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The European effort towards the development of a demo structural material: Irradiation behaviour of the European reference RAFM steel EUROFER

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Abstract

Worldwide programs aimed at developing materials for future fusion plants are presently concentrating on reduced activation ferritic/martensitic (RAFM) steels. In Europe, a Fusion Long Term Programme is being carried out under the coordination of European Fusion Development Agreement (EFDA) Close Support Unit (Garching, