Irradiation Effects of T91 Ferritic/Martensitic Steel

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**Abstract**

The harsh neutron irradiation environments in the core region of fast breeder reactors (FBRs) pose a unique challenge for cladding materials. Microchemistry and Microstructural changes resulting from displacement damage and creep rupture are anticipated for structural materials after extended neutron irradiation. Various irradiation effects on the service performance of cladding materials need to be understood. Because of their excellent thermal conductivity and irradiation resistance, ferritic/martensitic steels (FMS) with 9-12%Cr are considered the candidate cladding materials for the new generation FBRs. T91 with the nominal chemistry of 9%Cr-1%Mo-0.2%V-0.08%Nb-0.05%N-0.1%C has been used extensively for fossil power plants because of its excellent creep resistance up to approximately 600°C. As a candidate material for cladding, the fundamental of irradiation damage and its effects on T91 are reviewed in this paper. The objective is to provide an insight of neutron irradiation damage, microstructural and micro chemical changes, mechanical properties and facture behavior of T91. The chemistry modification of T91 is also discussed for the improvement of fracture toughness before and after irradiation. This review also provides some suggestions of additional investigations for the application of T91 in FBRs.

## INTRODUCTION

Modified 9Cr-1Mo or T91 is ferritic martensitic steel developed by ORNL [1]. Though the initial aim of this steel was for fast reactors, it had been extensively used in fossil-fired power plants from 1980s. The nominal composition of T91 is 9.0Cr, 1.0Mo, 0.5Mn, 0.22V, 0.08Nb, 0.25Si, 0.05N, 0.10C balance Fe (in wt. %) [2]. its creep rupture life under stress of 100-140MPa is long enough for application up to 550-593°C [3]. Like other ferritic martensitic steels, T91 has low void swelling rate under neutron irradiation and performs excellent after dose displacement up to 100-200 dpa [4-5]. The high thermal conductivity, low thermal expansion coefficient and good high temperature strength of T91 are also important for future advanced nuclear power plants, which would be operated at temperatures more than 320°C and in harsher irradiation environments than light water reactors [6].

Despite various advantages, some challenges hinder the usage of T91 in high-dose irradiation plants. The most critical issue is low-temperature irradiation embrittlement which affects the fracture resistance of most ferritic martensitic steels considerably after neutron irradiations at the temperature range of 200-450°C (below 0.3Tm)[7-9]. The representative behaviors of irradiation embrittlement are the increments of ductile-to-brittle transition temperature (DBTT) and the significant reduction of upper-shelf energy. Irradiation-assisted creep and the reduction of high-temperature strength is another issue for the implication of T91 in nuclear power energy systems [10]. The critical concern for the high-temperature degradation is the irradiation-enhanced diffusion and micro chemical changes, which have important effects on the formation of new phases and the stability of microstructures [11-12].

This review focuses on the irradiation effects of T91 steel. The current understanding on the irradiation damage, microstructural evaluation, and the degradation of mechanical properties of T91 will be presented. Considering that many ferritic martensitic steels share the same features as T91 steel, the following discussion will also include other type high-Cr steels.

## Irradiation Induced Microstructural Changes in T91 Steel

Irradiation basically caused three types of microstructural changes in ferritic martensitic steels involving voids, dislocations or dislocation loops, and precipitates. The results by Kai [13] show that the lath width of martensitic structures in tempered T91 specimens was about 0.5μm before irradiation and coarsened after neutron irradiation. Table 1 summarizes the void density, average diameter and total swelling of T91 and HT-9 after irradiation. The swelling value of T91 steel is 0.85%, while HT-9 shows a better swelling performance with the swelling value less than 0.1%. Even with higher void swelling compared with 12%Cr steels, the swelling resistance of T91 is still considerably better than that of austenitic stainless steels such as 316Ti[14], D9 [15] or modified 15-15Ti[16]. The swelling resistance of T91 steel could be attributed to the bcc crystal structure and complicated defect-sink interactions. The proposed mechanisms [6, 17] could be summarized as: (a) a lower dislocation movement and bias in bcc structure, (b) the extensive fine agglomerations in tempered conditions, (c) the character of dislocation loop structures, (d) the interactions between solute elements and vacancies, (e) a high density of precipitates and the agglomerates of interfaces for suppressing the void nuclei and agglomeration.

