Hybrid Nanometal Microtrusses

AmeriMech 2014 (2 - 4 April 2014)

Dynamics of periodic materials and structures

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VELUT ÆVO ARBOR

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- part of the University of Toronto Faculty of Applied Science and Engineering
- UTIAS is located in the north of Toronto, near the old Downsview air force base and the Bombardier Aerospace plant
- currently there are nineteen faculty members and about 170 graduate students at UTIAS
- active research groups in space robotics, combustion, experimental and computational fluid mechanics, autonomous vehicles, aerospace structures
- aviation and the environment is a key research focus at UTIAS

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Acknowledgements

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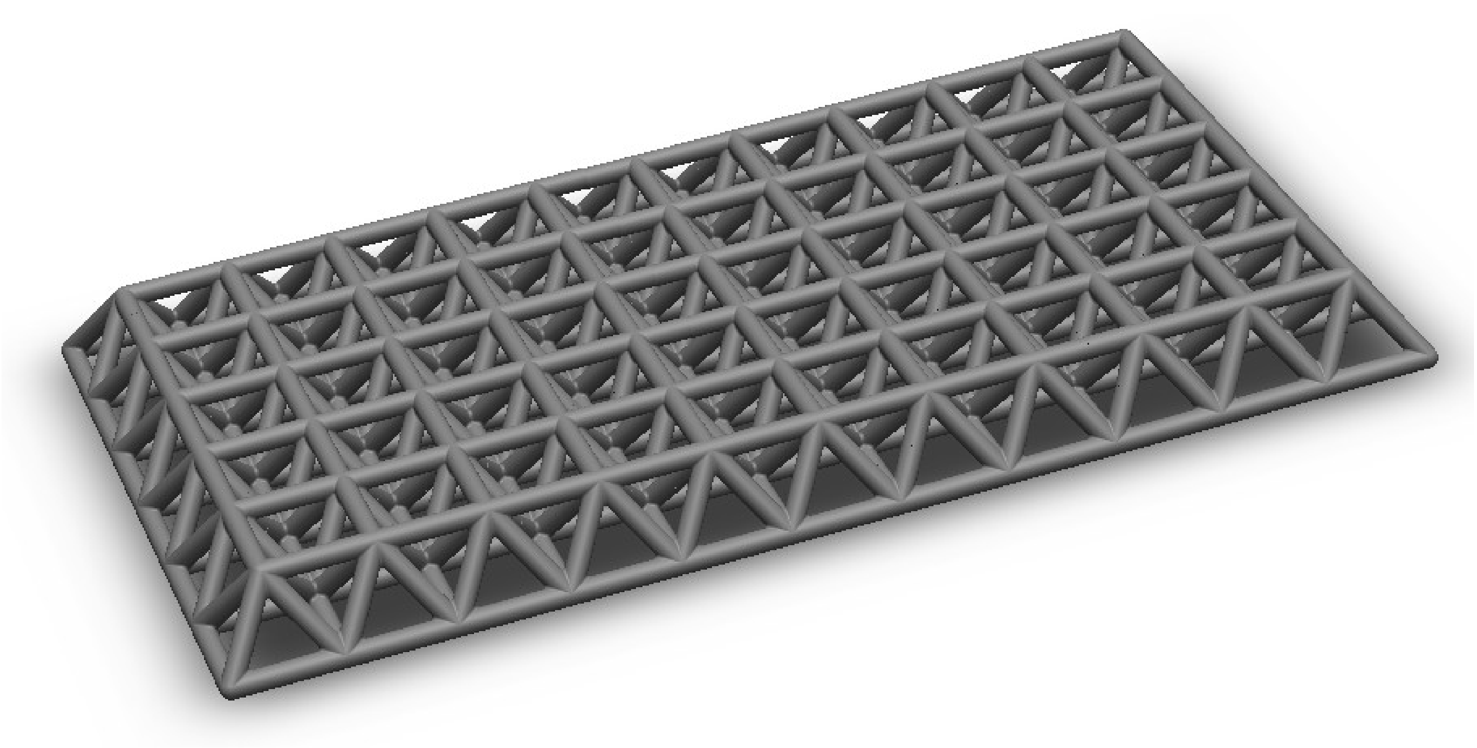
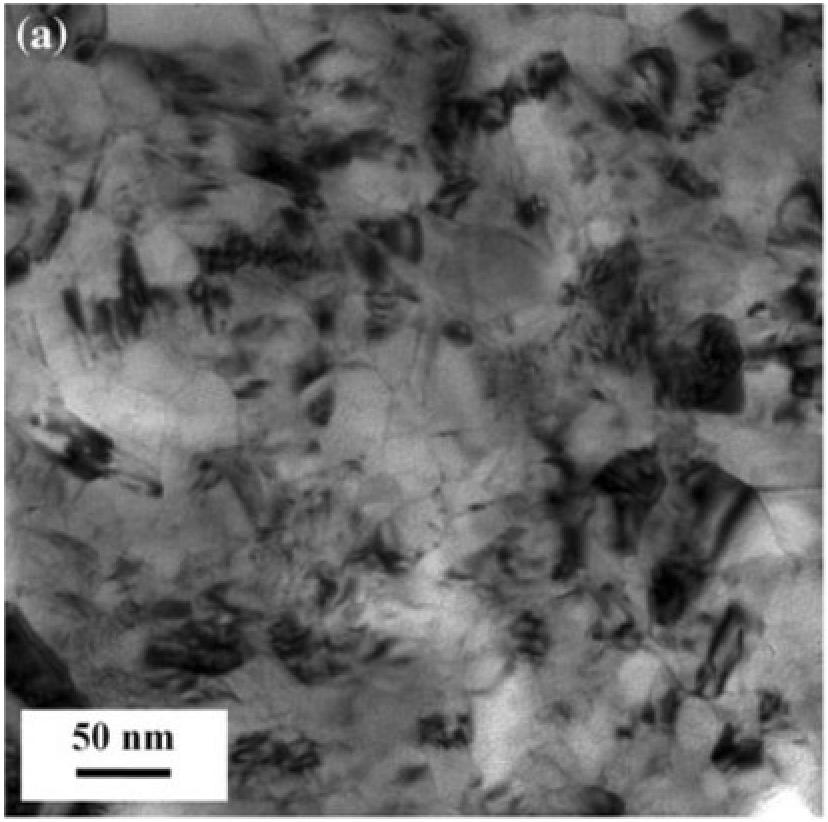
Hybrid Nanometal Microtrusses



- the goal is to fabricate truss-like panels of the sort shown here, because of their exceptional strength and stiffness to mass, and because the geometric complexity enables additional functionality (with proper design)
- also, we want to use very high performance materials, but this is often problematic because of manufacturing issues

Nanocrystalline Metals

- nanocrystalline metals have crystal grain sizes on the scale of nanometres; typically between 10 nm and 100 nm
- because of the Hall-Petch effect, this drives up the yield strength of the material: the large number of grain boundaries limits the travel of dislocations and hence prevents plastic flow
- nanocrystalline metals can be manufactured using a variety of techniques: inert-gas-condensation, mechanical attrition, chemical reactions, powder consolidation, electrodeposition



