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Viewpoint Set

On the status and prospects for nanostructured ferritic alloys for nuclear fission and fusion application with emphasis on the underlying science

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ABSTRACT

The status of nanostructured ferritic alloys (NFAs) is summarized. The science underlying NFAs has emerged as a remarkably comprehensive and high quality body of research. The sequence of events and composition-processing paths needed to form and sustain the performance enabling nano-oxides are well established. The nano-oxides are predominantly $Y_2Ti_2O_7$ pyrochlore, and their role in providing outstanding mechanical properties and unique irradiation tolerance is described. Notably, however, producing defect-free NFA components remains a work in progress. The paper argues that the costs and supply of NFAs will be consistent with its selective application to advanced fission and fusion reactors.

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1. Introduction

Success in developing new sources of large-scale, zero carbon emission Gen IV nuclear fission and future fusion energy will require advanced, high-performance structural materials that can safely support extended component lifetimes in extremely hostile environments. These environments include combinations of high temperatures and large time-varying stresses, chemically aggressive coolants and intense neutron fluxes [1]. Recently, extensive studies have shown that nm-scale dispersoids, that are stable under prolonged high temperature neutron service, offer the potential for both high strength and unique irradiation tolerance [2–5].

There are many combinations of nm-scale phases and host metal matrices that provide attractive microstructures, including a variety of steels, as well as nickel, titanium, aluminum and refractory metal-based alloys. In the case of steels, nano-dispersion strengthening has been applied to austenitic steels, heat-treatable 9 Cr ferritic-martensitic and higher Cr fully ferritic alloys. The dispersoids primarily include alloy carbonitrides [6] and oxides [2–15]. Processing paths range from modifications of classical melt-thermomechanical practice [6], to powder metallurgy routes [2–4,7–15]. Given this wide scope, and the rapidly growing worldwide interest in this class of materials, this Viewpoint Paper will focus on the status and prospects for so-called nanostructured ferritic alloys (NFAs), which are a variant of oxide dispersion strengthened (ODS) steels. There are several reasons for the choice, but it is arguable that NFAs present both the greatest opportunities, at least for some critical applications like first wall fusion structures, as well as the most imposing challenges.

Fe-12-16%Cr NFAs have very high tensile, fatigue and creep strengths over a wide range of temperature, unparalleled long-term thermal stability up to >900 °C, and unique irradiation tolerance,

especially in managing high levels of helium [2–5,7–9]. These outstanding properties directly, or indirectly, owe to small volume fractions (f order 0.5%) of an ultrahigh number density (N order $5 \times 10^{23}/m^3$) of nm-scale diameter (average d order 2.5 nm) nano-oxides (NOs) that provide a good balance of mechanical and functional properties. NFA microstructures also include submicron-sized grains (≈ 500 nm) and high dislocation densities ($\approx 10^{15}/m^2$) [2–4,7–15]. The NOs are typically Y-Ti-O based phases, although other Group 4 and 3 elements can be used to replace Ti (Zr and Hf) and Y (Sc).

Many of the concepts that apply to NFAs are also applicable to the 9 Cr, C-bearing tempered martensitic steel (TMS) variant of ODS alloys. The ODS TMS are in many ways more developed as engineering materials than NFA, particularly in terms of their fabricability. Further, highly oxidation and corrosion resistant Al bearing ferritic steels are attractive candidates for accident tolerant cladding and chemically aggressive environment applications, but generally suffer from replacement of the fine Y-Ti-O NOs with coarser scale Al-Y oxides. Fortunately, addition of Zr (or Hf) refines the Y-Zr(Ti)-O oxides in Al bearing NFAs [16]. However, given the length limit of this paper, the ODS 9Cr and Al added alloys will not be discussed further here, but notably are covered in detail in an excellent recent review [9].

