OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Neutron provides insights to engineering materials

Ke An

Neutron Scattering Division

U.S. DEPARTMENT of ENERGY

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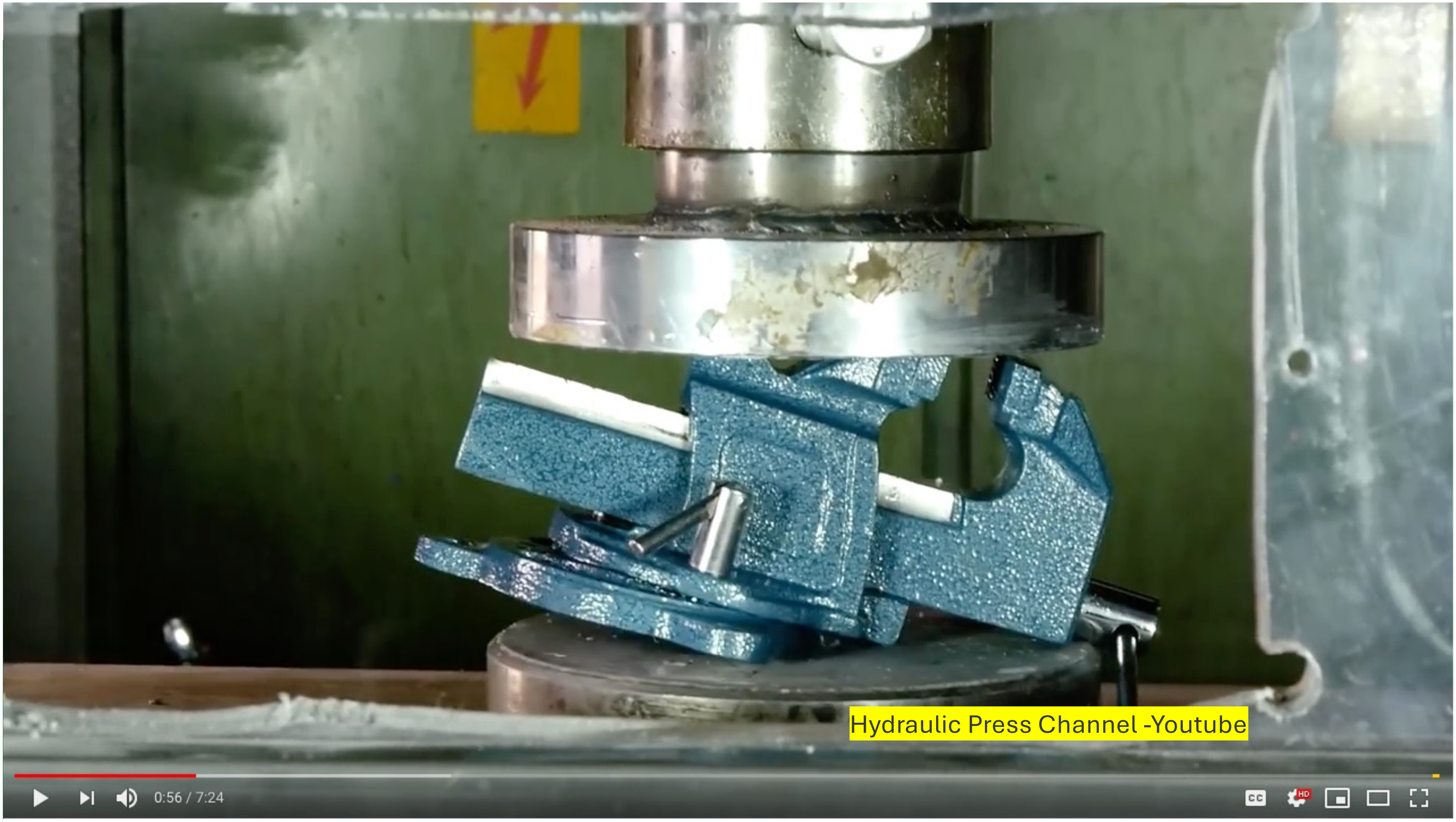
Hydraulic Press Channel -Youtube
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Hydraulic Press Channel -Youtube
0:59 / 7:24

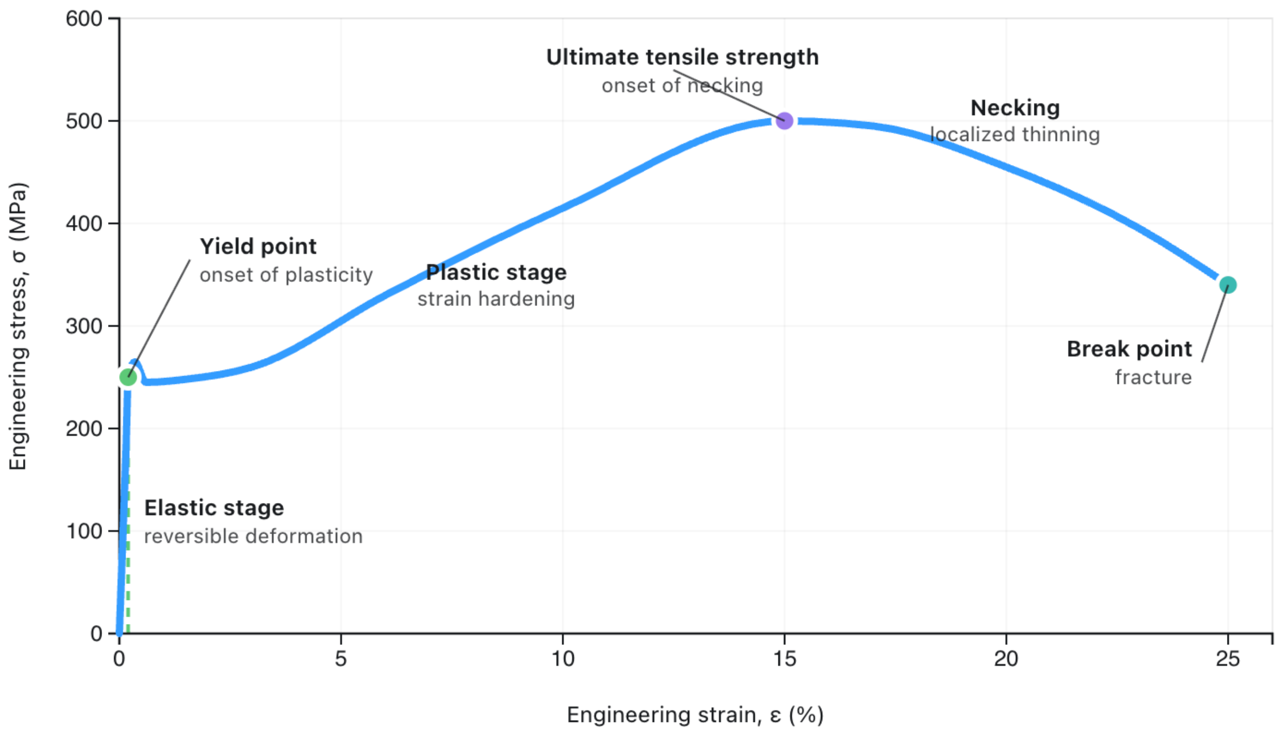
Materials under stress

Deform to Comply

kean@ornl.gov

Materials under stress

- Deform to comply by reversible elasticity, or irreversible plasticity before fracture.



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Tough materials need to be strong and flexible

