Development of next generation tempered and ODS reduced activation ferritic/martensitic steels for fusion energy applications

S.J. Zinkle[1,2], J-L. Boutard[3], D.T. Hoelzer[2], A. Kimura[4], R. Lindau[5], G.R. Odette[6], M. Rieth[5], L. Tan[2] and H. Tanigawa[7]

[1] University of Tennessee, Knoxville, TN 37996, USA
[2] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[3] CEA, Cabinet HC, 91191 Gif sur Yvette, France
[4] Institute of Advanced Energy, Kyoto University, Japan
[5] Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[6] University of California, Santa Barbara, CA 93106, USA
[7] Japan Atomic Energy Agency, Rokkasho, Aomori, Japan

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Abstract
Reduced activation ferritic/martensitic steels are currently the most technologically mature option for the structural material of proposed fusion energy reactors. Advanced next-generation higher performance steels offer the opportunity for improvements in fusion reactor operational lifetime and reliability, superior neutron radiation damage resistance, higher thermodynamic efficiency, and reduced construction costs. The two main strategies for developing improved steels for fusion energy applications are based on (1) an evolutionary pathway using computational thermodynamics modelling and modified thermomechanical treatments (TMT) to produce higher performance reduced activation ferritic/martensitic (RAFM) steels and (2) a higher risk, potentially higher payoff approach based on powder metallurgy techniques to produce very high strength oxide dispersion strengthened (ODS) steels capable of operation to very high temperatures and with potentially very high resistance to fusion neutron-induced property degradation. The current development status of these next-generation high performance steels is summarized, and research and development challenges for the successful development of these materials are outlined. Material properties including temperature-dependent uniaxial yield strengths, tensile elongations, high-temperature thermal creep, Charpy impact ductile to brittle transient temperature (DBTT) and fracture toughness behaviour, and neutron irradiation-induced low-temperature hardening and embrittlement and intermediate-temperature volumetric void swelling (including effects associated with fusion-relevant helium and hydrogen generation) are described for research heats of the new steels.

Keywords: radiation effects, thermal creep strength, ductility, void swelling, yield strength, fracture toughness, point defect sink strength

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1. Introduction

Reduced activation ferritic/martensitic (RAFM) steels such as F82H or EUROFER97 represent the most mature option for the fusion blanket structural material. The historical development [1–5] and current status [6, 7] of RAFM steels have been reviewed elsewhere and are summarized in a companion article [8] in this special issue. Although RAFM steels have numerous advantageous features including well-established large-scale industrial fabrication capability (leveraging the worldwide steel industries) and overall good thermomechanical properties and resistance to neutron irradiation-induced property degradation, the extremely challenging operating environment of deuterium–tritium (DT) fusion reactors has spurred interest in development of even higher performance steels as a risk mitigation strategy.

The main concerns with baseline RAFM steels include: (1) Poor long-term thermal aging behaviour and low thermal creep strength above 550–600 °C, which limits high temperature operation and therefore thermodynamic efficiency, (2) Fatigue and creep-fatigue cause cyclic softening in current RAFM steels, resulting in lower allowable design stresses, (3) Loss of uniform and total elongation and significant radiation embrittlement (increase in the ductile to brittle transition temperature, DBTT, and reduction in 'upper shelf' toughness) following low temperature fission neutron irradiation for doses above ~1–10 displacements per atom (dpa), all of which are expected to be further exacerbated in a fusion neutron irradiation environment, (4) Anticipated enhanced void swelling under fusion neutron irradiation conditions that may cause unacceptable dimensional changes for doses above 25–50 dpa, and (5) Numerous challenges associated with weldments including the requirement for post-weld heat treatments that may be difficult to achieve in complex, full-scale blanket components and radiation-induced degradation of mechanical properties in weld heat affected zones (HAZ). As a consequence, RAFM steels are considered to have a rather limited operating temperature range in nuclear energy systems to avoid both radiation embrittlement (lower viable operational temperature ~325 °C, for doses >10 dpa) and thermal aging instabilities and creep rupture failure (upper viable operational temperature <550 °C). For high temperature DEMO concepts, the heat fluxes incident on the blanket structures near the first wall regions are sufficiently high that He coolant technology may not be viable for RAFM steels (due to limitations in heat removal capability for He-cooled systems). Conversely, the required lower operating temperatures (<350 °C) for water-cooled designs would exacerbate radiation embrittlement in RAFMs. In addition, the operational lifetime dose of RAFM steels at intermediate temperatures is uncertain due to lack of fusion-relevant irradiation data on void swelling and other radiation degradation phenomena.

Due to the operating temperature limitations for current RAFM steels described above along with a general lack of information on the effects of DT fusion-relevant neutron irradiation for doses above 0.1 dpa, international fusion materials research programs are investigating several alternative (backup) options for RAFM steels that may provide improved performance and radiation resistance. Experimental studies suggest improvements in the operating temperature window may be achievable by utilizing new steels with improved resistance to radiation embrittlement and/or thermal creep deformation. For example, as summarized in [9], the irradiation temperature that induces a DBTT above room temperature varies from ~275 to ~375 °C for different heats of current-generation RAFM steels due to slight modifications to their composition and/or processing conditions.

The two main approaches under investigation for developing improved steels for fusion applications [10, 11] are based on an evolutionary pathway using computational thermodynamics modelling and modified thermomechanical treatments (TMT) to produce higher performance RAFM steels [12–18], and a higher risk, potentially higher payoff approach based on powder metallurgy techniques to produce very high strength oxide dispersion strengthened (ODS) steels capable of operation to very high temperatures [10, 19–27]. The latter ODS steels are sometimes called 'nanostructured ferritic alloys' (NFAs) in recent literature. Both of these approaches offer the potential for significant performance enhancements compared to existing RAFM steels. For example, these high performance steels may enable significant enhancements in thermodynamic efficiency due to increased operating temperature capabilities, and/or may provide longer operational lifetimes before repair or replacement. Many of the microstructural features responsible for improved mechanical performance in these new steels (ODS particles, high density of precipitates, etc) are anticipated to simultaneously impart improved radiation resistance due to an increased 'sink strength' that efficiently promotes recombination or self-healing of radiation-produced defects [22, 28–30]. In the following, these two potential pathways for achieving improved RAFM steels based on evolutionary improvements in composition and/or TMT processing and nanostructured ODS steels are discussed.

2. Prospects for improved performance in 8–9%Cr RAFM steels using compositional modifications and thermomechanical treatment

Steady improvements in steel performance have been achieved over the past 70 years; for example, the upper use temperature for ferritic/martensitic steels has increased by about 130 °C (from 520 °C to ~650 °C) since 1950 and the accompanying higher tensile and thermal creep strengths allow thinner sections to be utilized, resulting in considerable economic savings and improved flexibility in component construction [17, 31–33]. The current baseline RAFM steels under consideration for fusion energy applications (e.g. F82H or EUROFER97) are based on reduced-activation formulations [34] of the early 1980s alloy 91 that was originally developed as an alternative to austenitic stainless steel for sodium cooled fast breeder reactor applications [35] and subsequently was widely used for fossil energy applications [36–38]. In the intervening years, a series of higher performance commercial ferritic/martensitic steels have been developed that provide much higher strength and operating temperature capability compared to current

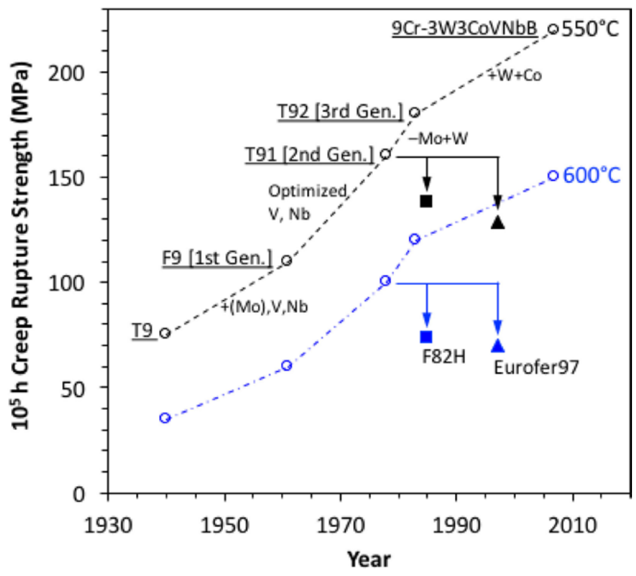

Figure 1. Comparison of the evolution in creep rupture strengths of ferritic/martensitic steels at 550 and 600 °C [31] with the corresponding strengths of current RAFM steels [39, 40].

baseline RAFM steels, as summarized in figure 1 [31, 39, 40]. It can be seen from this figure that the long term thermal creep performance of F82H and EUROFER97 at 550 and 600 °C is somewhat lower than that of ferritic/martensitic steels such as the 2nd-generation 9Cr steel T91 (upon which the RAFM steels were patterned in the early 1980s), whereas current state of the art steels such as 9Cr-3W3Co steels exhibit creep strengths that are more than 70% higher than the RAFM baseline steels. The best performance steels for fossil energy applications contain several elements (e.g. Co and Nb) that are unsuitable for reduced activation fusion service. These elements provide important solid solution (Co) and precipitate (Nb) strengthening, and other high-activation elements such as Ni increase austenite stability to enable improved heat treatments. However, analogous reduced activation steel formulations should be possible that would achieve strength performance approaching the current best performing ferritic/martensitic steels.

