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Mechanical properties of thermoelectric materials

Dr Hugo Williams

Ramy Mesalam

hugo.williams@le.ac.uk

Authors and acknowledgements

Hugo Williams, Ramy Mesalam, Richard Ambrosi and the Radioisotope Power Systems team
Department of Engineering and Department of Physics & Astronomy
University of Leicester

Mike Reece, Kan Chen, Huanpo Ning
Queen Mary University of London

Kevin Simpson, Mark Robbins and team
European Thermodynamics Ltd., Kibworth, Leicestershire

Keith Stephenson
European Space Agency, ESTEC, Noordwijk, The Netherlands

Colleagues at National Nuclear Laboratory and Airbus Defence and Space

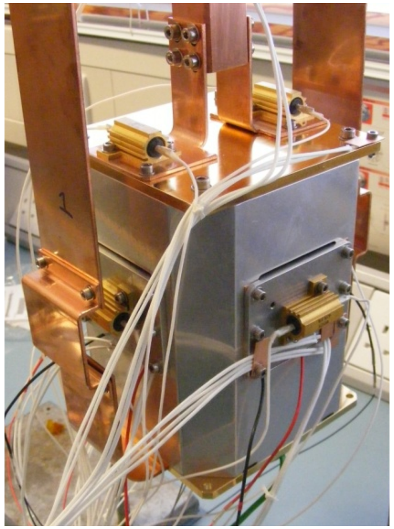
Contents

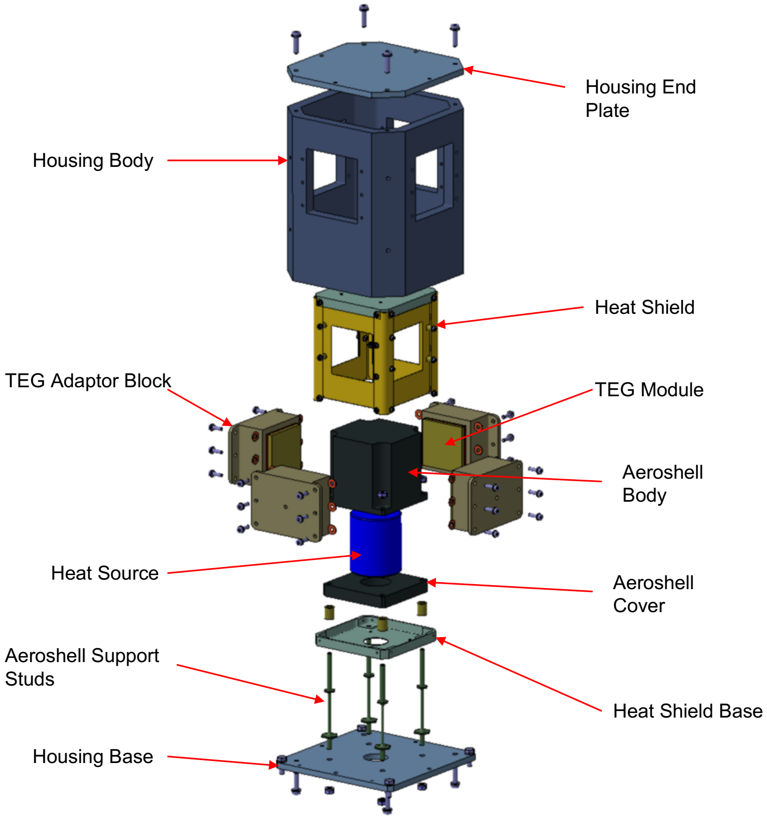
- European Radioisotope Thermoelectric Generator (RTG) development
- Pilot study on mechanical property enhancement using SPS and nano-B_4C.
- Mechanical challenges for Space RTGs
- Research challenges and future perspective