I. Brooks, G. Palumbo, G. D. Hibbard, Z. Wang, U. Erb, *J Mater Sci* 46 (2011) 7713.

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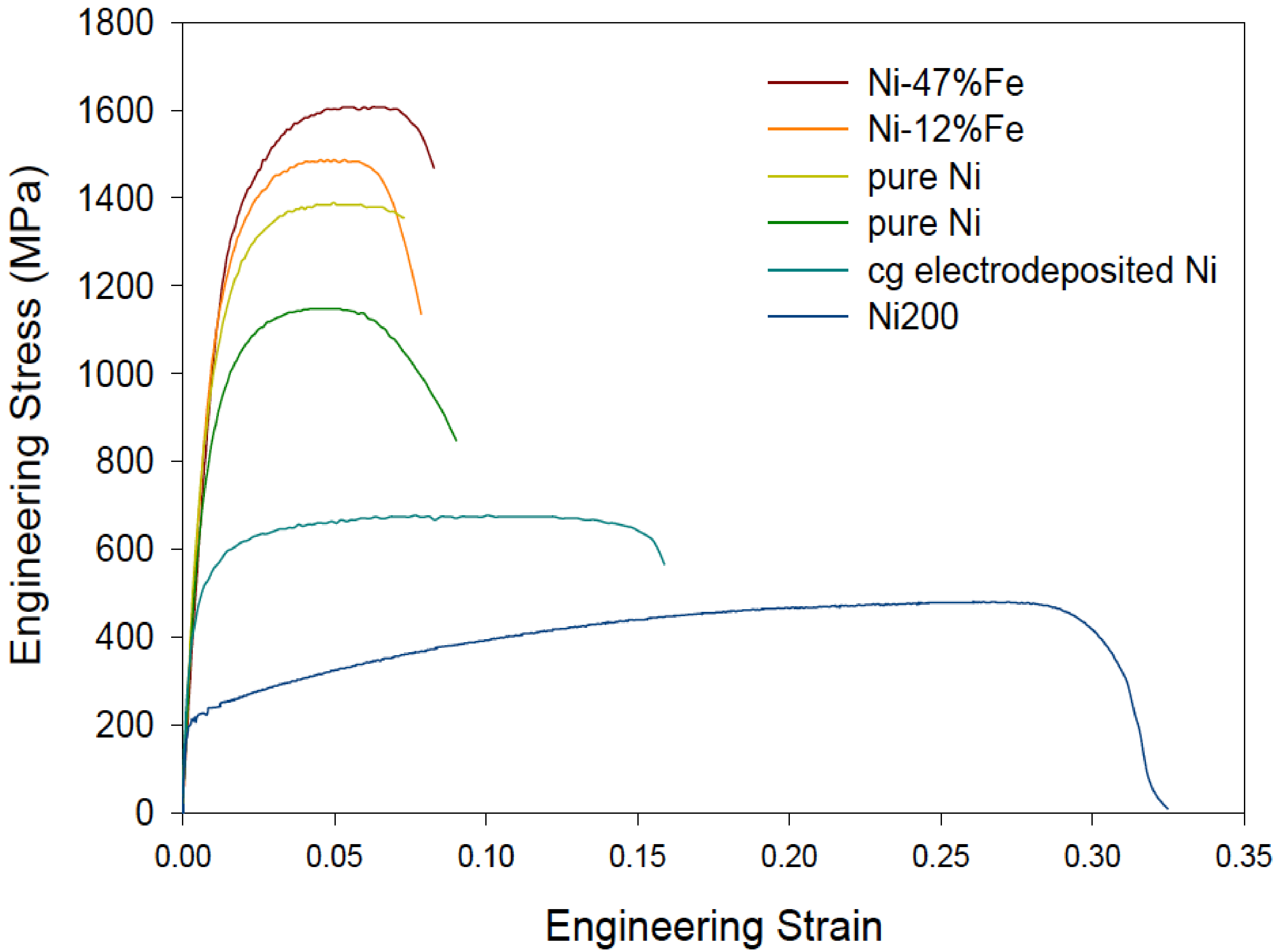
Nanocrystalline Metals



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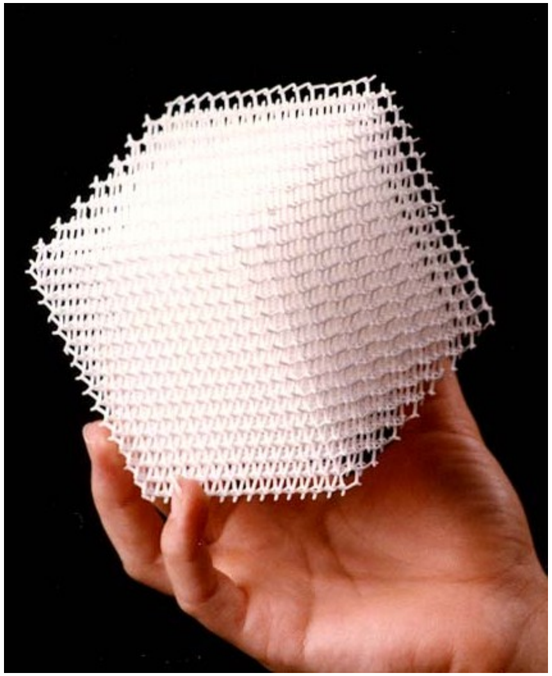
Polymer Additive Manufacturing

- we use a 3D Systems Projet HD 3500 3-D printer
- this uses a stereolithography process, which includes the deposition of wax as a scaffold
- the wax must be removed after construction, but this is not always straightforward
- we are able to achieve resolutions where we can reliably generate features with minimum dimensions of about 50 um

3D Systems, Projet HD 3500
http://printin3d.com/



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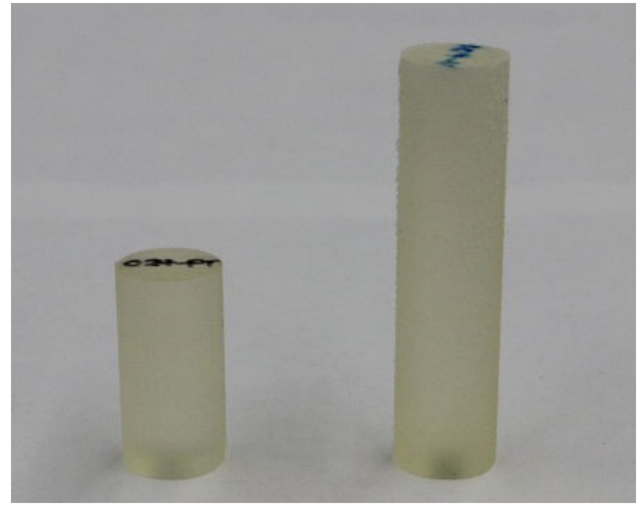
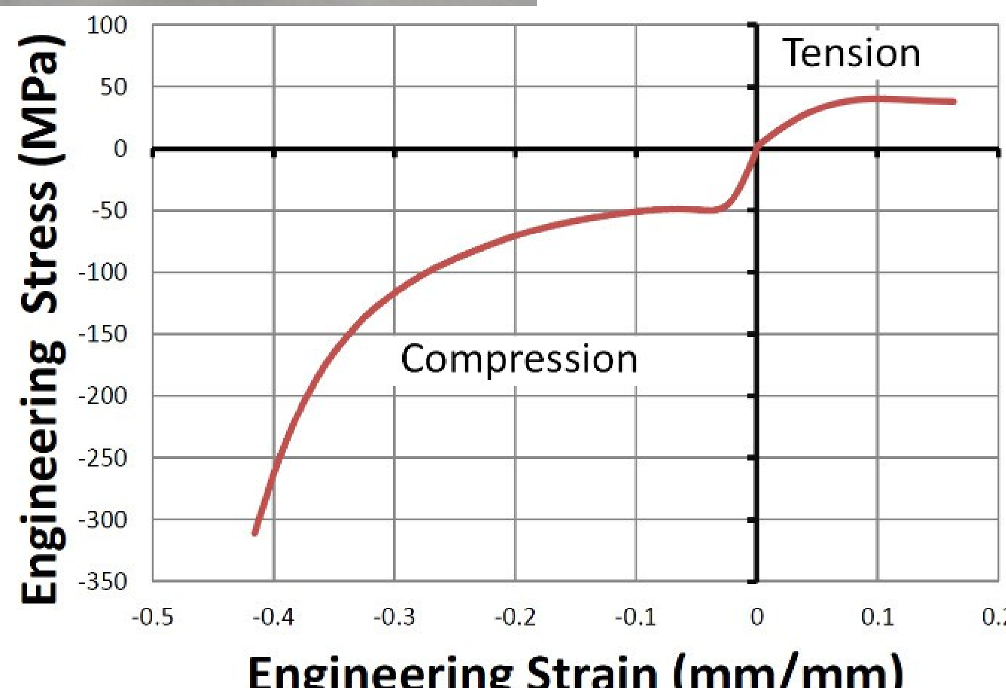
Polymer Additive Manufacturing

- the polymer that is generated (VisiJet Crystal is the trade name) is most similar to PMMA, although 3D Systems claims it is like ABS
- because of the high degree of cross-linking, the resulting polymer is somewhat brittle
- it is also somewhat anisotropic, probably due to the photolithography process
- also, the material properties are significantly different in tension and compression





