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MICROSTRUCTURAL EVOLUTION OF MARTENSITIC STEELS DURING FAST NEUTRON IRRADIATION

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INTRODUCTION

Irradiation of martensitic/ferritic steels with fast neutrons (E>0.1 MeV) to displacement damage levels of 30-50 dpa at temperatures of 300-500°C produces significant changes in the as-tempered microstructure [1-4]. Dislocation loops and networks can be produced, irradiation-induced precipitates can form, the lath/subgrain boundary structure and the thermal precipitates produced during tempering can become unstable, and if helium is present, bubbles and voids can form. These microstructural changes caused by irradiation can have important effects on the properties of this class of steels for both fast breeder reactor (FBR) and magnetic fusion reactor (MFR) applications. The purpose of this paper is to compare reactor-irradiated and long-term thermally aged 9Cr-1MoVNb specimens, in order to distinguish effects due to displacement damage from those caused by elevated-temperature exposure alone.

RESULTS

9Cr-1MoVNb Aged to 25,000h

Microstructures of specimens aged at 482-706°C for 10,000 and 25,000h have been examined using analytical electron microscopy (AEM) [5]. The microstructure of normalized-and-tempered (1h at 760°C) 9Cr-1MoVNb consists of lath/subgrain boundaries from the prior martensitic structure, some intra-lath dislocations, and mainly coarser $M_{23}C_6$ and some finer MC precipitation. This microstructure remains stable up to 600°C, but coarsens somewhat at higher temperatures. After 25,000h at aging temperatures below 600°C, a

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dense dispersion of fine V-rich MC needle precipitates was found within the laths together with a substantial increase in dislocation density, and coarser Laves phase particles were found along the subgrain boundaries. These aging effects appeared to be maximum at 482-538°C; the microstructure at 538°C is shown in Fig. 1.

9Cr-1MoVNb Irradiated in HFIR to 37-39 dpa

Microstructures of specimens irradiated at 300-600°C to 37-39 dpa (about 10,000h) in HFIR have also been examined using AEM [1-3]. In contrast to thermally aged material, the as-tempered microstructure is unstable during irradiation in HFIR at 300-500°C, but shows almost no effects of irradiation at 600°C. Irradiation induces recovery and coarsening of the lath/subgrain structure, dissolution of $M_{23}C_6$ and MC (with some coarsening and compositional evolution of the latter), and formation of dislocation loops and networks, with all of these effects being most pronounced at the lowest irradiation temperatures [1]. The microstructure produced in 9Cr-1MoVNb by HFIR irradiation at 500°C is shown in Fig. 1. This steel contains about 0.1 wt.% Ni, so that HFIR irradiation to 37-39 dpa also produced about 32 appm He [1,2]. Voids and fine helium bubbles were found at 400°C, and only small bubbles were detected at 600°C; no cavities were detected at 300 and 500°C [1,2]. No additional precipitate phases were produced in the 9Cr-1MoVNb steel during HFIR irradiation, although a variety of radiation-induced phases can form in similar martensitic/ferritic steels during reactor irradiation at 400-500°C [3].

DISCUSSION

Several differences in the microstructural evolution of 9Cr-1MoVNb steel are obvious from the comparison of thermally aged and HFIR-irradiated specimens: *(a)* the as-tempered subgrain structure and precipitates become unstable during irradiation, whereas they do not during aging; *(b)* Laves phase forms during aging, but not during irradiation; *(c)* the dislocation concentration within laths is higher after aging than after irradiation. The effects of irradiation are caused by several mechanisms acting in concert that includes: *(a)* cascade damage, *(b)* annihilation, accumulation and/or migration of radiation-produced point defects, and *(c)* radiation-induced segregation (RIS) and enhanced thermal diffusion caused by the fluxes of radiation-induced point defects. The effects of thermal aging are driven by thermal diffusion, solute supersaturation and recovery processes.

During long-term aging there appears to be no recovery of the as-tempered structure. The fine VC precipitation within laths is likely to be due to additional supersaturation of carbon at temperatures sufficiently below the tempering temperature. The development of Laves phase along subgrain boundaries and between or around carbide particles suggests that depletion of carbon from the matrix triggers formation of this carbon-free intermetallic [5,6].

During reactor irradiation, the temperature dependence of the microstructural changes, particular instability of the as-tempered structure, suggests that irradiation-induced point-defect effects are the cause, rather than radiation-enhanced thermal diffusion. However, the exact mechanism or mechanisms is not completely clear [1,2]. It does appear clear that Laves phase, which precipitates abundantly from 482-600°C during thermal aging, is retarded during

HFIR irradiation, at least at 500°C. This could be due to differences between thermal segregation and RIS, as well as due to matrix compositional differences in the two cases. If Laves forms due to carbon depletion during aging, then increased matrix carbon due to partial dissolution of as-tempered carbides with no additional precipitation may help explain the absense of Laves phase during irradiation.

