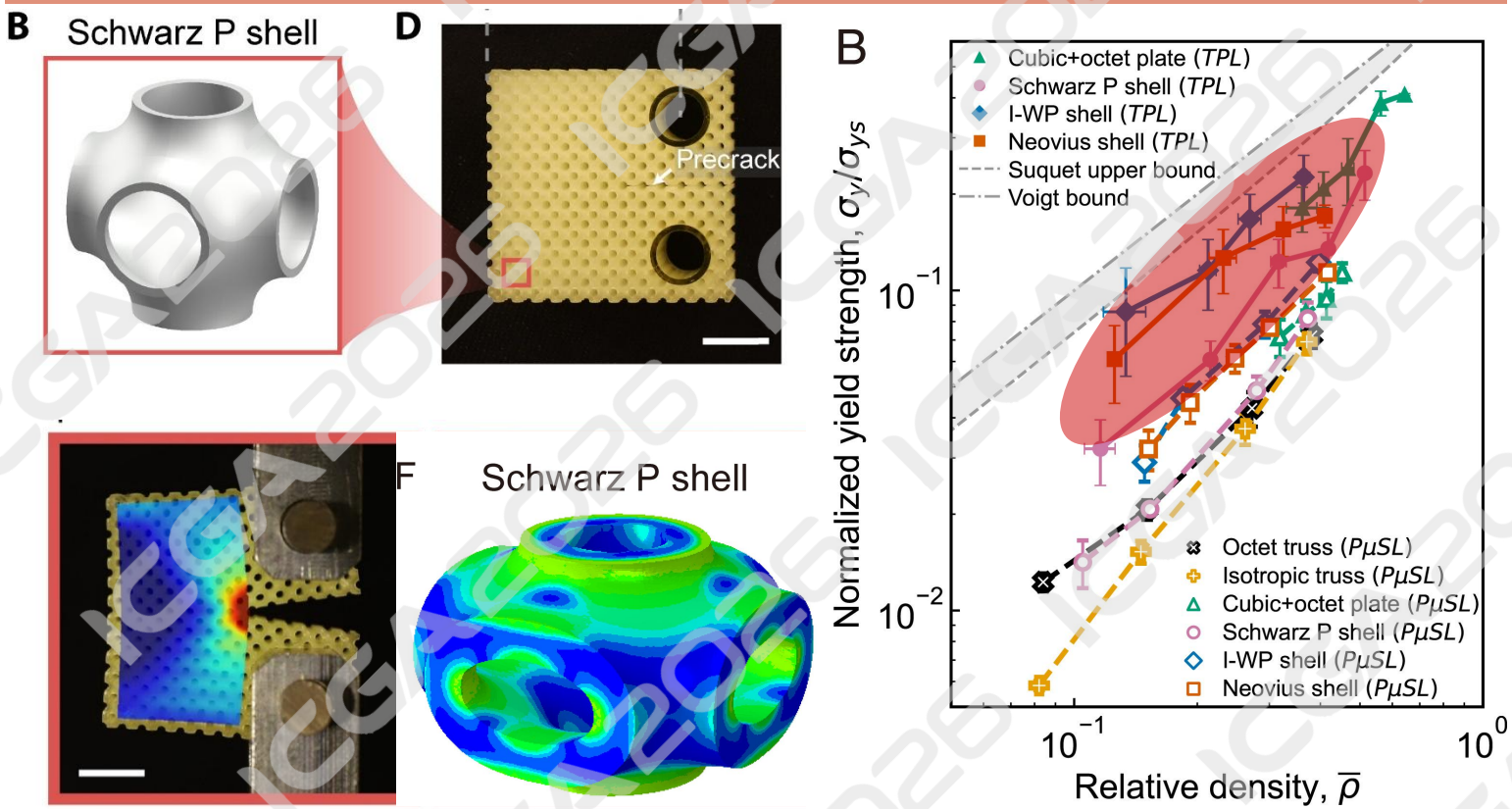


Bauer et al. (2017)

Buckling strength optimization is the key of designing ultralight and ultra-strong lattices

Challenge: how to design ultralight and ultra-strong lattice?