The challenges of practically developing NFAs remain significant, and currently reside primarily in the technological arenas of uniformity, fabricability, joining, cost, and industrial production capacity. This paper is not intended to be a review. Hence, the references are not comprehensive (which would be impossible). They include useful reviews [2–9] and three key PhD theses that contain material otherwise widely dispersed [11,13,15]. If a topic is covered in these sources, the primary references (often a very large number) are generally not repeated here.

In framing the viewpoints outlined in this paper, the author solicited the opinions of the long-time leaders in the NFA/ODS field, including

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Drs. Shigeharu Ukai, Akihito Kimura, Yann DeCarlan, Anton Moslang, Henning Zoz, Yong Jiang, Stuart Maloy, Iver Anderson and David Hoelzer. The author would like to specially acknowledge Professor Ukai for his pioneering and sustained contributions to NFA and ODS steels. While the viewpoints expressed here are the author's responsibility alone, where possible they attempt to reflect a more general consensus of these outstanding researchers, and the author thanks them for their very valuable input.

The paper first and mainly focuses on the underlying NFA materials science issues relating to processing, microstructure, thermal and irradiation stability, mechanical properties and irradiation tolerance. Difficult issues and challenges of deformation processing and joining NFA components cannot be adequately discussed here due to length limits; hence, they are only briefly noted. Finally, brief comments are offered on the critical broader questions of NFA costs and industrial supply capacity, other applications and the possible role of NFAs as an enabling part of hybrid materials systems for fission and especially fusion power reactors.

2. The materials science of NFAs

2.1. Powder metallurgy, processing paths and microstructures

NFAs are typically Fe 12 to 16-Cr based C-free fully ferritic bcc alloys that are microalloyed with Y, Ti and O, along with varying amounts of solid solution strengthening from W or Mo [2–4,7–15]. In most cases, rapidly solidified Fe-Cr-Ti-W powders are mechanically alloyed with small amounts of Y_2O_3 by high energy ball milling for tens of hours to dissolve the otherwise thermally insoluble Y and to introduce excess O. Attempts to lattice-trap Y by rapid powder solidification have not been successful, due to cellular phase separation of Y_2Fe_{17} [4,13,17].

Proper concentrations of O and Ti are critical to forming nm-scale oxides [2–4,7–15,17–21]. Oxygen must be in excess of that introduced by the Y_2O_3 alone, and Ti must be balanced to form ultrafine, ≈ 2 –3 nm diameter $Y_2Ti_2O_7$ pyrochlore complex NOs. This alloy recipe is driven by fundamental thermodynamics and kinetics related to phase selection and the scale of precipitation [19,20]. Oxygen can be introduced during rapid solidification or impurity pickup during milling, and by ball milling with Fe-oxides. Other Group 4 element-bearing compounds (like hydrides) may also be used to introduce Y, Ti and O that are unreacted with fine scale Y-Ti oxides and N impurity contamination generally should be avoided. When the compositions are properly balanced, the mole fraction of the fine NOs scales directly with the alloy Y content [21].

NO precipitation during powder consolidation is extremely rapid, but shows classical C-curve type temperature kinetics [2,3,10–12] with a nose at ≈ 650 °C. For typical consolidation conditions between 850 and 1150 °C, N and f decrease, while d increases at higher temperatures. The NOs are reasonably well distributed throughout the matrix in properly processed NFAs, and also form on grain boundaries, where they are somewhat larger [13].

Other key features of consolidated NFA microstructures are the grain sizes and crystallographic textures, as illustrated in the electron backscatter diffraction (EBSD) inverse pole figure map in Fig. 1a, for an extruded and cross-rolled NFA plate with pancake shaped grains [22]. The strong texture viewed in the thickness direction (the top surface) shows the dominance of (100) planes running parallel to the plate faces. The views in the extrusion and cross-rolling directions (front and side sections) show a strong $\langle 110 \rangle$ -fiber texture. Notably, the bcc $\{100\}\langle 110 \rangle$ system manifests very low cleavage toughness in Fe, which results in microcracks in the extruded and cross-rolling direction views (shown in white on the side section of Fig. 1).