SUMMARY

The microstructure of 9Cr-1MoVNb steel evolves quite differently during thermal aging and during neutron irradiation. These differences in microstructural evolution may help explain differences in mechanical properties behavior in the two exposure environments. Furthermore, they may provide additional insight into new potential avenues for alloy development to improve the properties, and suggest that the avenues for optimum performance will most likely be different for high-temperature and for reactor service environments.

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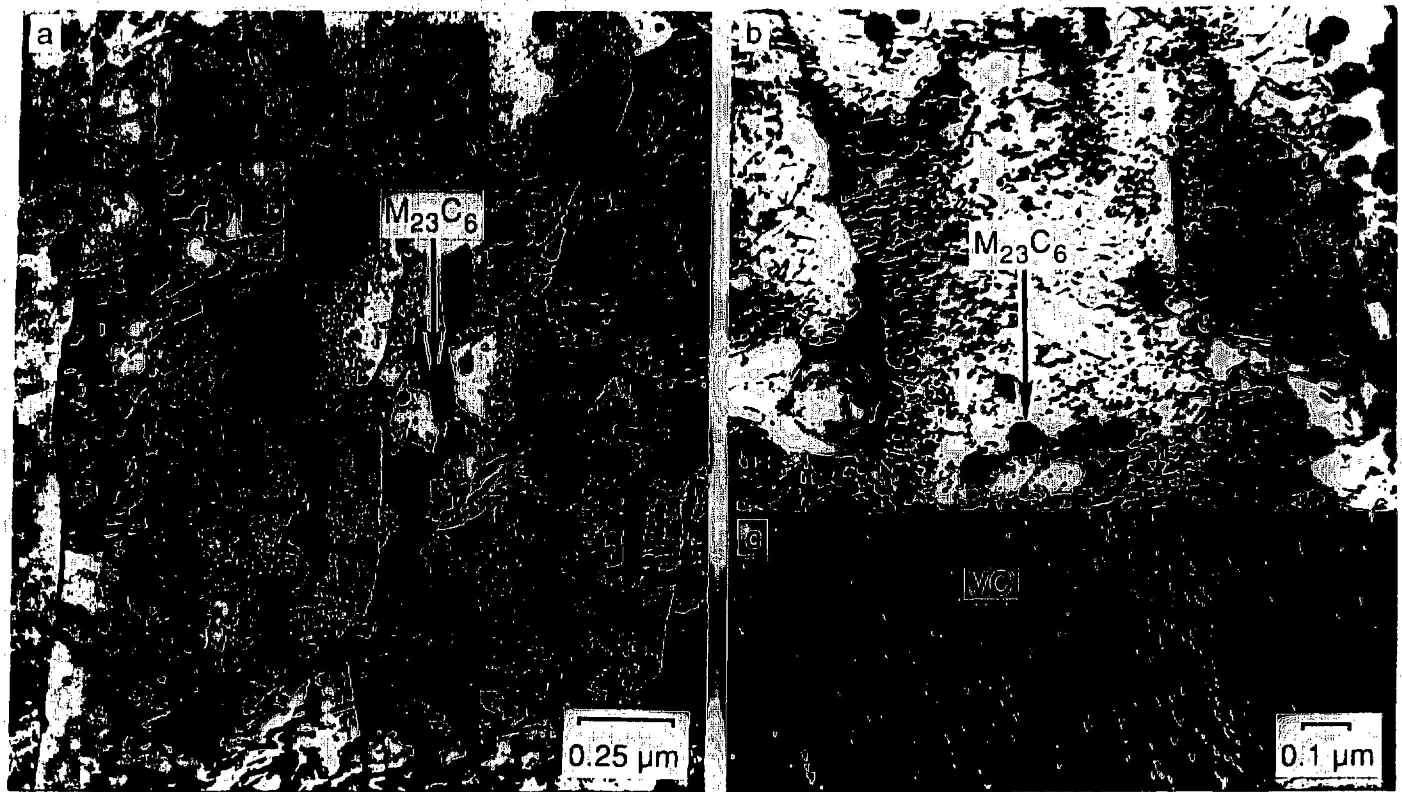
Figure 1 Transmission electron microscopy of 9Cr-1MoVNb after a.) HFIR irradiation at 500°C to 38 dpa, and b.) and c.) thermal aging at 538°C for 25,000h. a.) and b.) are at the same magnification, while c.) shows fine VC precipitates imaged in dark-field at higher magnification.


a
$M_{23}C_6$
0.25 μm
b
$M_{23}C_6$
c
VC
0.1 μm