Influence of Oxide Dispersion and Chromium Content on Ferritic Steels for Nuclear Structural Applications

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Abstract—
This Oxide Dispersion Strengthened (ODS) ferritic steels are considered promising candidate materials for advanced nuclear reactor applications due to their superior high-temperature strength, creep resistance, radiation tolerance, and thermal stability. Future fusion and Generation-IV nuclear systems demand materials capable of operating under extreme conditions, including elevated temperatures, intense neutron irradiation, and high heat flux. Conventional ferritic and martensitic steels often exhibit degradation in mechanical properties and reduced creep resistance under such environments, highlighting the need for advanced materials like ODS steels. This study presents a comparative analysis of 12Cr and 14Cr ODS ferritic steels based on reported experimental investigations. The comparison includes chemical composition, microstructure, thermo-physical properties, mechanical performance, creep behavior, and high heat flux response. The incorporation of nano-sized Y_2O_3 particles significantly enhances strength, radiation resistance, and microstructural stability. The analysis reveals that both steels perform well under reactor-relevant conditions; however, 14Cr ODS steel generally exhibits higher hardness, improved tensile strength, better thermal conductivity, and enhanced structural stability. Overall, both materials are suitable for advanced nuclear applications, with 14Cr ODS steel showing comparatively superior performance for future fusion and Generation-IV reactor systems.

Keywords— Oxide Dispersion, Chromium, Ferritic Steels, Nuclear Applications .

I. INTRODUCTION

Advanced nuclear energy systems, including fusion and Generation-IV reactors, demand structural materials capable of operating under extreme conditions such as high temperatures, intense neutron irradiation, and severe thermal loads. Conventional ferritic and martensitic steels, though widely used, exhibit limitations including reduced creep strength, radiation-induced swelling, and degradation of mechanical properties at elevated temperatures. These challenges necessitate the development of advanced materials with superior structural stability and long-term performance. Oxide Dispersion Strengthened (ODS) ferritic steels have emerged as promising candidates due to the incorporation of fine, stable oxide particles—typically yttrium oxide (Y_2O_3)—uniformly dispersed within the ferritic matrix. These nano-sized particles act as effective barriers to dislocation motion and grain boundary migration, thereby enhancing high-temperature strength, creep resistance, and radiation tolerance. Additionally, the presence of oxide dispersoids improves microstructural stability by inhibiting grain growth under prolonged thermal exposure.

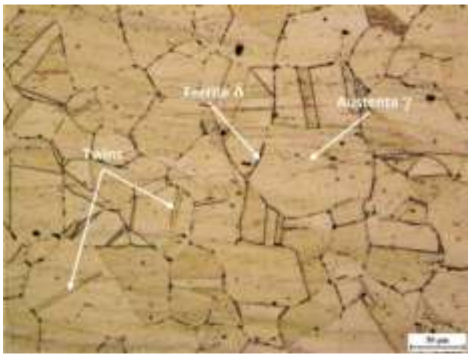

Figure 1: Austenitic stainless steel Microstructure

Ferritic Matrix (Fe-Cr):

The continuous phase consisting mainly of iron (Fe) with chromium (Cr), providing corrosion resistance and structural stability. Nano-sized Oxide Particles Uniformly distributed fine particles (typically 5–50 nm) that:

- Strengthen the material by hindering dislocation motion
- Improve creep resistance at high temperatures
- Enhance radiation tolerance by trapping defects

Fine grains contribute to improved mechanical strength and thermal stability. Oxide particles act as pinning points, preventing dislocation movement, which increases strength.

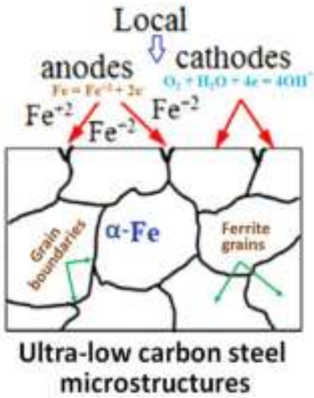

Figure 2: Corrosive behaviour of carbon steel

The figure illustrates corrosion behavior in ultra-low carbon ferritic steel, showing localized anodic and cathodic reactions. Grain boundaries and ferrite grains act as electrochemical sites where iron oxidizes to Fe^{2+} at anodes, while oxygen reduction occurs at cathodes, leading to localized corrosion and material degradation. Oxide Dispersion Strengthened (ODS) ferritic steels have been extensively investigated as potential structural materials for advanced nuclear systems due to their excellent high-temperature strength, radiation resistance, and creep performance. Several studies have focused on understanding the role of oxide particles and chromium content in determining their microstructure and mechanical behavior.

II. LITERATURE REVIEW

Oksiuta and Baluc [1] investigated the microstructure and Charpy impact properties of 12–14Cr ODS ferritic steels and reported that 14Cr steels exhibit heterogeneous grain structures, while 12Cr steels show improved toughness after heat treatment. Similarly, Li et al. [2] analyzed 12Cr ODS ferritic steel and confirmed that nano-sized Y–Ti–O particles significantly enhance mechanical strength and structural stability.