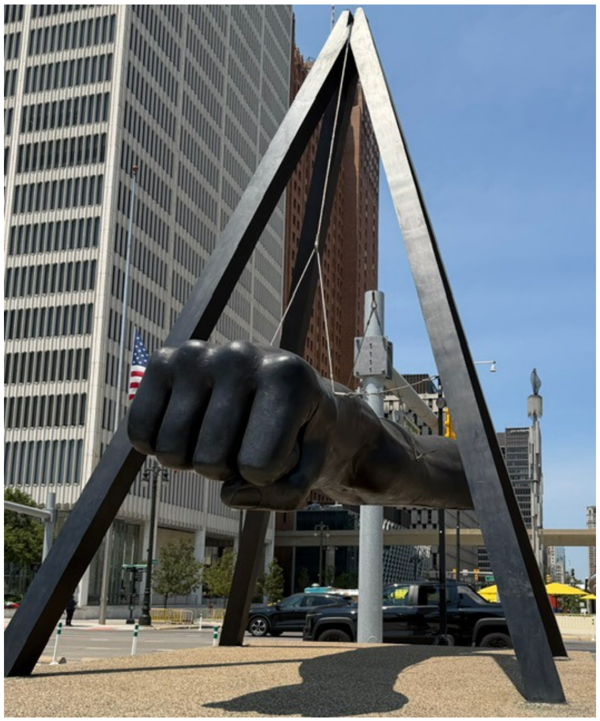
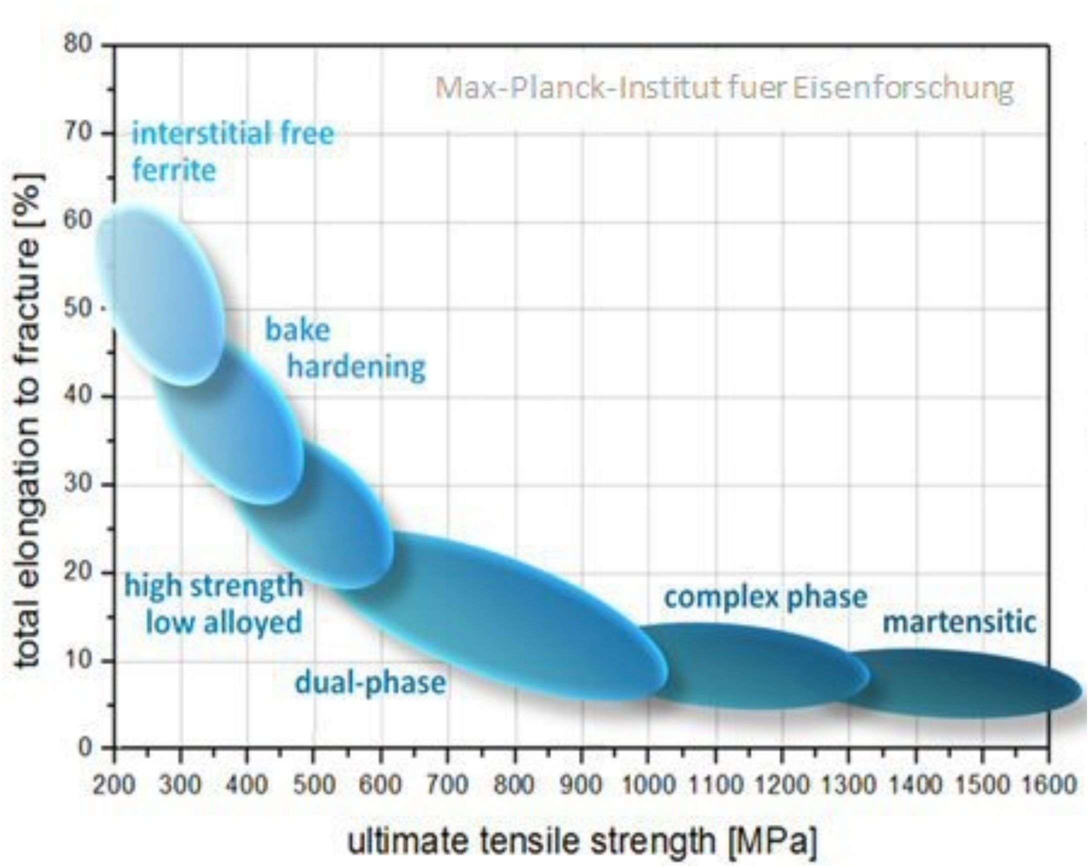


Photo taken by K.A.

