THERMOPHYSICAL AND MECHANICAL PROPERTIES OF Fe-(8-9)%Cr REDUCED ACTIVATION STEELS — S. J. Zinkle, J. P. Robertson and R. L. Klueh (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this report is to summarize the thermophysical and mechanical properties of 8-9%Cr reduced activation ferritic/ martensitic steels in order to provide a reference design basis for the Advanced Power EXtraction (APEX) project.

SUMMARY

The key thermophysical and mechanical properties for 8-9%Cr reduced activation ferritic/ martensitic steels are summarized, including temperature-dependent tensile properties in the unirradiated and irradiated conditions, stress-rupture behavior, elastic constants, thermal conductivity, thermal expansion, specific heat, and ductile-to-brittle transition temperature. The estimated lower and upper temperatures limits for structural applications are 250 and 550°C due to radiation hardening/embrittlement and thermal creep considerations, respectively.

PROGRESS AND STATUS

Introduction

In order to provide a reference design basis for the Advanced Power EXtraction (APEX) project, published data on the thermophysical and mechanical properties for 8-9%Cr reduced activation ferritic/ martensitic steels have been compiled. Due to the large existing data base on these steels, a comprehensive evaluation of all published data was not attempted. Only a limited amount of property data for these steels is contained in the most recent version (Pub. 5) of the ITER Materials Properties Handbook (IMPH). The IMPH should be used as the reference point for design calculations if the full property database is included in a future version of the Handbook.

1. Ultimate tensile strength (unirradiated)

The ultimate tensile strength for several heats of Fe-(8-9)%Cr reduced activation steels has been measured by numerous researchers. The tensile properties have been found to be comparable to those of conventional Fe-(8-9)%Cr steels. Figure 1 summarizes some of the ultimate tensile strength (UTS) data obtained in tensile tests on F82H (Fe-8%Cr-2%WVTa) and other heats of 8-9Cr (conventional and reduced activation) ferritic/martensitic steels [1-6]. The least squares fitted equation for the ultimate tensile strength over the temperature range of 20-700°C is

$$\sigma_{UTS}(\text{MPa}) = 682.8 - 1.1617{*}T + 0.005472{*}T^2 - 1.1166\text{e-}05{*}T^3 + 6.2357\text{e-}09{*}T^4$$

where the temperature (T) is in °C. The correlation coefficient for the plotted data using this equation is R=0.8955.

2. Yield strength (unirradiated)

Figure 2 summarizes the yield strength data obtained on several heats of Fe-(8-9)%Cr conventional and reduced activation steels. The least squares fitted equation for the yield strength over the temperature range of 20-700°C is

$$\sigma_Y(\text{MPa}) = 531.4 - 0.38794{*}T + 0.001482{*}T^2 - 2.3965\text{e-}06{*}T^3 - 1.4506\text{e-}10{*}T^4$$

where the temperature (T) is in °C. The correlation coefficient for the plotted data using this equation is R=0.8835. The corresponding least squares equation fitted only to the yield strength data of F82H reduced activation Fe-8Cr steel is

$$\sigma_Y(\text{MPa}) = 544.2 - 0.18491{*}T - 0.0003603{*}T^2 + 2.2141\text{e-}06{*}T^3 - 3.5596\text{e-}09{*}T^4$$
$$R=0.96242$$