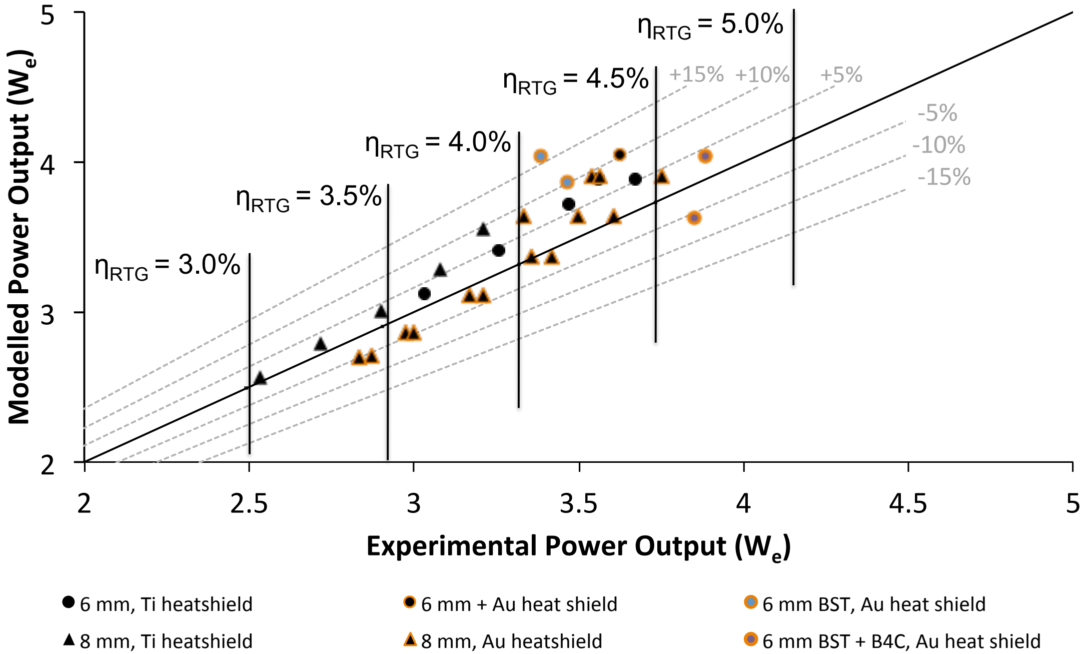
RTG Development in the UK

- UoL has led RTG development in UK under contract to ESA since 2010:
  - PI: Prof. Richard Ambrosi, UoL
- Aim: Develop a first iteration RTG design for Europe optimised for ^{241}Am fuel
- Designed, built and tested a small-scale lab prototype:
  - Target power 5 W_e from 83 W_{th} (electrically heated)
  - Develop a test bed for the integrated system performance of thermoelectric materials & modules
- Produced a 10 W_e refined flight design based on this architecture
- Next phase of work will be a ’breadboard’ for the refined flight design