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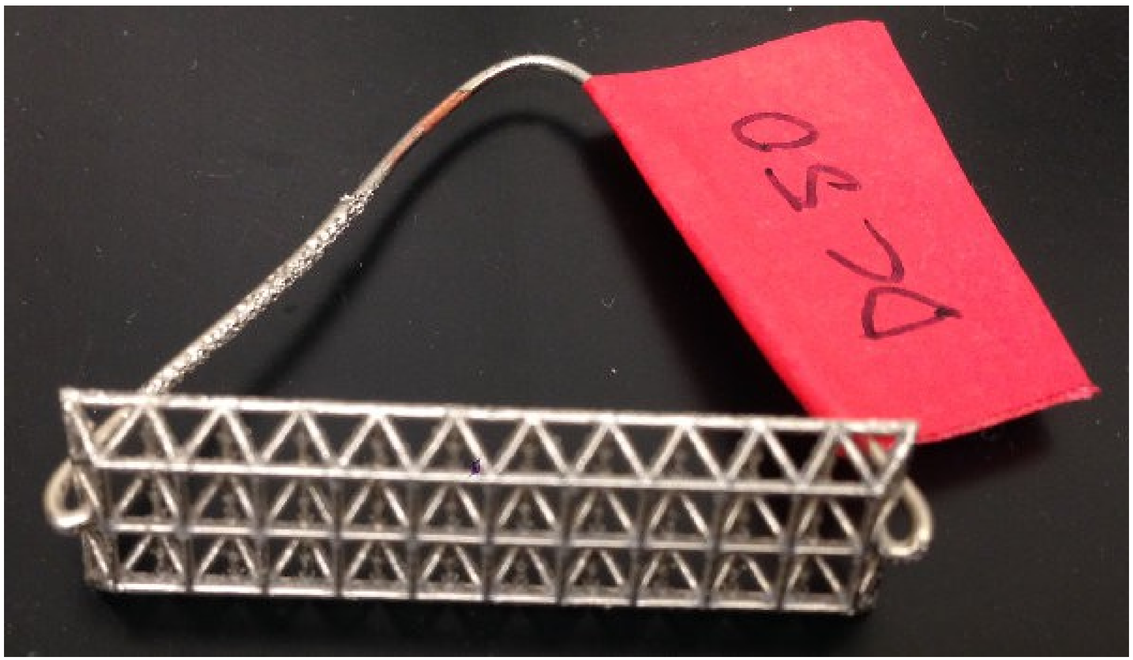
Metallisation and Electrodeposition



- we need a technique that combines the geometric complexity that we can achieve using additive manufacturing with the high performance available from nanocrystalline metals
- electrodeposition is the answer: because it is a non-line-of-sight process, it can be used to coat the microtrusses in which we are interested
- the first step is metallisation of the polymer preform: we can do this through a variety of methods, including electroless deposition of copper, dip coating with a conductive layer or sprays
- Integran has a proprietary process for this

Metallisation and Electrodeposition

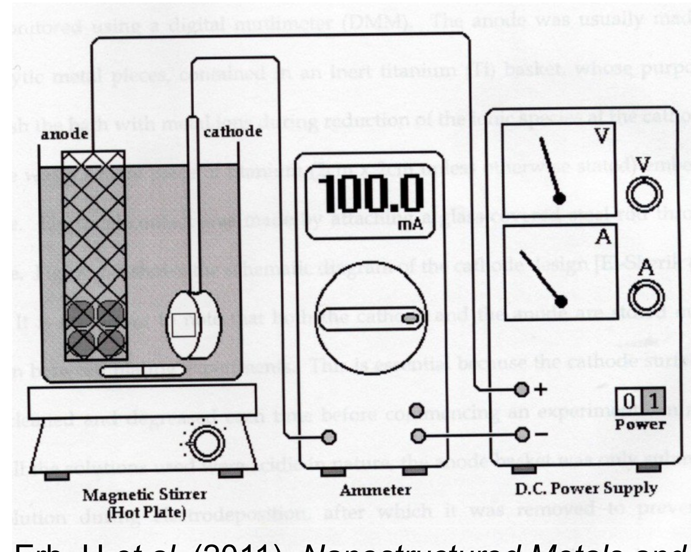
- electrodeposition is a standard technique for fabricating metal coatings; has been used since the early years of the nineteenth century

- the piece to be coated acts as a cathode, with metal ions recombining on the surface

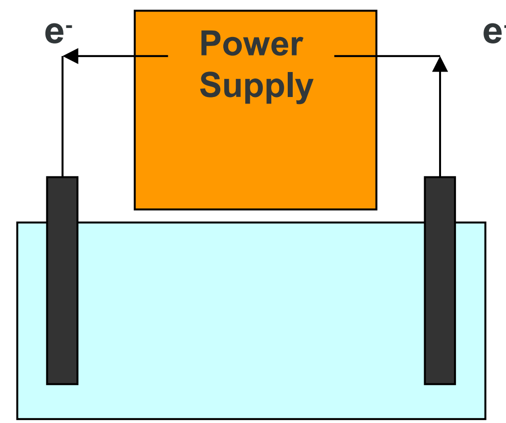
- the coating properties become a function of:

1) bath chemistry and pH
2) electrolyte flow
3) temperature
4) current density
5) waveform

- this is a relatively inexpensive method to process materials



Erb, U *et al*. (2011). *Nanostructured Metals and Alloys*, Cambridge, UK: Woodhead Publishing.



Cathode:
$M^{z+} + Ze^- \rightarrow M$

Anode:
$M \rightarrow M^{Z+} + Ze^-$

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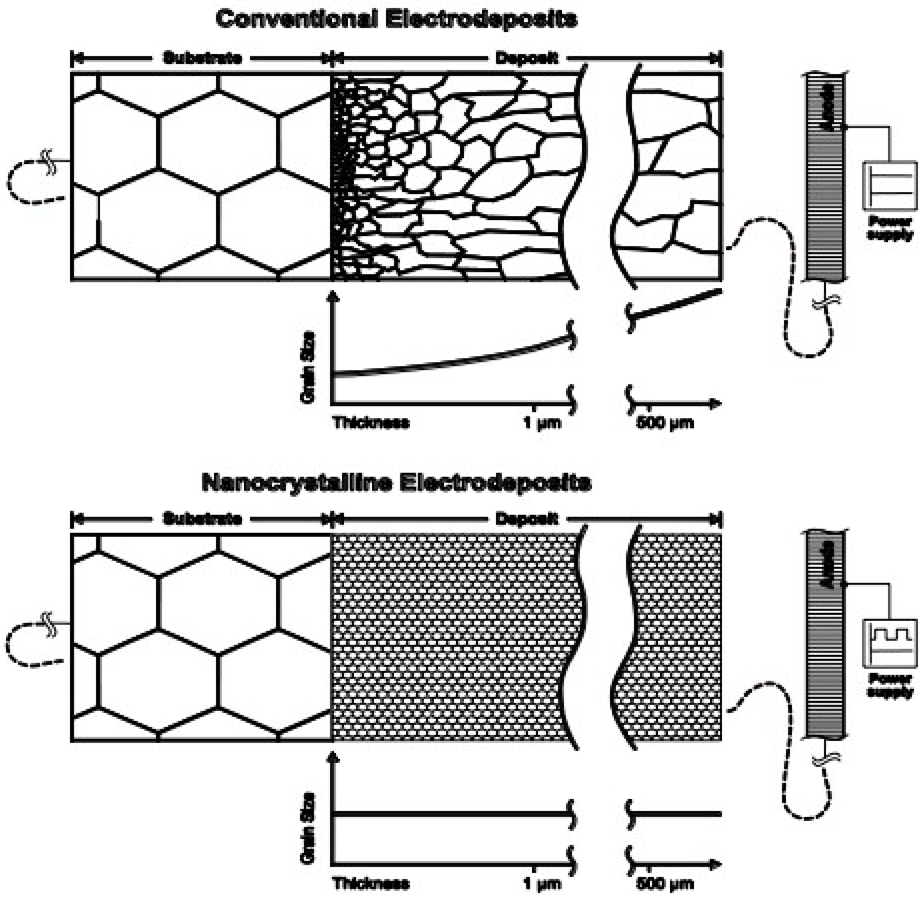
Metallisation and Electrodeposition



- the process that we employ uses pulsed electrodeposition
- this prevents the crystal grain sizes from increasing with increasing thickness of the coating, as would happen with conventional electrodeposition
- most of the proprietary technology associated with this is, again, owned by Integran
- there are several critical features:

1) nearly fully dense
2) large thickness (up to 1 mm)
3) decent ductility

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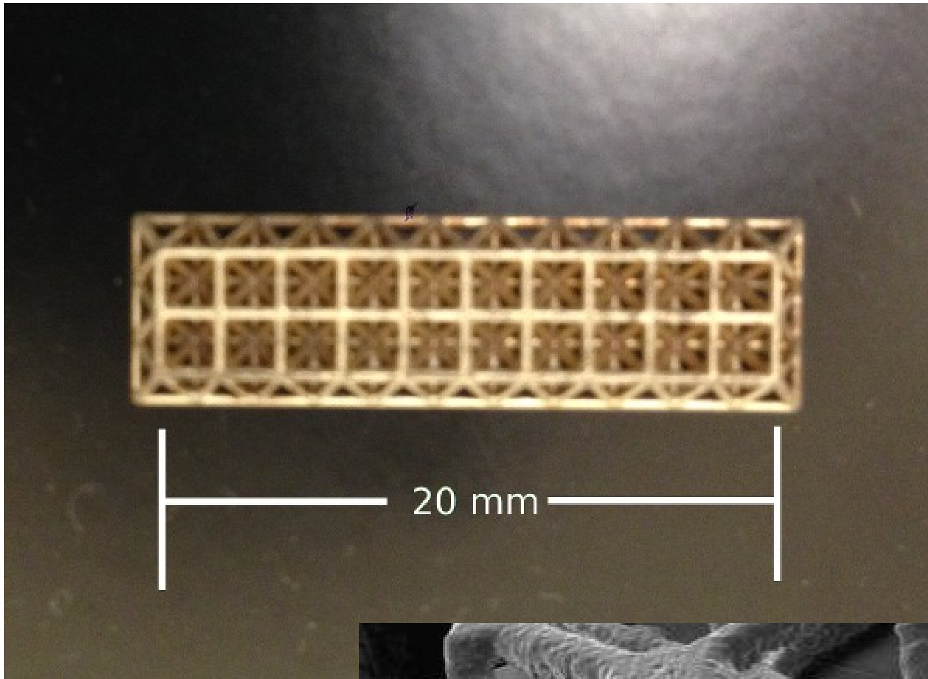
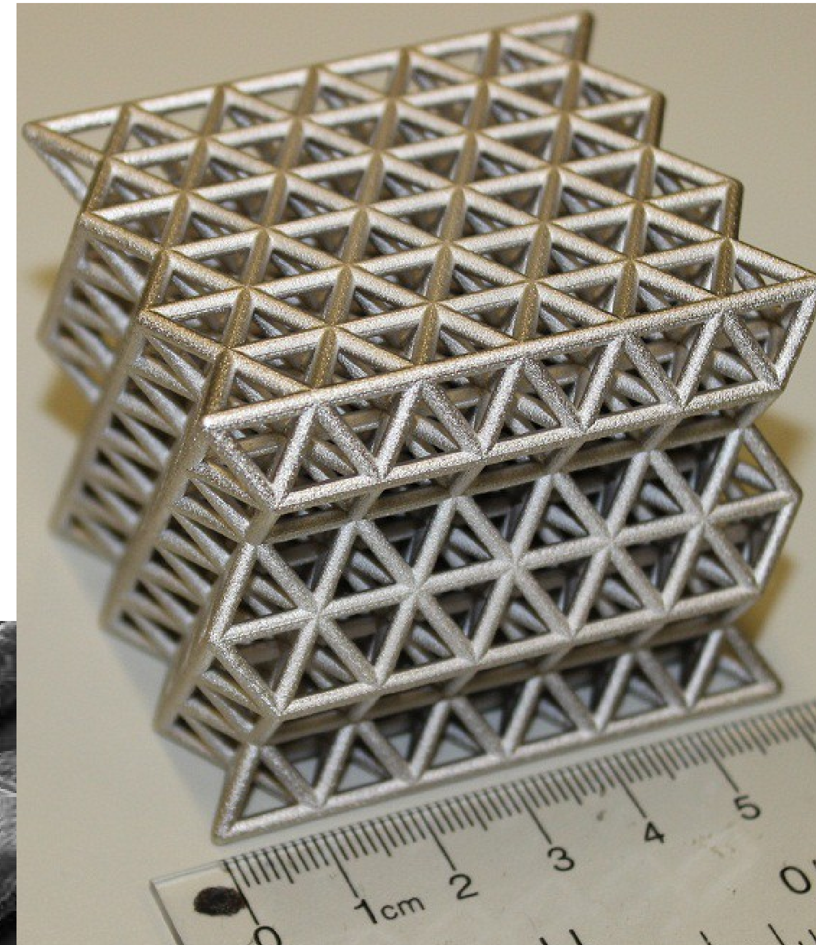
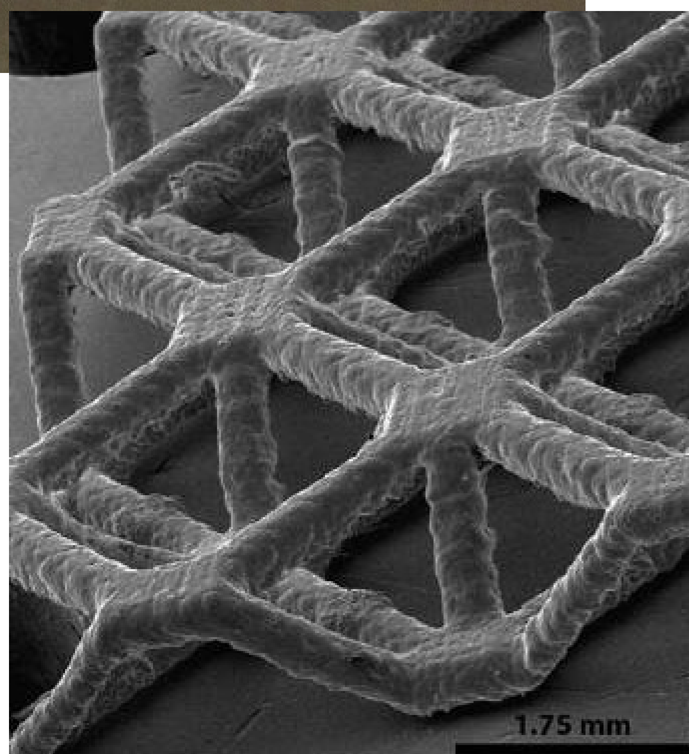
Hybrid Nanometal Microtrusses







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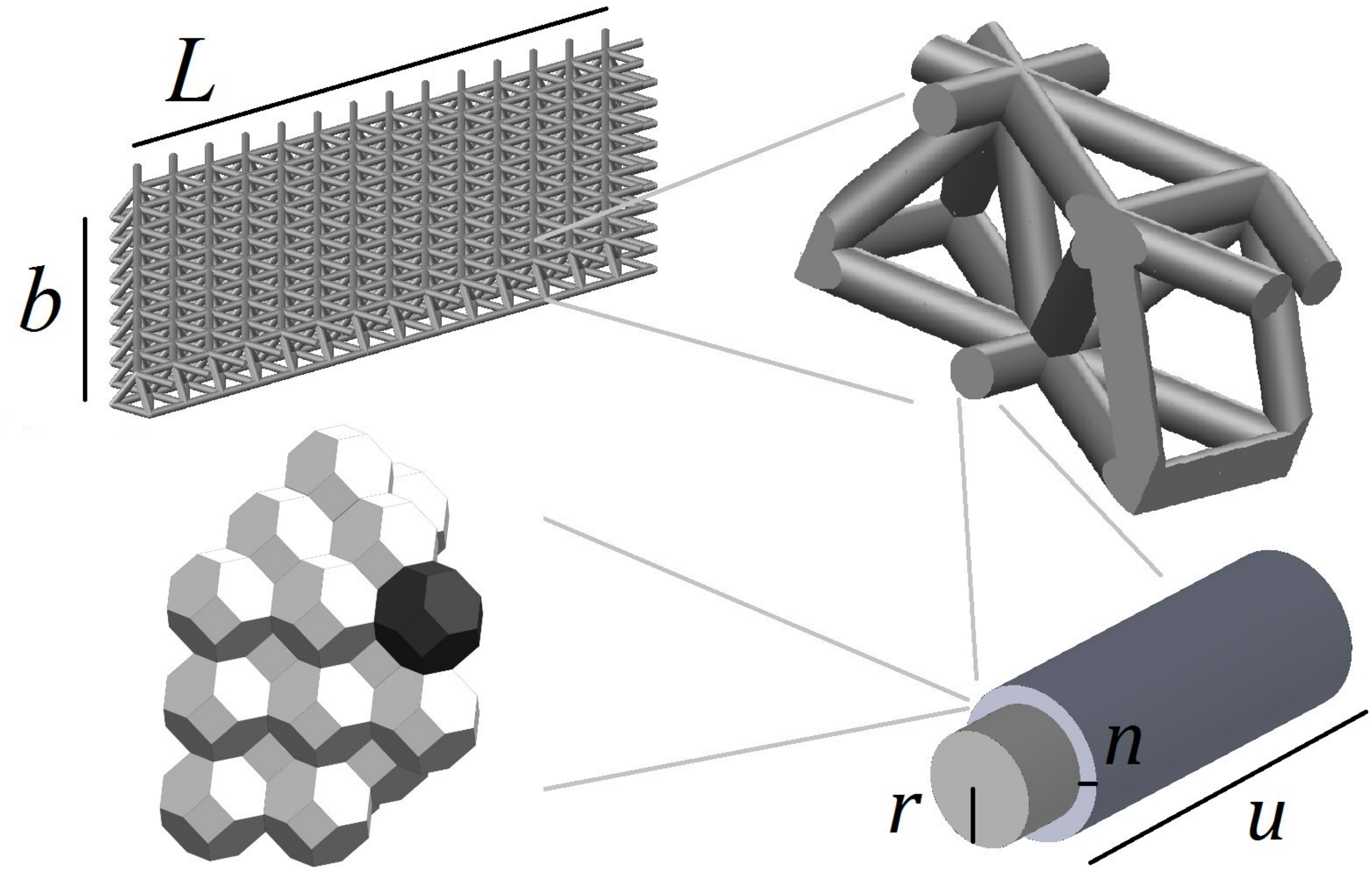