In almost all cases, the NFA grain size distributions are bimodal, and are dominated by small submicron grains (averaging ≈ 500 nm in Fig. 1), with far fewer, larger grains extending up to > 10 μm . Contrary to a previous belief, however, the NOs are distributed in both large and

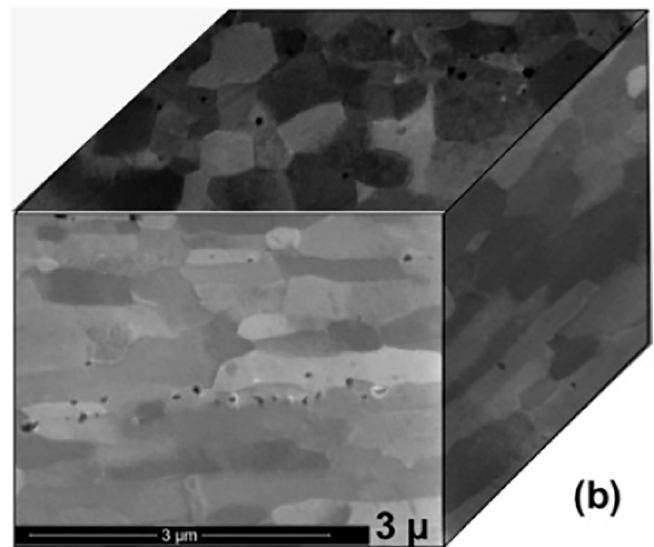
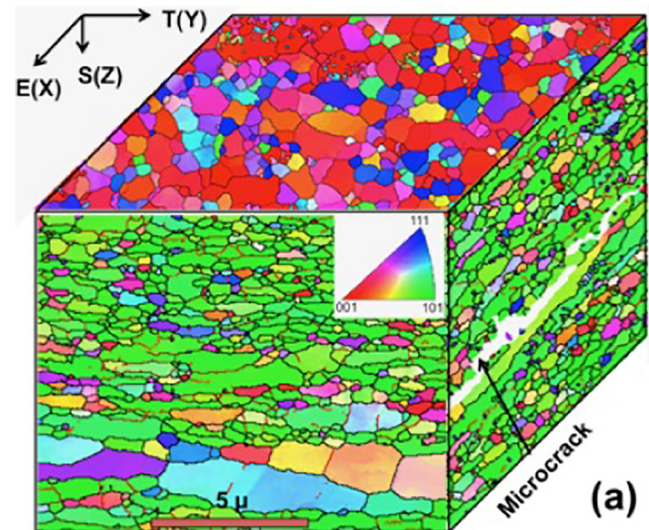


Fig. 1. a) Three-dimensional electron backscatter diffraction (EBSD) maps and b) SEM images of a section of the NFA plate showing the bimodal grain size, the (100) plane and $\langle 110 \rangle$ -fiber texturing and the presence of a microcrack. Note the various views are not for the same location in the plate, thus do not align with one another in three-dimensions.

small grains [13,15,23,24]. The growth of some grains is likely due to large differences in the ultra-high dislocation densities in the milled powders that produce pressures on grain boundaries that far exceed Zener pinning forces, especially before the NOs have fully precipitated [15,23,24]. Lower temperature consolidation results in smaller fine grain sizes and fewer larger grains [11].

2.2. Nature of the NOs and their ferrite matrix interfaces

Early atom probe tomography (APT) studies were interpreted to suggest that the NOs were coherent sub-oxide transition phases enriched in Ti and O, but containing relatively small amounts of Y, coupled with large quantities of Fe [25]. It is now widely accepted that this conclusion stemmed from a variety of APT artifacts [26]. Further, some transmission electron microscopy (TEM) studies found the NO to be either amorphous [27], or TiO dominated oxides with rock salt structures [28]. However, based on a large and growing body of TEM data [28–35], as well as more limited x-ray measurements [9,36–38], there is now a general consensus that, in most cases, the smaller NOs

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