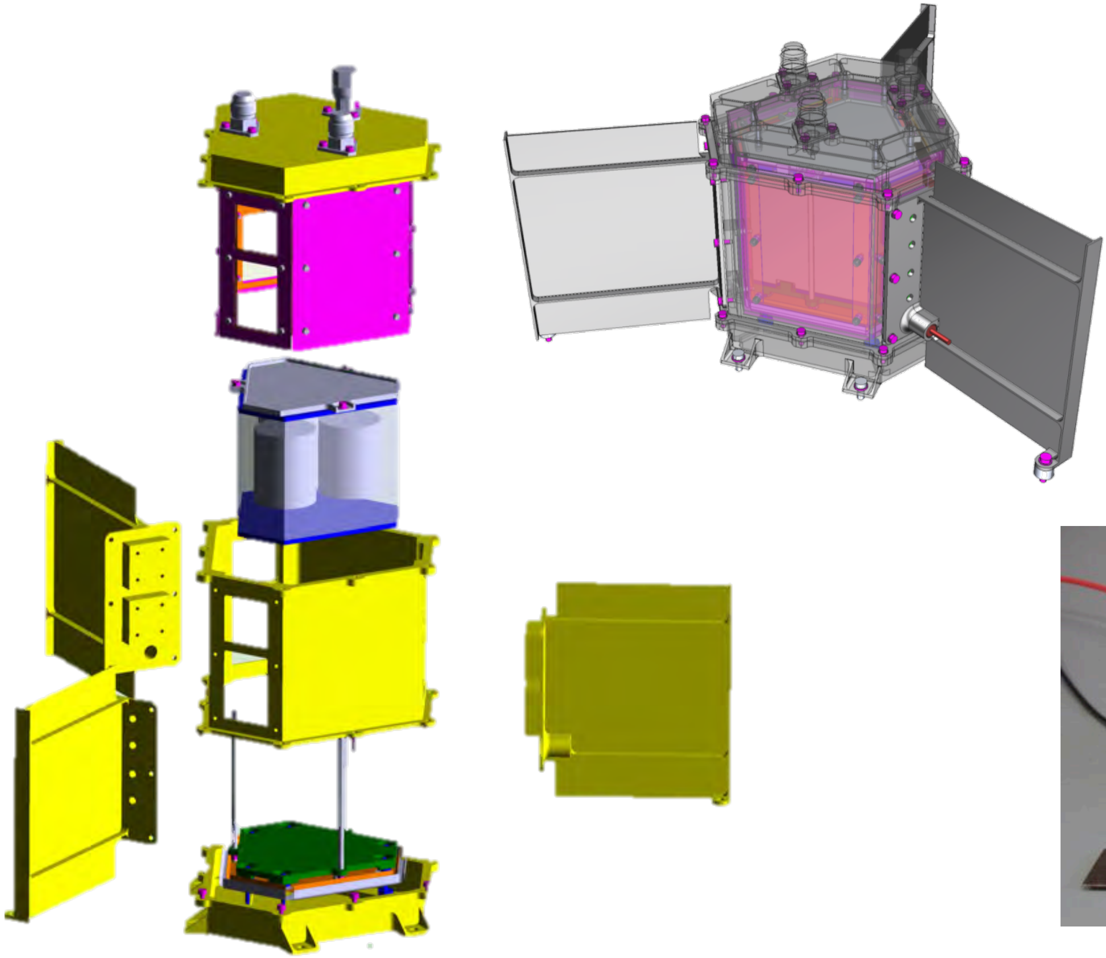
RTG Laboratory prototype





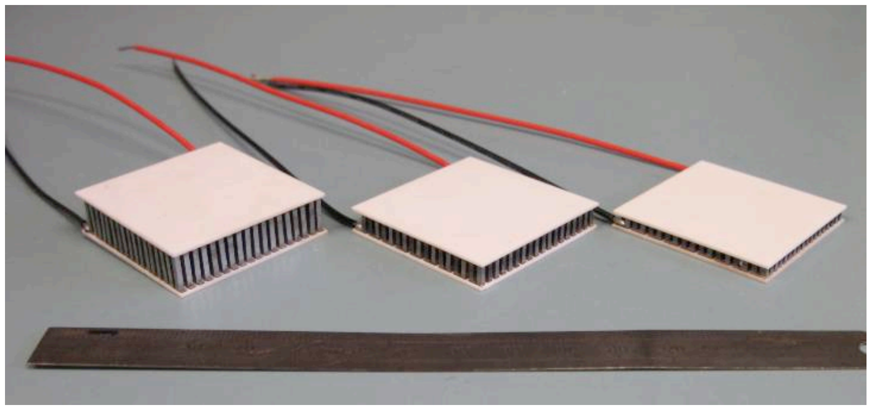


RTG Architecture & implications



For the thermoelectrics:

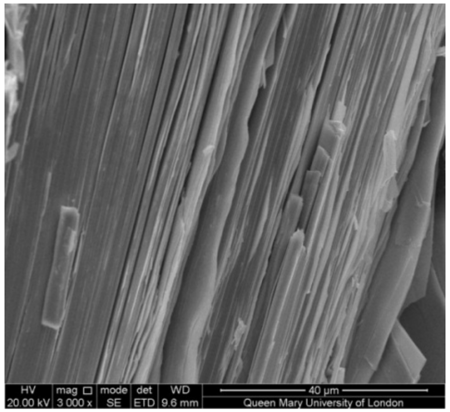
- Bi_2Te_3 based materials
- Compression & shear loading
- Modules with high aspect ratio legs



