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Revealing the chemical environment of Cr, Fe, and Ni in high temperature-ultrafine precipitate strengthened steel subjected to low fluence neutron irradiation

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ABSTRACT

High temperature-ultrafine precipitate strengthened (HT-UPS) steel has potential applications in advanced nuclear reactors as a structural material. However, little is currently known about its response to neutron irradiation. This research provides insight into the neutron irradiation-induced physicochemical changes of the major constituents in HT-UPS steels, including Fe, Cr, and Ni, using synchrotron X-ray absorption near edge structure (XANES) and diffraction. This study is the first known investigation using XANES to characterize HT-UPS steel to analyze the evolution of the atomic level chemistry. It was found that following neutron exposure, radiation-induced nucleation, growth, and/or ballistic dispersion of $Cr_{23}C_6$ precipitates occurred at very low neutron irradiation fluences, from 0.003 displacements per atom (dpa) up to 0.3 dpa, at 600 °C, which were at least an order of magnitude lower than previous studies. Calculations of the angular momentum projected partial density of states and the XANES spectra confirmed the experimental findings of the $Cr_{23}C_6$ precipitate evolution. In contrast, the local atomic structure around Fe and Ni atoms demonstrated irradiation resistance.

1. Introduction

High temperature-ultrafine precipitate strengthened (HT-UPS) steel is an advanced, austenitic stainless steel that was primarily developed for advanced fossil fuel power facilities as a structural material [1]. It exhibits higher strength and creep resistance at elevated temperatures (>600 °C) in comparison to conventional 300 series austenitic stainless steels due to the presence of nm-sized metal carbide (MC) (M: Ti, Nb, and V) precipitates [1–7]. These precipitates decrease the strain accumulation through pinning of dislocations, preventing both glide and climb [2–4,6,7]. Creep studies at 700 °C and 170 MPa for 18,000 h indicated the formation of these stable precipitates and resistance to the formation of creep-induced-voids and detrimental Lave and sigma phases [2,4]. A numerical simulation study of HT-UPS steel based on classical nucleation theory and thermodynamic extremum principles predicted the formation of stable MX (M: Ti, Nb; X: C, N) precipitates 80 nm in size and the formation of $M_{23}C_6$ (M: Fe, Cr, Mn) precipitates 100 nm in size after ageing at 700 °C for 100,000 h [8].

Due to the aforementioned microstructural and mechanical property attributes, HT-UPS steel is also being considered for structural material use in advanced nuclear reactors [2,3]. It is expected to be neutron irradiation tolerant due to the presence of point defect annihilation sites in the form of MC and $M_{23}C_6$ type precipitates, as well as the existence of traps for helium (He) atoms by MC precipitates [2,6,9–11]. Due to the annihilation of point defects, vacancy supersaturation will not occur, which otherwise could lead to the formation of voids and/or unstable growth of He bubbles formed via transmutation reactions during neutron irradiation [4]. Thus, HT-UPS steel has the potential to alleviate issues such as He embrittlement and irradiation-induced void swelling typically observed in structural materials for nuclear reactor applications [2–4].

Although HT-UPS steel was first developed in the 1980s, its neutron irradiation response is not well understood due to few studies performed. In one study, HT-UPS steel was neutron irradiated to 3 displacements per atom (dpa) at 500 °C. Frank loops, as

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