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A comparative assessment of the fracture toughness behavior of ferritic-martensitic steels and nanostructured ferritic alloys

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ABSTRACT

The Fe-Cr alloys with ultrafine microstructures are primary candidate materials for advanced nuclear reactor components because of their excellent high temperature strength and high resistance to radiation-induced damage such as embrittlement and swelling. Mainly two types of Fe-Cr alloys have been developed for the high temperature reactor applications: the quenched and tempered ferritic-martensitic (FM) steels hardened primarily by ultrafine laths and carbonitrides and the powder metallurgy-based nanostructured ferritic alloys (NFAs) by nanograin structure and nanoclusters. This study aims at elucidating the differences and similarities in the temperature and strength dependences of fracture toughness in the Fe-Cr alloys to provide a comparative assessment of their high-temperature structural performance. The K_{JQ} versus yield stress plots confirmed that the fracture toughness was inversely proportional to yield strength. It was found, however, that the toughness data for some NFAs were outside the band of the integrated dataset at given strength level, which indicates either a significant improvement or deterioration in mechanical properties due to fundamental changes in deformation and fracture mechanisms. When compared to the behavior of NFAs, the FM steels have shown much less strength dependence and formed narrow fracture toughness data bands at a significantly lower strength region. It appeared that at high temperatures $\geq$600 °C the NFAs cannot retain the nanostructure advantage of high strength and high toughness either by high-temperature embrittlement or by excessive loss of strength. Irradiation studies have revealed, however, that the NFAs have much stronger radiation resistance than tempered martensitic steels, such as lower radiation-induced swelling, finer helium bubble formation, lower irradiation creep rate and reduced low temperature embrittlement.

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1. Introduction

The iron-chromium (Fe-Cr) alloys have been developed for high-temperature reactor applications because of their high resistance to corrosion, microstructural instability, creep deformation, and radiation-induced damage. Thus far, the Fe-Cr alloys for nuclear reactor applications have been studied primarily in two types: the melt-based ferritic-martensitic (FM) steels [1–7] and powder metallurgy-based nanostructured ferritic alloys (NFAs) [8–14]. In particular, the Fe-9Cr and Fe-12Cr ferritic-martensitic (FM) steels and Fe-9Cr and Fe-14Cr nanostructured ferritic alloys (NFAs) became primary candidate materials for various components of advanced nuclear power systems, such as the first-wall and breeding blanket structures of fusion reactors, fuel cladding and duct of fast reactors, and cladding for spallation targets in the accelerator driven systems [2–7,12–16]. In fact, some FM steels have been successfully applied to reactor core components, e.g., the HT9 steel (12Cr-MoVW steel) for the fuel cladding and duct of sodium-cooled reactors (SFRs) [7,17–26]. For the majority of the new Fe-Cr alloys, however, any reactor core application will require a new assessment of mechanical stability in high temperature irradiation and their compatibility with the coolant at high temperatures [4–7,15–21].

It is believed that the most important characteristics of the Fe-Cr based alloys that enable applications in such high-temperature and high-flux irradiation environments originate from their highly

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stable ultrafine microstructures. In general, such desirable fine microstructures with high strength can be achieved through existing processing routes with a wide range of Fe-Cr compositions: that is, the quenched and tempered FM steels are hardened primarily by ultrafine laths and carbonitrides while the NFAs by nanograin structure and nanoclusters (or fine oxide particles) [1–3,8–13]. Many past studies have confirmed that the nanoparticles in NFAs have relatively higher stability in high temperature irradiation, and therefore they help retain nanograin structures and associated resistance to radiation-induced damage such as embrittlement and swelling [1–7,27–34]. Although significant characterization results support possible applications of new Fe-Cr alloys in various irradiation conditions, however, some structural integrity controlling properties, such as the fracture toughness in the as-fabricated condition, need to be separately assessed because they can limit the fabrication processes of components and such baseline properties also determine much of the in-service performance [32–34].

The objective of the research was to assess the baseline mechanical properties of the Fe-Cr alloys, focusing on the high-temperature fracture toughness behavior. A large number of fracture toughness data, including both published [7,17–26,30–35] and newly produced datasets, were integrated into the fracture toughness versus strength plots [37–39] and fracture toughness versus test temperature plots. These plots were designed to reveal the best contrasts between developed and underdeveloped materials (in NFAs, in particular) and between FM steels and NFAs, as well as to help find real drawbacks in performance and a direction for further development. Discussion is focused primarily on the four alloy systems, i.e., 9Cr and 12Cr FM steels and 9Cr and 14Cr NFAs, which are among the most frequently studied as the future nuclear reactor core materials.

2. Experimental

2.1. Materials and specimens

Table 1a and b lists the two types of Fe-Cr alloys compared in the study, along with their chemistries and final thermomechanical treatments (TMTs). In the discussion the Fe-Cr alloys are categorized into four groups: 9Cr and 12Cr FM steels and 9Cr and 14Cr NFAs. As is well known, the FM steels, strengthened by fine laths and carbide particles, can be used up to about 550 °C, for example, in the sodium-cooled fast reactors [7,18–22,25,26]. Meanwhile, during the past few decades, the NFAs, a new grade of oxide dispersion strengthened (ODS) steels, have been developed as high energy mechanical milling and high power consolidation enabled the production of the nanograin structures of high strength Fe-Cr alloys, which are further stabilized by the high density of Y-Ti-O enriched nanoclusters [8–14,29–36]. Primarily in the fast reactor and fusion reactor communities, the NFA developments have aimed at expanding the application capability of Fe-Cr alloys to a higher temperature region of 500–700 °C.