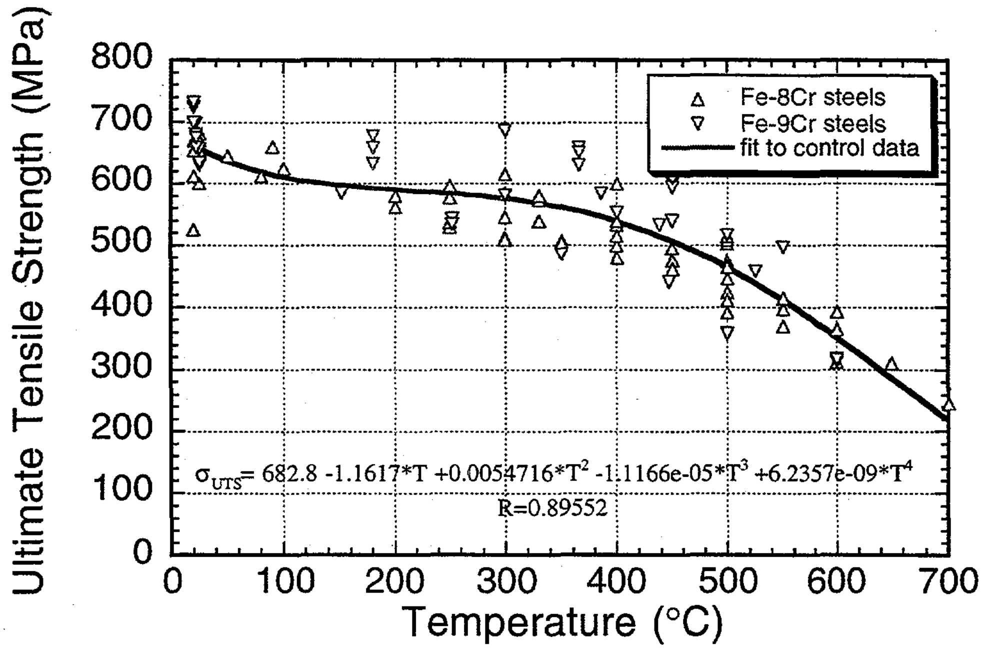

Fig. 1. Ultimate tensile strength of unirradiated 8-9%Cr steels [1-6].

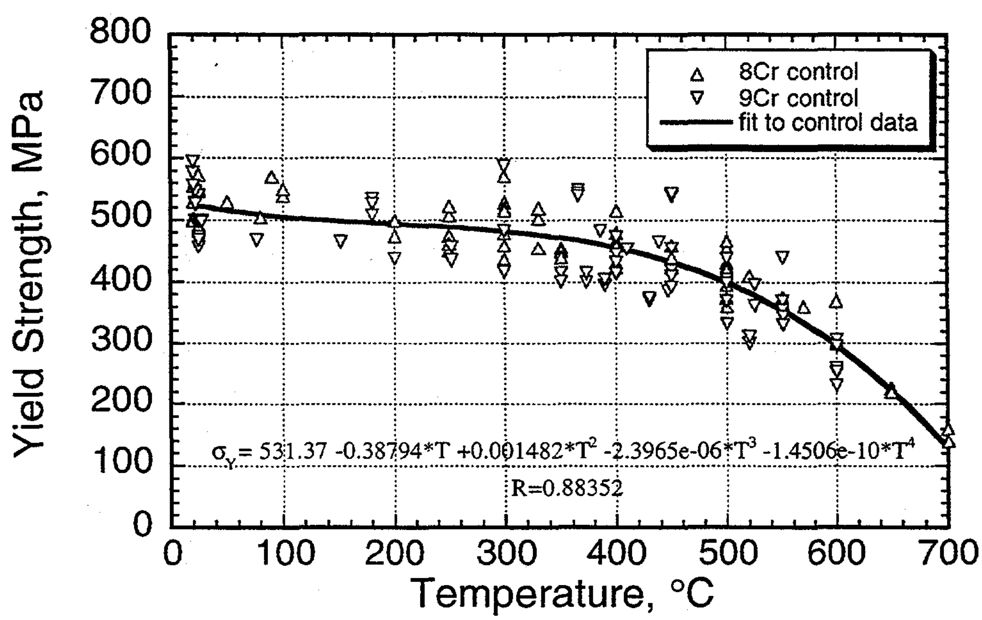

Fig. 2. Yield strength of unirradiated 8-9%Cr steels [1-4,6].

3. Yield and ultimate strength (irradiated)

Neutron irradiation causes a pronounced increase in the yield and ultimate tensile strength of 8-9%Cr conventional and reduced activation steels at temperatures below ~400°C, but has little effect on the strength at higher temperatures. Figure 3 shows a comparison of the unirradiated and irradiated yield strength for irradiation temperatures between 50 and 600°C. The effects of fusion-relevant helium generation on the yield and ultimate strength have not been adequately studied, although only minor changes have been observed in studies performed to date [7-9].