Enhanced Bi_2Te_3 thermoelectrics

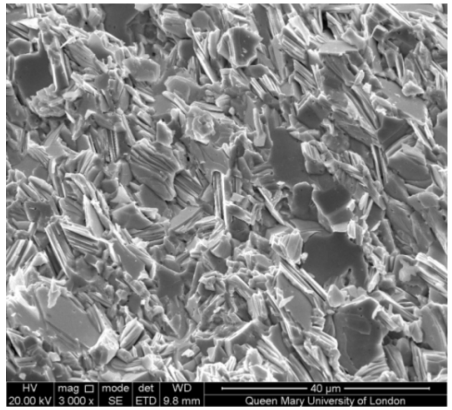
- Most active research on thermoelectric materials focuses on zT
- Mechanical properties and behaviour of materials and modules is under-represented in the literature.

Conventional material production is by directional solidification



← Very poor strength and/or toughness due to cleavage along the basal crystallographic plane // to growth

Polycrystalline, fine grained materials: better mechanical properties



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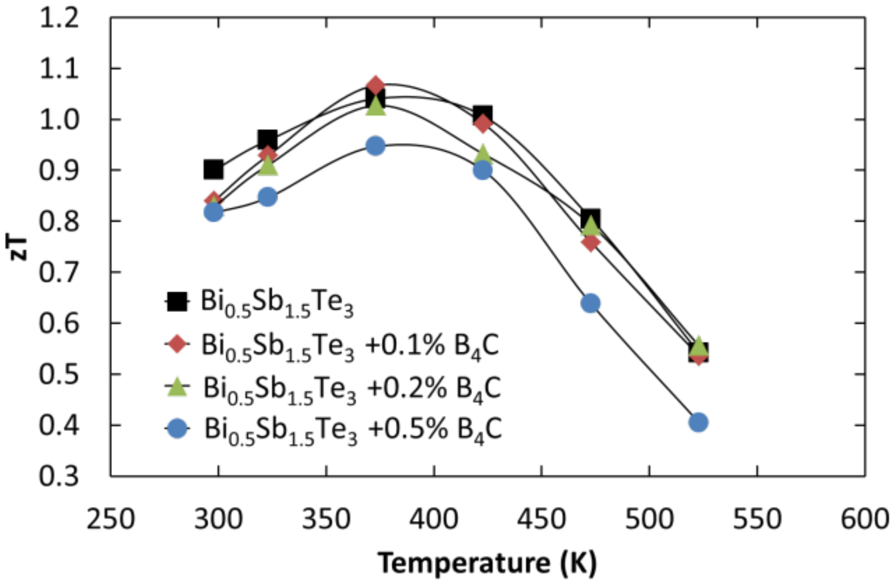
Enhanced Bi_2Te_3 thermoelectrics

- Literature indicates that addition of small volume fraction of nanoscale particles can enhance mechanical properties further and maintain/increase zT.
- Nano-scale B_4C added at up to 0.5 vol% to p-type $Bi_{0.5}Sb_{1.5}Te_3$ produced by mechanical alloying and Spark Plasma Sintering (SPS).



- p-type selected because generally more mechanically challenging than n-type
- Up to 0.2 vol% B_4C the effect on zT is negligible.

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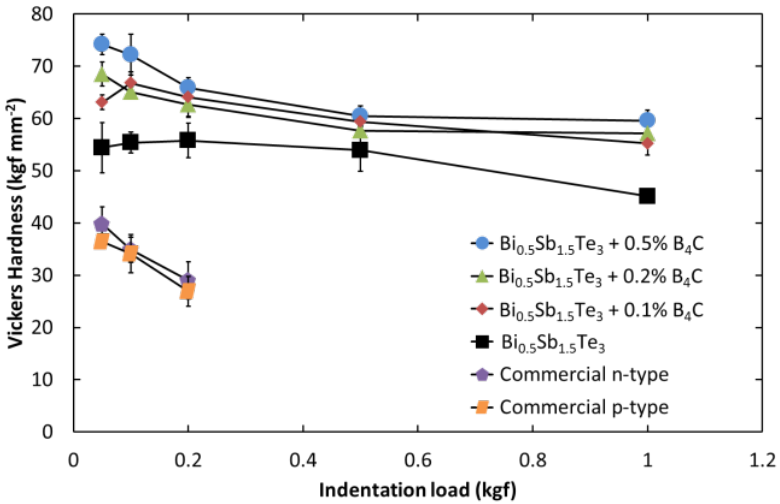
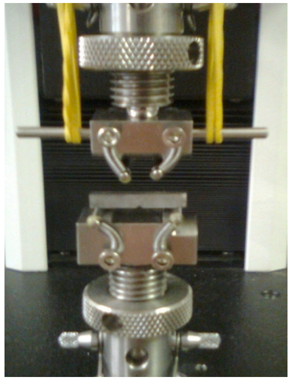
Enhanced Bi_2Te_3 thermoelectrics