Ultra thin shell



Xiaoyan Li & Huajiang Gao et al. PNAS (2022), Sci. Adv. (2024)

Ribbing



- **Where** to arrange ribs for buckling strength optimization?
- **How** to design ribs on complex triply periodic minimal surfaces?

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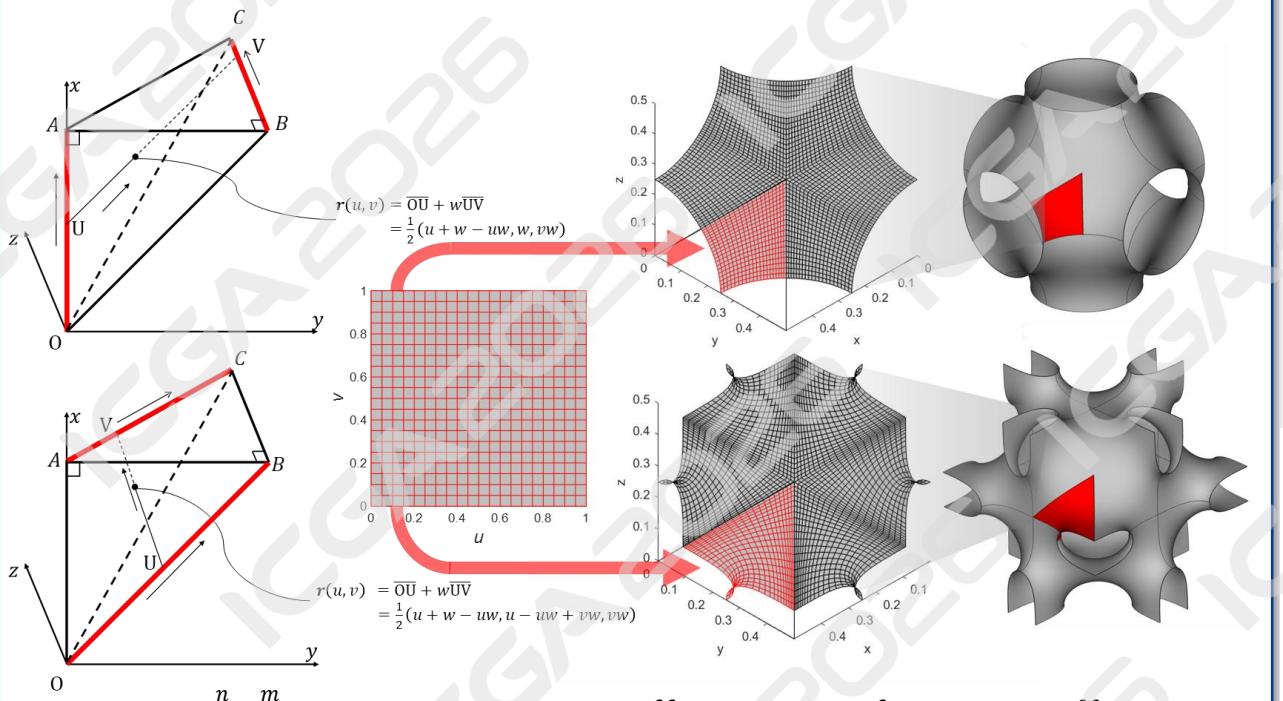
4 Conclusions and outlook

The intrinsic relation between geometric and mechanical behavior

Accurate geom. model to uncover the intrinsic geometry-mechanics relation of TPMS thin shell lattice