As summarized in Table 1a and b, all of the FM steels were tested in typical normalized and tempered conditions, while the Fe-9Cr and Fe-14Cr NFAs are in a variety of TMT conditions as they are still under development. Note that some alloys were tested in two specimen orientations: L-T and T-L orientations, where L-T means that the principal loading at crack tip is parallel to the rolling (L) direction and crack propagation occurs in the transverse (T) direction while T-L specifies the orientation of the 90° turned specimens. If not specified, the specimens were assumed to be tested in the L-T orientation, with which specimens are generally tougher than those with the other orientation. The plots for the fracture toughness (K_{JQ}) versus yield stress (YS) relationship [37–39] and K_{JQ} versus temperature relationship for those types of materials aim to reveal the relative performance of these materials groups as well as the influence of processing route in NFAs.

Table 1(a)
List of high-chromium ferritic-martensitic (FM) steels compared in the study.

#	Materials identification	Nominal chemistry	Specimen Type/ Orientation	Final TMT	Ref.#
A1	9Cr-MoWVNb (NF616)	Fe-9Cr-1.9W-0.45Mn-0.45Mo-0.2Ni-0.1Nb-0.2Si-0.1C-0.05Cu-0.011S	DCT/L-T	1079°C/0.5 h + AC (air-cooled) & 746°C/1 h + AC	
A2	9Cr-MoWVNb (NF616-1539ST)	Fe-9Cr-1.06W-0.5Mn-0.01Mo-0.14Ta-0.25Si-0.32V-0.109C-0.055N	DCT/L-T	1070°C/0.75 h + AC & 760°C/ 0.75 h + AC	
A3	9Cr-1MoVNb (T91-Huang et al., 1992)	Fe-8.92Cr-1.09Mo-0.39Mn-0.2V-0.07Nb-0.1C	DCT/T-L 2.54 mmB/11.94 mmD	1038°C/5 min + AC & 760°C/1 h + AC	[18]
A4	9Cr-1MoVNb (T91-Jia et al., 2006)	Fe-8.32Cr-0.86Mo-0.48Mn-0.2V-0.15Si-0.06Nb-0.09C (heat 30,176)	TPB 2 × 4 × 20 mm	1050°C/0.5 h + AC & 760°C/1 h + AC	[17]
A5	9Cr-1MoVNb (T91-Maloy et al., 2001)	Fe-9.24Cr-0.96Mo-0.47Mn-0.16Ni-0.21V-0.05Nb-0.089C	DCT/L-T&T-L	1038°C/1 h + AC & 760°C/1 h + AC	[7]
A6	9Cr-1WVTa (Eurofer-97 Chaouadi et al., 2010)	Fe-8.99Cr-1.1W-0.44Mn-0.19V-0.13Ta-0.12C	TPB 6 × 9 × 45 mm	980°C/27 min + AC & 760°C/ 1.5 h + AC	[20]
B1	12Cr-1MoVW (HT9-FFTF-TL)	Fe-11.87Cr-1.02Mo-0.58Mn-0.55W-0.53Ni 0.27Si-0.3V-0.2C (heat 84,425)	DCT/T-L 2.54 mmB/11.94 mmD	1065°C/0.5 h + AC & 750°C/1 h + AC (ACO-3 duct)	[25]
B2	12Cr-1MoVW (HT9-INL-LT)	Fe-12Cr-1Mo-0.6Mn-0.55W-0.5Ni-0.3V-0.3Si-0.2C	DCT/L-T	1030°C/0.5 h + AC & 760°C/1 h + AC	
B3	12Cr-1MoVW (HT9-INL-TL)	Fe-11.9Cr-1.0Mo-0.6Mn-0.55W-0.5Ni-0.3V-0.3Si-0.2C	DCT/T-L	1030°C/0.5 h + AC & 760°C/1 h + AC	
B4	12Cr-1MoVW (HT9-FFTF-Reuse)	Fe-11.87Cr-1.02Mo-0.58Mn-0.55W-0.53Ni 0.27Si-0.3V-0.2C	SEB/L-T 3.05 × 4 × 13.5 mm	1065°C/0.5 h + AC & 750°C/1 h + AC (ACO-3 duct)	[24,25]
B5	12Cr-1MoVW (HT9-FFTF-Huang et al., 1984)	Fe-11.88Cr-1.02Mo-0.50Mn-0.50W-0.58Ni 0.23Si-0.34V-0.2C (heat 91,354)	DCT/T-L 11.9/32 mm	1149°C/1 h + AC & 740–760°C/ 1 h + AC	[19]
B6	12Cr-1MoVW (HT9-FFTF-Huang et al., 1992)	Fe-11.87Cr-1.02Mo-0.58Mn-0.55W-0.53Ni 0.27Si-0.3V-0.2C (heat 84,425)	DCT/T-L 2.54 mmB/11.94 mmD	1038°C/5 min + AC & 760°C/ 0.5 h + AC	[18]

Note-1: Three-point bend (TPB) specimen: 2.5 mm (thickness) × 5 mm (width) × 15 mm (length) if not specified otherwise.
Note-2: Disk compact tension (DCT) specimen: 3.05–4.6 mm (thickness) × 12.5 mm (diameter) if not specified otherwise.