Focus on plasma-facing materials in nuclear fusion reactors

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EDITORIAL

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Abstract

Fusion energy is a promising, safe, and reliable green energy solution to the increasing energy demand. However, there are several materials challenges that need to be overcome to increase the technical readiness to a level that enables a fusion pilot plant on the grid. This focus issue aims to identify and address a set of such key impediments for realizing deuterium-tritium (D–T) fusion power in a tokamak reactor and highlight the most recent progress on those research frontiers. The main emphasis of this collection is on materials development challenges resulting from helium irradiation, neutron-induced degradation, thermomechanical loading, and the corrosive environment faced by the divertor and first-wall materials, commonly known as plasma-facing components, and blanket systems for tokamak fusion reactors.

Fusion energy is a promising, safe, and reliable base-load solution to two of the major conflicting concerns of the 21st century: increasing energy availability to meet increased projected demand and reducing the carbon footprint consistent with environmental considerations. However, challenges in integrating materials science and plasma physics into fusion technologies have long delayed the cherished goal of building a reactor to harness the immense potential of nuclear fusion. In the past two decades, significant scientific [1] and technological progress has been made to overcome some of the impediments to realizing the promise of nuclear fusion; because of such progress, according to the recent IAEA World Fusion Outlook 2023 [2], over 130 experimental fusion devices are operating, while several demonstration fusion power plants are currently in their design stage. Most operational fusion facilities are magnetic confinement devices in a tokamak design using deuterium–deuterium (D–D) fuel; going forward, considering energy efficiency and operational challenges, deuterium–tritium (D–T) fuel will be the most common choice for fusion power plants. The development of commercially viable, controlled fusion power still faces a host of engineering challenges, which include long-lasting confinement of the hot plasma, with a plasma core temperature exceeding 100 million degrees Celsius, inside the reactor chamber; creating and securing an adequate tritium supply to fuel a D–T fusion reactor and closing the fuel cycle to sustain it; the design and demonstration of materials for the reactor plasma-facing components (PFCs) which are able to withstand the extreme reactor operating conditions and the development of strategies to minimize detrimental effects on reactor materials by fusion reaction by-products; and extracting and harnessing the energy released by the fusion reactions. Considering the future potential of fusion, along with the challenges to realizing its implementation, the United States National Academy of Engineering has ranked the quest for fusion as one of the major grand challenges for engineering in the 21st century [3]. This *Materials Research Express* (*MRX*) article collection focuses on the aforementioned critical issues, primarily related to materials science and engineering.

In the D–T fusion reaction, deuterium and tritium within the plasma undergo nuclear fusion which results in the production of a high-energy helium atom (alpha particle) and a 14.1 MeV neutron per reaction. In a magnetic confinement device, where the plasma is confined using strong magnetic fields, the high-energy neutron escapes from the plasma core and directly penetrates the PFCs and blanket materials surrounding the plasma core, causing significant degradation of the structural materials. The divertor and first-wall armor materials, commonly known as plasma-facing components (PFCs), act as the interface between the plasma boundary and the remaining reactor components. The 'breeder blanket' is the layer just beyond the first wall surrounding the reactor core. The function of this blanket is multi-fold, primarily for tritium production from neutron reactions with lithium, which is a crucial step since tritium is scarce [4]. Additionally, the blanket must function to translate the kinetic energy of the neutrons to heat, which can be extracted and converted to electricity, and the blanket can also assist in shielding the magnets from the 14 MeV-peaked neutron flux. On the other hand, to maintain a constant fusion power during operation, helium ash generated as a nucleus (alpha) at extremely high kinetic energies (3.5 MeV per alpha particle) needs to be constantly removed from the reactor core and replaced with additional D–T fuel. Typically, the helium nucleus is swept up by the magnetic field and undergoes energy loss before extraction as a neutral gas particle at near room temperature in a region outside of the fusion plasma, called divertor, which acts as the exhaust system of the fusion reactor. Tungsten is the plasma-facing material of choice for ITER (International Thermonuclear Experimental Reactor), currently under construction in southern France [5]. Due to its low hydrogen solubility, low sputtering yield, and high melting point, tungsten is considered a suitable candidate for withstanding the extreme fusion environment. However, under low-energy (10–100 eV) but high-flux helium implantation tungsten undergoes major surface modifications with the observed formation of dislocation loops, bubbles, or tungsten nanotendrils (so-called 'fuzz') in the crystal [6]. If the same inert gas (*i.e.*, helium which also is insoluble in metals) at intermediate (>1 keV) or high ($\sim$1 MeV) energy impinges into the inner wall, then it can produce helium bubbles and cavities or cause blistering and spallation, which have detrimental effects on the operational efficiency of the reactor and the properties of the plasma-facing materials.