this process gives us control over four different length scales in the structure: the overall structural scale; the unit cell topology; the strut radius and coating thickness; and the nanoscale crystal grain size and elemental composition

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Hybrid Nanometal Microtrusses

what we can control during the fabrication process:

- at the atomic scale: grain size distribution, elemental composition:
  - strength, ductility, modulus,thermal expansion

- at the strut scale: thickness of coating, size and shape of preform
  - relative proportions of polymer and metal, degree of polymer crosslinking

- at the cell scale: unit cell topology, grading or non-uniformity of the lattice

- structural scale

what does this control over the fabrication process give us?

Microtrusses as Structures

the microtrusses are configured as beams; we are going to look at bending structures

the goal of the optimisation process is to find the beam with the minimum mass that will support a load *P* applied at the centre of span *L*

minimise a non-dimensional mass index:

$$\hat{M} = 8\pi\bar{u}\bar{r}^2\left(\tilde{\rho} + 2\bar{u}\bar{n}\right)$$

subject to the constraints that the beam must support the load that will be applied to it

there is one such constraint for each failure mechanism to which the beam might be subject

Microtruss Optimisation

sandwich beams with metal-coated polymer struts are subject to three main failure mechanisms: overall yield of the metal coating; global buckling of the struts in compression; and local shell buckling of the coating in compression

each of these is modelled, again non-dimensionally:

yield:

$$\hat{P}_y = 4\pi\tilde{\sigma}\bar{r}^2\bar{u}^2\bar{n}\left(\bar{n}+2\right)\left(2\bar{r}+\frac{1}{\sqrt{2}}\right)$$

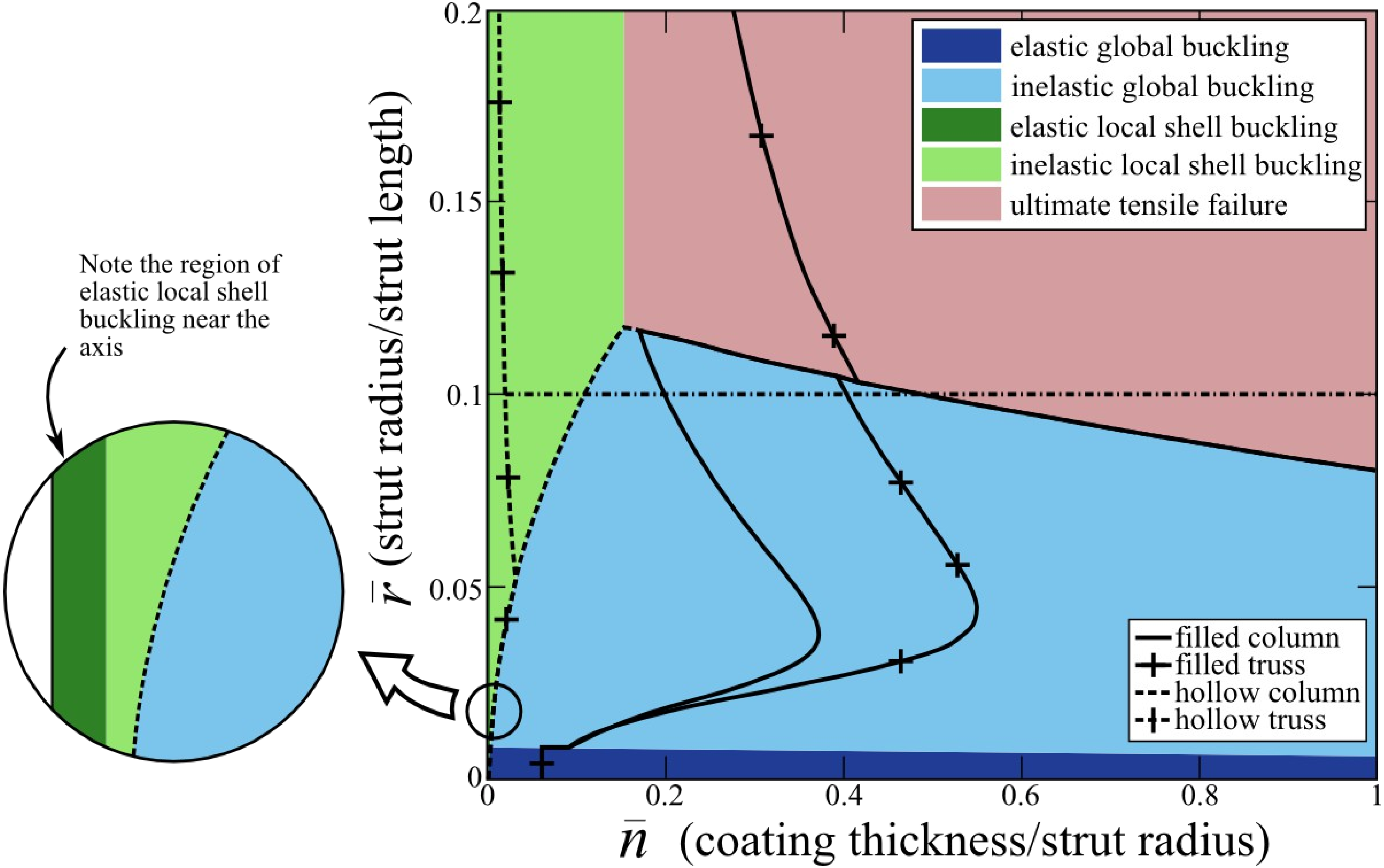
global buckling:

$$\hat{P}_b = \frac{\pi^3}{4}\tilde{E}\bar{r}^4\bar{u}^2\bar{n}\left(\bar{n}^3+4\bar{n}^2+6\bar{n}+4\right)\left(2\bar{r}+\frac{1}{\sqrt{2}}\right)$$

local shell buckling:

$$\hat{P}_{lsb} = \frac{4\pi\gamma\tilde{E}}{\sqrt{3\left(1-\nu^2\right)}}\bar{u}^2\bar{r}^2\bar{n}^2\left(\bar{n}+2\right)\left(2\bar{r}+\frac{1}{\sqrt{2}}\right)$$