2.1. Motivation for pursuing next-generation RAFM steels

The fundamental materials science principles for designing high performance steels for moderate to high temperature conditions are now well established [12, 15, 17, 41–47]. In short, high performance steels consist of moderate grain sizes, high densities of fine precipitates that are resistant to coarsening, and absence of known embrittling phases and large precipitates that can act as undesirable stress concentrators. Several examples have been recently obtained on the design of new 9%Cr ferritic/martensitic steels with room temperature strengths >1 GPa while still retaining good tensile ductility [15], and VN precipitation strengthened 9%Cr steels with significant improvements in long term creep strength at 650 °C with no degradation in weldments [17]. Recent improvements in the phase equilibrium databases associated with computational thermodynamics evaluations now allow reasonably accurate predictions of phase formation to be rapidly made in numerous alloy systems including Fe–Cr steels. This breakthrough is enabling development of new high performance steels and other structural alloys for a variety of energy applications. The importance of using computational thermodynamics to guide and focus R&D efforts can be understood by recognizing only about 10% of ternary phase diagrams have been experimentally studied to sufficient accuracy [48], due to the long times and relatively high costs of comprehensive experimental phase stability studies and the wide range of experimental variables that need to be investigated. Leveraging recent advances in the fossil energy and other advanced steel research programs, computational thermodynamics can be utilized to design new RAFM steel heats with improved thermodynamic stability and increased density of desirable precipitates [13, 16, 18, 45, 49, 50]. Judicious utilization of thermomechanical processing (hot-working or cold-working) can greatly increase nucleation of fine-scale precipitates on dislocation sites, particularly if the hot working is performed at a temperature where desirable precipitation occurs [13]. The cost to fabricate these newly designed steels should be nearly equal to the cost for current RAFM steels since the compositional changes are minor (<1%) and the new steels utilize well-established steel processing technologies (the key difference being that the processing temperature is controlled at specified values during some fabrication steps rather than being allowed to vary over a relatively wide temperature range).

In addition to providing improved mechanical performance, it has long been recognized that high densities of precipitates can provide improved radiation resistance by increasing the 'sink strength' for recombination of radiation-produced point defects [22, 30, 45, 51, 52]. In this approach, it is of crucial importance that the precipitates exhibit good thermal and irradiation stability during prolonged exposure times. The thermal stability of various phases can be estimated using current computational thermodynamics and kinetics models. The stability of nanoscale precipitates due to irradiation effects is more difficult to estimate by current models due to the competing effects of ballistic dissolution and radiation enhanced diffusion; the former process will promote precipitate dissolution, whereas the latter process promotes precipitate growth [53–56]. An additional complication regarding precipitate stability during irradiation is the possibility of radiation induced solute segregation processes that can lead to depletion or enrichment of individual solute species depending on the specific irradiation conditions and solute [55, 57–59], and unknown effects associate with whether or not the precipitate interface exhibits coherency with the matrix [55]. However, recent ion irradiation studies on nanoscale precipitates that were selected based on their high thermodynamic stability in 9%Cr ferritic/martensitic steels suggest that the precipitates also exhibit good stability during ion irradiation up to at least 50–100 dpa [59–61]. This suggests these newly designed steels with high precipitate densities could simultaneously provide improved thermomechanical performance and improved radiation resistance.

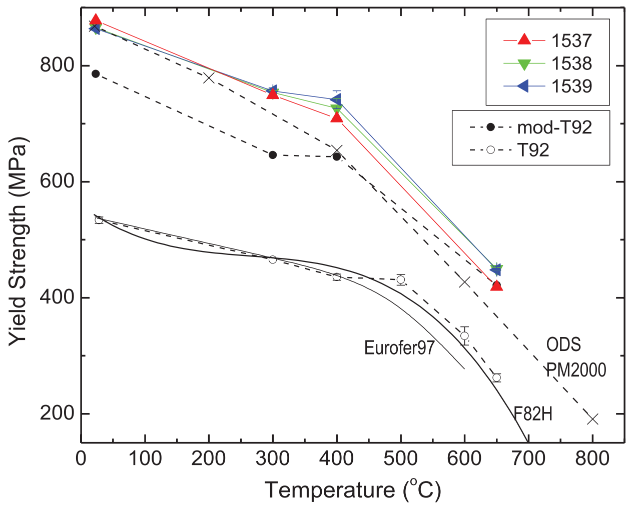

Figure 2. Comparison of the temperature-dependent yield strengths of TMT FM heats (filled triangles, heats 1537–1539) to conventional steels (T92 and two current RAFMs F82H, EUROFER97) and a commercial ODS steel PM2000 [18].

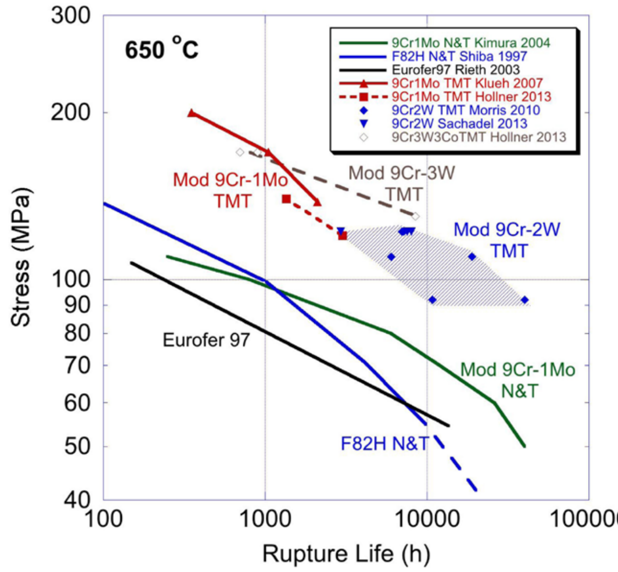

Figure 3. Thermal creep strength of TMT steels versus conventional steels (EUROFER97, F82H, Mod 9Cr–1Mo) at 650ºC [14, 16, 39, 47, 72–74].

Based on modeling and experimental observations after fission neutron and simultaneous dual- or triple- ion beam irradiations [62–66], the radiation resistance of current RAFM steels such as F82H or EUROFER97 is considered to be adequate only for fusion neutron doses of 20–50 dpa based on void swelling at ~400–500 °C [8, 9, 30], and even lower allowable doses might occur at lower or higher temperatures due to radiation hardening/embrittlement and high temperature He embrittlement, respectively. Therefore, improved high-performance radiation-resistant RAFM steels (such as RAFM steels with high precipitate densities) may be required for DEMO fusion devices to demonstrate the technological and economic viability of fusion energy.

2.2. Development status for next-generation 8–9%Cr RAFMs

The design of new steels utilizing computational thermodynamics to tailor the composition and TMT in order to improve the microstructure and properties of 8–12% Cr FM steels is being investigated by several research groups for fossil energy [17, 47], fission [16, 50] and reduced activation fusion energy [18, 61, 67, 68] applications. Traditional compositional variant efforts [69–71] are also being pursued on several RAFM steels in order to explore possible expansion of the operating temperature window by improvements in the low temperature ductile to brittle temperature behaviour (unirradiated and irradiated) and high temperature thermal creep deformation.