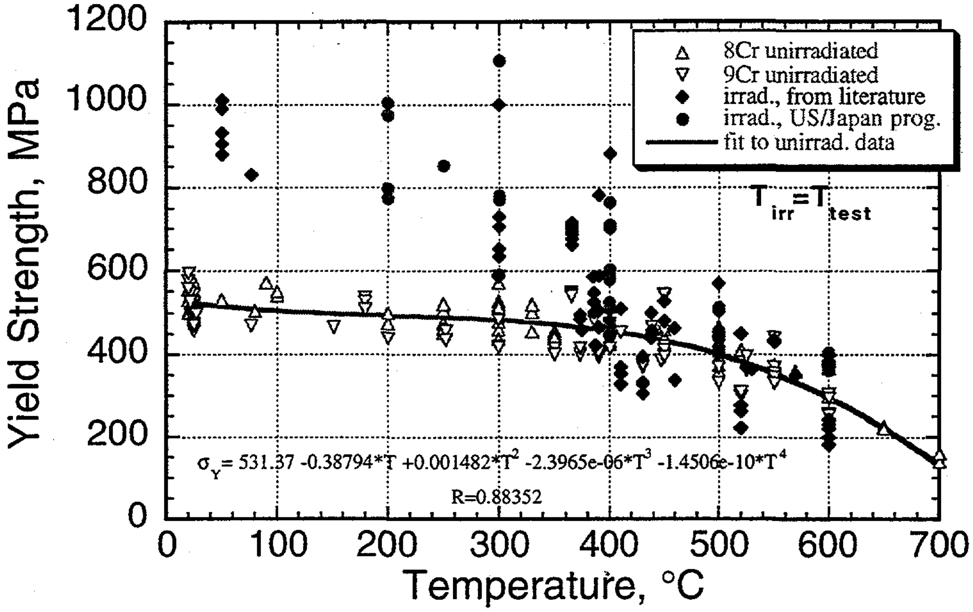

Fig. 3. Comparison of the yield strength of unirradiated and irradiated 8-9%Cr steels [6].

4. Uniform and Total Elongation (unirradiated and irradiated)

The uniform elongations of unirradiated 8-9%Cr conventional and reduced activation steels exhibit relatively low values (≤5%) at all temperatures from 20 to 700°C [6]. As shown in Fig. 4, the unirradiated uniform elongation decreases slowly from ~5% to ~1% over this temperature range. The corresponding total elongations range from ~10 to 30%. The low uniform elongation is a typical feature associated with the martensitic structure. Uniform elongations of >5% at temperatures from 20 to 650°C have been observed in oxide dispersion strengthened ferritic steel [10,11], which is a promising alternative to ferritic/martensitic steel (see section 8). As shown in Fig. 5, irradiation causes a decrease in the uniform and total elongations, particularly for irradiation temperatures below 400°C [1-3,6,9,12]. Data for both reduced-activation and conventional Fe-(8-9)%Cr steels are plotted in this figure. The uniform elongation is very low (<3%) at all investigated irradiation temperatures. The total elongation remains above ~7% for all irradiation conditions investigated to date, and it increases with increasing irradiation temperature (Fig. 5). The effects of fusion-relevant helium generation on tensile elongation have not been adequately studied.