In addition to ejection of high-Z tungsten into the plasma core, which causes rapid cooling of the plasma, generation of brittle 'fuzz' under helium-plasma exposure poses other significant challenges including tritium inventory management. Helium bubbles that form close to the plasma-exposed surface trap hydrogenic species. Retained helium and hydrogenic species, in any form (blisters, in 'fuzz', and/or bubbles) lead to a significant decrease in the thermal conductivity and mechanical strength of tungsten, which is further accelerated under neutron irradiation. In a reactor environment, the feedback effect from materials into the plasma such as fuel recycling would decrease plasma confinement and increase energy loss; an electric sheath is formed above the material surface due to the neutralization of plasma particles, which further accelerates ions toward the material surface and increases materials damage. Furthermore, under burning plasma conditions, PFCs are expected to experience a steady thermal load on the order of 10 MW m^{-2} which can further increase to $\sim$1 GW m^{-2} during transient plasma conditions such as type I Edge-Localized Modes (ELMs). Plasma-material interactions under the harsh conditions in a fusion reactor pose arguably the single greatest materials engineering challenge, as well as a challenge for designing in-plasma sensors and diagnostics to monitor the physical conditions in the plasma.

This *MRX* focus issue consists of a collection of 3 topical review articles and 12 contributed original research articles, and provides an excellent representative *snapshot* of the ongoing effort in overcoming a set of such key impediments for realizing deuterium-tritium (D–T) fusion power in a tokamak reactor. This focus issue highlights the most recent progress on those research frontiers, by placing emphasis on materials development challenges resulting from helium irradiation, neutron-induced degradation, thermomechanical loading, and the corrosive environment faced by PFCs and blanket systems for tokamak fusion reactors. Additional emphasis is placed on examining the characterization techniques for plasma-surface interactions toward advancing both *in situ* and *in operando* diagnostic tools.

The central thrust of materials research on PFCs is to understand fusion environment-induced damage mechanisms over a long operating period and use that knowledge to develop improved materials and design strategies that mitigate deleterious radiation effects, providing improvements in safety and lifetime, as well as increasing efficiency and performance of materials and components. Due to a lack of experimental testing facilities that replicate the extreme operating environment of the fusion reactor, computational materials modeling is the mainstay of this research field. Research advances on plasma-facing materials in nuclear fusion reactors based on both computer simulation findings and experimental studies are covered in this focus collection. While the materials science community has a long history of conducting fundamental and applied research on plasma-materials interactions [6–8], this collection focuses on the same type of physics with respect to a nuclear fusion environment. The topics covered are unique to '*Plasma-Facing Materials in Nuclear Fusion Reactors*' such as: deuterium and tritium retention in PFCs [9–13]; fundamental processes at the plasma-surface interface [10, 14–20]; evolution of structure and properties under fusion-reactor-relevant heat loads [21]; material degradation under ion exposure [15, 16, 19]; material degradation under neutron irradiation [9, 21];

material erosion, migration, and deposition [14, 15, 18, 20, 22]; plasma fueling [12]; and diagnostics for plasma-materials interactions [23]. Although the details of the underlying mechanisms that govern the above phenomena remain largely unresolved, the results presented here will drive the emergence of engineering solutions to the amelioration of plasma-facing materials degradation. It is our hope and goal that this focus collection will encourage the broader materials research community to join the effort in mitigating materials challenges to accelerate the promethean effort of bringing fusion energy to the electrical power grid.

Data availability statement

No new data were created or analysed in this study.

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