Yield strength results summarized in figure 2 indicate the new RAFM steels designed with the assistance of computational thermodynamics (modified composition and TMT optimization) have significantly improved strength compared to conventional commercial FM or RAFM steels [18]. In this study, the alloy composition was optimized to enhance the formation of $M_{23}C_6$ and (V, Ta)-rich nitride and carbide precipitates and the TMT conditions guided by computational thermodynamics involved a simple 60% hot-rolling step and water quench after standard normalization heat treatment and before tempering at standard conditions. With these slight changes in chemical composition and TMT conditions, the room temperature yield strength for three research heats (1537–1539) of new RAFM steels exhibited >50% higher room temperature yield strength compared to conventional (T92) and baseline RAFM (F82H and EUROFER97) steels, without any degradation in tensile ductility. The yield strengths of the new RAFM steels are comparable to that of a commercial ODS steel (PM2000). Similar improvements in tensile properties over a broad range of temperatures have been observed for other newly designed RAFM steels [67]. A moderate strength increase has been observed in EUROFER97 RAFM steel by modifying the ausforming TMT conditions [68].

The new RAFM steels have also demonstrated significantly improved short-term thermal creep resistance at high temperatures. Figure 3 summarizes some short-term (500 to ~50 000 h) thermal creep rupture strength results at 650 °C for four TMT heats of 9%Cr ferritic/martensitic steel compared to the behaviour for conventional 9%Cr steels (F82H RAFM and modified 9Cr–1Mo alloy Grade 91) [14, 16, 39, 47, 72–74]. The detailed composition and heat treatment conditions for the new steels are provided in the original references, but in general involved increased N and lower C and tailored additions of V, Ta along with warm rolling at 600–700 °C and/or multi-stage austenitization and tempering to promote *MX* and M_2X precipitates (M = V or Ta and X = N or C). The measured creep rupture strength of the TMT steels is nearly double that of the conventional steels, and the corresponding creep rupture lifetime at a given stress is about ten times higher for the TMT steels. Even higher thermal creep strengths have been observed in TMT ferritic/martensitic steels containing 3%W [72]. The long term thermal creep behaviour and overall microstructural stability of the TMT steels still needs to be investigated, although the computational thermodynamic evaluations predict good long-term stability in the newly designed RAFM steels. Several phase instabilities that can

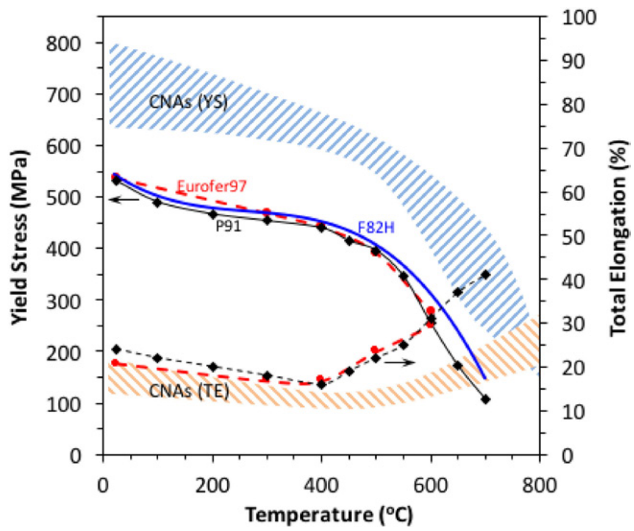

Figure 4. Comparison of temperature-dependent yield strength (YS) and total elongation (TE) for new 'castable nanostructured alloys' (CNAs) versus conventional (P91) and RAFM (F82H, EUROFER97) steels [76, 77].

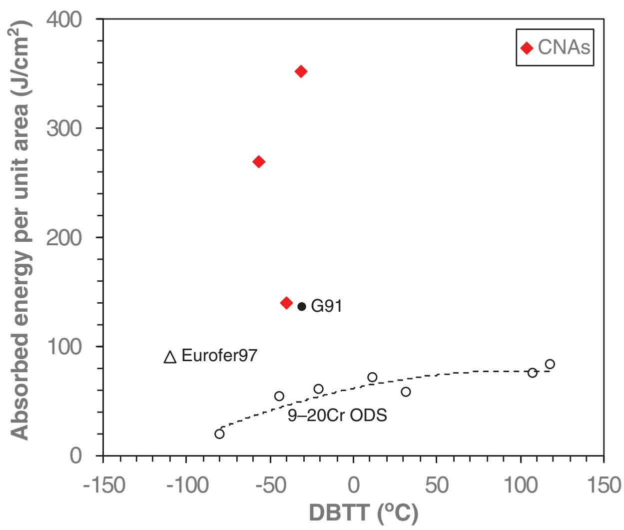

Figure 5. Comparison of the Charpy V-notch impact behavior of new 'castable nanostructured alloys' (CNAs) versus commercial grade 91 ferritic/martensitic steel, EUROFER97 RAFM steel and 9-20Cr ODS steels [76, 77]. Miniature Charpy specimens were used in the tests with fracture ligaments under the V-notch of $4 \times 5\,\text{mm}^2$ for the CNAs and G91 and $3 \times 3\,\text{mm}^2$ for EUROFER97 and 9–20Cr ODS steels. The DBTT was determined at half of the upper shelf absorbed energy.

lead to strength reductions have been observed in 9Cr–1Mo [37] and F82H RAFM [75] steels during long term aging at temperatures above 600 °C.

Fatigue properties have not yet been thoroughly investigated for any of the new TMT steels. Improved fatigue behaviour (compared to grade 91 steel) has been reported for a TMT Fe–9Cr–3W–3Co ferritic/martensitic steel during testing at 550 °C [72]. Significant cyclic softening (comparable to that in conventional FM steels) was observed.

In some cases it may not be possible to perform TMT processing due to complex geometries or thick sections. Therefore, scoping research has recently used computational thermodynamics to promote the formation of high densities of nanoscale TaC, TaN and VN precipitates without deformation [60]. As summarized in figure 4, these 'castable nanostructured alloys' (CNAs) illustrated with the shaded data bands exhibit 20–35% higher yield strengths than conventional 9Cr–1Mo (P91) or RAFM steels with only a slight reduction in elongation [76, 77]. Charpy impact testing of these steels has also found favorable performance. As shown in figure 5, the DBTT (determined at half the upper shelf energy) for the new steels is comparable to Grade 91 steel [76, 77]. In addition, the upper shelf energies of the new steels are comparable or significantly higher than Grade 91 steel and are much higher than typical ODS ferritic/martensitic steels. Eurofer97 exhibited the lowest DBTT, but exhibited a reduced upper shelf energy compared to conventional Grade 91 steel. Good precipitate stability in the CNA steel has been reported following ion irradiation up to ~50 dpa [60, 61], which implies that the nanoscale precipitates will provide improved radiation resistance for these steels. Neutron irradiation data on mechanical properties and precipitate stability have not yet been reported for these new steels. Overall, despite the impressive improvements in unirradiated mechanical properties obtained in these exploratory small research heats, all of these alloys are still in the pre-commercial R&D stage.

2.3. Technical challenges for next-generation 8–9%Cr RAFMs

Scoping results have demonstrated substantial improvement in mechanical properties such as yield strength, fracture toughness (DBTT and upper shelf toughness), and thermal creep strength can be achieved compared to current baseline RAFM steels for small research heats of unirradiated base metal steels. However, there are numerous technical issues that need to be satisfactorily resolved before these new advanced RAFM steels would be viable candidates for next generation fusion energy system applications.

The most basic issues are the current lack of industrial-scale fabrication technology for the newly designed RAFM steels and incomplete materials property data, particularly for long-term thermal aging and creep-fatigue conditions. These are not insurmountable technical barriers (although they obviously have a major impact on engineering design) and can be resolved over time with sufficient resources. In particular, fabrication of industrial-scale 6–20 tonne heats of current-generation RAFM steels to tight chemical specifications with good impurity control has been demonstrated in Japan (F82H, JLF-1), Europe (Eurofer97) and China (CLAM). Experimental confirmation of the long-term stability of the nanoscale precipitate structure (thermal aging and irradiation conditions) is a crucial near-term priority, since it is essential to know during the early stages whether any significant alterations in the alloy composition or processing conditions are needed.