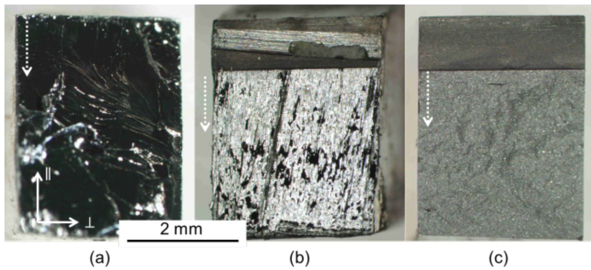


- Addition of nano-scale B_4C significantly improved Vickers hardness over and above the benefit of a polycrystalline material.
- Fracture toughness also measured for polycrystalline material, conventional materials were so brittle that few valid failures were obtained

First SEVNB measurement of Bi_2Te_3 materials:



Material	Fracture toughness K_{Ic} (MPa $m^{1/2}$) $\pm 1\sigma$
Conventional Directional Solidified	Invalid failures
SPS	0.79 ± 0.03
SPS + 0.2 vol% B_4C	0.80 ± 0.01



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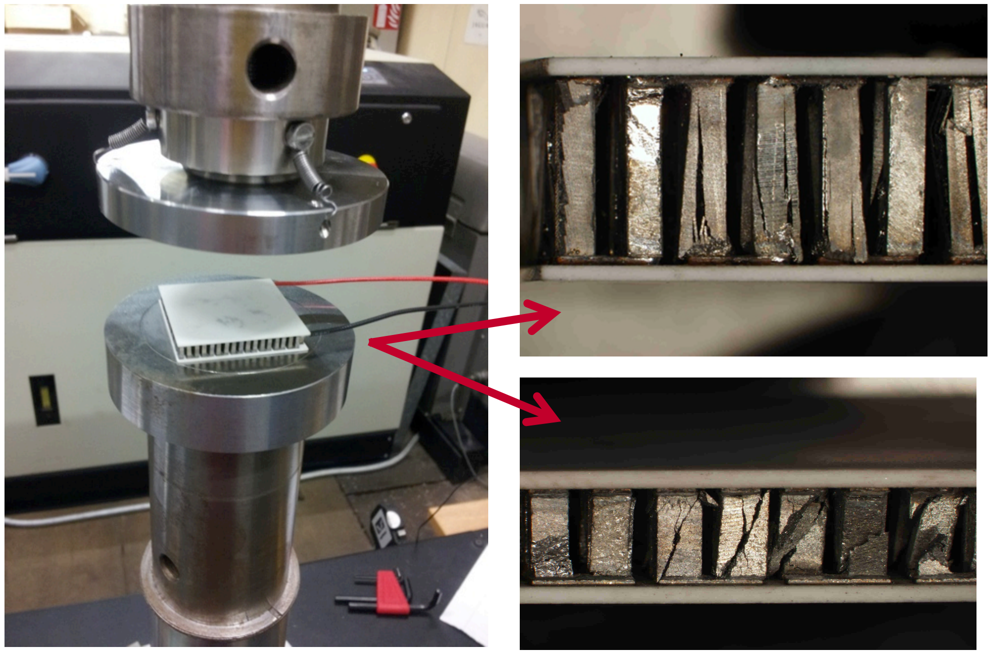
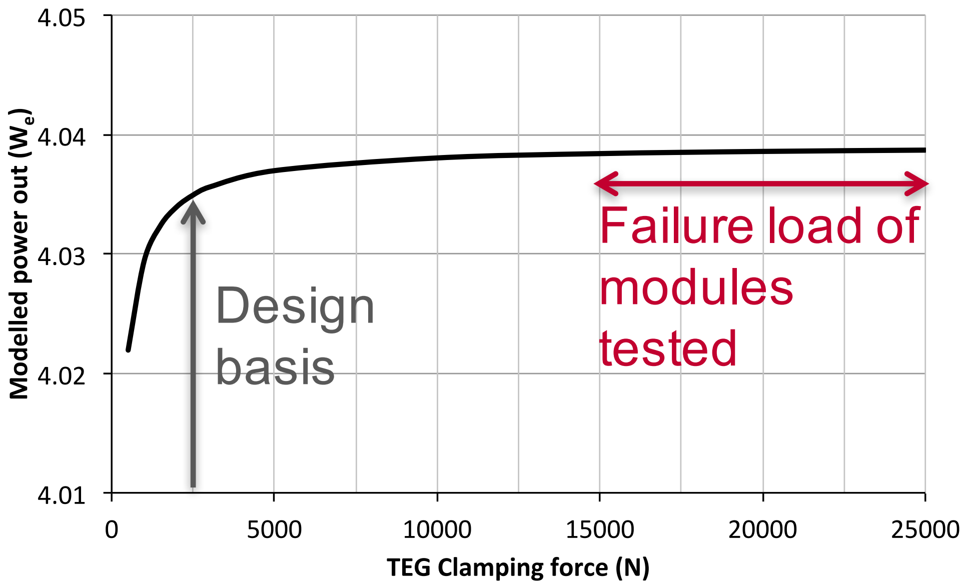
Bi_2Te_3 module mechanical integration