High heat flux performance of 12Cr and 14Cr ODS steels was studied by Rieth et al. [3], who observed similar thermal shock resistance for both steels, although 14Cr exhibited slightly higher hardness and tensile strength. The creep behavior of these steels was examined by Aktaa et al. [4], indicating that 12Cr ODS steels demonstrate marginally better creep resistance under certain stress conditions compared to 14Cr steels. Capdevila et al. [5] provided a comprehensive overview of ODS strengthening mechanisms, emphasizing the role of nano-oxide particles in impeding dislocation motion. Serrano et al. [6] studied anisotropy in ferritic ODS steels and highlighted that processing routes significantly influence mechanical properties due to microstructural variations. Further studies on 14Cr ODS steels by Oksiuta et al. [7] revealed that thermomechanical processing refines grain structure and enhances tensile properties. Research on irradiation effects by Zhang et al. [8] demonstrated that increasing chromium content reduces irradiation hardening due to suppression of defect cluster growth.

Recent studies on FeCrAl-based ODS steels [9] showed that higher chromium content improves oxidation resistance and thermal stability, making them suitable for accident-tolerant fuel cladding. Mohan et al. [10] reported that the stability of nano-clusters depends on alloying elements, with Y–Zr–O clusters offering improved stability compared to Y–Al–O clusters. Additionally, Raman et al. [11] reviewed ODS steels and concluded that dispersion of oxide particles plays a critical role in improving creep resistance, radiation tolerance, and high-temperature performance.

III. METHODOLOGY

The following materials has used for this study

TABLE I

Martials and composition

Material	Composition
12Cr	Fe–12Cr–2W–0.25Ti–0.25Y
ODS 14Cr ODS	Fe–14Cr–2W–0.26Ti–0.29Y

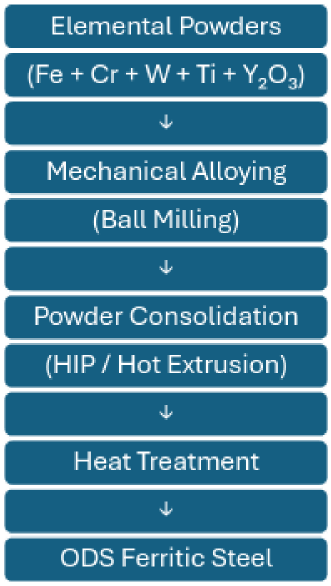

Figure 3: Manufacturing process of ODS

ODS steel manufacturing process involves a powder metallurgy route designed to achieve a uniform distribution of nano-oxide particles. First, elemental powders such as iron (Fe), chromium (Cr), tungsten (W), titanium (Ti), and yttria are selected. These powders undergo mechanical alloying, where high-energy collisions repeatedly fracture and weld the particles, ensuring homogeneous mixing and fine dispersion of oxide particles. Next, the alloyed powder is subjected to powder consolidation, typically using Hot Isostatic Pressing (HIP) or hot extrusion, which densifies the material under high temperature and pressure to eliminate porosity. Heat treatment is performed to stabilize the microstructure, refine grains, and enhance mechanical properties.

IV. RESULTS AND DISCUSSION

The microstructures in both images confirm a ferritic (α-Fe, BCC) phase with a distinct bimodal grain distribution. Fine grains in the range of 100–500 nm contribute to high strength through grain boundary strengthening, while larger grains, extending to several micrometers, improve ductility. A dense dispersion of Y–Ti–O nanoclusters (~5 nm) is also evident, which effectively impedes dislocation movement and enhances creep resistance. These stable nanoparticles further act as sinks for radiation-induced defects. Overall, the combined presence of bimodal grains and uniformly distributed nanoclusters results in improved mechanical performance and thermal stability of the steels.

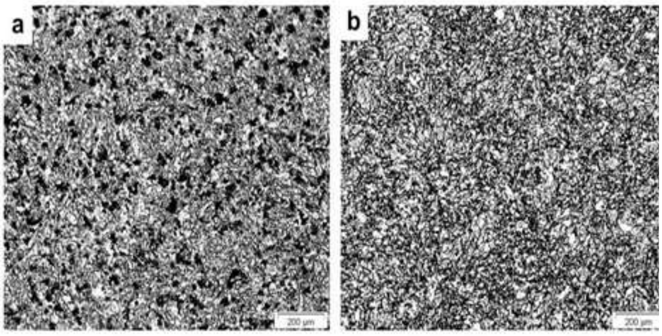

Figure 4: Microstructure of a) 12Cr b) 14Cr ODS

Table I: Comparison of 12Cr & 14Cr ODS

Feature	12Cr ODS	14Cr ODS
Matrix	Ferritic α-Fe	Ferritic α-Fe
Fine Grain Size	100–500 nm	100–500 nm
Coarse Grains	Present	Present
Y–Ti–O Clusters	Present	Present
Nanocluster Size	~5 nm	~5 nm

Both steels exhibit a ferritic (α-Fe, BCC) microstructure with a bimodal grain distribution. Fine grains (100–500 nm) enhance strength, while coarse grains improve ductility. A high density of ~5 nm Y–Ti–O nanoclusters strengthens the matrix, impedes dislocation motion, and improves creep resistance and radiation tolerance effectively.