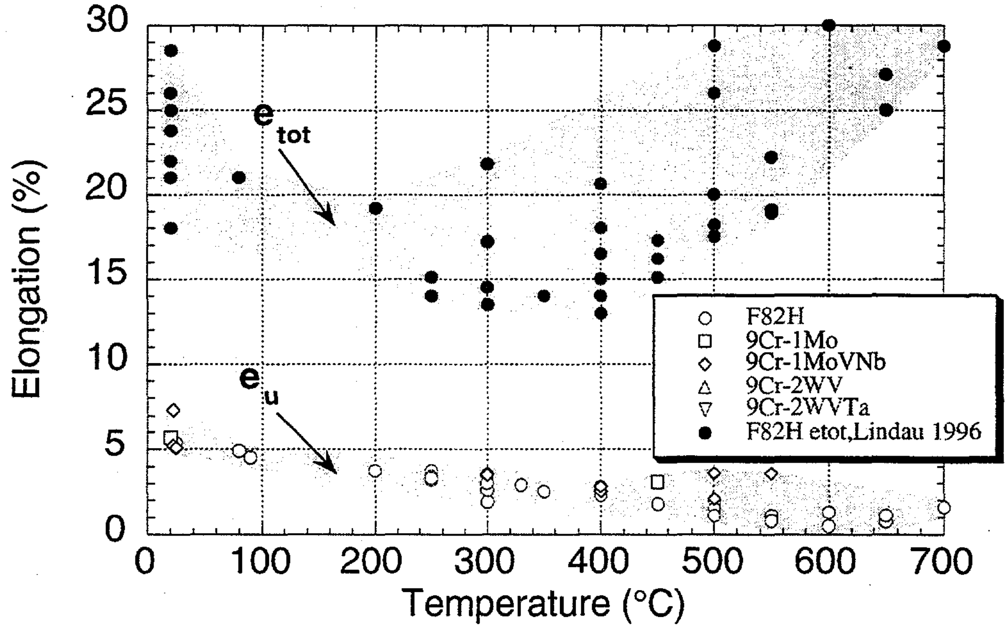

Fig. 4. Uniform and total elongation of unirradiated 8-9%Cr steels [1-3,6].

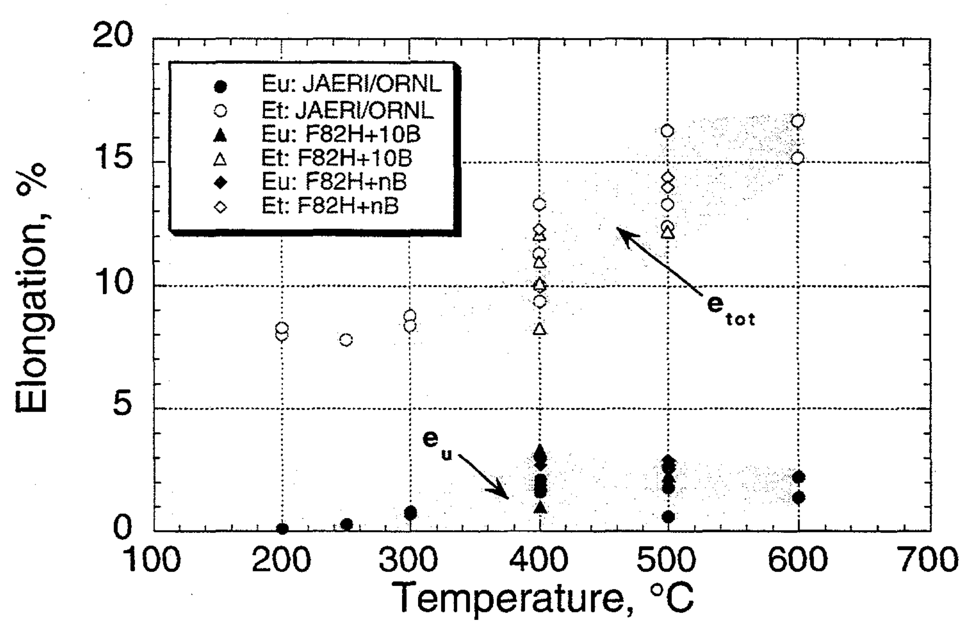

Fig. 5. Uniform and total elongation of irradiated 8-9%Cr steels [1-3,6]. The test temperature equals the irradiation temperature.

5. Reduction in area

The reduction in area (RA) as measured on unirradiated and irradiated 8-9%Cr steel tensile specimens is shown in Fig. 6 [1,3,5,6]. The unirradiated reduction in area is high (>80%) at all test temperatures between 20 and 700°C. Irradiation causes a decrease in the RA (particularly at low irradiation and test temperatures), but the reduction in area remains acceptably high in the limited number of tensile specimens examined to date. Helium effects have not been adequately studied.