A related basic issue is the near complete lack of information on the properties of the new steels following joining operations. Unresolved questions include: Can the benefits of thermomechanical treatment be realized in fabricated fusion blanket structures? How can these materials be joined while retaining optimized properties? This may be a profitable activity for utilization of advanced manufacturing techniques such as additive manufacturing [78, 79]. In general, it is expected that high performance bulk properties may not be achievable in weldments (and/or would require considerable R&D). If the new high performance steels were to be used in restricted high temperature zones near the first wall with conventional RAFM steel used for the rest of the structure, the issue of dissimilar welding (TMT steel to RAFM steel) is less challenging since the weld properties may be comparable to the (relatively weak) baseline RAFM steel, particularly if post-weld heat treatment is feasible [80]. However self-welding of TMT steel that requires high performance properties in the joint (e.g. much better strength than conventional RAFM steel joints with adequate toughness) may be a major challenge and has yet to be demonstrated on even idealized joints. Currently, no information is known about the performance of TMT steel joints following irradiation.

In general, there is a lack of data on high temperature compatibility of the new RAFM steels with potential coolants such as Pb–Li. Therefore, it may not be possible to take advantage of the high temperature mechanical properties of the new steels if corrosion is severe; development of coatings/protection barriers would require sustained R&D. (pebble bed concept is an alternative up to ~650 °C).

The most significant shortcoming for the new RAFM steels is lack of information on the effects of neutron irradiation (including DT fusion-relevant He and H transmutation effects) on microstructural stability and mechanical properties of the base metal and joints. Some low dose neutron irradiation data are just becoming available, and several years will be required before higher dose neutron irradiation studies will be completed [76, 77]. These irradiation studies should explore three general temperature regimes: Low temperatures (250–400 °C) where radiation hardening and embrittlement are of particular concern; 400–525 °C, where dimensional instabilities due to void swelling and irradiation creep are of concern and where radiation-induced-solute segregation and—precipitation are most pronounced; and 525–650 °C, where thermal creep, thermal aging, and high temperature helium embrittlement of grain boundaries are expected to be prominent. A major unresolved question for low temperature irradiations is whether the high point defect sink strength in the new RAFM steels is sufficient to significantly suppress the high radiation hardening and embrittlement associated with Cr solute clustering (alpha prime precipitation) and dense loop formation [81–85], along with possible enhanced low temperature embrittlement due to DT fusion-relevant helium transmutation [86–88]. A related question is whether the desirable microstructural features in the new steels (primarily the finely dispersed nanoscale precipitates) are retained during long-term thermal aging and neutron irradiation at various temperatures. Although high temperature helium embrittlement has not been reported to be a major concern in current RAFM steels [89–91] (due in part to their relatively poor creep strength at high temperatures), further research is needed to quantify the susceptibility of the new high strength RAFM steels to high temperature helium embrittlement that may emerge at higher operating temperatures.

As noted elsewhere [92–95], improved science-based high temperature design rules for irradiated structures are needed to replace current empirical and incomplete design criteria. These improved design rules would be of particular importance to take full advantage of the higher temperature capability of the new RAFM steels.

Some of the TMT steels under consideration for fusion structures have high tungsten content (2–3%) in order to enhance high temperature strength. This increased W content may cause an unacceptable reduction in the tritium breeding ratio for some blanket concepts due to the relatively high neutron absorption by tungsten [4]. Allowable W levels need to be established from iterative neutronics evaluations of proposed breeding blanket concepts. The tritium breeding ratio depends on the specific blanket design and therefore needs to be examined for specific DEMO designs.

3. Status and challenges for 8–16%Cr ODS RAFM steels

3.1. Motivation for pursuing ODS RAFM steels

ODS steels containing high concentrations of uniformly distributed nanoscale particles offer the prospect for very high mechanical strength and nanocluster stability under extreme operating conditions [20–22, 27]. Since the nanoclusters are relatively chemically inert, the particles are resistant to coarsening up to temperatures in excess of 900 °C for annealing times up to 32 000 h and up to 1300 °C for 24 h thermal exposures [96, 97]. The maximum potential operating temperatures of ODS ferritic/martensitic steels depends on the Cr concentration, but in all cases can be significantly higher than traditional ferritic/martensitic steels. ODS alloys containing ~8–9%Cr typically must be kept below ~650 °C to maintain the tempered martensitic structure, although low carbon ODS steels that avoid martensite formation have also been explored [98]. Alloys containing higher Cr concentrations are fully ferritic structures and can potentially be operated at temperatures up to 800 °C or higher. Although the high Cr ODS alloys offer higher potential operating temperatures and superior high temperature thermal creep strength, the lower Cr tempered martensitic ODS steels provide several offsetting advantages. Because of the possibility to heat treat the steel after forming operations (martensitic transformation), the 8–9%Cr tempered martensitic ODS steels can exhibit more isotropic mechanical properties compared to high-Cr ferritic ODS steels and generally exhibit more favorable fracture toughness properties such as lower DBTT and higher upper shelf energy [10, 20]. The high-Cr ODS steels are also potentially susceptible to alpha prime precipitate embrittlement at low to intermediate operating temperatures (300–500 °C) since the Cr content is significantly above the solubility limit at these temperatures [84, 99, 100].

In addition to superior strength and high temperature operation capability, a major motivation for investigating ODS ferritic/martensitic steels is the potential for exceptional neutron irradiation resistance due to the very high point defect sink strength associated with the nanoclusters and other

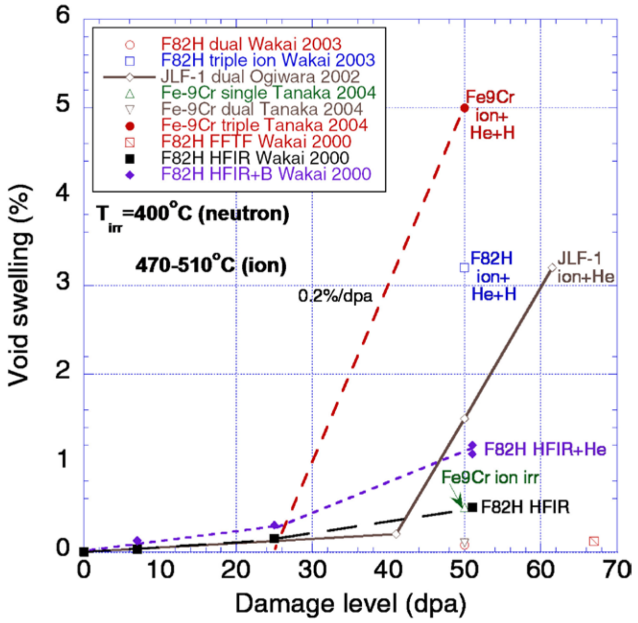

Figure 6. Summary of the effects of simultaneous DT fusion-relevant He and H production on volumetric void swelling in ion and fission neutron irradiated Fe-9%Cr and RAFM steels [62–65]. The experimental studies include simultaneous heavy ion and He or He + H implantation at 470–510 °C and fission reactor (HFIR or FFTF) irradiation at 400ºC of standard or boron-doped (to generate He) samples. The multi-ion beam irradiations used gas implantation rates of 10–18 appm He/dpa and 40–70 appm H/dpa. The boron-doped HFIR neutron irradiated F82H samples generated ~60 or ~300 appm He, mainly created at doses <1 dpa.

fine-scale microstructural features [9, 22, 27, 30]. It has been recognized for many years that the elevated concentrations of He and H induced by DT fusion neutron transmutations in materials will enhance radiation degradation processes such as void swelling [101–103]. Therefore, the good void swelling resistance exhibited by conventional ferritic/martensitic steels following fission neutron irradiation [104] is expected to be severely impaired for DT fusion irradiation conditions. Figure 6 summarizes some experimental studies on the effects of fusion-relevant coimplantation of H and He on void swelling in ion and fission neutron irradiated Fe–9%Cr and RAFM steels [62–65]. The 0.2%/dpa post-transient steady state swelling rate for fission neutron irradiated ferritic martensitic steels [104] is also shown in the figure. Whereas void swelling is low (<0.5%) for fission and single ion irradiation conditions up to doses in excess of 100 dpa [104], it can be seen the amount of void swelling is progressively larger for conditions that simultaneously introduce DT fusion-relevant He and He + H gas solute during irradiation. The simultaneous ion + He + H 'triple beam' irradiations produced 3.2%, 4% and 5% volumetric swelling in type F82H RAFM, Fe–12%Cr and Fe–9%Cr, respectively after 50 dpa. Since the transition dose to the high steady-state swelling regime is significantly less for low-dose rate conditions (relevant for fission and fusion reactors) compared to the high dose rates for ion irradiations [105, 106], the dose to produce unacceptably high (>5%) volumetric swelling in RAFM steels during DT fusion neutron irradiation might be significantly less than the