Rib design guidelines from geometric information

Implicit B-spline surface Monge Patch Model

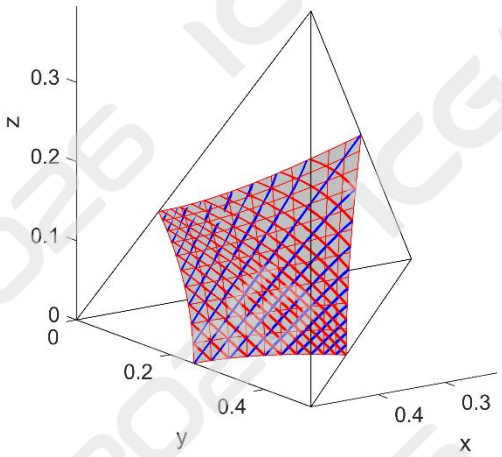


$$w(u,v) = \sum_{i=1}^{n}\sum_{j=1}^{m} N_{i,p}(u) M_{j,p}(v) W_{i,j}$$

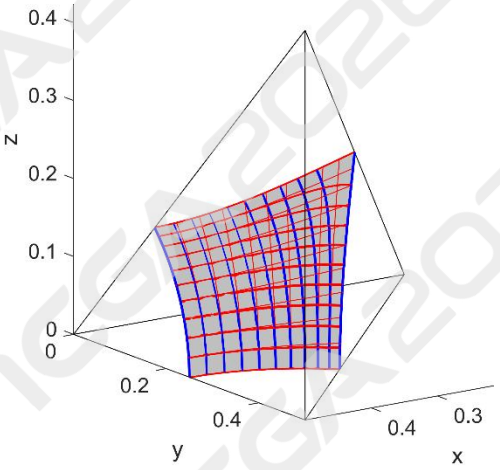
Implicit B-spline surface

$$\iint_S \nabla_s \cdot \boldsymbol{F}\, dA = \int_{\partial S} \boldsymbol{m} \cdot \boldsymbol{F}\, ds - \iint_S 2H\boldsymbol{n} \cdot \boldsymbol{F} dA$$

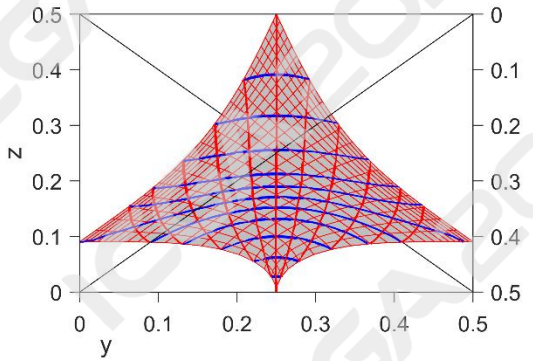
PDE for minimal surface



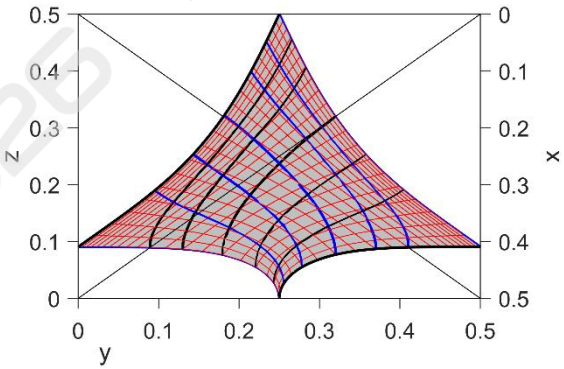
LOA (Line of Asymptote) of Primitive surface