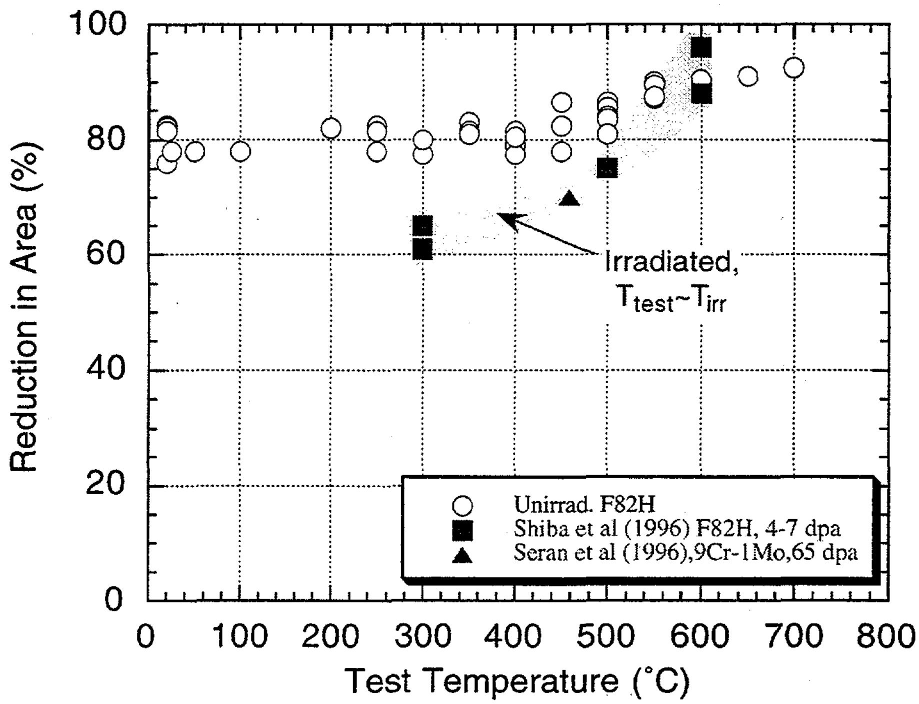

Fig. 6. Reduction in area of unirradiated and irradiated 8-9%Cr steels [1,3,5,6].

6. Stress-strain curves

Figure 7 shows representative stress-strain curves obtained on miniature "type SS-3" sheet tensile specimens (0.76 × 1.52 × 7.6 mm gage dimensions) for F82H steel tensile tested at a strain rate of 1.1×10^{-3} s^{-1} following neutron irradiation at 200-600°C [6,9,12]. Pronounced flow localization is observed for irradiation temperatures below ~400°C, whereas adequate strain hardening capacity occurs at temperatures ≥400°C.

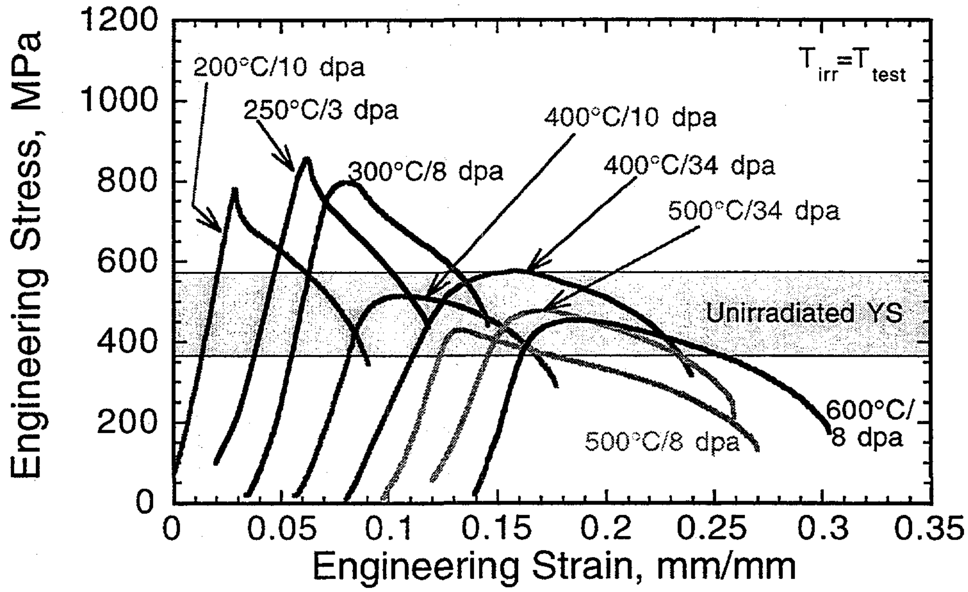

Fig. 7. Load vs. normalized crosshead displacement tensile curves for F82H irradiated to 3-34 dpa at 200-600°C [6,9,12].