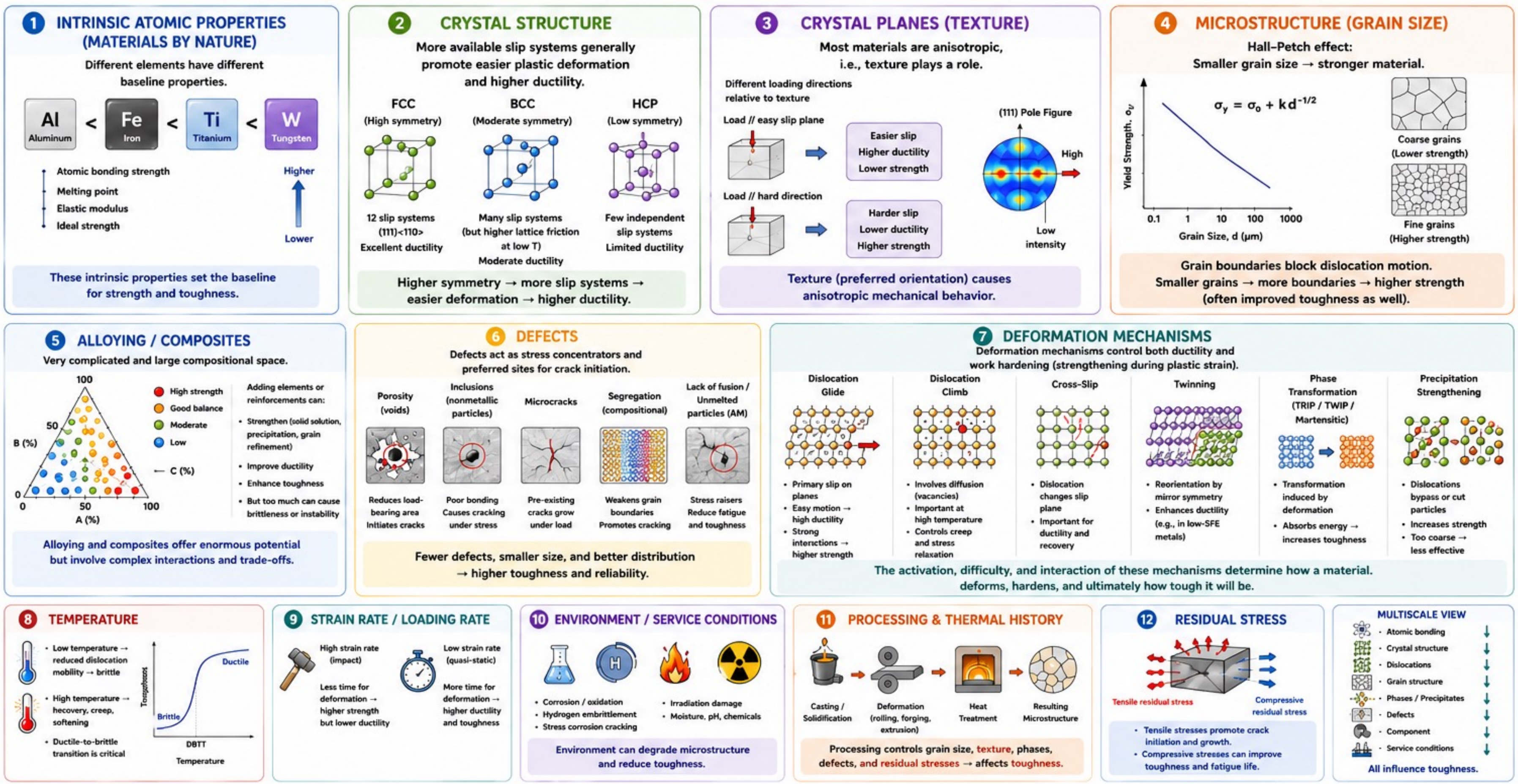
www. carexpert.com.au

Strength and ductility are commonly exclusive

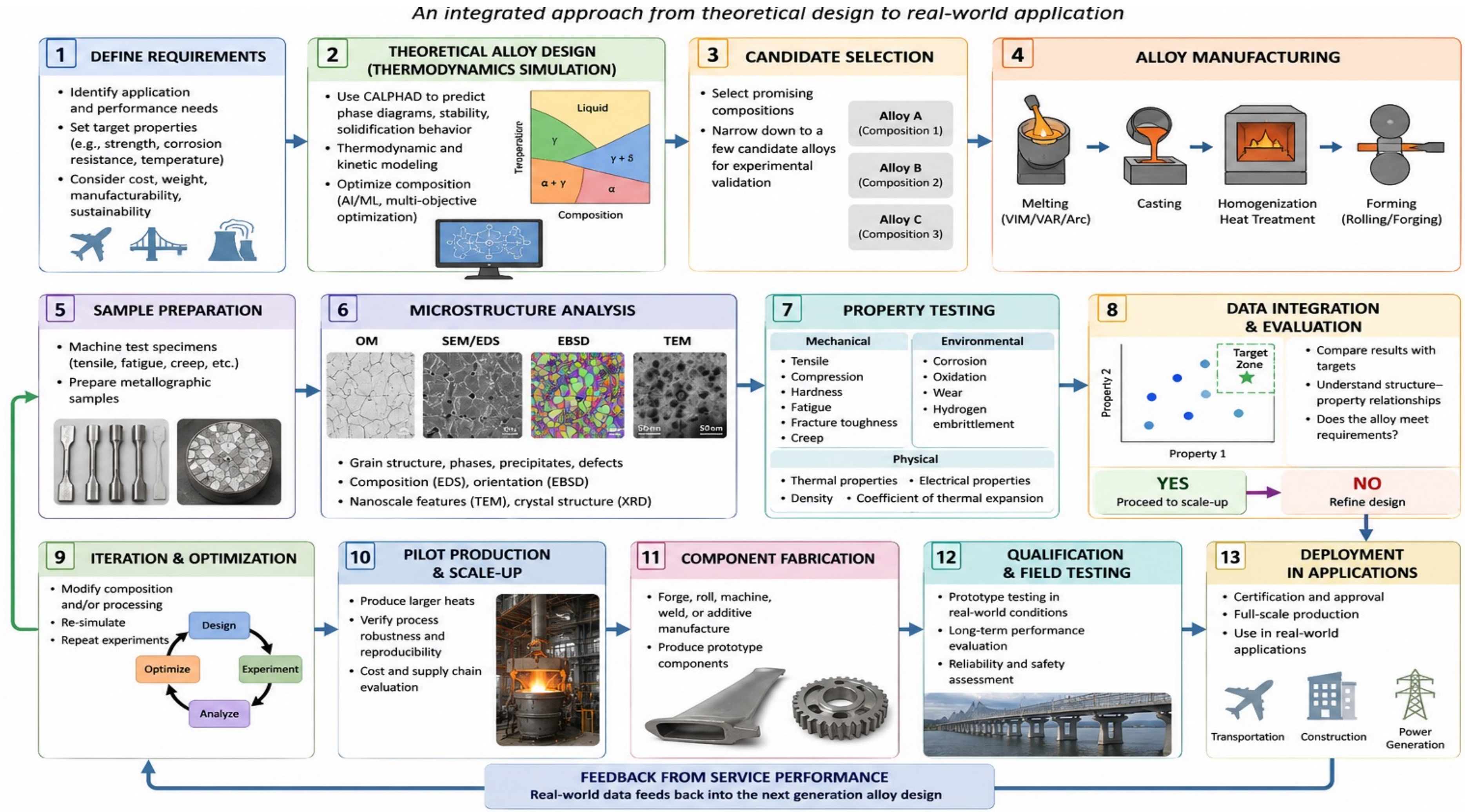


http://www.dierk-raabe.com/steels-science/

Toughness depends on many aspects

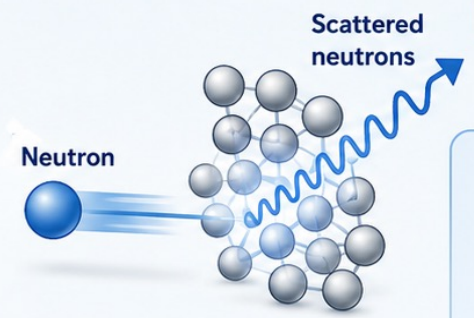


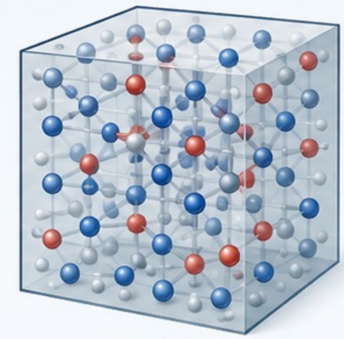
The alloy design takes time (years) before it can be widely used



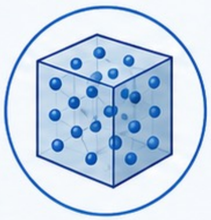
NEUTRON SCATTERING

A Unique, Powerful Probe of Materials



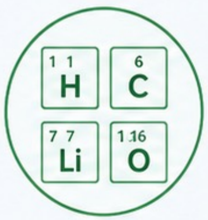


Neutron scattering provides a unique, **non-destructive**, **bulk-sensitive** probe of both morphological and crystallographic structures, with advantages including sensitivity to **light elements**, **isotopes**, **magnetic ordering**, and **deep penetration** under complex environments.



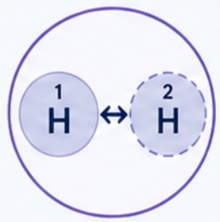
BULK SENSITIVE

Neutrons penetrate deep into materials (mm–cm), probing the bulk rather than just the surface.



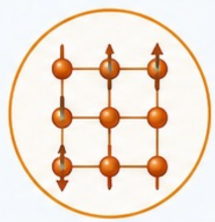
SENSITIVE TO LIGHT ELEMENTS

Strong interaction with light atoms (e.g., H, Li, C, O) that are difficult to detect with X-rays.



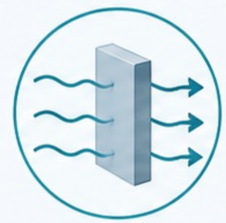
ISOTOPE SENSITIVITY

Different isotopes scatter neutrons differently, enabling isotope-specific studies and contrast variation.



MAGNETIC ORDERING PROBE

Unique sensitivity to magnetic moments—ideal for studying magnetic structures and excitations.



DEEP PENETRATION

Probes through thick samples, pressure cells, furnaces, batteries, and shielding materials under realistic conditions.

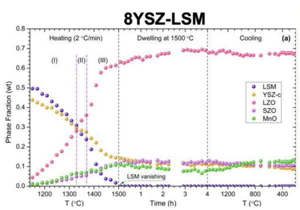
WORKS UNDER COMPLEX ENVIRONMENTS

Operates under extreme conditions: high pressure, high temperature, strong magnetic fields, and reactive or confined environments.

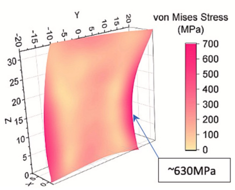
Neutrons reveal what others cannot—*deep inside materials, in real-world conditions.*

Neutrons can help alloy design and provide insights

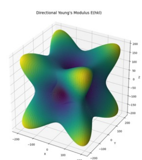
- *Understanding materials behavior from design and to operation under complex environments to accelerate the materials discovery cycle.*