- Manufacture challenges for long legs with conventional materials
- RTG efficiency is linked to static compression strength of modules:
  - Study suggests good thermal conduction well within compression capability of modules, even with conventional materials
- Launch vibration imposes compression and shear





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Mechanical Properties of Interest

Machinability

Reduce Strength Limiting Flaws!

$$\propto \left(\frac{HE}{(K_{Ic})^2}\right)^{-1}$$

Reduce Brittleness Index

Thermomechanical Response

Thermoelastic Approach

$$R = \frac{\sigma_f k(1-\nu)}{E\alpha_{CTE}}$$

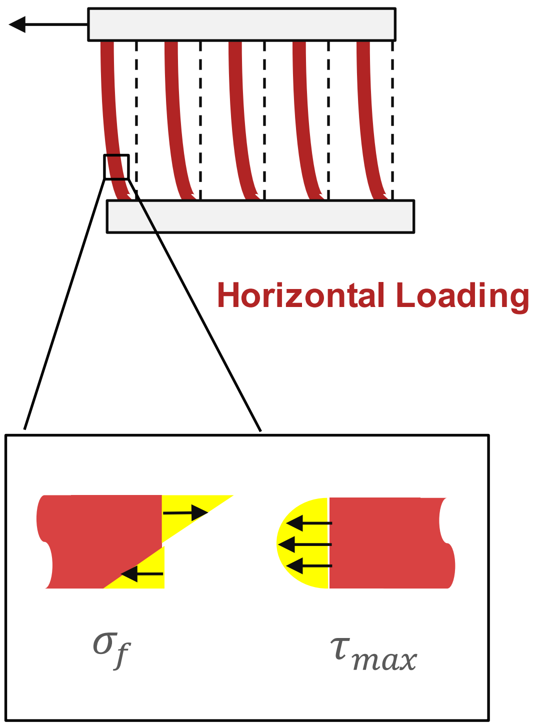
Energy Balance Approach

$$R = \frac{K_{Ic}(1-\nu^2)^{0.5}}{E\alpha_{CTE}}$$

Increase Resistance Index

Modal Response

$$([K]-\omega^2[M])\{\varphi\} = 0$$



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Mechanical Characterisation of Thermoelectric Materials

