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Deformation mechanisms in ferritic/martensitic steels and the impact on mechanical design

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ABSTRACT

Structural steels for nuclear applications have undergone rapid development during the past few decades, thanks to a combination of trial-and-error, mechanism-based optimization, and multiscale modeling approaches. Deformation mechanisms are shown to be intimately related to mechanical design via dominant plastic deformation modes. Because mechanical design rules are mostly based on failure modes associated with plastic strain damage accumulation, we present here the fundamental deformation mechanisms for Ferritic/Martensitic (F/M) steels, and delineate their operational range of temperature and stress. The connection between deformation mechanisms, failure modes, and mechanical design is shown through application of design rules. A specific example is given for the alloy F82H utilized in the design of a Test Blanket Module (TBM) in the International Thermonuclear Experimental Reactor (ITER), where several constitutive equations are developed for design-related mechanical properties.

1. Introduction

F/M steels are under intensive world-wide development for applications in the nuclear industry. Structural applications encompass pressure vessels in Light Water Reactors (LWRs), cladding and core structure materials in Gen-IV fission systems, advanced pressure vessels in high-temperature Gen-IV reactors, as well as in structural materials for the First Wall/Blanket (FW/B) of Magnetic confinement Fusion Energy (MFE) reactors, and in the chamber of Inertial Confinement Fusion (IFE) systems. The performance and reliability of F/M steels in such diverse structural applications requires an understanding of their mechanical properties and deformation mechanisms under external loads, high heat flux, and neutron irradiation. Although the properties of F/M alloys are controlled by their specific composition and microstructure, some generic characteristics can be understood when one investigates various databases.

Mechanisms that lead to failure of F/M structural components in a nuclear environment are dependent on a number of variables, which can be grouped into two main categories: (1) *operational variables*, such as mechanical load, temperature, cycling, transients, and coolant type and (2) *material variables*, such as the composition and microstructure (dislocation density, grain size, lath boundaries, precipitates, solution hardening elements, etc.). The thrust of alloy and material optimization efforts is to control material variables so as to meet the demands imposed by operational variables.

Development of F/M steels has relied mostly on empirical, but sometimes on mechanistic procedures, in order to optimize steel compositions and processing methods for desired microstructure, which are known to engender excellent mechanical properties. The general methodology for the optimization of steel properties has been based on finding correlations between material processing techniques and the microstructure on the one hand, and the microstructure and the mechanical properties on the other. An illustration of the progress made on the improvement of the creep strength of F/M alloys is shown in Fig. 1, where the creep rupture strength is shown for various steel generations [1,2].

The driving force behind optimization of Gen-III and Gen-IV steels has been the long-term creep strength for service lifetimes greater than 10^5 h. One of the areas of concern here is the coarsening of carbide formers, such as $M_{23}C_6$ and M_X type carbides after many years of service under stress conditions. The creep rupture strength when plotted versus service time shows a "sigmoidal" behavior, tending to a lower level of strength beyond 10^4–10^5 h. Such behavior is attributed to the equilibrium concentration of elements like W, Mo and V in precipitates and in the matrix, giving rise to "solution hardening" as the eventual controlling mechanism of steels operating at long service lives. Thus, steel optimization efforts focused on the long-term stability of carbides in these systems. The fact that the service lifetime of the steel in the FW/B in fusion energy systems is expected to survive only a few years has led to a different development path regarding the long-term stability of carbide precipitates as compared to Gen-III and Gen-IV steels, developed for fission reactors.

Although development of specific grades of F/M steels for fusion energy applications followed a parallel path to the larger effort of

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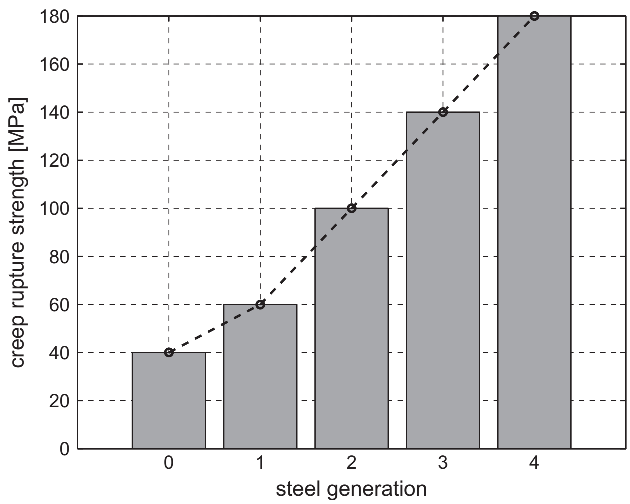

Fig. 1. The 10^5 h creep rupture strength (at 600 °C) of consecutive generations of steel for power plant applications [1].

their development for the power industry, we mention here two fundamental differences. First, early efforts in introducing generations of fusion steels have recognized the importance and possibility of developing steels that have the characteristic of being "low activation" [3]. Second, the expected lifetime of structural materials in FW/B applications is only a few years, as opposed to the 40–60 year target for steels employed in most power industries. The first constraint has led to the elimination of Mo, Nb, Ni, Cu and N, and the introduction of W and V as carbide formers in place of Mo, while Ta was introduced as a replacement for Nb. In addition, the 7–9% Cr range was found to be very suitable in elimination of the δ-ferrite phase, which causes a reduction in fracture toughness.