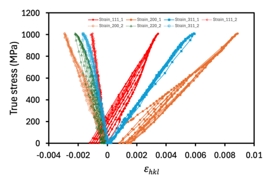


Phase evolutions

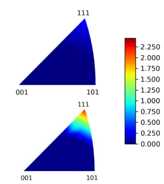


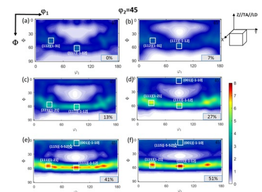
Residual stresses

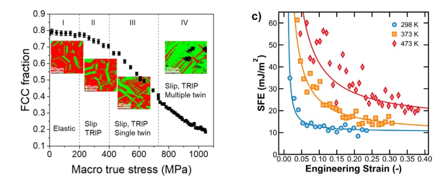

Anisotropy of Elasticity



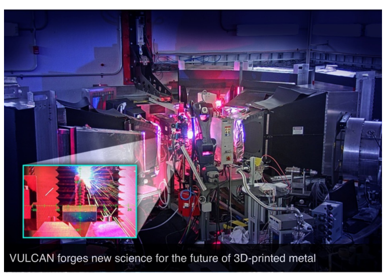
Intergranular behavior


Inverse pole figure

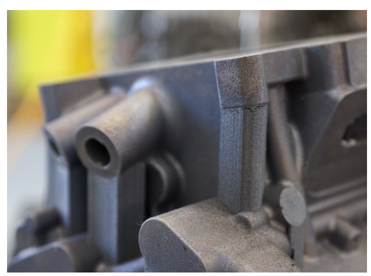

Preferred Orientations

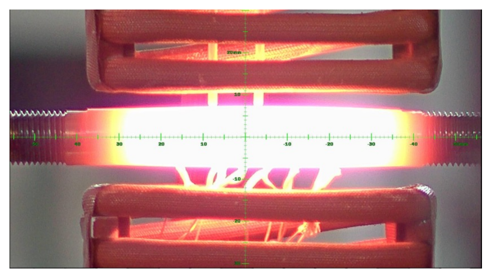


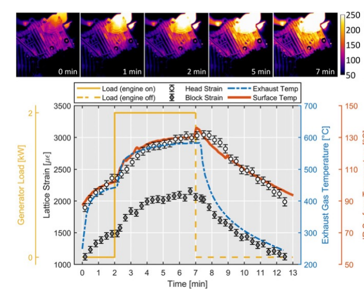
Dynamic Deformation Mechanisms



Operando fabrication

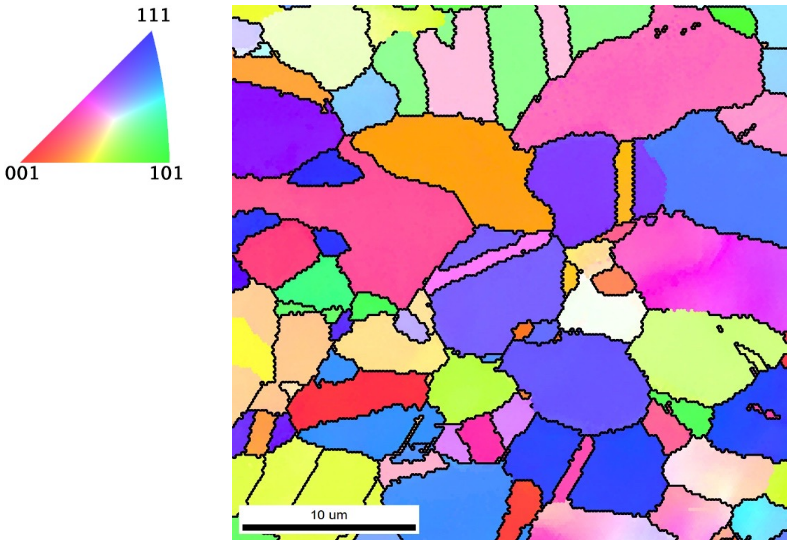

Accommodating
Large structure

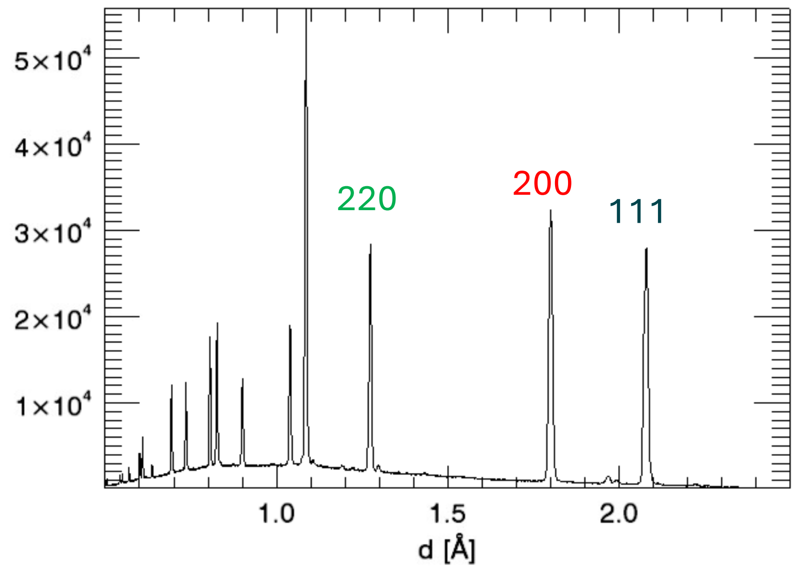

Extreme condictiones



Operando in Real Devices

Neutron diffraction approach to index grain level behaviors



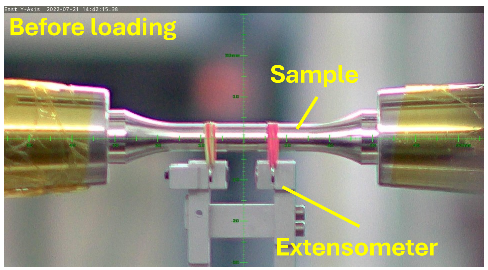


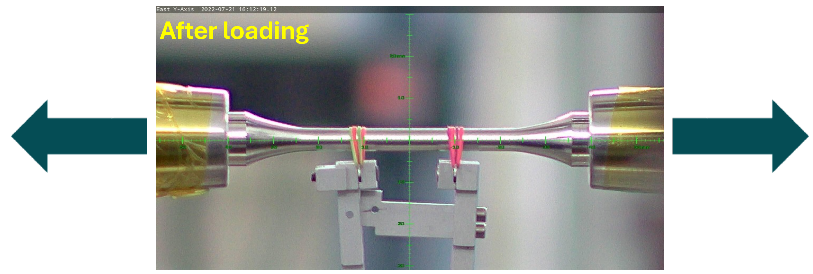
Diffraction lines measure the lattice of grains whose normals parallel to diffraction vector.

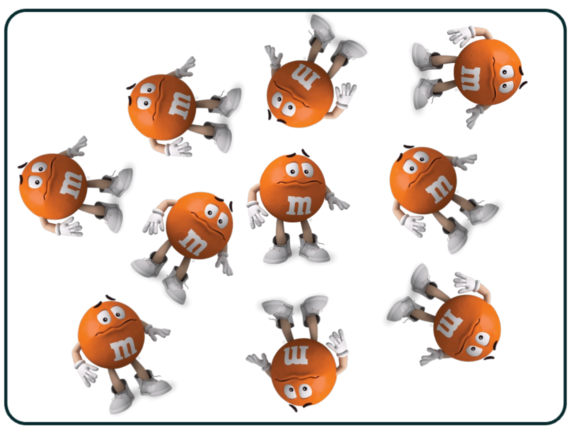
hkl specific diffraction peaks thus reveal the corresponding lattice information including lattice strain, crystallographic orientations and defects.

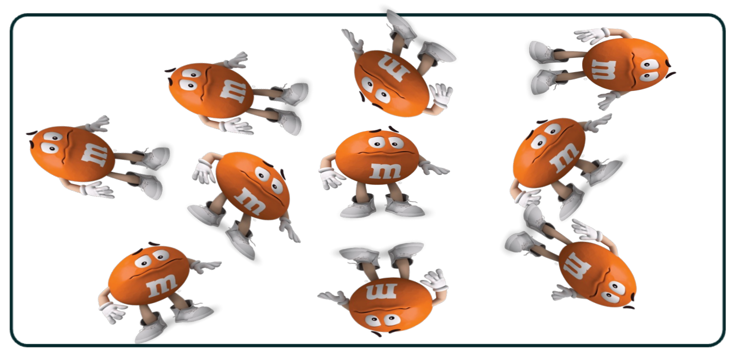
Neutrons reveal evolutions of different grain groups

Anisotropic strains develop within different grain families under plastic deformation.

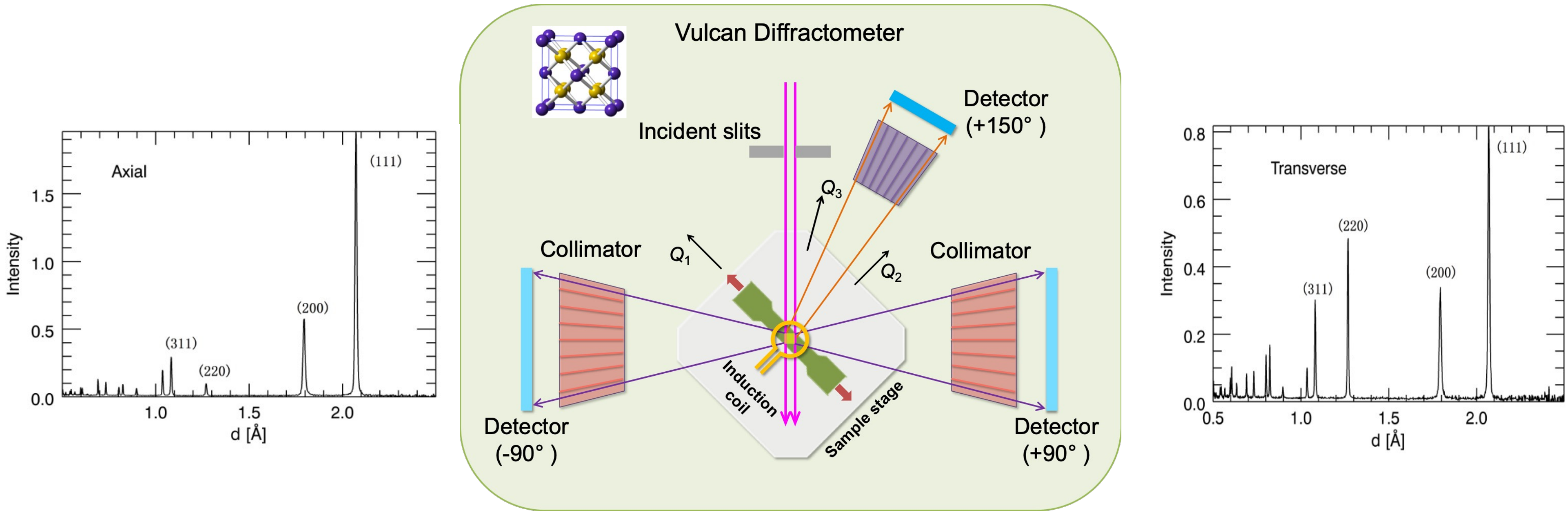








Engineering Neutron Diffraction Technologies



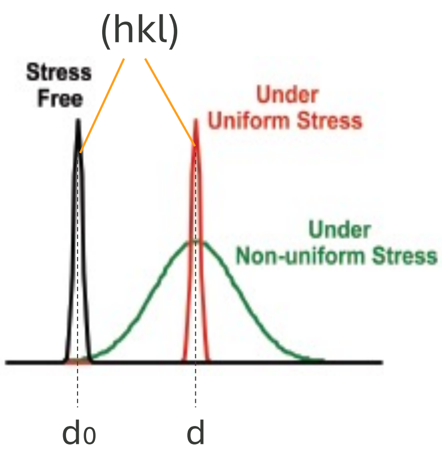
Schematic illustration of the bead-on-plate experimental set-up on engineering diffractometer like VULCAN at SNS (top view, not to scale). The -90° and +90° detector banks record diffraction peaks of the (h k l) lattice planes whose normals are parallel to Q_1 and Q_2, respectively. Strain components along these two directions are measured simultaneously. The bead-on-plate specimen is positioned on top of the sample stage and aligned at 45° from the incident beam.

