Understand the Thermal Aging Effect on Mechanical Response of a Duplex Stainless Steel by *In Situ* Synchrotron Wide-Angle X-Ray Scattering

YU LU, YIREN CHEN, JEFFREY TERRY, and YONG YANG

Duplex stainless steels (DSSs) are widely used in the energy and chemical industries due to their favorable combination of mechanical strength and corrosion resistance. However, long-term thermal aging can degrade their performance by inducing microstructural changes, particularly in the ferrite phase. In this study, the deformation behavior of DSSs thermally aged at 475 °C for 400, 1000, and 3000 hours was investigated using *in situ* synchrotron Wide-Angle X-ray Scattering (WAXS) tensile testing, with calculated dislocation densities validated by post-mortem Transmission Electron Microscopy (TEM) analysis. Macroscopic tensile results show that thermal aging increases the ultimate tensile strength (UTS) and reduces ductility, with the UTS plateauing after 1000 hours. Phase-specific analysis reveals that austenite maintains a stable mechanical response with minimal change in lattice strain and yield strength (~194 MPa), while ferrite exhibits pronounced aging effects, including increased lattice strain, progressive hardening up to ~ 1837 MPa, and enhanced dislocation multiplication. Load partitioning becomes increasingly asymmetric with aging, shifting more stress to ferrite and intensifying interfacial constraints. And microstructural characterization further shows that long-term aging promotes pore formation at austenite–ferrite boundaries, contributing to earlier fracture and reduced ductility. Together, the *in situ* WAXS and TEM results provide a mechanistic understanding of how thermal aging selectively alters the ferrite response, driving embrittlement in DSSs.

https://doi.org/10.1007/s11661-026-08156-5

I. INTRODUCTION

DUPLEX stainless steels (DSSs) are widely used in the energy and chemical industries due to their excellent mechanical properties and corrosion resistance.[1–4] Featuring a dual-phase microstructure of austenite and ferrite formed during solidification, DSSs offer a well-balanced performance compared to single-phase austenitic or ferritic stainless steels. The ferrite phase enhances tensile strength and resistance to stress corrosion cracking, while the austenite phase improves ductility and weldability.[5]

However, the service life of DSSs can be significantly limited by thermal aging embrittlement. Prolonged exposure to moderate temperatures (280 °C to 500 °C) has been shown to increase hardness and tensile strength, while reducing impact strength and ductility.[1–4,6–8]

Thermal aging embrittlement in DSSs is typically attributed to two microstructural phenomena within the ferrite phase: spinodal decomposition and G-phase precipitation. Spinodal decomposition produces nanoscale compositional fluctuations, forming Fe-rich α and Cr-rich α' coherent domains within the body-centered cubic (bcc) ferrite matrix. In parallel, G-phase precipitates, with a nominal composition of $A_6Ni_{16}Si_7$ (A = Cr or Mn, and Fe may partially substitute for Ni), form during aging and generally exhibit a cube-on-cube orientation relationship with the ferrite matrix.[9]

While spinodal decomposition is widely recognized as the dominant mechanism behind ferrite embrittlement, the role of G-phase precipitates remains debated. Some studies using atom probe tomography (APT) have reported a strong correlation between ferrite hardening and Cr fluctuations from spinodal decomposition, with negligible influence from G-phase precipitates.[4,6] In

YU LU and YONG YANG are with the Nuclear Engineering Program, Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611. Contact e-mail: yongyang@ufl.edu YIREN CHEN is with the Nuclear Engineering Division, Argonne National Laboratory, Lemont, IL 60439. JEFFREY TERRY is with the Department of Physics, Illinois Institute of Technology, Chicago, IL 60616.
Manuscript submitted November 5, 2025; accepted February 3, 2026.

Published online: 18 February 2026