Following parallel lines of development to fission reactor steels, the following generations of "fusion steels" have been developed (all compositions are in wt.%):

1. *Gen-I. Low Activation F/M Steels (LAFMs):* The first low-activation steel was developed in the mid eighties on the basis of radioactivity and decay chain analysis of the main elements, and substitutions of Mo in low-Cr steels with V and W. The first such steel is the vanadium steel UCVS-1, with composition: 0.11C, 0.3Mn, 0.3Si, 2.46Cr, 0.05Ni, 1.5V, 0.02Mo, 0.007P, 0.015S, 0.015N, 0.043Al, 0.003Ti, 0.04Cu [4].
2. *Gen-II. Reduced Activation F/M Steels (RAFs):* These steels have the composition range: ~0.1C, 0.04–0.3Si, ~0.45Mn, 8–9.4Cr, 1–2W, ~0.25V, 0.04–0.08Ta, 0.01–0.03N, 0.003–0.006B. They have been developed as follows:
   (a) Japan: F82H, JLF-1.
   (b) Europe: Eurofer, Optifer-I, Optifer-II.
   (c) US: 9Cr-2WVTa.
3. *Gen-III. Oxide Dispersion Strengthened Reduced Activation F/M Steels (ODS-RAFM).* These steels contain dispersoids of oxide particles (yttrium oxide and titanium oxide). Examples of steels under development are: PM2000, MA957, experimental grades of 9–12% Cr (martensites) and 12–20% Cr (ferrites). Although these steels are developed for fusion, they are also being considered for Gen-IV fission reactor steel applications in the cladding and structural supports. The alloy MA957 has a nominal composition 13.87Cr, 1.05Ti, 0.30Mo, 0.22Y_2O_3, 0.014C, 0.04Si, 0.13N, 0.1Al, 0.006S, while the alloy PM2000 has the composition of 19Cr, 5.5Al, 0.5Ti, 0.5Y_2O_3. W is sometimes used to replace Mo in fusion ODS steels, with lower Ti concentrations.
4. *Gen-IV. Super ODS-RAFM.* Mechanical alloying of metal and oxide powders is being developed to produce oxide dispersion-strengthened (ODS) ferritic alloys containing nano-scale oxide dispersoids. For example, the alloy 12YWT has the composition: 13.3Cr, 0.92W, 0.46Ti, 0.13Y, 0.19O. The stability of these dispersoids at high temperature and under irradiation has been studied recently. Ultrane Ti-, Y- and O-enriched particles were found to be extremely resistant to coarsening during isothermal aging at 1300 °C [5]. However, under heavy ion irradiations, nanoclusters were found to be unstable for high dose/dose-rate, and low temperature, while they were found to be stable at high dose/dose-rate, and high temperature. On the other hand, neutron irradiations in ATR up to 3 dpa, and at 500 °C contradict the results of ion irradiations, and thus further analysis is needed [6].

The objective of this paper is to investigate the deformation mechanisms of F/M steels on the basis of existing databases. Since failure modes are associated with the accumulation of plastic strain, we present the connection between operational and material variables through application of ASME and ITER design rules for mechanical components in a nuclear environment.

This paper is organized as follows. The basic mechanisms of deformation of F/M steels that lead to the accumulation of mechanical damage or the eventual failure by rupture or fracture are presented in Section 2, where we also discuss the main failure modes. Failure modes are primarily driven by the accumulation of plastic strain damage, and hence are largely determined by the rate of deformation (strain rate). The connection between mechanical design that attempts to meet the operational environment, and deformation mechanisms (determined by material properties) is made in Section 3. Finally, discussion and conclusions are given in Section 4.

2. Deformation mechanisms of F/M steels

Structural deformation beyond the elastic range results in permanent displacements within the material that creates dislocations, gaps, voids, and cracks as sites of material damage. The type and severity of each damage site is dependent on its specific location within the structure, and is thus difficult to pin point on a global scale. Mechanical design codes for inelastic structures are based on an acknowledgment of this fact; that damage accumulation is driven by plastic strain. It is thus prudent to set a global strain limit, since it is not possible to specify local strain limits at the level of the microstructure itself. Thus, there is a tacit assumption here that plastic deformation leads to failure. For example, both fatigue and creep limits are based on life fraction rules that measure damage in terms of fractions of accumulated strain to a maximum specified value. In this section, we first discuss the main failure modes of F/M steels in nuclear applications, and then focus on how these modes are driven by the rate of strain accumulation.

Development of structural components must consider possible failure modes of FW/B components. Thus, one must be cognizant of the connections between mechanical design and operation of FW/B components on the one hand, and material design for optimum performance on the other. Failure modes of FW/B components can be immediate at the start of operations, or delayed by prolonged damage accumulation due to thermal, stress and radiation effects on the microstructure. In developing and qualifying structural materials, one must therefore consider the following possible modes of failure:

1. Monotonic-type damage induced failure:
   (a) Immediate plastic collapse.