Lattice and stress measurement by diffraction

Lattice strain measurement

$$\varepsilon^{hkl} = \frac{d_{hkl} - d_{hkl}^0}{d_{hkl}^0}$$

where d_{hkl}^0 is the lattice spacing at zero applied stress.

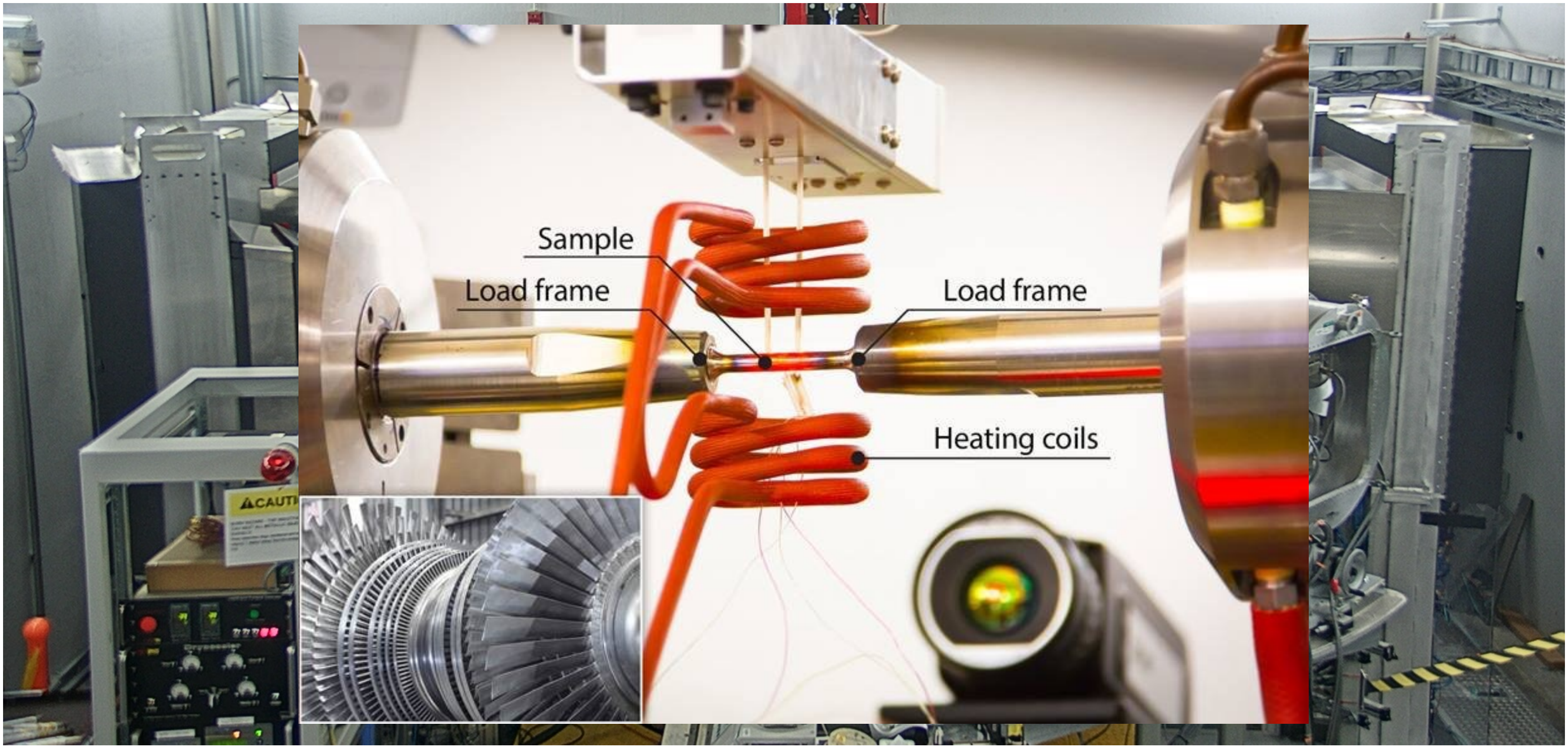


Stress tensor calculation

$$\sigma_{ij} = \frac{E^{hkl}}{(1+v^{hkl})}\left\{\varepsilon_{ij}^{hkl} + \frac{v^{hkl}}{1-2v^{hkl}}\left(\varepsilon_{11}^{hkl} + \varepsilon_{22}^{hkl} + \varepsilon_{33}^{hkl}\right)\right\}$$

where *i*,*j*=1,2,3 indicate the components relative to **three-dimensional orthogonal axes**.

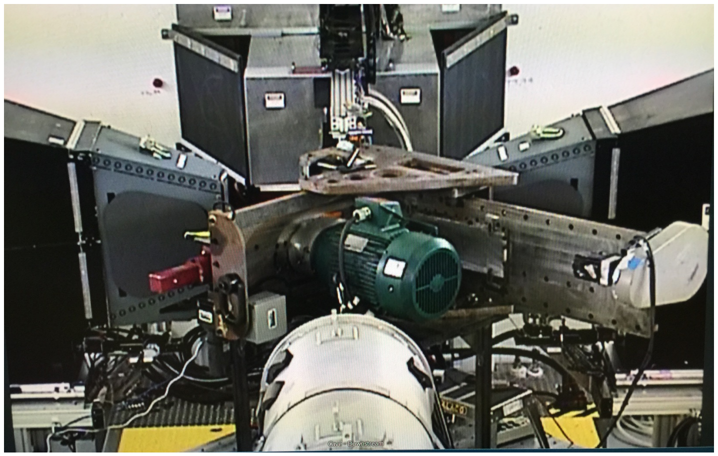
E^{hkl} and v^{hkl} are [hkl] specific “diffraction elastic constants”.



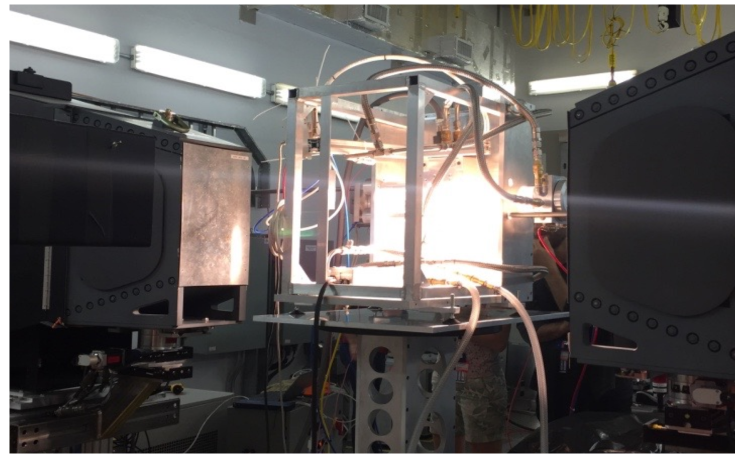
VULCAN – Diffractometer for Materials Engineering and Applied Physics