Microtruss Optimisation



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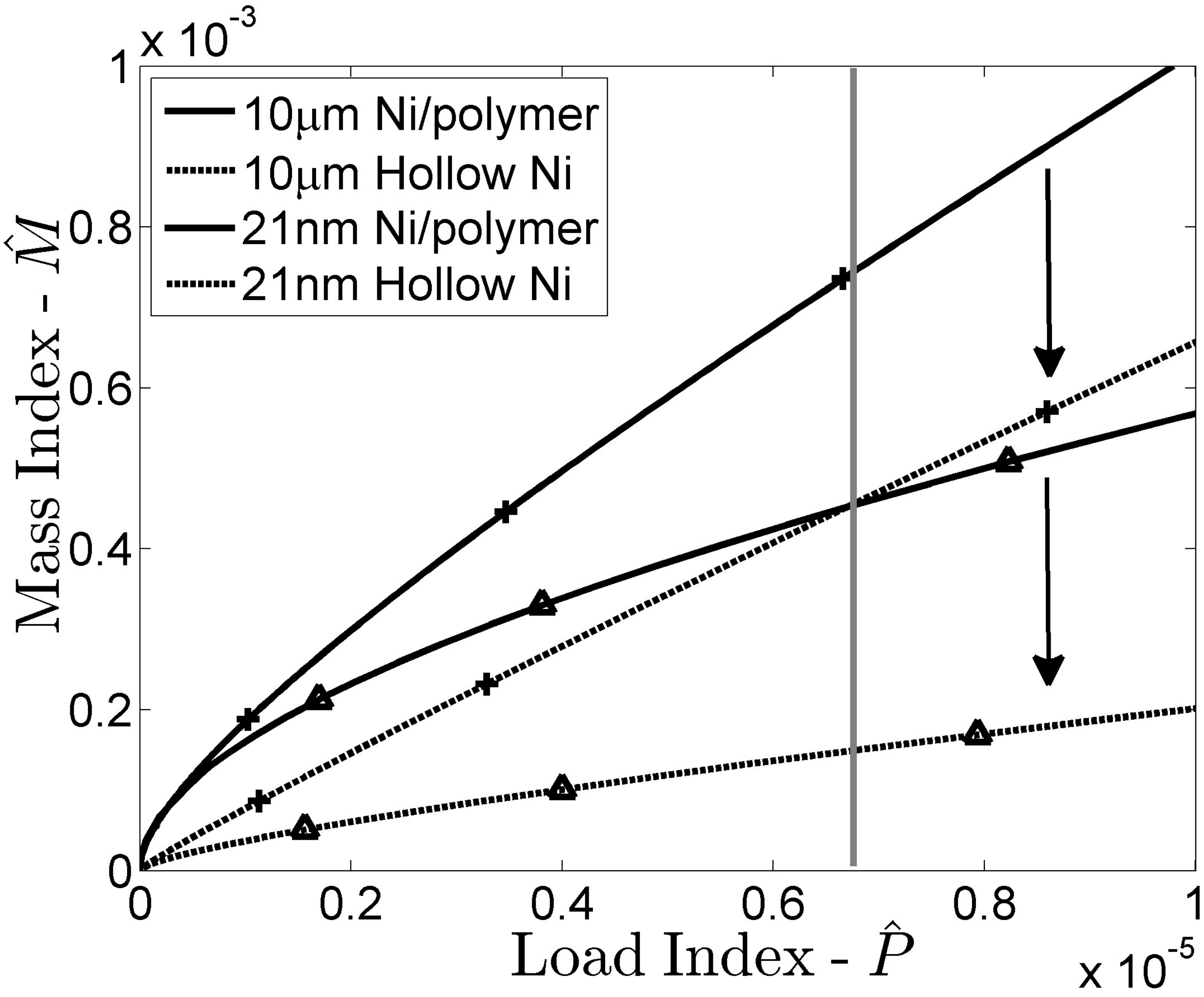
Microtruss Optimisation



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Microtruss Wave Propagation

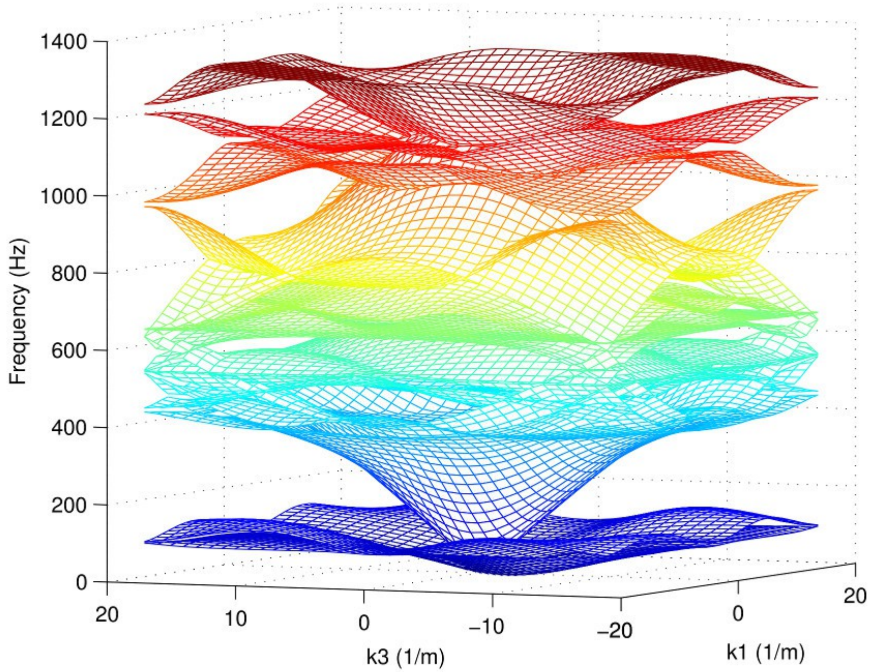
waves propagating through an infinite lattice can be modelled using Floquet-Bloch theory, which states that if a wave is attenuated in a single unit cell, it will be fully attenuated in the lattice as a whole

waves are dispersive in lattices: waves of differing wave vector propagate with different frequency and speed

what is important is that at some frequencies, NO waves propagate in any direction

thus the microtrusses can be used as vibration filters

this is particularly appealing because the effective density and the effective bending stiffness can be varied independently



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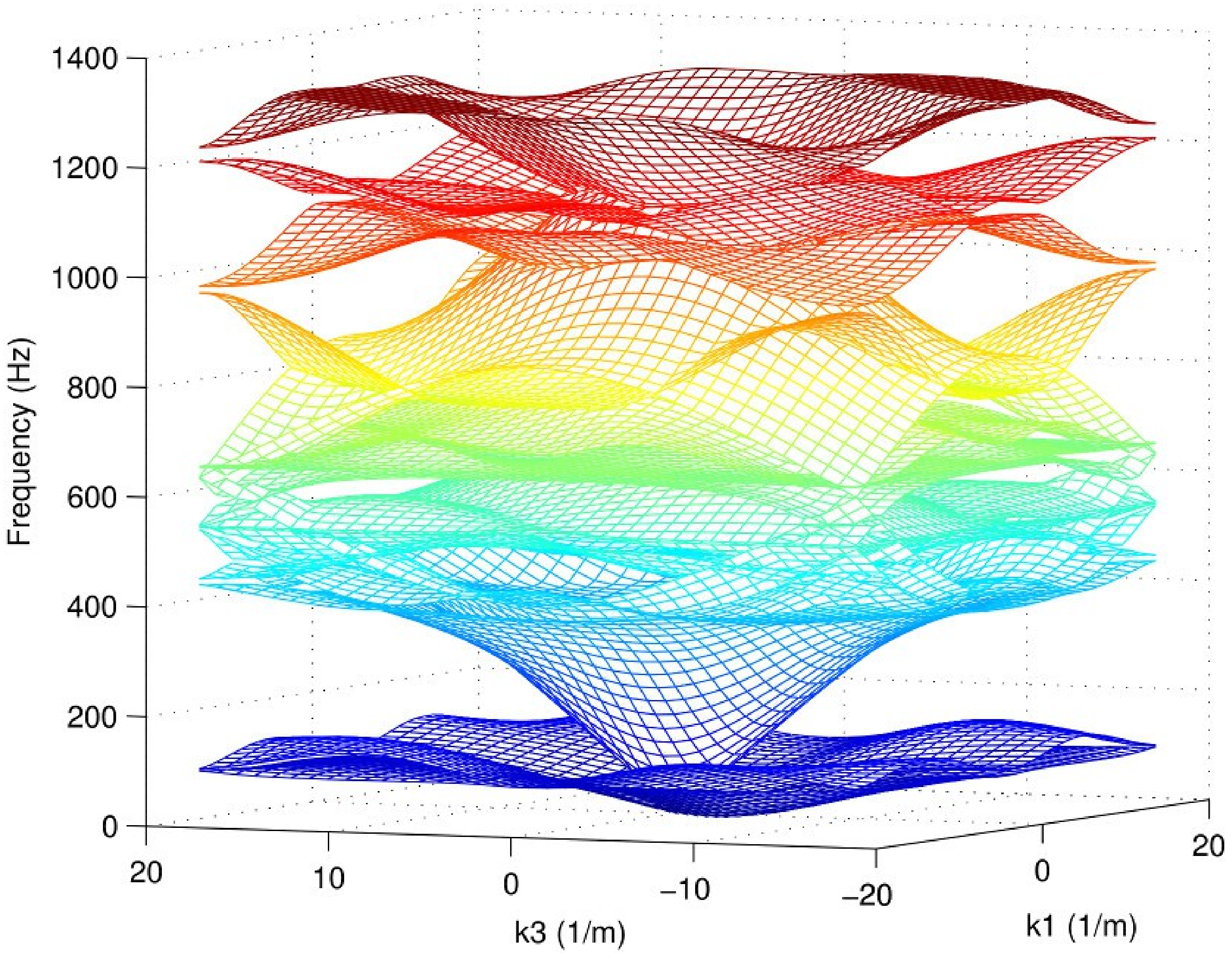