LOC (Line of principal Curvature) of Primitive surface

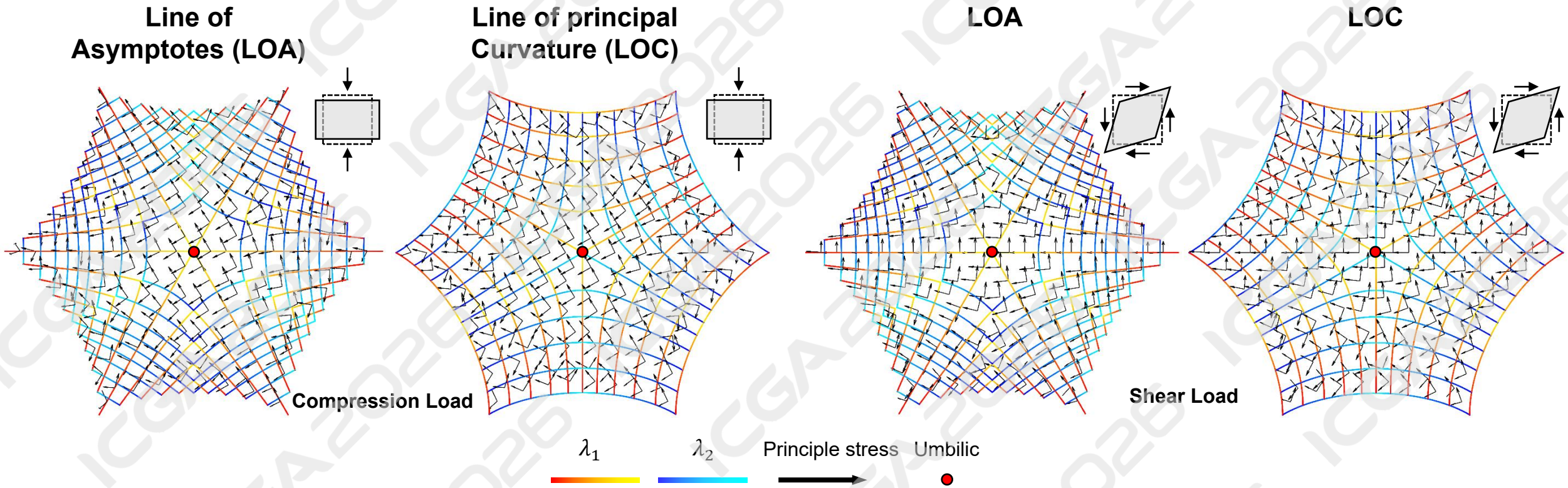


LOA of Neovius surface



LOC of Neovius surface

The intrinsic relation between geometric and mechanical behavior

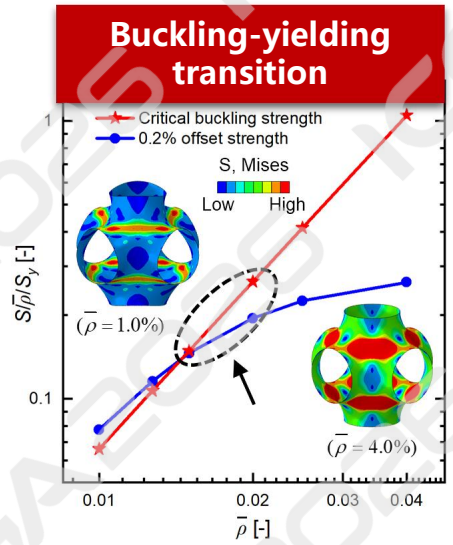


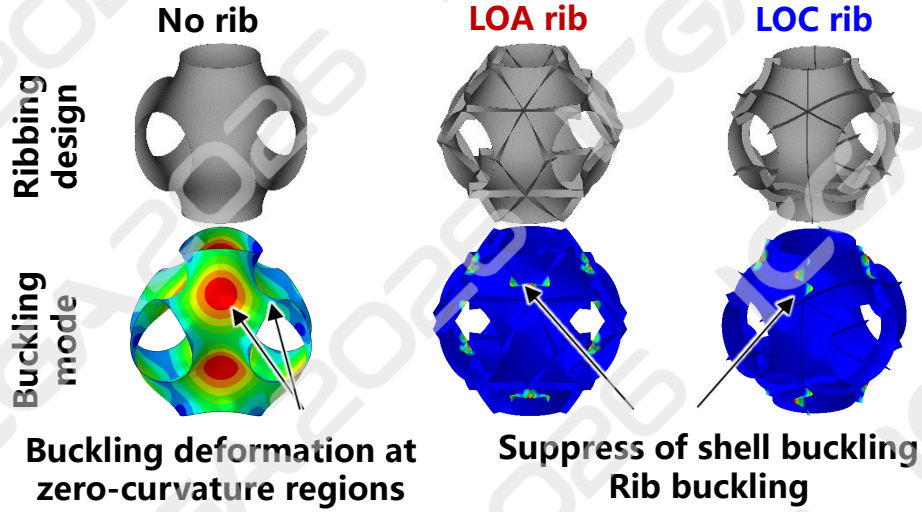


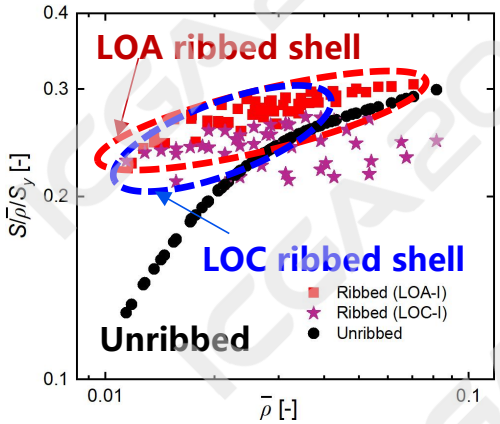
- **Principal stress // LOA directions**
- **Max shear stress // LOC directions**
- **Findings are valid regardless of external loads**

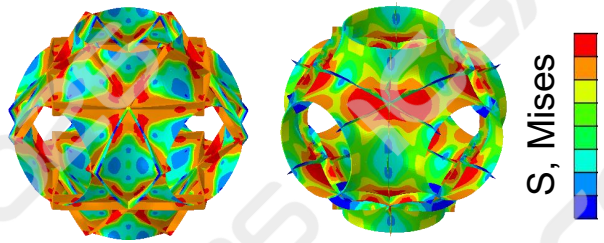
Optimization of rib layout