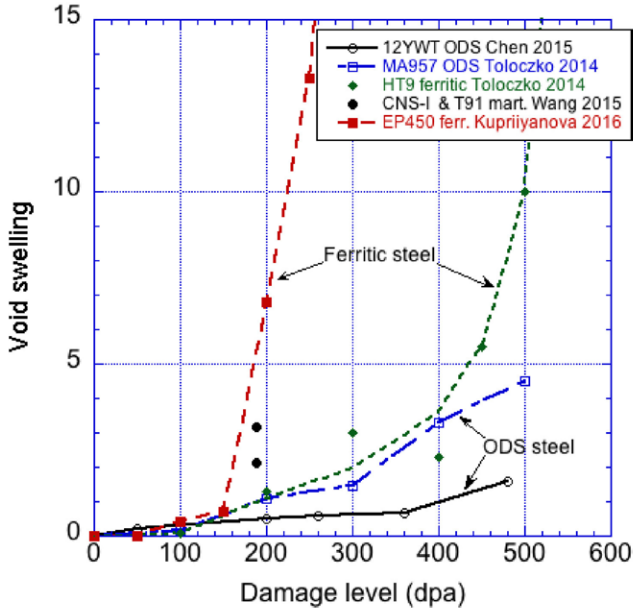

Figure 7. Comparison of void swelling due to single ion irradiation at 450–480 °C in conventional ferritic/martensitic and ODS steels [107, 109, 111, 112].

value of ~50 dpa for ion-irradiated samples shown in figure 6. This could cause unacceptably short operation lifetimes for first wall and blanket components in fusion reactors.

Several single-, dual-, and triple- ion beam irradiation studies have recently observed superior radiation resistance for ODS ferritic/martensitic steels compared to conventional or RAFM steels [66, 107–111]. In particular, as shown in figure 7, void swelling is significantly suppressed in single ion irradiated ODS steels compared to ferritic/martensitic steels for doses up to 500 dpa [107, 109, 111, 112]. The good swelling resistance is attributable to efficient recombination of vacancies and interstitials at the boundary regions between the nanoscale particles and the surrounding steel matrix. The nanoscale particles in the ODS steels have been reported to exhibit good stability following fission neutron or ion irradiation at temperatures 300–750 °C and doses of 50–100 dpa [109, 113–118]. Since these damage levels involve multiple ballistic dissolution events by energetic displacement cascades for the nanoscale particles, this observed stability implies the particles will remain stable up to even higher doses.

Based on preliminary irradiation studies and radiation effects modeling considerations, both classes of ODS steels are expected to provide superior radiation resistance compared to traditional ferritic/martensitic steels due to the very high additional point defect sink strength associated with the nanoclusters. Therefore, the ODS steels provide a high performance, high radiation resistance option in case the DT fusion neutron-induced property degradation of traditional RAFM steels proves to be unacceptably severe compared to data obtained from fission neutron irradiations. The 8–9%Cr tempered martensitic ODS steels may be more favorable for intermediate temperature fusion applications, and the higher Cr ferritic ODS steels are best suited for high temperature fusion applications.

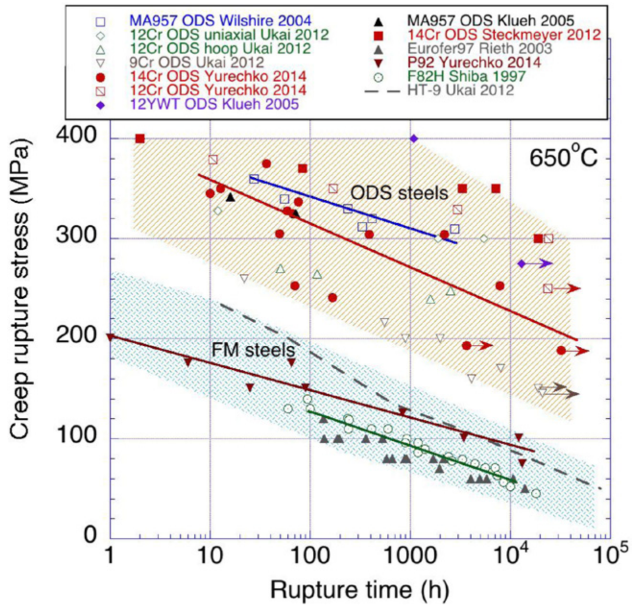

Figure 8. Comparison of the thermal creep behavior at 650°C for ODS versus conventional ferritic/martensitic steels [21, 39, 40, 127–130].

3.2. Development status for ODS RAFM steels

International research activities on ODS ferritic/martensitic steels are being pursued at multiple institutions for potential fossil, fission and fusion energy applications [10, 20, 23, 24, 119–126]. High tensile and thermal creep strengths with acceptable ductility and fracture toughness have been achieved in research heats of ODS steels, with the specific strengths dependent on the composition and processing conditions. Careful control during the mechanical alloying process is needed to maintain good homogeneity and minimize the introduction of harmful inclusions that could degrade tensile ductility and induce premature failure under thermal creep conditions [21]. The ODS steel strength is typically weaker perpendicular to the extrusion direction (particularly for ferritic ODS steels containing >11%Cr). As summarized in figure 8 for data obtained at 650 °C [21, 39, 40, 127–130], ODS steels have superior high temperature thermal creep strength compared to current commercial 9%Cr–1Mo and RAFM steels. The highest ODS steel creep strengths have been achieved in the ODS ferritic steels (12–18%Cr) in the extrusion direction, with relatively weaker values observed in ODS martensitic (9%Cr) and ODS ferritic steels perpendicular to the extrusion direction (e.g. hoop stress condition for tubular product). The measured creep rupture strengths of the best ODS steels are nearly triple that of the conventional steels, and the corresponding creep rupture lifetime at a given stress is about 1000 times higher for the ODS steels. From a comparison of figures 3 and 8, it can be seen that the best performing ODS steels also offer significantly higher thermal creep strength than the TMT ferritic/martensitic steels. Due to this superior thermal creep resistance and their favorable radiation resistance (see figure 7 and discussion later in this section), these ODS steels could be used in the most demanding blanket structure regions near the first wall, thereby potentially allowing increased operating temperatures and improved thermodynamic efficiency. The high operating temperature could eliminate any concerns regarding low temperature radiation hardening and embrittlement and could lessen intermediate-temperature void swelling and solute segregation/phase instability degradation concerns, but might exacerbate high temperature helium embrittlement effects.

Although relatively few studies have been performed on the cyclic fatigue behavior of ODS ferritic/martensitic steels, the available results indicate favorable low cycle fatigue resistance [27, 131–133]. In particular, low cycle fatigue tests at elevated temperature [131–133] have observed significantly higher fatigue strengths, longer fatigue lifetimes and practically no cyclic softening (as opposed to the pronounced cyclic softening typically observed in conventional FM steels, which requires a reduction in allowable design stress). Favorable fatigue crack growth behavior has been reported [132]. Further research is needed on low amplitude, high cycle fatigue, although favorable behavior is expected based on traditional scaling laws due to the high material strength [27].

Traditionally, one of the shortcomings for ODS steels has been inferior fracture toughness properties (higher DBTT and lower upper shelf energy) compared to conventional ferritic/martensitic steels [10, 128, 134, 135]. In addition, considerable anisotropy is typically observed in ODS steels due to elongated grain structure in the extrusion direction [128, 136, 137]; the lowest toughness is typically observed for the TL orientation (crack oriented along the thin plate axis with the crack propagation along the longitudinal rolling or extrusion direction) [27]. Recent improvements in fracture toughness and mechanical property isotropy for ODS ferritic/martensitic steels has been achieved in small research heats by controlled cross rolling to produce high strength grain boundaries with a small grain size [26, 98], although some anisotropy in toughness was still present. Figure 9 compares the fracture toughness behavior of several ODS steels with conventional ferritic/martensitic steels [26]. Whereas ODS ferritic/martensitic steels have traditionally exhibited relatively low fracture toughness values of ~20–100 MPa·m$^{1/2}$, recent processing modifications have produced a 9%Cr ODS steel with higher fracture toughness comparable to traditional ferritic/martensitic steels and with brittle-ductile transition temperatures well below room temperature. Similarly, improved control of interstitial solute (C, O, N) contamination during the mechanical alloying process has led to high fracture toughness in 14%Cr ODS steels over a wide temperature range [138].