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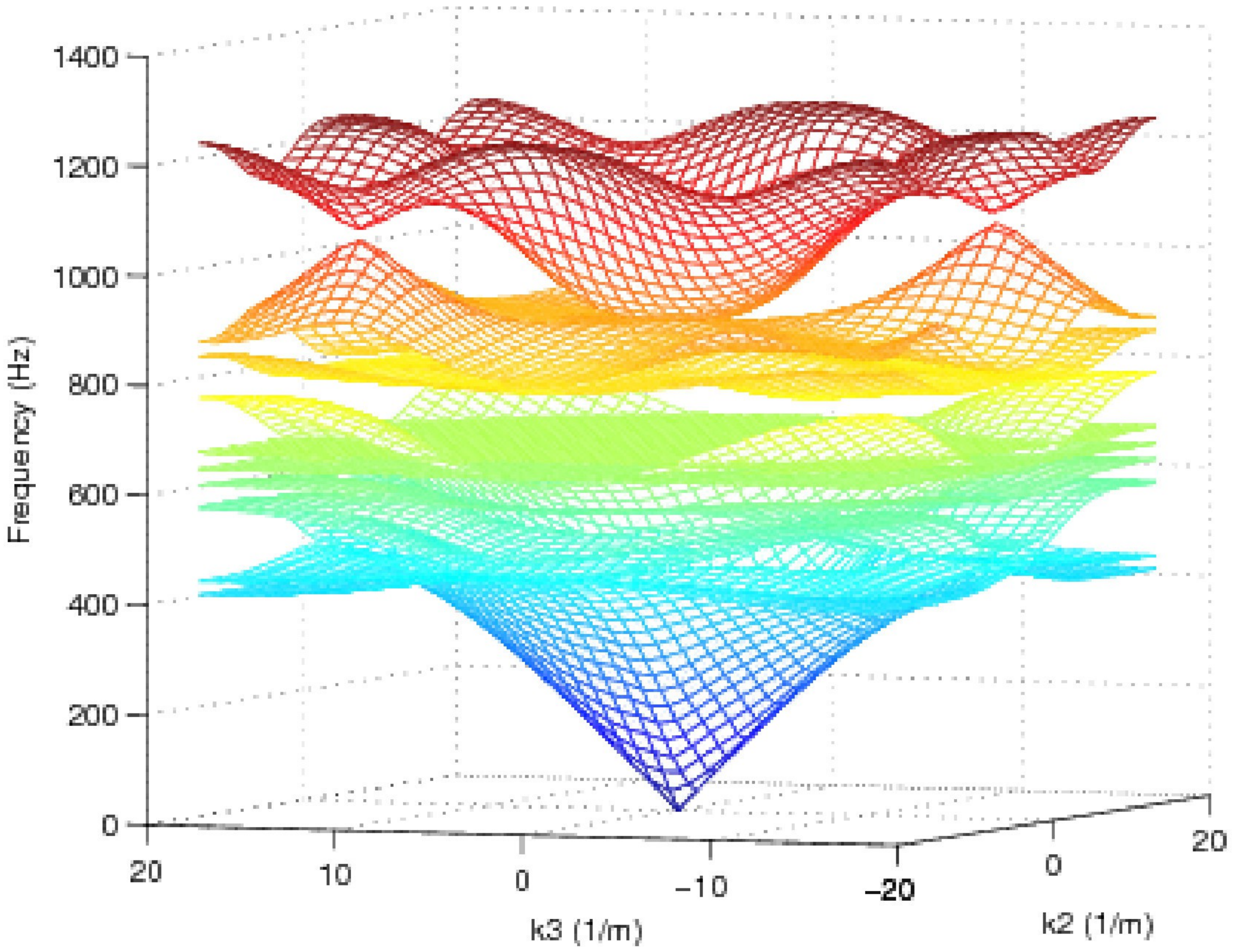

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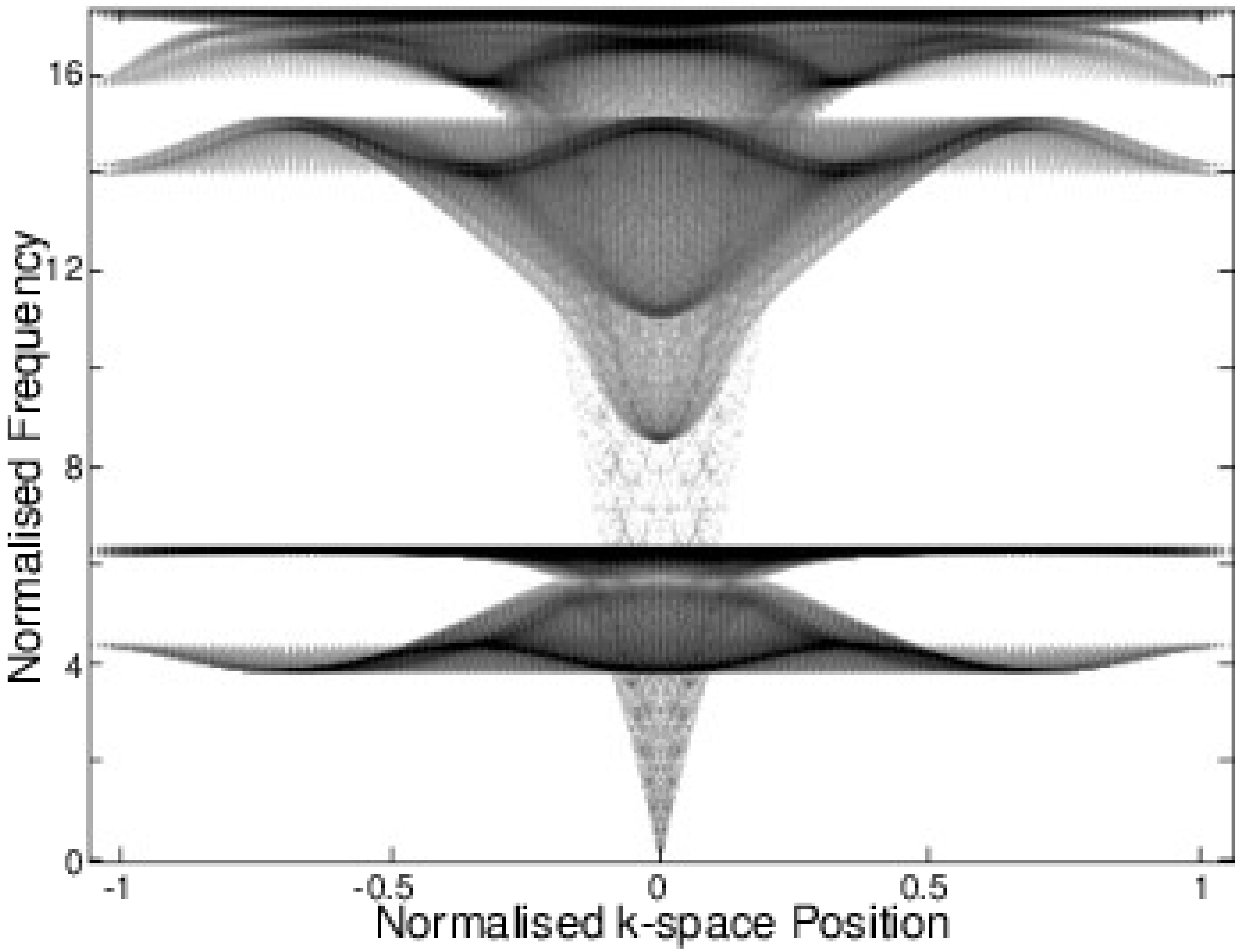

