PhD PROJECT PROPOSAL

PhD Project Title

Evolution of topological microstructures during irradiation in Ti alloys for particle accelerator facilities and fusion reactors

PhD Supervisory Team

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Project Abstract

Titanium alloys with complicated topological microstructures are essential materials in the particle accelerator facilities, and are attractive for fusion reactors, particularly for heat sink elements. However, data related to its radiation resistance are very sparse and is at an unsatisfactory stage. The aim of this PhD project is to contribute to the understanding of degradation of topological microstructure under irradiation in advanced Ti alloys using high energy proton radiation. The work will lead to topological microstructural design of new Ti alloys with superior irradiation resistance.

Detailed Project Description

Research background, intended outcomes and methodology;

Titanium alloys are attractive materials for fusion reactors, particularly for heat sink elements, because of their good strength, fatigue and creep rupture properties, heat capacity, low coefficient of thermal expansion, low activation, high corrosion resistance, good weldability and commercial availability. There are a wide variety of titanium alloys with complicated topological microstructures used for different industrial application as aerospace or medicine which are classified into three groups: single α-phase (hcp lattice), dual α+β phase (hcp + bcc lattice), and metastable β phase alloys. Although their microstructure has much tunability, radiation effects data available for titanium alloys are very sparse and is at an unsatisfactory stage.

While titanium alloys have only episodic attention from the fusion energy community, among other factors because of a lack of data on their irradiation performance, titanium alloys are essential materials in the particle accelerator facilities, like T2K, HyperK and LBNF – flagship neutrino physics experiments, where titanium is used as structural neutrino production target components and exposed to radiation damage for very high energy (>100 GeV) protons with very high levels of transmutation (>500 He ppm/dpa). University of Birmingham and the MRF UKAEA collaborate with the Rutherford Appleton Laboratory (Harwell, STFC, UK) on titanium alloys radiation resistance R&D for LBNF and HyperK neutrino experiments, and the current PhD project aims to benefit from the existing findings and available samples and extend knowledge towards fusion energy needs, particularly high-temperature intermediate to high-dose resistance of titanium alloys.

Aims and objectives

The aim of this PhD project is to contribute to the understanding of degradation of topological microstructure in Ti alloys under high energy proton radiation.

Objective 1: Irradiating Ti-based alloys (α+β Ti-6-4 and one α Ti alloy) up to 1 dpa at temperatures ranging from 150 to 600oC, using the high energy proton beam MC40 cyclotron and up to 20 dpa using the high-energy ion beam irradiation facilities (planned DCF or Surrey ion beam facilities).

Objective 2: Mechanical performance assessment of irradiated Ti-based alloys using micros-scale mechanical testing, nano-indentation and microcantilever bending and fracture. In situ synchrotron diffraction experiments will also be performed to study micro-mechanics of irradiated Ti alloys.

Objective 3: Interpretation of the observed topological evolution using the advances microstructural characterisation technique: TEM, atom probe tomography, and X-ray scattering/diffraction;

Data and understanding generated from this project can feed into the EU DEMO and UK STEP materials property database and handbooks.

α+β Ti-6Al-4V, the most commonly used Ti-alloy, will be used as a benchmark in the project. The alloy will be investigated in two states: industrially available with commercial purity and after additive manufacturing process. The alloy performance under irradiation will be compared with the performance of the fully α-alloy (typically demonstrate higher stability of mechanical properties under irradiation) and β-alloy (typically has much higher resistance to hydrogen related properties degradation and has a potential to have the lowest residual activity under fusion reactor irradiation). We will choose a β-alloy composition with low activation. Radiation damage will be induced using the MC40 cyclotron and other high-energy ion beam irradiation facilities (DCF). The characterization of irradiation induced microstructure changes will be carried out by TEM, Small angle scattering techniques based on synchrotron X-rays (SAXS), and X-ray diffraction, which are suitable for acquiring bulk-scale, statistically sound data on the irradiation induced voids and precipitates [3-5]. To form a complete picture on the role of irradiation damage in the integrity of the materials, small-scale mechanical tests will be carried out on the irradiated samples at MRF so that we can establish the correlation between radiation damage and mechanical degradation. Within the project, micro- and nano-indentation will be used to determine the radiation induced hardening, small punch and microcantilever bending tests to estimate the ductility and fracture properties degradation of the irradiated samples, atomic-force microscopy will be used for comparison of swelling behaviour of different alpha/betta constituents of binary alloys.

Dr Biao Cai (Metallurgy and Materials)
Lecturer of Metallurgy and Materials at University of Birmingham. Dr Cai's research focuses on in situ data-driven characterisation of physical and mechanical metallurgy for nuclear materials. He is currently supervising 4 PhD students whose research topic is directly relevant to nuclear fission and fusion. He has received funding from the Royal Society, EPSRC, Midland Innovation, UKAEA and Alan Turing Institute as a PI. As a Co-I, he is actively involved in several multi-million projects including EPSRC funded NNUF grant (Development of an in-situ characterisation facility for both proton and neutron irradiation). He has published over 40 journal papers, 10 of which in Acta Materialia, 2 in Additive Manufacturing, 5 in Scripta Materialia, and 1 in Nature Communication. He is also an inventor for two patent applications.

Dr Slava Kuksenko at MRF, UKAEA
Experimental Materials Scientist in the Materials Science & Scientific Computing Department. His investigations are focused on radiation damage effects on materials for fission and future fusion reactors, spallation neutron and neutrino sources. He has expertise in investigations of radiation effects on microstructure and properties of beryllium, Fe-Cr alloys and ferritic martensitic steels, and extensive experience of handling and sample preparation from activated and hazardous materials.

Prof Martin Freer (School of Physics and Astronomy)
Professor Martin Freer is a nuclear physicist, and Director of the Birmingham Energy Institute (BEI) at the University of Birmingham. He is also Director of the Energy Research Accelerator (ERA), which comprises eight internationally-renowned Midlands universities which are part of the Midlands Innovation partnership, together with the British Geological Survey.