All fabrication methods for ODS steels are still based on relatively time-consuming and costly powder metallurgy methods. The key fabrication steps involve [128]: (1) fine powders of the constituent materials are initially prepared by commercial vendors; (2) these powders are subsequently blended and ball milled in small batches; (3) the ball-milled powder is canned and consolidated by extrusion or hot isostatic pressing and then further processed by parallel and/or cross-rolling at elevated temperature to produce consolidated plates or bars.

A major challenge for implementation of ODS ferritic/martensitic steels is the development of joining methods for

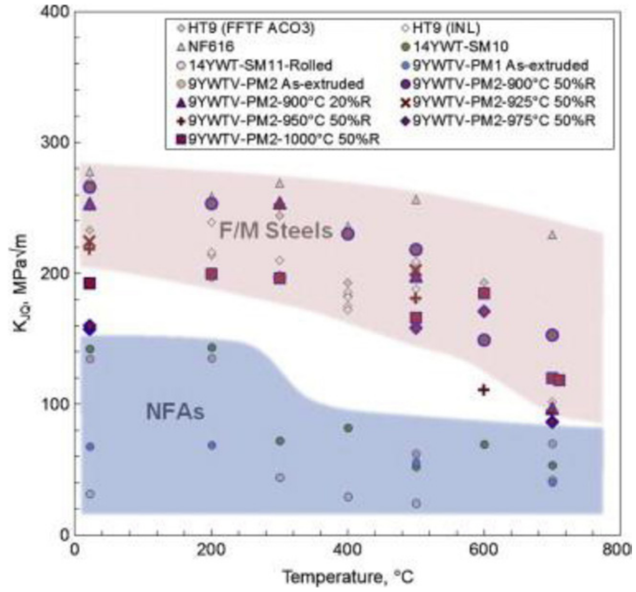

Figure 9. Comparison of the temperature-dependent fracture toughness of several heats of ODS steel versus conventional ferritic/martensitic steels (HT9, NF616) [26]. The upper shaded region illustrates typical toughness values for conventional FM steels. The large filled symbols designate data for 9%Cr ODS steels with modified processing, whereas the shaded region labeled as 'NFAs' denote traditional ODS steels.

complex geometries that maintain acceptably high strength and particle dispersion in the joint. In general, ODS steels cannot be joined by traditional welding methods without a pronounced loss of strength due to coagulation of the nanoscale particles in the melted region. Moderate improvement in joint properties can be achieved following traditional welding methods such as electron beam welding if post-weld heat treatment is feasible [80, 139]. However, the joint strength of the weld following heat treatment is significantly lower than that of the base ODS metal. Several research groups have demonstrated high quality, high strength joints can be made for relatively simple ODS steel geometries such as plates or tubes using solid state joining methods such as diffusion bonding or friction welding [24, 140–147]. However, joining for the large and geometrically complex components that are envisioned for fusion blanket structures is currently not possible in ODS steels without substantial loss of strength in the joint.

In general, ODS steels exhibit exceptional void swelling resistance following ion [66, 107, 109] or fission neutron [148–150] irradiation. As previously noted in the discussion of figure 7, whereas conventional FM steels exhibit good void swelling resistance up to 200–400 dpa during single ion irradiation near 450–480 °C, ODS steels exhibit low void swelling (<5% volume change) up to doses of at least 500 dpa. The superior void swelling resistance can be understood by recognizing the high sink strength of the nanoclusters in the ODS steels, which leads to very efficient recombination of radiation defects along with strong trapping of He produced by neutron transmutation reactions. The density of nanocluster precipitates in the ODS steels is >100 times the typical void nuclei density at irradiation temperatures 400–500 °C (peak void swelling regime), and therefore the nanoclusters have a high probability of intercepting most of the migrating radiation defects. The nanoclusters, which are the dominant contributor to the high point defect sink strength responsible for this radiation resistance, generally appear to be very stable even after prolonged irradiation at elevated temperatures under energetic displacement cascade conditions [109, 113–118]. For fusion neutron irradiation conditions, the demonstrated effectiveness of the nanoclusters in ODS steels for trapping helium in small He-vacancy cavities provides additional void swelling resistance [27, 66, 88, 151–153]. The high nanocluster density induces very effective partitioning of the He amongst multiple cavity sites and therefore the He concentration in any given cavity is far below the critical concentration for conversion to voids [22, 27, 88, 102].

Mixed results have been reported regarding the susceptibility of ODS steels to low temperature radiation hardening and embrittlement. Several studies on ODS steel heats with intermediate nanoparticle densities have reported significant radiation hardening and DBTT increases comparable to that of traditional RAFM steels irradiated at comparable conditions [154–156]. Some neutron irradiation data suggest low temperature radiation hardening and embrittlement may be suppressed in ODS steels with ultrahigh precipitate sink densities [9, 30, 157–159]. A comparison of the uniaxial tension stress versus strain curves for a typical RAFM steel (EUROFER97) and an ODS steel (Eurofer ODS) following fission neutron irradiation at 250 °C to ~16 dpa is given in figure 10 [160]. Whereas substantial radiation hardening was observed in both materials, the magnitude of the radiation hardening was somewhat lower and the work hardening capacity following yielding was significantly higher for the ODS steel: the measured uniform elongations were ~0.3% and ~7% for the RAFM steel and ODS steel, respectively following irradiation. Higher room temperature tensile ductility has also been observed in MA-957 ODS steel compared to standard FM and RAFM steels following spallation neutron irradiation to 19 dpa at ~360 °C that generated ~1700 appm He; whereas the conventional steels exhibited brittle tensile behavior with intergranular fracture surfaces, the irradiated ODS steel had a uniform elongation of ~6% and ductile fracture surfaces [159].

Figure 11 summarizes the effect of initial point defect sink strength on radiation hardening observed in several ferritic/martensitic steels irradiated with fission neutrons near 300 °C [9, 30, 155–158]. The sink strength was calculated from microstructural data obtained on the unirradiated samples using standard kinetic rate theory expressions [29, 51]; the nanoclusters were treated as precipitates. No remarkable effect of sink strength is observable for sink strengths below ~5×10^{15} m^{-2}, which encompasses typical sink strengths for conventional ferritic/martensitic steels and some ODS steels. Some evidence for reduced radiation hardening [157, 158] (and accompanying reduced fracture toughness embrittlement [158]) has been observed at sink strengths above ~10^{16} m^{-2}, which is achieved in some recent high-performance heats of ODS ferritic/martensitic steels. The apparent reduction in radiation hardening occurs when the average spacing between the nanocluster sinks becomes very small, <0.1 times the average

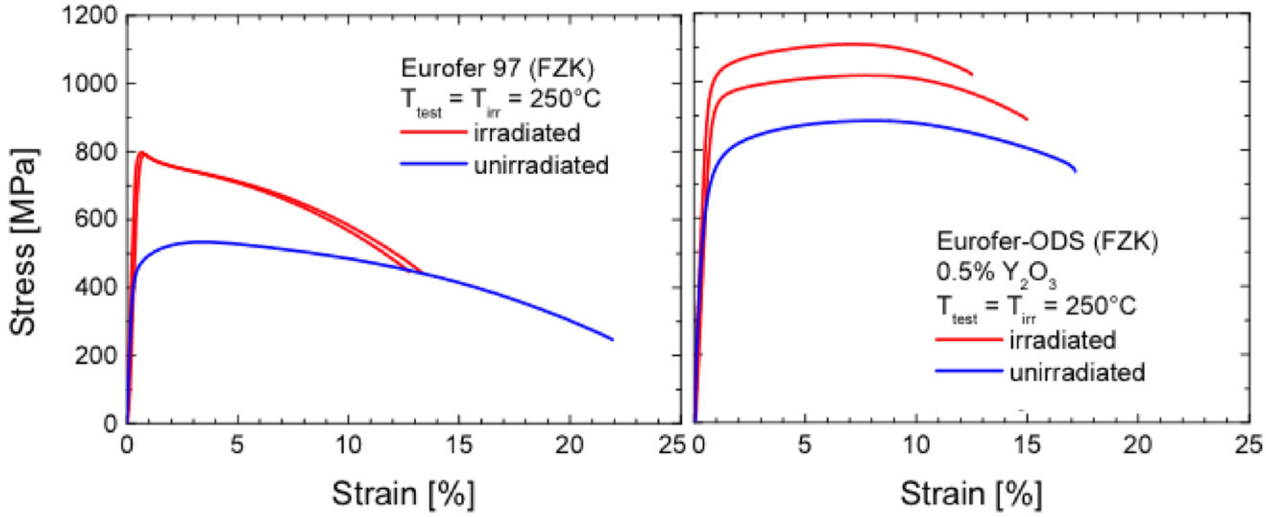

Figure 10. Comparison of the uniaxial tensile stress–strain behavior for a typical RAFM steel (EUROFER97) and a 9%Cr ODS steel (Eurofer ODS) following fission neutron irradiation to ~15 dpa at 250 °C [160]. Duplicate specimens were tested for each irradiation condition.