Before irradiation, the density of dislocations in tempered T91 steel is approximately 1015 m-2. After irradiation of 35dpa as illustrated by Klueh and Kai [18],the dislocation reactions progressed and its density was reduced to about 2×1014 m-2. High density of dislocation loops with large diameters was produced by irradiation as shown in Table 1. And the T91 steel contains lower density of loops and with the equal average loop diameter. Chen observes that the density and size of dislocation loops varied with irradiation temperature and its influence was much larger than the accumulation of displacements. Above 600°C, no loop could formed or just be stable because of the recovery reactions under irradiation. In the temperature range of 0.3-0.5Tm, the average size of loops increases with the elevated irradiation temperature, while with the decreasing density. The study showed by Gibbon and Rivera [19], the significant recovery occurred in the HT-9 steel above 550°C, which could be appreciate for T91 steel.

The in-core temperature of future nuclear power plants may be higher than 400°C, and even up to 700°C in sodium-cooled fast reactors. Under high temperature environments, the migration of elements in metallic materials is important for its variation of properties in terms of long time service. Irradiation enhances this progress and induces some transport processes involving two mechanisms: atomic mixing and radiation-enhanced diffusion. In a complex system with numerous components, tempered precipitates could be dissolved by atomic mixing during irradiation, but can also be coarsened by radiation-enhanced diffusion. The most significant phenomenon of ferritic martensitic steels during irradiation is the radiation-induced segregation around an intermediate irradiation temperature.

Radiation-induced segregations play a significant role in the microstructural stability of ferritic/martensitic steels. After tempering at 750-780°C Cr-rich M23C6 and MX are present in the T91 steel. M23C6 usually forms at prior austenite grain and martensitic lath boundaries. Small amount of MX presents in the lath or near the sub-boundaries. During long-term exposures at elevated temperatures, M23C6 coarsens into large particles with dimension up to about 0.2-0.5μm, while MX particles are stable with the size in the range of 40-100nm. Cr-rich Z phase is also presented by consuming the pre-exit MX particles. However, the pre-existing precipitates in ferritic/martensitic alloys may become unstable under irradiation. Irradiation accelerates the amorphization or coarsening of precipitate in T91 at high doses. In addition to pre-existing precipitates, radiation-induced precipitates in T91 may cause severe hardening and embrittlement. The G-phase particles (Mn6Ni16Si7) were also observed in T91 irradiated to less than 39 dpa at 300–600°C in HFIR, to 47dpa at about 400°C in FFTF. Cu-rich precipitates are observed in T91 after irradiation at 400°C to 7dpa. Chi-phase particles are identified in T91 steel with a Mo-enriched chemistry, which is believed to be due to the Mo content in the matrix or from decomposed M23C6 during irradiation.

## Irradiation Induced Mechanical Property Changes

The irradiation induced hardening of ferritic martensitic steels is complicated because of the interactions of irradiation dose, temperature and He. Tensile test results of T91 obtained from irradiations are plotted as a function of dose in table 1. Irradiation hardening arises due to the formation of voids, precipitates, and/or dislocation loops that impede the motion of dislocation lines. At low irradiation temperatures (lower than 0.3Tm), the irradiated T91 steel shows an increased yield strength and reduced ductility. The low-temperature irradiation hardening is mainly caused by dislocation loops and defect clusters resulting from displacement damage. Thus, the degree of hardening is expected to increase with irradiation dose and He but eventually saturate when defect overlapping starts to occur. With the temperature gradually increasing from 50°C to 500°C, irradiation hardening effects decrease because the significant recovery showed by Gilbon and Rivera. The temperature range for obvious hardening is below 450°C. It could also be concluded from FIG.1 that irradiation-induced hardening seems to saturate between 5 and 10 dpa for T91 steel.