	Property	Procedure	Coupon Size	Sample Size	Statistical Analysis
σ_f	Flexural Strength	ASTM C1161 (4pt-Bending)	1.5 x 2.0 x 25 mm³	30	Weibull
K_{Ic}	Facture Toughness	ISO 23146 (SEVNB)	3.0 x 4.0 x 25 mm³	30	Weibull
E	Elastic Modulus	ISO 14577 (Nanoindentation)	N/S	30	Gaussian
H	Hardness	ASTM C1327 (Vickers Ind)	N/S	30	Gaussian

Supporting crystallography (e.g. XRD) and Fractography (SEM)
Sample size for full 'flight' qualification – research studies in literature have used using smaller specimen groups

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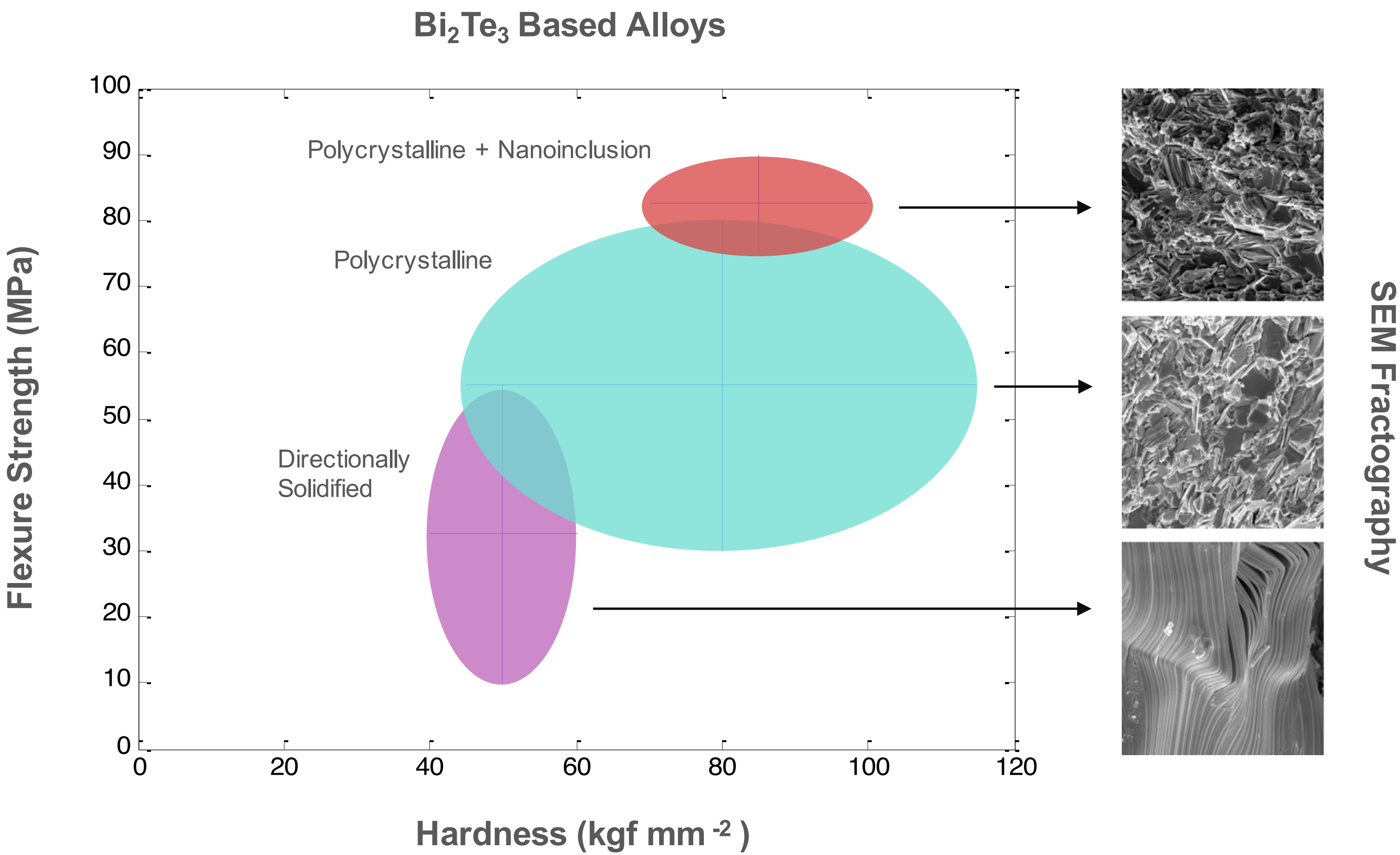
Polycrystalline & enhancements