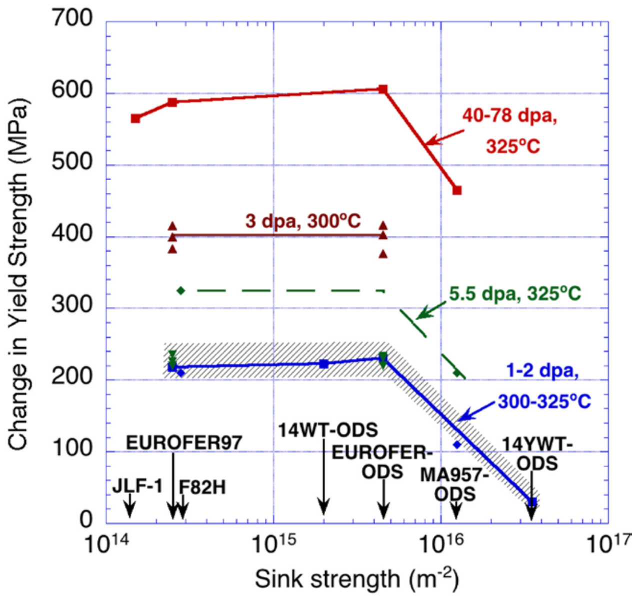

Figure 11. Effect of initial sink strength on the low temperature radiation hardening behavior of fission reactor irradiated ferritic/martensitic steels [9, 30, 154–158]. The tensile test temperatures were equal to the irradiation temperatures. Materials include conventionally fabricated RAFM steels (JLF-1, F82H and EUROFER97) and several oxide dispersion–strengthened (ODS) steels. The initial sink strength was calculated from the reported nanocluster, grain boundary, and network dislocation parameters.

spacing between visible dislocation loops (the dominant contributor to radiation hardening), which requires ultra-high sink densities due to the relatively high density of dislocation loops during irradiation of ferritic/martensitic steels near 300 °C. Some radiation hardening data (e.g. figure 10 [160], or obtained from room temperature tensile measurements [159]) suggest that reduced radiation hardening occurs even at moderate sink strengths (10^{15}–10^{16} m^{-2}). This may in part be associated with hardening superposition effects [161–163] due to the typically higher unirradiated hardness in the high sink strength materials. Further research is needed to quantify the beneficial importance of sink strength on suppressing radiation hardening in steels at low irradiation temperatures (i.e. monotonic reduction in hardening with increasing sink strength, or only important at ultra-high sink strengths). The data in figure 11 suggest typical sink strengths in the TMT steels discussed in section 2 (~10^{15}–10^{16} m^{-2}) may not be sufficiently high to provide beneficial resistance to low temperature radiation hardening and embrittlement.

Relatively little information is known about the long-term resistance of ODS ferritic steels to high temperature helium embrittlement. In general, ODS ferritic/martensitic steels appear to have good resistance to high temperature helium embrittlement [164–166] although a recent study [167] observed a factor of two reduction in creep rupture lifetime at 650 °C for short-term high stress test conditions. Due to the observed good resistance of ferritic/martensitic steels to high temperature helium embrittlement [89–91] along with the high density of nanoclusters that may act as effective traps to prevent He migration to grain boundaries [27, 88, 151, 153], there is a strong basis for optimism that the ODS ferritic/martensitic steels will exhibit good resistance. However, if high operational stresses are employed for ODS steels (in order to take full advantage of their high creep strength at elevated temperatures) then high temperature helium embrittlement could be stimulated due to stress-enhanced growth of He cavities [89]. Since the helium bubbles in ODS steels would be relatively small (due to the efficient partitioning of He amongst numerous cavity nucleation sites), relatively high stresses are required to activate this stress-enhanced growth mechanism.

3.3. Technical challenges for ODS RAFM steels

There are numerous materials engineering issues that are not yet resolved for ODS ferritic/martensitic steels, largely due to a relatively immature industrial capability. Regarding unirradiated material, these issues include (1) variable quality of experimental heats due to nonstandardized fabrication methods (scientific studies are still in progress to identify optimized material processing conditions); (2) lack of industrial-scale heats and fabrication methodologies; (3) suitable joining technologies for complex engineering structures are not yet developed—reference joining technologies such as friction welding or diffusion bonding need to be developed that do not produce unacceptable property degradation and are viable for fusion blanket geometries; (4) lack of comprehensive unirradiated engineering properties database; and (5) lack of advanced structural design criteria suitable for high temperature reactor operations.

In general, the current high cost and anisotropic properties associated with powder metallurgy fabrication are strong disadvantages that limit the widespread commercial application of ODS steels. A major drawback is that most experimental heats of ODS steels currently exhibit low ductility and poor fracture toughness at room temperature. The fracture toughness is typically very low for cracks orientated in the extrusion direction. However, some progress has been made for both martensitic (~9%Cr) and ferritic (>11%Cr) ODS steels to utilize post-consolidation heat treatments [10, 20], improved control of interstitial solute contamination during mechanical alloying [138], and/or modified fabrication schedules such as controlled cross rolling [26, 27, 98] to produce improved DBTT values. Additional R&D is needed to identify optimized processing conditions to further improve ductility and fracture toughness while retaining high strength and thermal stability.

There is not yet a clear consensus regarding which category of ODS steel (8–9% tempered martensitic versus >11%Cr ferritic) is most suitable for fusion applications: 8–9%Cr ODS steels might offer the potential for more isotropic strength and more attractive fracture toughness properties, whereas 12–16%Cr ODS ferritic steels may provide better oxidation/corrosion resistance and potential for operation at higher temperatures than 8–9%Cr ferritic/martensitic ODS steels. One potential blanket strategy would involve use of high performance ODS steels near the first wall where thermomechanical stresses and radiation damage is most pronounced and RAFM steels in the balance of the blanket. Although ultimately the preferred category of ODS steel may depend on the desired operating temperature of the fusion blanket (>11%Cr ODS steels offering the possibility of operating temperatures up to 750–800 °C versus a maximum of ~650 °C for martensitic ODS steels), it may prove to be easier to integrate martensitic ODS steels with RAFM steels that might be used in other portions of the blanket. Further research is needed to identify viable joining processes (ODS steel self-bonding joints as well as ODS steel joining to dissimilar metals).

A major uncertainty is the magnitude of radiation hardening and embrittlement at low operating temperatures (<350–400 °C), which in turn will define the lower operating temperature limit. As summarized in figure 10, limited experimental studies and simplified modeling analysis suggest that low temperature hardening and embrittlement may be suppressed at ultra-high nanocluster precipitate densities that occur in advanced ODS steels, but these high densities require sophisticated processing and are not present in many traditional grades of ODS steels. There is experimental evidence of enhanced hardening and embrittlement in ferritic/martensitic steels when helium is generated during the irradiation [88], but it is not known whether ODS steels could effectively suppress this low temperature embrittlement effect due to sequestration of He in finely dispersed cavities (thereby minimizing He hardening). Further research is needed to evaluate the magnitude of low temperature hardening and embrittlement in ODS steels under fusion-relevant DT neutron irradiation conditions. An additional technical challenge is the uncertain impact of alpha prime precipitation, which could lead to higher hardening and embrittlement in the high Cr ODS alloys. Alpha prime precipitates occur in neutron-irradiated Fe–Cr alloys and ferritic/martensitic steels at ~250–400 °C when the Cr content exceeds ~8–9% [82, 84]. Cr solute enrichment is also commonly observed at dislocation loops and other features following low temperature irradiation [83, 168, 169]. These Cr-enriched solute clusters can lead to increased radiation hardening even if alpha prime precipitates are not formed [170]. Further research is needed on alpha prime precipitation and Cr segregation hardening and embrittlement in irradiated ODS steels.