Table 1. Statistics of dislocation and void features of T91 and HT-9 steels after irradiation [13]

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Steel | Void density | Void mean diameter (nm) | Void swelling (%) | Dislocation loop diameter (nm) | Loop density (m-3) | Dislocation density (m-2) | Irradiation temperature (°C) | Dose (dpa) |
| HT-9 | 5×1018 | 30 | 0.007 | 100 | 5×1020 | 5×1014 | 420 | 35 |
| T91 | 6×1020 | 30 | 0.85 | 100 | 5×1019 | 2×1014 | 420 | 35 |



Fig.1.Dose Dependence of Yield Strength for T91 Irradiated below 500°C [20]

Irradiation creep is a time-dependent plastic deformation phenomenon and is attributed to the supersaturation of point defects resulting from displacement damage. The irradiation creep strain rate:, can be expressed in terms of stress [22-23], σ as:

 (1)

This conclusion is not as well supported by conclusions drawn from comparison of the swelling rates conducted by real investigation during irradiation. The database for HT-9 steel has been carried out from 1990s and an increasing amount of irradiation creep data on ferritic steels, especially HT-9 [6], has recently become available. For T91 steel, however, the creep database during irradiation at the target temperature of future nuclear systems has not been collected and established.

##  Irradiation Induced Toughness Reduction

Irradiation can cause an increase in the ductile-brittle transition temperature (DBTT), accompanied by an increase in strength. DBTT values can be raised to well above room temperature as reviewed by Koutsky and Kocik [24]. The DBTT values of T91 steel vary between -30°C~-80°C as presented in FIG.2. After irradiation without numerous He production, the DBTT values of T91 specimens are about 27~80°C. Under irradiation conditions where HT-9 develops an increase in the ductile-brittle transition temperature of 120~150°C, T91 steel develops a shift of 56~160°C.



Fig.2.Transition temperature curves for T91 steel [11, 25]

FIG.3 is a schematic diagram showing the influence of irradiation hardening on the shift in DBTT. Hardening can be caused by radiation-produced point defects, which collect into dislocation loops to form barriers to dislocation motion, and by irradiation-induced precipitates as reviewed in the section “Irradiation Induced Microstructural Changes in T91 Steel”. An increase in DBTT can be affected by less resistance to the propagation of a crack. Coarsened M23C6 carbides in long-term aging or after irradiation are sources of micro cracks and gradually become a fracture in T91 steel.



Fig.3.Schematic diagram of irradiation hardening from he, defects and precipitation of T91 steel

##  METALLURGICAL MODIFICATION FOR T91 STEEL WITH IMPROVED TOUGHNESS

Irradiation hardening is a major factor affecting embrittlement of ferritic martensitic steels. Factors which influence the behaviour of hardening will influence the embrittlement performance under displacements. The most effective factors are: (a) steel composition and microstructural control, (b) temperature, and (c) neutron environment.

The modifications of T91 steel in the present review are from the first factor, namely, steel composition and microstructural control. The most promising modification of T91 steel compositions is: (a) the substitute of Mo by W, (b) alloying addition of Ta to reduce the grain size or (c) the addition of Hf for stabilizing MX phases and reducing the grain size, (d) the effective C and N content for elimination the interaction between free interfacial atoms and the dislocations. The microstructural modification could be used for T91 steel is: (a) fine grain size using heat treatment, (b) more stable precipitates during aging or irradiation such as MX, (c) elimination of δ-ferrite, (d) the stability of martensitic structures in terms of lath boundaries and sun-boundaries during irradiation and (e) the applications of thermo-mechanical treatment.

##  CONCLUSIONS

T91 steel is a promising candidate material for sodium nuclear energy systems with high operating temperatures. It has excellent swelling resistance and adequate high-temperature properties which have been confirmed during irradiation experiments and application for fossil power plants. Long-term irradiation creep data has also collected for the in-core applications. The most critical issue that may limit the usage of T91 steel in the future nuclear power plants is the irradiation embrittlement at low temperatures. A shift in DBTT between 27-160°C can be observed after neutron irradiation below 500°C. Irradiation hardening, radiation-induced precipitation is the major factors for the low-temperature irradiation embrittlement. Some recommendations from the chemistry modification and microstructural control have been illustrated for the toughness enhancements of T91 steel for future applications.

While the current information about the creep behaviour of irradiated T91 is comprehensive, the existing database for future nuclear system applications does not completed. The current understanding on phase stability and precipitation under irradiation environments needs to be improved. Systemic investigations on the fracture behaviours are also needed at a wide range of doses and temperatures relevant to the in-core conditions in the future.

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