Research group	Year	Thermoelectric Material	Processing Method	Enhancement Mechanism	Fracture Toughness improvement (%)	ZT Improvement (%)
Duan et al.	2012	$CoSb_{2.875}Te_{0.125}$	BM-SPS	$nano_p$-TiN	40	10
Schmidt et al.	2015	Mg_2Si	BM-SPS	$nano_p$-SiC	33^v	NS
Zhao et al.	2008	Bi_2Te_3	MA-BM-SPS	$nano_p$-SiC	18^v	2
Liu et al.	2010	$Bi_{0.5}Sb_{1.5}Te_3$	BM-SPS	$nano_p$-SiC	12^v	10^*
Duan et al.	2014	$Co_4Sb_{11.5}Te_{0.5}$	BM-SPS	$nano_p$-$Co_4Sb_{11.5}Te_{0.5}$	11	0
Akao et al.	2014	Zn_4Sb_3	BM-HP	$nano_w$-SiC	10^v	-30
Akao et al.	2014	Zn_4Sb_3	BM-HE	$nano_w$-SiC	9^v	-30
Wan et al.	2015	$CeFe_4Sb_{12}$	MA-M-SPS	Short C_f	4	2

^{v} Measured by Vickers indentation method

The Current Trend



Challenges and next steps

- Most thermoelectric development work reported is focused on zT enhancement.
- Literature on mechanical property enhancement requires review and consolidation, but there are promising approaches for improving properties
- Critical mechanical properties are almost certainly different for different configurations of thermoelectric device.
- Larger test campaigns will be required to generate statistically meaningful data for engineering application.
- In published literature, the direction of mechanical (and thermoelectric) property measurements is often not clearly stated, making comparisons difficult!
- Next phase of ESA project at UoL (working with QMUL/ETL) will investigate n-type Bi_2Te_3-based material, but also develop wider mechanical testing expertise and capability which we hope will support wider thermoelectric applications.

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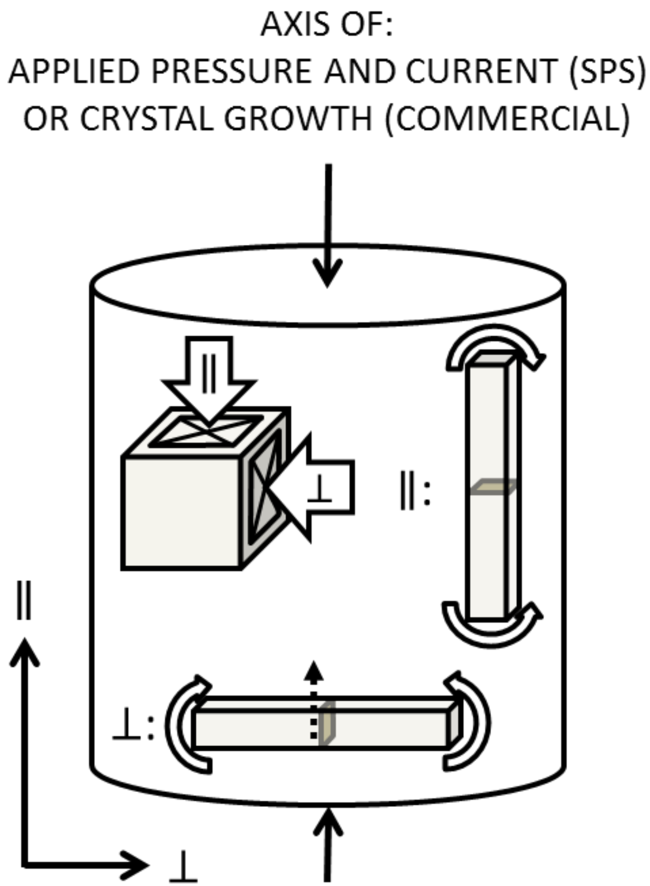
Support slides: material orientations



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