7. Elastic constants

The elastic constants for F82H (8Cr-2WVTa) have been measured between 20 and 700°C [3,5], and Young's modulus has been measured from -150 to 350°C for several other reduced-activation steels including Fe-9Cr alloys [13]. The temperature-dependent elastic constants for F82H exhibit approximately bilinear behavior, which a slope change occurring near 450-500°C. The change in the temperature dependence of the elastic constants at 450-500°C was attributed to annealing effects on the martensitic structure at the higher temperatures [3,5]. The following equations for Young's modulus (E_Y) and the shear modulus (G) are obtained from the F82H experimental data [3,5] in the temperature interval between 20 and 450°C:

$$E_Y \text{ (GPa)} = 233 - 0.0558{*}T \qquad \text{(T in Kelvin)}$$

$$G \text{ (GPa)} = 90.1 - 0.0209{*}T \qquad \text{(T in Kelvin)}$$

At temperatures above 450°C, Young's modulus for F82H decreases approximately linearly from E_Y=193 to 160 GPa as the temperature is increased from 450 to 700°C. The shear modulus similarly decreases from G= 75 to 60.5 GPa as the temperature is increased from 450 to 700°C. Poisson's ratio ($\nu=(E_Y/2G) - 1$) is constant up to 500°C with a value of 0.29, and then slowly increases to 0.31 at 700°C.

8. Stress-rupture

There have been numerous studies of the creep and stress-rupture behavior of unirradiated and irradiated 8-9%Cr steels at temperatures up to 650°C (0.5 T_M) [1,2,5,14]. Good creep resistance exists for temperatures up to ~550°C (0.45 T_M), but poor creep resistance occurs at 600°C and above. For example, the 10,000 h creep rupture strength of F82H is 200 MPa at 550°C, 120 MPa at 600°C and 50 MPa at 650°C [1,5]. Improvements in the thermal creep resistance of reduced-activation ferritic steels can be achieved with oxide dispersion strengthened (ODS) alloys

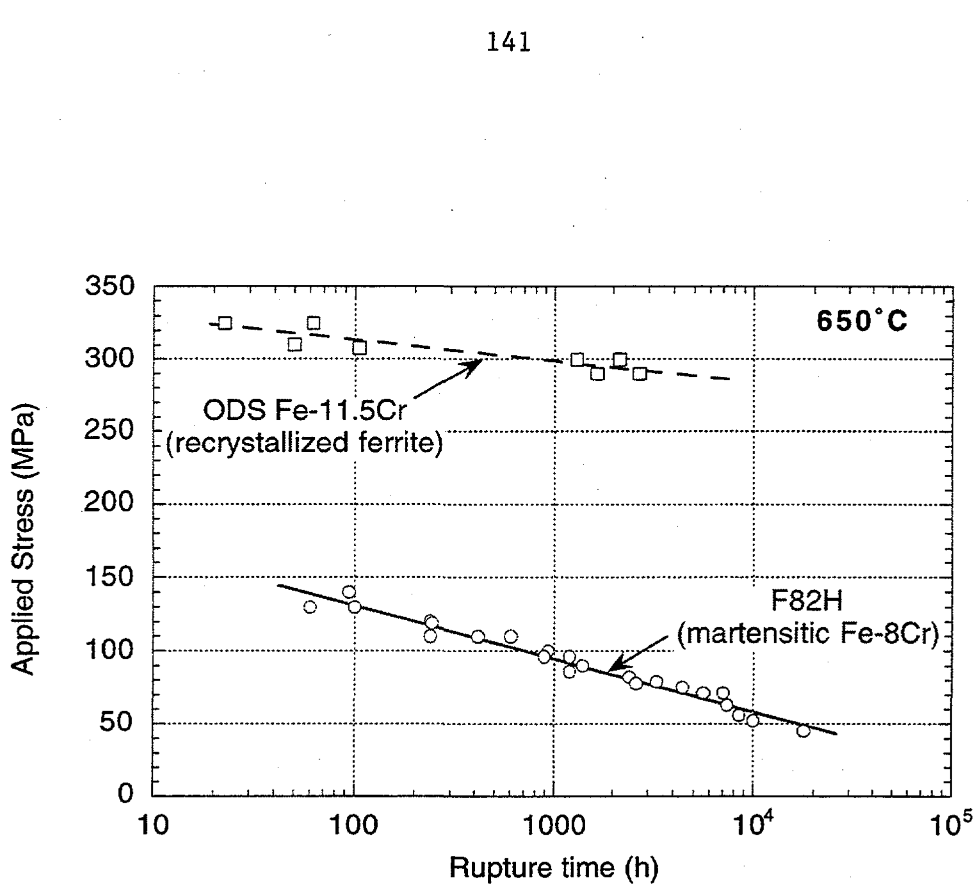

Fig. 8. Creep rupture strength of F82H martensitic steel and ODS ferritic steel [1,5,10,15].

