Materials for fusion reactors: Containing a star on Earth

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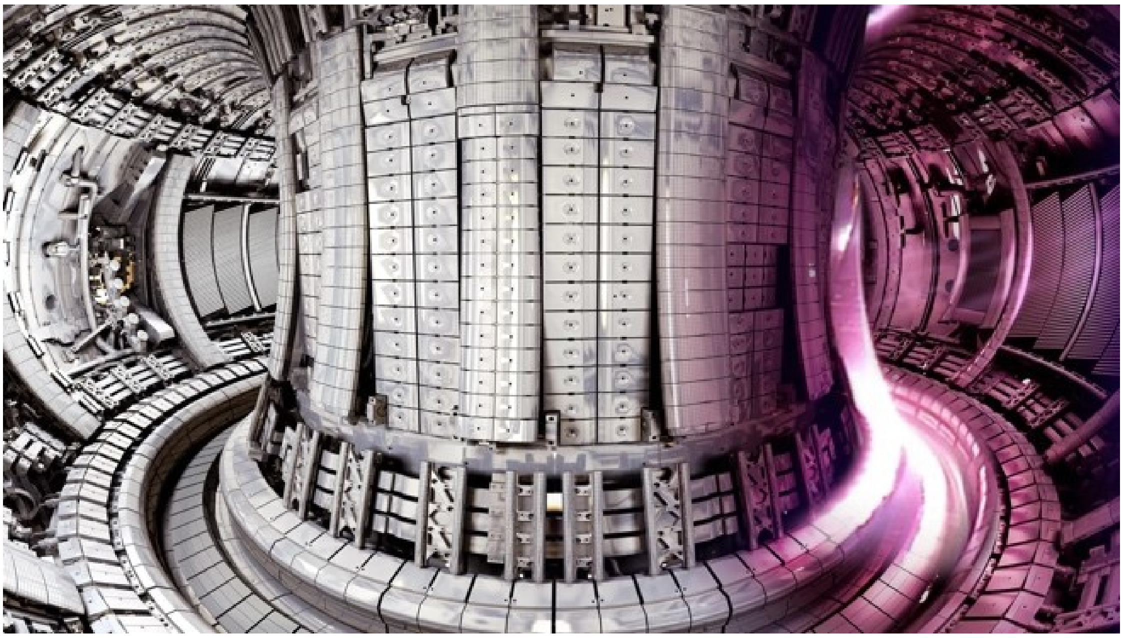

Figure : Joint European Torus (JET), credit UKAEA

Experimental metallurgy research: Structural materials to withstand the extreme temperatures inside nuclear fusion reactors

Fusion Energy – a Star on Earth

Fusion Energy offers the tantalising promise of near limitless energy without generating carbon emissions, or long-live radioactive waste. Furthermore, it is energy dense with small land usage, and capable of providing stable base-load electricity, making it an ideal solution to our present energy challenges. Fusion is undergoing a transformative period, with tremendous progress and new records from national and international facilities, in terms of maximum energy, power out vs in, and duration from experiments at JET, NIF and EAST. This is in addition to the $21bil 'ITER' International Thermonuclear Experimental Reactor, currently under construction toward first plasma 2027, which is anticipated to generate 500MW output from 50MW input, and so demonstrate fusion's viability (1).

A host of private companies have also joined the race for commercial fusion energy, with >$5bil raised from investors across Commonwealth Fusion Systems, Helion, General Fusion, First Light Fusion and Tokamak Energy, among multiple other ventures.

These companies are seeking new approaches to fusion with aggressive development & deployment timelines, ultimately seeking to bring fusion to market sooner, potentially before 2040.

Challenges for Fusion Reactors

However, a common challenge remains for all fusion reactor types: how can we contain and withstand the massive energy realised during the fusion reaction? In many fusion reactor designs this is largely achieved using magnetic confinement, but even with this, ultimately a physical structural barrier is needed, which could be exposed to temperatures of 1000-1500°C – hotter than lava! What materials can withstand such temperatures, and also maintain their properties for 20+ year reactor design lives?