Table II: Comparison of thermo physical properties

Temp (°C)	Thermal Conductivity (12Cr)	Thermal Conductivity (14Cr)
20	22.3	21.8
200	23.1	23.2
400	22.8	24.6
600	23.6	25.6
800	22.2	

Both materials exhibit similar thermal conductivity at room temperature. However, with increasing temperature, 14Cr steel consistently shows higher thermal conductivity than 12Cr. The maximum difference is observed around 600°C. This improved thermal conductivity enhances heat dissipation, making 14Cr ODS steel more suitable for high-temperature nuclear reactor applications.

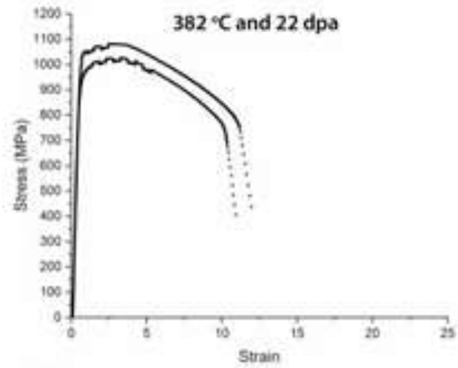

Figure 5: Stress strain curve of 12Cr and 14Cr ODS

compares the tensile behavior of both steels. ODS 14Cr exhibits higher yield and ultimate tensile strength, while ODS 12Cr shows greater elongation, indicating better ductility. The difference reflects the influence of grain size and oxide dispersion on deformation mechanisms

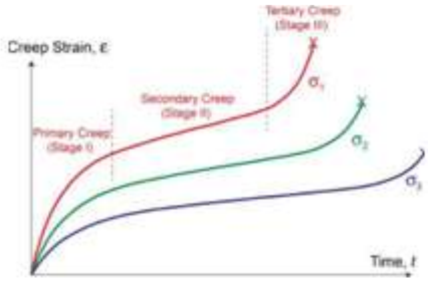

Figure 6: Creep behaviour

shows the creep performance of both materials. ODS 14Cr steel demonstrates a longer secondary creep stage and lower creep rate, indicating superior high-temperature stability. This behavior is attributed to stronger particle pinning and reduced dislocation mobility. Under high heat flux conditions, both 12Cr and 14Cr ODS steels show similar performance, with melting onset at 1–1.5 MJ/m², outperforming stainless steel. Under irradiation and creep at 650°C and 190–400 MPa, both exhibit excellent creep resistance. Thermal behavior remains comparable, while long-term mechanical performance confirms ODS steels as strong reactor candidates.

Table III: Over all Comparison

Parameter	12Cr	14Cr	Better
Hardness	360 HV	370 HV	14Cr
Density	7.75	7.78	14Cr
Tensile Strength	Lower	Higher	14Cr
Charpy Impact	Lower	Better	14Cr

Thermal Conductivity	Lower at high T	Higher at high T	14Cr
HHF Performance	Similar	Similar	Tie
Creep Performance	Excellent	Excellent	Tie

The comparison indicates that 14Cr ODS steel demonstrates superior mechanical properties, including higher hardness, tensile strength, and better impact resistance than 12Cr steel. It also exhibits improved thermal conductivity at elevated temperatures, enhancing heat transfer capability. However, both materials show comparable performance under high heat flux (HHF) and creep conditions, indicating similar thermal stability and long-term durability. Overall, while 14Cr offers better strength and thermal efficiency, both steels remain excellent candidates for nuclear reactor applications due to their outstanding creep resistance and high-temperature stability.

V. CONCLUSION

Both 12Cr and 14Cr ODS ferritic steels demonstrate excellent high-temperature performance, making them promising candidates for advanced nuclear reactor applications. Their ferritic microstructure, combined with a bimodal grain distribution and finely dispersed Y–Ti–O nanoclusters, significantly enhances strength, thermal stability, and radiation resistance.

Comparatively, 14Cr ODS steel exhibits slightly superior mechanical properties, including higher hardness, improved tensile strength, and better Charpy impact behavior, indicating enhanced structural stability. It also shows marginally higher thermal conductivity at elevated temperatures, which is beneficial for efficient heat dissipation.

However, under high heat flux conditions, both steels display similar thermal shock resistance, with melting observed only at high energy densities (1–1.5 MJ/m^2). Furthermore, creep studies confirm that both materials maintain excellent performance at 650°C within the stress range of 190–400 MPa.

Overall, while 14Cr ODS steel offers modest improvements in mechanical and thermal properties, both steels exhibit outstanding high-temperature strength and durability, reinforcing their suitability for long-term nuclear applications.

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