[10,11,15,16]. Figure 8 compares the creep rupture strength at 650°C of F82H ferritic/martensitic steel and a recently developed ODS ferritic steel (Fe-11.5Cr-2.2W-0.23Ti-0.015C-0.2Y_2O_3) which has uniform creep rupture properties in the longitudinal and transverse direction [1,5,10,15].

9. Thermal expansion, specific heat and thermal conductivity

The thermophysical properties for several different heats of F82H (8Cr-2WVTa) have been measured from room temperature to 700°C [1,3,5]. The mean coefficient of thermal expansion (α_{th}) varied from 10.4 ppm/°C at room temperature to 12.4 ppm/°C at 700°C. The specific heat at constant pressure (C_P) varied from 470 J/kg-K at 20°C to 810 J/kg-K at 700°C. The specific heat increase was approximately linear with temperature between 20 and 500°C, and was strongly nonlinear above 500°C. The thermal conductivity at 20-800°C was determined from thermal diffusivity measurements using laser flash techniques and was found to be nearly independent of temperature, with an average value of 33 W/m-K between 20 and 700°C for two different heats of F82H.

10. Ductile to brittle transition temperature (unirradiated and irradiated)

The measured value of the ductile to brittle transition temperature (DBTT) in body-centered cubic materials depends on numerous experimental parameters, including the specimen geometry, strain rate, and the sharpness of the notch where the crack is initiated (notch acuity) [17]. The measured DBTT in miniature unirradiated F82H machined Charpy vee-notch (MCVN) specimens ranges from about -60°C to -110°C, where the lower DBTT was obtained using 1.5 mm thick Charpy impact specimens [2,9,18]. The DBTT for unirradiated F82H measured on precracked compact tension specimens is near -50°C [19]. Low temperature irradiation causes a moderate increase in the DBTT (ΔDBTT~20 to 100°C) of advanced reduced activation 8-9Cr steels for the damage levels investigated to date [2,9,12,18,20,21]. Very small changes in the DBTT (ΔDBTT <50°C) have been observed in 8-9%Cr steels irradiated at temperatures above 400°C. The effect of fusion-relevant helium generation rates on the DBTT in irradiated specimens has not been adequately studied.

11. Magnetic properties

Ferritic steels are ferromagnetic, and could affect the plasma operation by introducing perturbations in the local magnetic field, depending on the details of the reactor design. The saturation magnetic flux density (B_s) of unirradiated F82H varies from 1.95 T at room temperature to 1.75 T at 400°C [5]. The magnetic field strength required to produce complete saturation is approximately 3000 Oersted (2.4×10^5 A/m) for temperatures between 20 and 400°C [5]. The remanent magnetic flux density (B_r) decrease from 0.21 T to 0.17 T over this temperature range. Changes in coercive force, B_r, and permeability may occur under irradiation, whereas changes in B_s are not expected to occur during irradiation unless there is a phase transformation [22]. Ferromagnetic properties of ferritic steels have not been measured following high-dose irradiation. No measurable radiation-induced changes have been observed at low doses (<<1 dpa) [22].

12. Recommended reference operating temperature limits

The maximum operating temperature limit for 8-9%Cr reduced activation ferritic/martensitic steels is ~550°C, due to thermal creep considerations. Somewhat higher temperatures could be tolerated for components exposed to low mechanical stresses. Oxide dispersion strengthened ferritic alloys under development may be capable of operation up to temperatures of 650°C or higher [10,11,15,16]. Additional work on irradiated specimens is needed before the minimum operating temperature limit can be established. The reference minimum operating temperature limit will be controlled by radiation hardening, which causes loss of ductility and an increase in the ductile to brittle transition temperature. According to the available irradiation data, the DBTT of 8-9%Cr steels remains near or below room temperature following neutron irradiation at temperatures between 200 and 550°C [2,9,12,18,20,21]. There is some limited evidence that fusion-relevant helium generation rates may cause a further increase in the DBTT beyond that attributable to matrix hardening (defect cluster) effects [8,9,20]. Further work is needed to determine the effect of helium on fracture properties. For the purposes of the APEX design study, the proposed reference minimum operating temperature for 8-9%Cr steels is 250°C.

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