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On the effects of irradiation and helium on the yield stress changes and hardening and non-hardening embrittlement of ∼8Cr tempered martensitic steels: Compilation and analysis of existing data

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Abstract

Data on irradiation hardening and embrittlement of 8–10Cr normalized and tempered martensitic steel (TMS) alloys has been compiled from the literature, including results from neutron, spallation proton (SP) and He-ion (HI) irradiations. Limitations of this database are briefly described. Simple, phenomenological–empirical fitting models were used to assess the dose (displacement-per-atom, dpa), irradiation temperature (T_i) and test temperature (T_t) dependence of yield stress changes ($\Delta\sigma_y$), as well as the corresponding dependence of sub-sized Charpy V-notch impact test transition temperature shifts (ΔT_c). The $\Delta\sigma_y$ are generally similar for SP and neutron irradiations, with very high and low helium to dpa ratios, respectively. Further, the $\Delta\sigma_y$ trends were found to be remarkably consistent with the T_i and dpa hardening-dependence of low alloy steels irradiated at much lower doses. The similar T_i and (low) dose dependence of $\Delta\sigma_y$ and ΔT_c, as well as an analysis of paired ΔT_c–$\Delta\sigma_y$ datasets, show that embrittlement is typically dominated by a hardening mechanism below about 400 °C. However, the corresponding hardening-Charpy shift coefficient, $C_c = \Delta T_c/\Delta\sigma_y \approx 0.38 \pm 0.18$ °C/MPa is lower than that for the fracture toughness reference temperature, T_0, with $\Delta T_0/\Delta\sigma_y \approx 0.58 \pm 0.1$ °C/MPa, indicating that sub-sized Charpy tests provide *non-conservative* estimates of embrittlement. The C_c increases at $T_i > 400$ °C, and $\Delta T_c > 0$ are sometimes observed in association with $\Delta\sigma_y \leqslant 0$, indicative of a non-hardening embrittlement (NHE) contribution. Analysis of limited data on embrittlement due to thermal aging supports this conclusion, and we hypothesize that the NHE regime may be shifted to lower temperatures by radiation enhanced diffusion. Possible effects of helium on embrittlement for T_i between 300 and 400 °C are also assessed based on observed trends in C_c. The available data is limited, scattered, and potentially confounded. However, collectively the database suggests that there is a minimal NHE due to helium up to several hundred appm. However, a contribution of helium to NHE appears to emerge at higher helium concentrations, estimated to be more than 400–600 appm. This is accompanied by a transition from transgranular cleavage (TGC) to

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intergranular fracture (IGF). IGF generally occurs only at high $\Delta\sigma_y$. Synergistic combinations of large $\Delta\sigma_y$ and severe NHE, due to helium weakening of grain boundaries, could lead to very large transition temperature shifts in first wall and blanket structures at fusion spectrum dose levels above 50–75 dpa and in SP irradiations at much lower doses.

1. Introduction

An important objective for the fusion materials community is to develop a high quality database on the effects of irradiation on the constitutive and fracture properties of 8–10Cr normalized and tempered martensitic steel (TMS) alloys. This paper focuses on changes in the tensile yield stress ($\Delta\sigma_y$) and irradiation embrittlement, characterized by transition temperature shifts (ΔT_c), measured in sub-sized Charpy V-notch impact tests. A high quality database is needed to develop predictive models of the changes in $\Delta\sigma_y$ and ΔT_c (and other properties) as a function of the *combination* of all significant metallurgical and irradiation variables. The metallurgical variables include the start-of-life alloy composition (wt%), microchemistry and microstructure, including the effects of thermo-mechanical processing treatment (TMT). The primary irradiation variables include irradiation temperature (T_i) and the neutron flux (ϕ), energy spectrum [$\phi(E)$] and fluence (ϕt). The neutron irradiation variables are best represented in terms of the total and rates of production of damaging species, including displacements-per-atom (dpa), helium, hydrogen and solid transmutation products (appm). Post-irradiation testing and data analysis variables are also significant. For example, $\Delta\sigma_y$ depends on the test temperature (T_t). Ultimately a comprehensive and high quality database will be analyzed with physically based, multiscale models [1–3]. Such models will sequentially relate (a) the primary variables to microstructural evolutions; (b) the effects of these evolutions on fundamental structure-sensitive constitutive and local fracture properties; (c) and the consequences of changes in these fundamental properties to more complex engineering properties, like ΔT_c (and corresponding shifts in the fracture toughness reference temperature, ΔT_0 [1–3]). In the interim, simpler phenomenological–empirical models and physically motivated correlations will be used to analyze the growing, but imperfect database.

There have been many irradiation studies aimed at contributing to such a database. Among the most notable are the International Energy Agency (IEA) round robin project on the Japanese F82H steel [4,5], as well as the large program in Europe currently focusing on various heats of the Eurofer steel [6–8]. There are also other data based on irradiations of TMS with spallation protons (SP), which generate very high levels of helium and hydrogen [9–13]. Other pertinent data includes accelerator based ion irradiations, including with high energy He-ions (HI) [14,15]. In this paper, we summarize the preliminary results of an ongoing effort to tabulate and analyze existing $\Delta\sigma_y$ and ΔT_c data on TMS alloys. One objective is to gain a practical, working knowledge of what is required in a mechanical property database to make it functionally useful and of 'high quality'; and to assess the state of the existing data in this context. A second objective is to carry out a simple preliminary analysis to gain insight on the variables that control $\Delta\sigma_y$ and ΔT_c, including high levels of transmutation product helium.

The effects of high levels of helium under conditions of simultaneous displacement damage production and irradiation embrittlement are two of the most important issues facing the development of TMS for fusion applications. Indeed, it is largely concerns about helium that have motivated the need for the International Fusion Materials Irradiation Facility. Because of the high sink density that acts as traps, martensitic steels are generally believed to be relatively immune to helium effects [16–18]. However, at high helium levels, a significant population of bubbles forms, with number densities, sizes and spatial distributions that depend on the irradiation temperature and the alloy microstructure. The amount and distribution of helium on grain boundaries is likely to be particularly significant [19]. One school of thought has asserted that helium plays a dominant role in embrittlement [20–28], in some cases [20–22] even apparently showing a linear correlation between helium concentration and ΔT_c. A contrary view attributes a dominant role to irradiation hardening induced embrittlement, where the hardening is primarily associated with displacement