Materials under Extreme

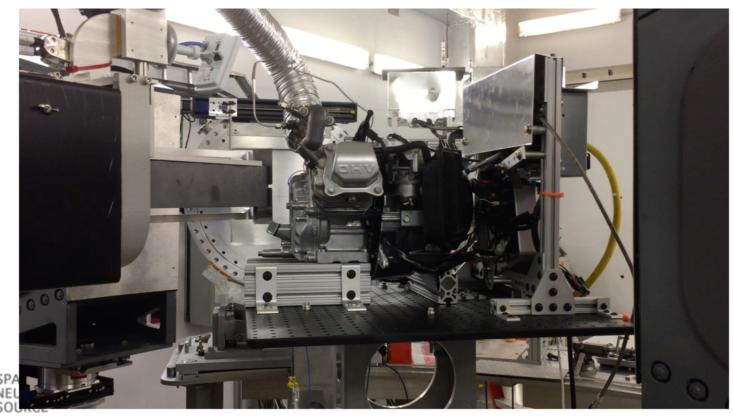
Friction stirring welding/processing



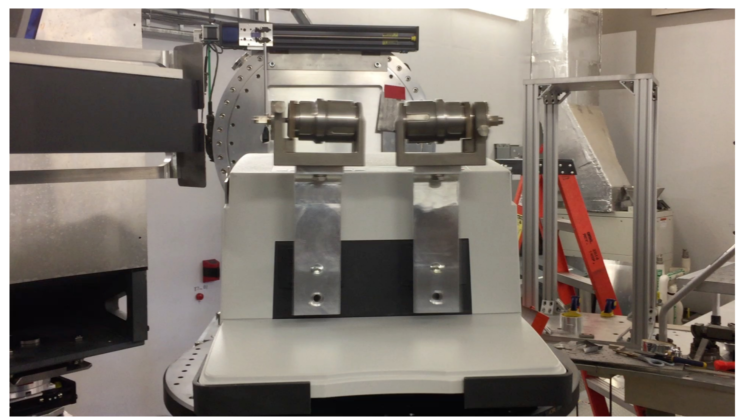
In-situ reduction



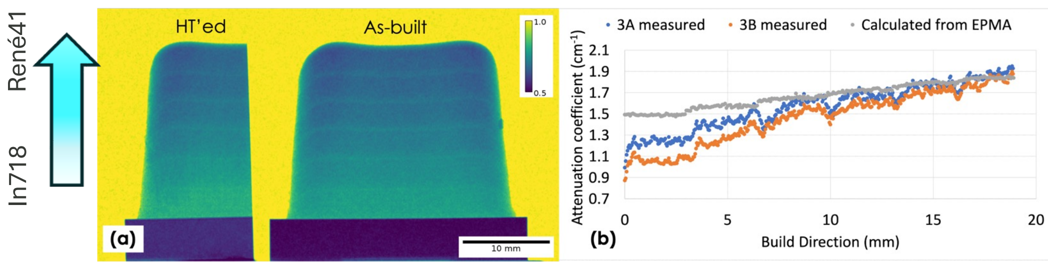
Running engine



Ball milling

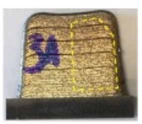


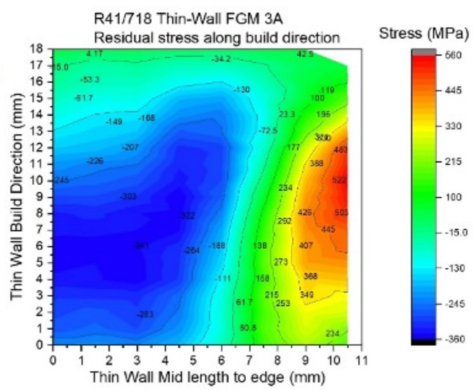
Understand the residual stress development in additively- manufactured compositionally graded superalloy

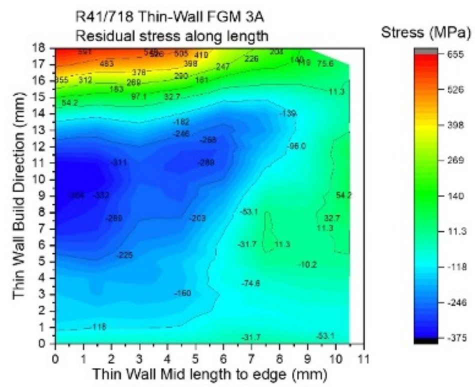


The neutron imaging revealed the chemical composition gradient of the as-built and high temperature treated graded structure.

As-built 3A





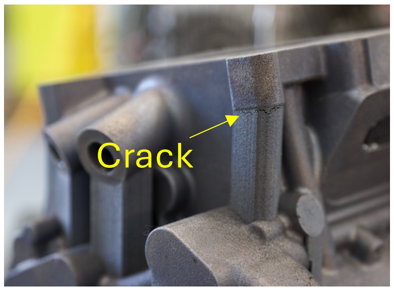


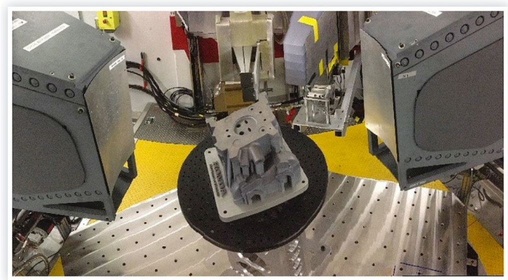
The residual stress in an as-built sample was resolved with rapid neutron diffraction mapping.

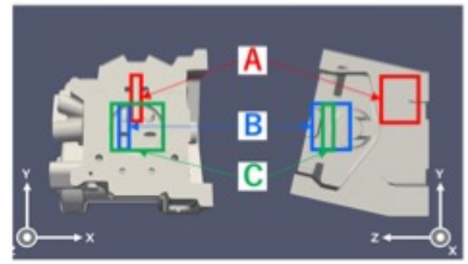
The composition variation and residual stress distribution in additively-manufactured graded superalloy are non-destructively revealed by neutron imaging and neutron diffraction, and the residual stress is not compositionally dependent but more geometry and process dependent.

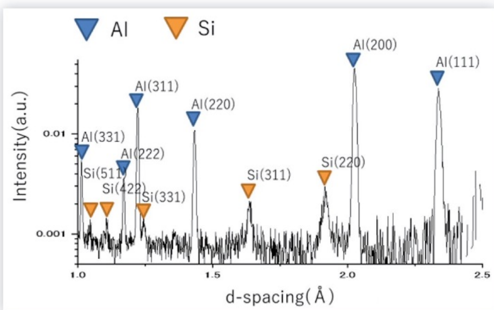
S. Huang, C. Shen, K. An, Y. Zhang, I. Spinelli, M. Brennan and D. Yu, *Frontiers in Metals and Alloys*, 1:1070562, (2022).

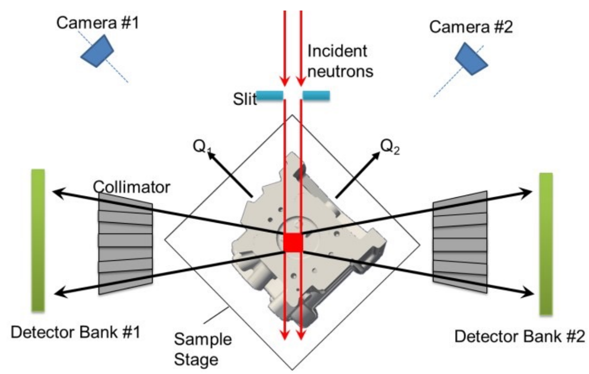
Residual Stress Build-ups in Complex 3D Printed Automobile Structure

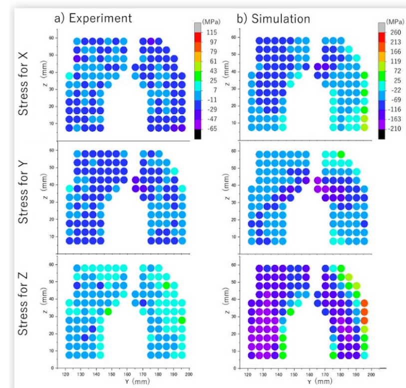












Neutron diffraction evaluates non-destructively the residual stress buildups and provides computation modeling validation for process optimization and mechanical integrity assurance.