Optimal ribs: passing through the umbilics (zero-curvature point)









Strengthening Mechanism

- Buckling suppression
- Stress redistribution
- Extra Load path

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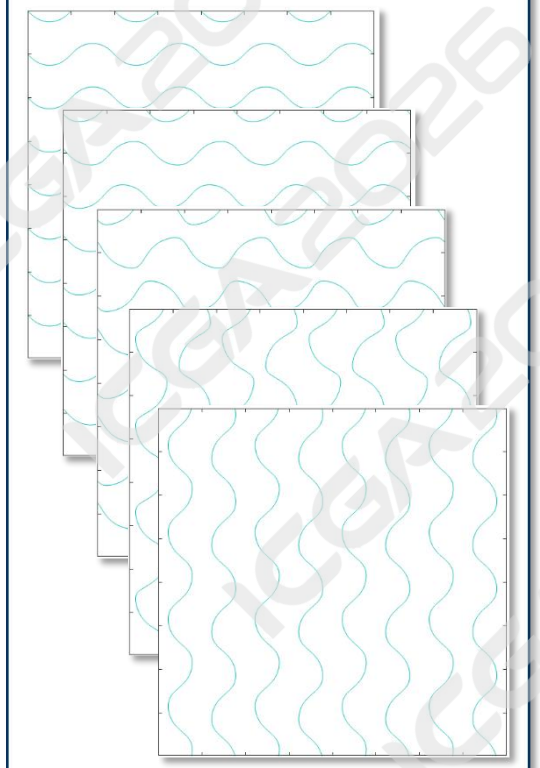
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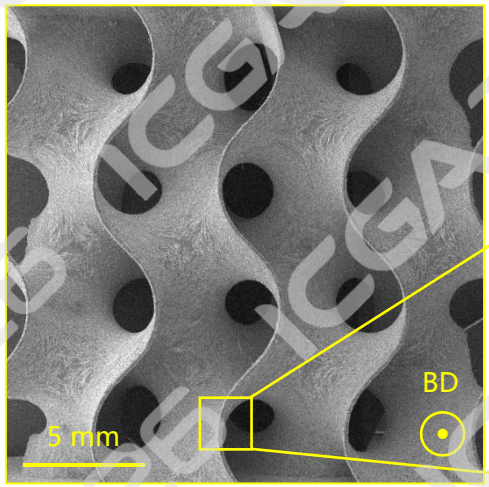
Single-track scanning strategy: laser AM of ultra-thin shell lattices

Single-track laser scanning strategy: reduce the printable min. thickness to a single melt-pool width, **achieving the physical limit of the printing resolution**