The effects of DT fusion-relevant neutron irradiation on elevated temperature radiation degradation processes such as cavity swelling and high temperature helium embrittlement of grain boundaries are difficult to quantify in the absence of an intense fusion neutron irradiation source. Results obtained from dual ion (damage plus He coimplantation) and fission neutron irradiation *in situ* He implantation studies indicate that the ODS steels have superior cavity swelling resistance compared to FM steels [27, 66, 88]. Quantification of the suppression of elevated temperature radiation damage degradation due to the high defect sink strengths in ODS steels needs further study.

4. Next steps in development programs for new fusion steels

A parallel R&D program is envisioned for the evolutionary next-generation ferritic/martensitic steels and the ODS steels. The key R&D activities for development of the next-generation RAFM steels for fusion include:

- Design and fabrication of small developmental heats of next-generation RAFMs. This research would use computational thermodynamics to guide the specification of the composition and processing conditions. Options involving specialized TMT and standard cast/wrought processing ('cast nanostructured alloys') should be considered;
- Property testing (mechanical, physical, joining, long term thermal stability, chemical compatibility, radiation effects) and identification of the preferred next-generation RAFM steel. These tasks will be crucial for identifying the magnitude of improved performance that might be achievable. Long term (>20 000 h) thermal aging and

high temperature creep testing will be particularly important to verify whether the observed impressive short term mechanical properties of next-generation RAFMs are maintained up to reactor-relevant times. Since these next-generation steels depend on a high density of precipitates for their good performance, identification of a viable joining process that does not produce unacceptable property degradation is another crucial R&D task. Although many of the new steels may exhibit mechanical strength suitable for operation to much higher temperatures than current RAFMs, it will be important to determine whether the operating temperature limit will be controlled by chemical compatibility issues with the coolant. This will require exploratory corrosion loop testing and may require investigation of corrosion coating barriers. Fission neutron and ion irradiation studies are needed to investigate the effects of defect sink strength (nanoscale precipitate density) on suppressing low temperature radiation hardening & embrittlement, intermediate-temperature void swelling, and high temperature He embrittlement of grain boundaries;
- If promising results have been obtained on one or more of the research heats, then down-selection to a reference advanced RAFM steel could be performed. This would be followed by procurement from industry of one or more large heats for fabrication of blanket mockup components, additional materials engineering testing, etc.

ODS RAFM steels are considered to be a potential very high performance option, but are very early in their development lifecycle. The strategy would be to build upon current worldwide scoping research programs on 9–16%Cr ODS ferritic/martensitic steels to identify candidates with potential compelling advantages over conventional RAFMs. The general R&D activities would be similar to that outlined above for next-generation RAFMs, and include:

- fabrication of small developmental heat(s) of reduced activation ODS steels (including exploration of both 8–9%Cr ferritic/martensitic and 12–16%Cr ferritic ODS steels at this stage). This task involves optimizing the chemical composition and manufacturing conditions at the laboratory scale and, at the same time, launching the fabrication of ODS ferritic steels at semi-industrial or industrial scale in order to investigate and resolve potential scaleup issues including fabrication of geometrically complex components. Unfortunately, a current weakness is the lack of industrial partners which could speed up the development process;
- property testing (mechanical, physical, joining, long term thermal stability, chemical compatibility, radiation effects) and identification of a preferred fusion ODS steel. An important aspect of this R&D will be the eventual downselection between the 9% martensitic and 12–16% ferritic ODS options (each of which has attractive features). Development of suitable fabrication processes, including joining technologies and exploring prospects for using additive manufacturing on complex geometry components will also be an important feasibility task;
- procurement of a larger heat of the reference fusion ODS steel for fabrication of blanket mockup components, additional materials engineering testing, etc (if promising results have been obtained).

5. Recommendations and conclusions

There is a significant risk mitigation value to investigate very high performance options to 'traditional-route' RAFM steels for the first wall and blanket structure of DT fusion reactors. Utilization of higher performance materials could enable improvements in operational lifetime and reliability, thermodynamic efficiency, and reduced construction costs. Exploration of high performance steel options is particularly important considering some of the uncertainties of DT neutron-induced property degradation in structural materials due to the current lack of suitable intense fusion neutron irradiation facilities. Building upon decades of knowledge obtained on fabrication, creep-fatigue testing, and radiation effects research on RAFM steels, it is conceivable to envision rapid deployment of next-generation RAFM steels in time to support potential fusion electricity production by the middle of this century (the time-limiting step will likely be controlled by availability of key facilities such as a high-intensity fusion neutron source rather than unirradiated steel design, fabrication and testing). The relative fraction of effort that should be devoted to high performance options versus current RAFM steel R&D depends on the degree of conservatism or aggressiveness assumed in national DEMO fusion reactor designs: relatively aggressive DEMO designs (in terms of operating temperature, dose, and applied stress) should devote a higher fraction of resources to next-generation steel R&D. In general, the recommended timeframe for potential down-select decisions are on the order of one decade (dependent on national program fusion energy roadmap timelines) in order to allow sufficient time for meaningful advanced steel R&D while still allowing the possibility to demonstrate large-scale fusion electricity production by the middle of this century.

There are valuable potential leveraging opportunities with non-fusion steel programs (fission energy, fossil) for the development of next-generation steels. An important aspect for the development of these steels is to fully utilize industry expertise. The steel makers will bring practical implementation ideas regarding thermo-mechanical (rolling) and other special thermal treatment cycles, along with scale-up knowledge needed to fabricate multi-hundred tonne blanket components. The evolutionary next-generation high-temperature RAFM steels are expected to be easier to progress to fabrication and joining on an industrial scale than ODS steels. The next-generation TMT steels are based on innovative composition and/or processing modifications but otherwise utilize standard industrial steelmaking techniques. Conversely, an analogous 'simple substitution' pathway does not currently exist for ODS steel where the processing and joining techniques are markedly different from conventional steelmaking practice and there is limited commercial production. Nevertheless, it will be crucial to involve industry in the development of the ODS steels since large-scale industrial fabrication is required for DEMO components. Whereas there would be multiple international steel firms capable of fabricating DEMO-relevant large heats of an RAFM steel, construction using a significant quantity of ODS steel would not be a feasible development at present. This situation will only change by bringing industry in at the stage of the large heat developments and fostering broader use of ODS steels for multiple commercial applications (beyond fusion), since the required major capital investment by industry likely cannot be supported by a single application such as fusion energy.

The evolutionary next-generation RAFM steels offer the potential for significant improvements in performance compared to current RAFM steels with no increase in fabrication cost. Results obtained on small research heats designed using computational thermodynamics to optimize composition and thermomechanical processing conditions indicate it may be possible to achieve a doubling of the thermal creep rupture strength at 650 °C for new 9%Cr TMT steels compared to current RAFM steels (with a corresponding ten times improvement in creep rupture lifetime at 650 °C for a given applied stress) while simultaneously achieving comparable tensile elongations and fracture toughness. Similar research on new alloys that do not involve TMT processing suggest it is possible to obtain 20–35% improvement in yield strength compared to current RAFM steels with no degradation in elongation or fracture toughness. All of these newly designed steels rely on a high concentration of uniformly dispersed nanoscale precipitates that are designed to be highly stable under prolonged thermal annealing conditions. These nanoscale precipitates are predicted to provide improvements to neutron radiation-induced property degradations such as void swelling by promoting radiation point defect recombination.

ODS RAFM steels are a higher risk, high performance option that could provide dramatic performance improvements but are commercially immature at the present time. ODS steels can provide as much as three times higher creep rupture strength at 650 °C compared to current RAFM steels (with a corresponding ~1000 time increase in creep rupture lifetime). The tensile elongations and fracture toughness parameters are generally lower for ODS steels and the fabrication costs can be significantly higher compared to current RAFM steels. In addition to cost, one of the biggest obstacles for widespread utilization of ODS steel may be development of viable joining techniques for large, complex engineering structures. Conversely, the very high solute cluster densities that are achievable in some heats of ODS steels can provide very high radiation resistance that may ultimately prove to be essential for the extreme neutron irradiation environment near the first wall of a fusion reactor.

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