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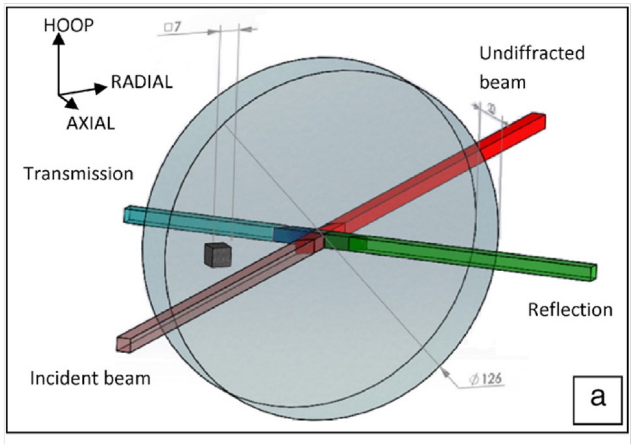
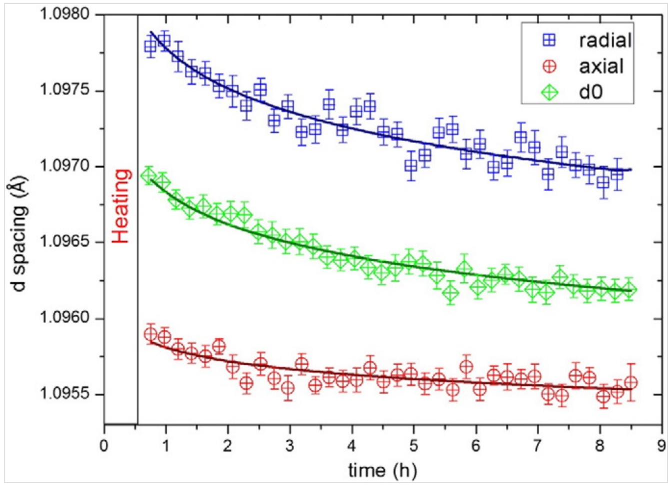
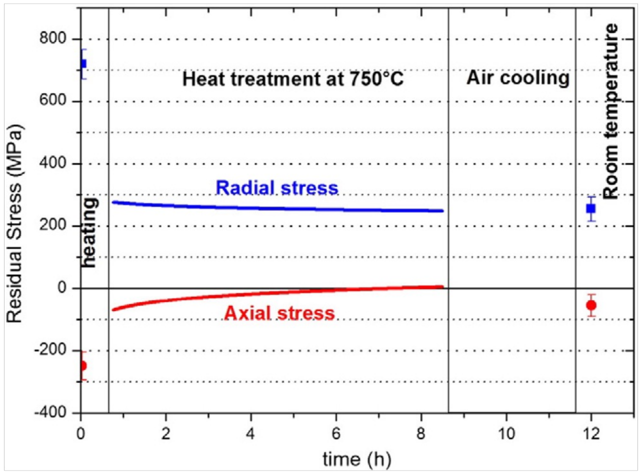
T. Ikeda, S. Hirose, H. Uozumi, K. An, Y. Chen, A. Seid, T. Okayama,T. Katsurai, SAE International Technical Paper 2020-01-1071 (2020).

In-situ residual stress relaxation during annealing treatments

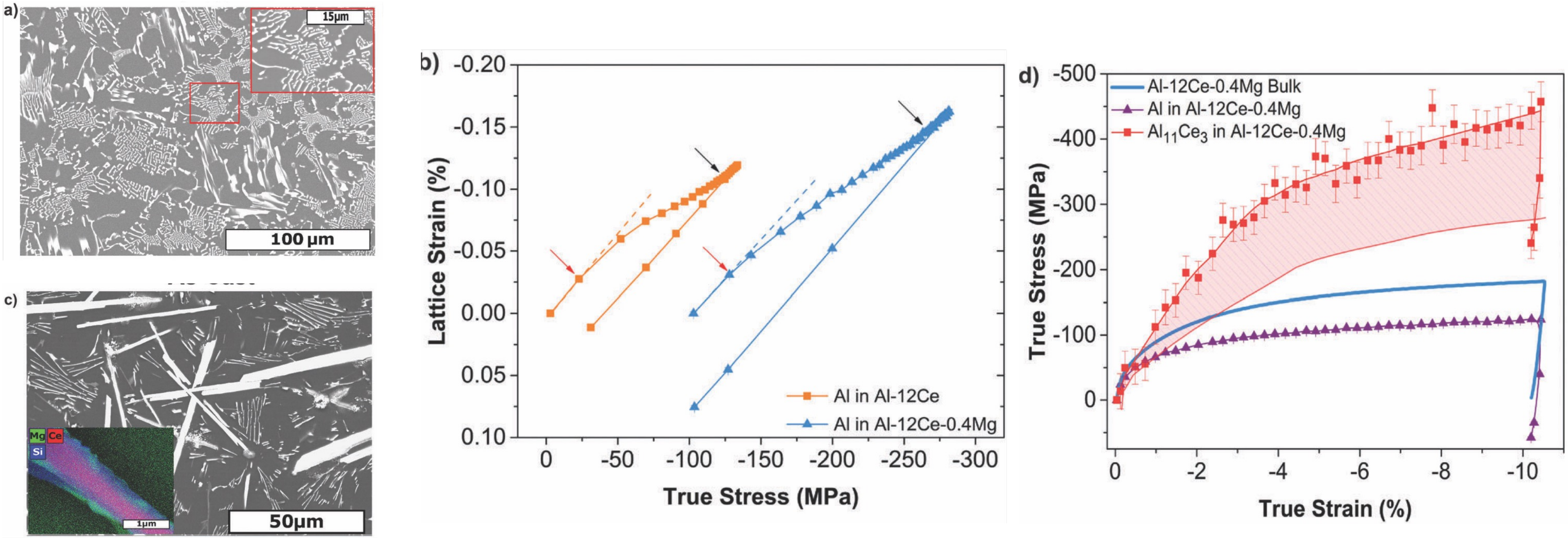






Aba-Perea et al., "In Situ Study of the Stress Relaxation During Aging of Nickel-Base Superalloy Forgings", Metallurgical and Materials Transactions A, 50, 8, 3555–3565 (2019).

Neutron unravels deformation mechanism of high-performance aluminum–cerium alloys for high-temperature applications



a) SEM of Al-Ce, b) The Al lattice strain behavior of Al-Ce, Al-Ce-Mg, c) SEM of Al-Cel-Mg, d) load sharing of Al and precipitates in the two alloys during different stages.

In-situ neutron diffraction unraveled the loadsharing of Al matrix and the hardening precipitates at different loading stages.

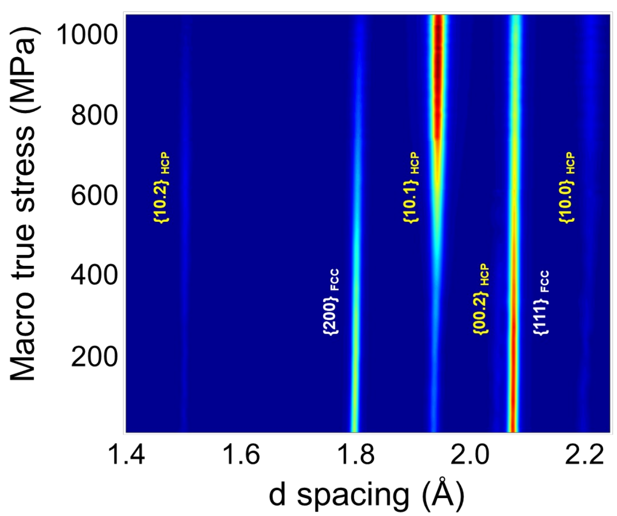
Alloying aluminum with cerium creates a highly castable alloy, that exhibits dramatically improved high-temperature performance. Neutron diffraction under load provides insight into the unusual mechanisms driving the mechanical strength.

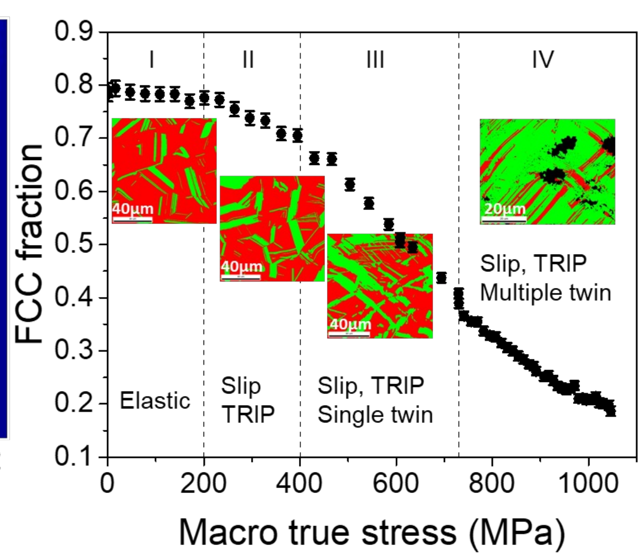
Z. C. Sims et al. Mater. Horiz., 2017, 4, 1070 , DOI: 10.1039/c7mh00391a

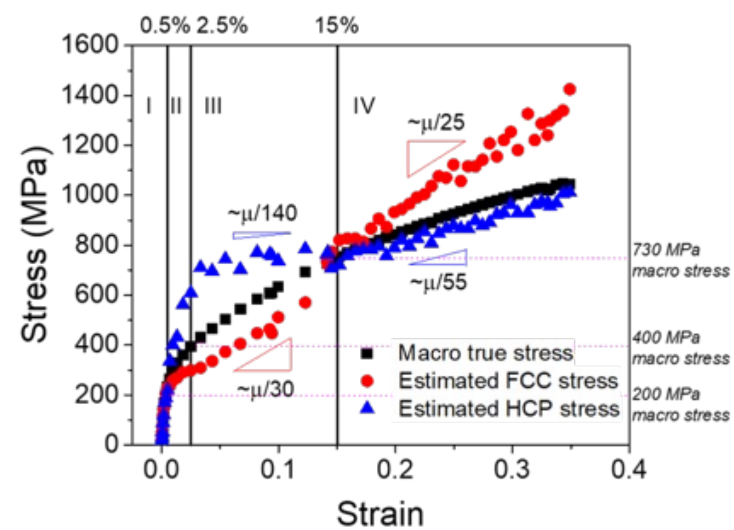
Probe deformation/hardening mechanism by neutron diffraction

The FCC-based TRIP-HEA is strengthened by persisting transformation to the hard HCP phase with a potential work-hardening capacity.