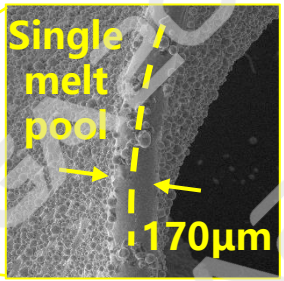
Single-track laser path



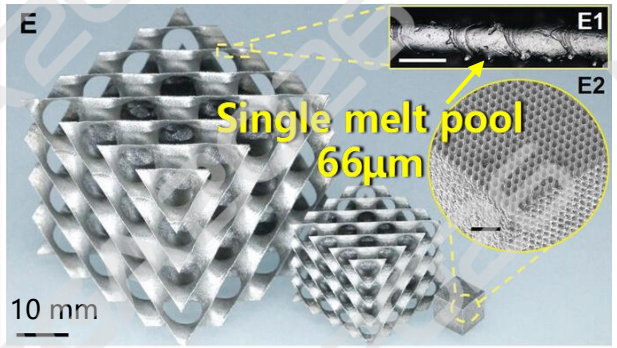
Laser AM of ultra-thin shell lattices

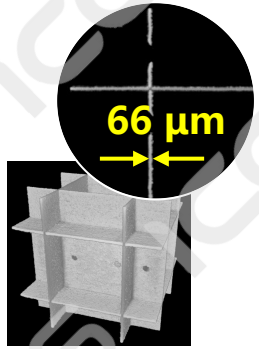


Conventional LPBF
Min. thickness
>300μm→170μm



High-res LPBF Min. thickness: 120μm→66μm





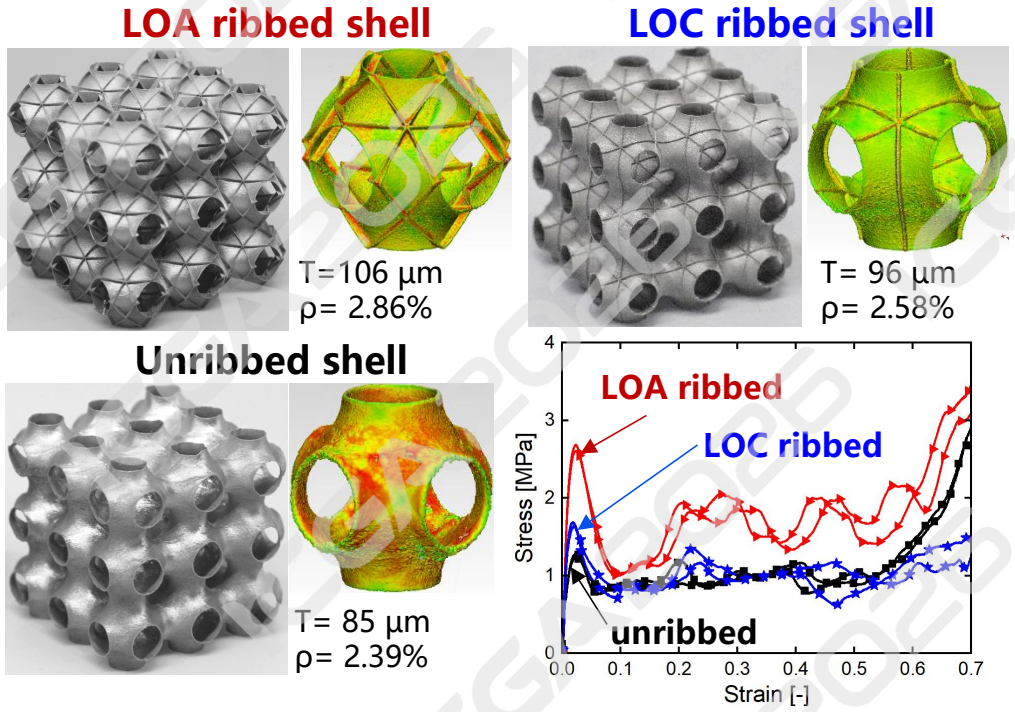
Materials & Design Cover paper

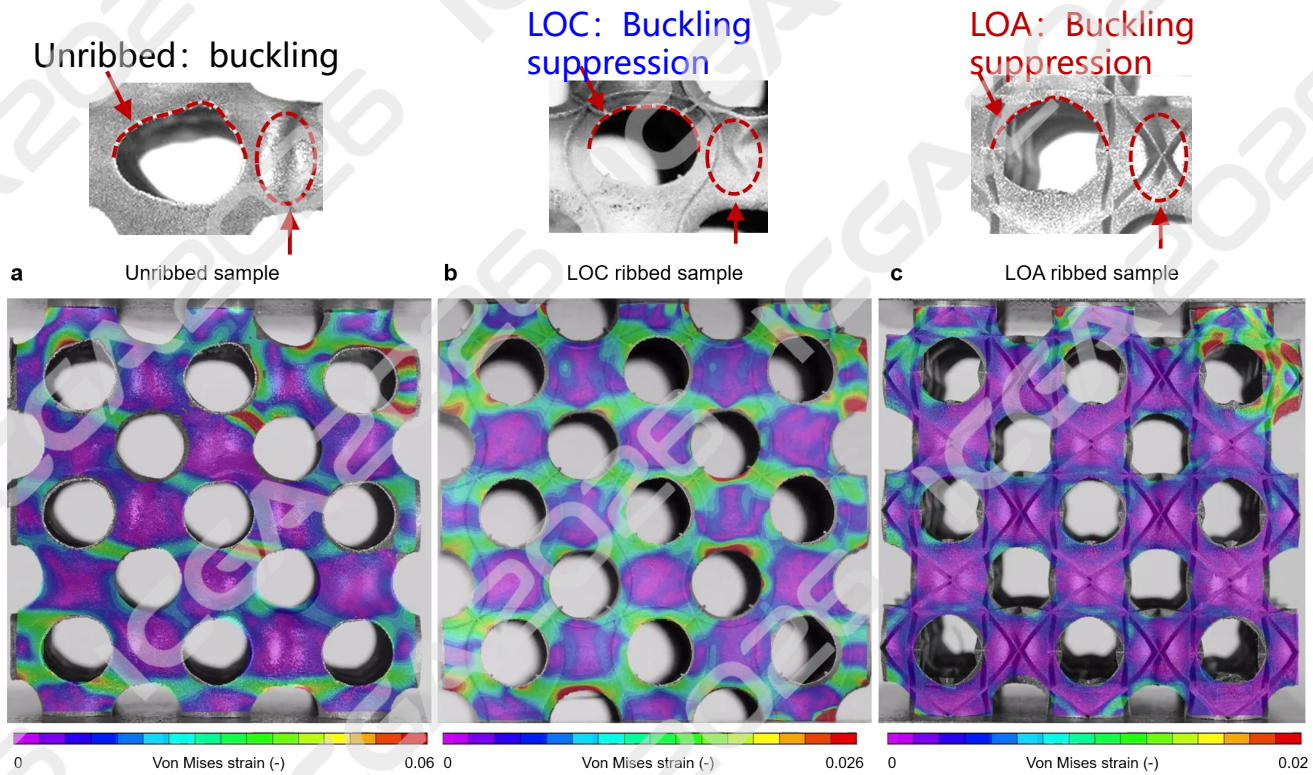


Zhang L. et al. J. Manuf. Process (2026); **Zhang L.** et al. Mater. Des. (2025); Ding J., Ma WWS, Li X., **Zhang L.** et al. Adv. Sci. (2024)

Experimental validation

Opt. ribs enable buckling suppression and stress redistribution, enhancing strength and energy absorption up to 101% and 61%.





Experimental validation



Application: lightweight design and AM of moving components for high-end CNC machine tools





- ✓ Swing head box weight reduction 60%
- ✓ Stiffness requirement satisfied
- ✓ Added heat dissipation





Five-axis gantry CNC machine tool





Moving beam weight reduction 20%

Total length of the beam: **2.16m** (inc. 6 sections)
Total unit cell numbers >22000

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Conclusions and outlook

Conclusions

- Buckling strength optimization is the key of designing ultralight and ultra-strong lattices
- Rib-reinforcement design is an effective way to improve the strength of ultralight shell lattices
- The intrinsic relations between the geometric and stress directions of thin shells provide insights and guidelines for designing ribs

Outlook

- **Material-structure-process-performance integrated and intelligent design** is highly promising for next-generation aerospace structures with **extreme performance under extreme working conditions**

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Thank You!



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