The challenges for fusion reactor materials have been the focus of our recent UK Fusion Materials Roadmap (2) that identified five priority areas:

(1) Novel low activation materials,
(2) Compounds & structures for breeding of tritium fuel, (3) Magnets and insulators resistant to irradiation, (4) Structural materials that retain strength under neutron bombardment at >550°C, (5) Engineering assurance for fusion materials, to ensure plant designers, operators and regulators have confidence in materials for future commercial power stations.

Amanda Quadling, PhD Director of Materials UKAEA, said:

“Fusion is the most efficient way we know to create energy for human use. We can make fusion happen commercially if our future fusion powerplants last years, rather than months. One of the key challenges is to develop and qualify materials which are smarter at surviving sustained neutron exposure –by adding small secondary phases that stop defects spreading for example, or by making materials from elements which don’t decay as long lived radio-isotopes. We need innovative scientists who can think creatively about microstructures as complex patterns and who are interested in novel processes to achieve them!”

Fusion Materials Innovation

In the Materials for Extremes (M4X) Research Group at University of Birmingham (3) we are devising fundamentally new alloys for extreme environments, including nuclear fusion and next-generation fission/advanced modular reactors (AMRs), gas turbines and thermal solar, in close partnerships with National Nuclear Laboratory (NNL) on fission, and UK Atomic Energy Authority (UKAEA) on fusion.

Tungsten is the leading candidate material from which to construct the first wall of a fusion reactor. It offers a number of advantages for fusion: high melting point – avoiding melting, high ionisation energy – avoiding plasma contamination, low solubility for hydrogen – minimising tritium retention, as well as reduced activation following fusion neutron irradiation – avoiding long-lived radioactive waste post reactor shut down.

However, tungsten has issues in its toughness at room temperature, and with degradation of its properties under irradiation through-life. New materials are being sought to increase performance, as well as the durability required for commercial plants with >20 year design lives. Novel design strategies are being pursued between UoB, UKAEA and NNL to develop fundamentally new materials for fusion to meet the performance and resilience demanded, namely (1) Nanostructured alloys and (2) High entropy alloys.

(1) Nanostructured alloys, specifically using the concept of ‘bcc-superalloys’ (4) is a specialism of the UoB M4X Group, which for fusion comprise a tungsten matrix reinforced by nano-scale precipitates of intermetallic compound TiFe. We have demonstrated that such reinforcement confers substantial benefits to the strength and high temperature performance of the materials. Further, it has been suspected that the high area density of interfaces may act as sinks for irradiation defects, which our preliminary experimental findings support, with onward work underway using the state-of-the-art irradiation facilities at UoB, part of the UK National Nuclear User Facility (5).

(2) High entropy alloys (HEAs) are highly topical branch of materials science that has rapidly grown over the last ~10 years. HEAs are defined by comprising multiple components, typically 5+ elements mixed in near-equal quantities, which can entropically stabilise a simple crystal structure, over the formation of complex intermetallics that may otherwise be anticipated. HEAs can demonstrate impressive strength and durability toward nuclear applications. At UoB we are seeking new HEAs, firstly with low activation – for fusion applications, and secondly with low neutron cross section – for fission/AMR fuel cladding and fusion tritium breeding modules (6). In addition to improved mechanical behaviour, we are also investigating their irradiation response, as some HEAs demonstrate exceptional resistance to irradiation damage.

Growing the Fusion Workforce

New technology is only part of the equation of realising fusion, which requires a high-skill, diverse and growing workforce. Fusion represents a ‘moonshot’ innovation, with equivalence to the moon landing in terms of the pace and scale of developments needed. This collaborative societal grand challenge is a fantastic opportunity to inspire new generations of people into science, technology, engineering and mathematics (STEM), at all levels, from schools to universities, into the workplace and across different industry sectors. We must ensure that training, re-training, mentorship and development opportunities are made available to the widest possible talent pool, supporting individuals to join the fusion moonshot whilst also strengthening the wider STEM community.

References

1 – https://www.iter.org
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3 – https://more.bham.ac.uk/M4X/
4 – https://doi.org/10.1016/j.apmt.2021.101014 5 – https://www.nnuf.ac.uk
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Please Note: This is a Commercial Profile