$Fe_{50}Mn_{30}Co_{10}Cr_{10}$







Fu S. et al, Materials Research Letters 6 (11), 620-626

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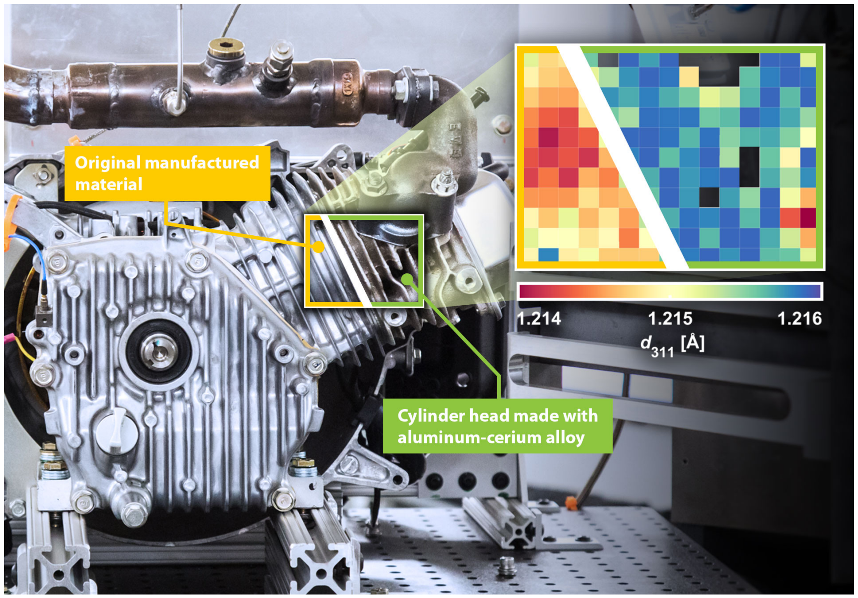
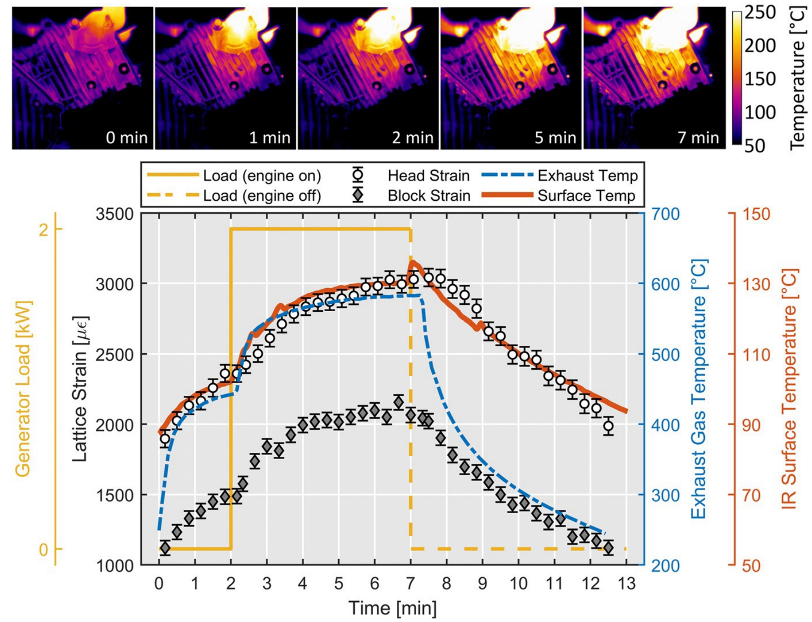
Real-Time Diagnostics for Better Engines





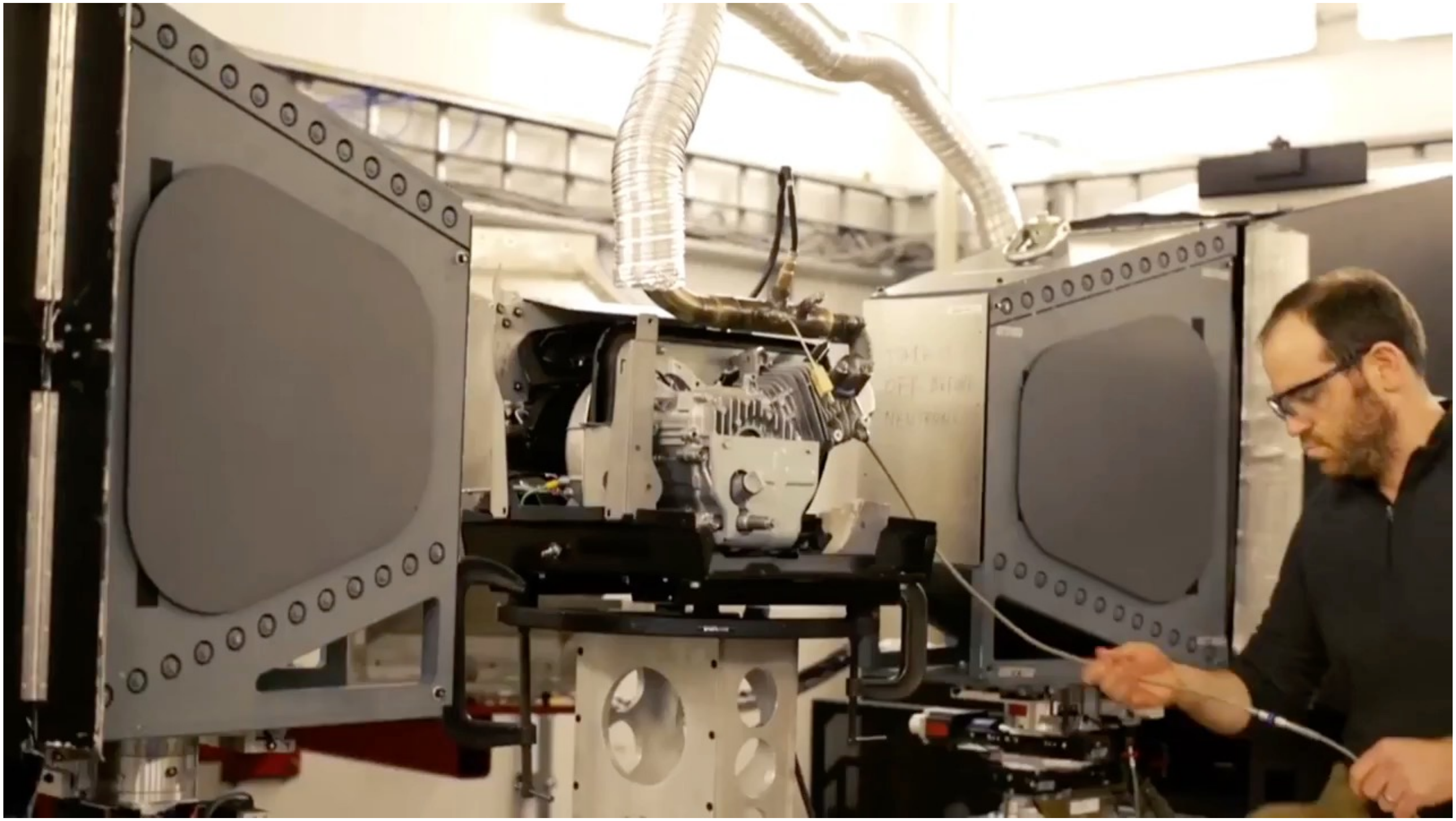
Neutrons provide noninvasive measurement of lattice strains inside components of a firing engine, enabling the operando study of complex load states and thermal gradients throughout the solid materials in the running engine.

– A commercial generator engine was mounted in the VULCAN diffractometer.

– Dynamic response of the lattice strain in the engine body during transient operation was resolved.

Wissink et al "Operando measurement of lattice strain in internal combustion engine components by neutron diffraction", Proceedings of the National Academy of Sciences of the United States of America, (2020). https://doi.org/10.1073/pnas.2012960117
and https://science.osti.gov/bes/Highlights/2022/BES-2022-06-e

Team Work on A Running Engine Test!



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