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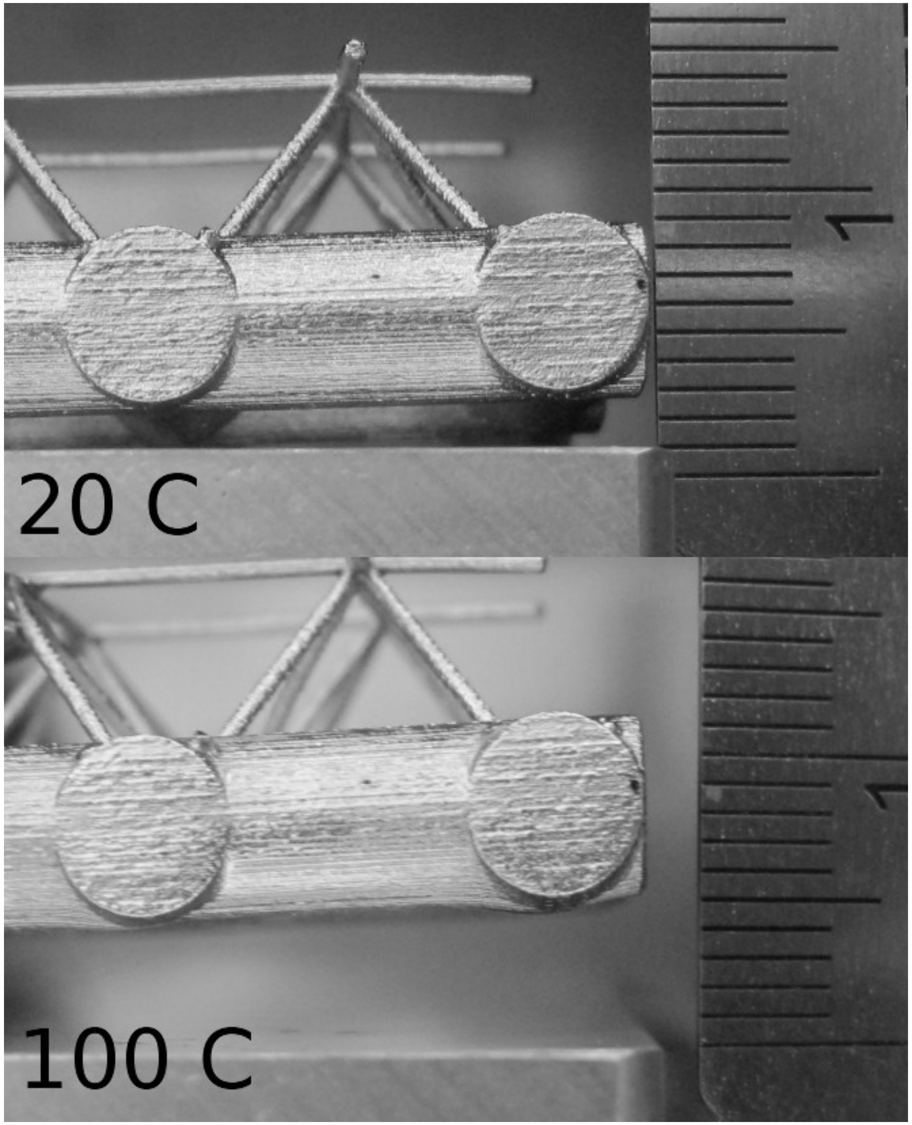
Microtruss Morphing

because each strut is a composite of metal and polymer, the overall coefficient of thermal expansion of a strut is determined by the relative quantity of each material

by selecting these quantities carefully, we can tune the local CTE of each strut member

this could enable compatibility with another structural element without the generation of thermal stresses

alternately, differential thermal expansion within a single structure can be employed to change the shape of a structure during temperature changes



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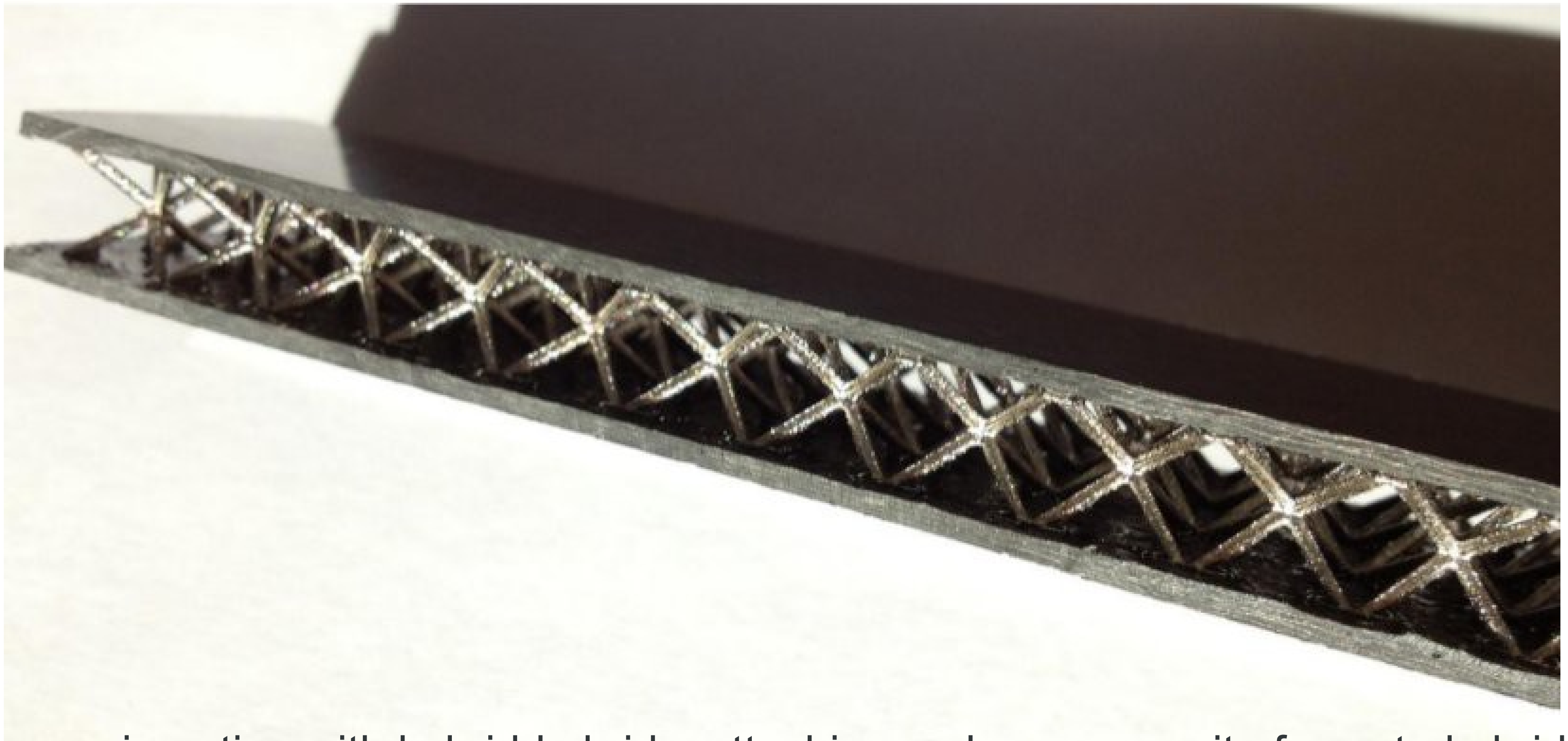
Hybrid Hybrids



we are experimenting with hybrid-hybrids: attaching carbon composite faces to hybrid polymer-nanometal truss cores

this provides us with excellent tailorability, but the attachment process remains to be refined

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Thanks!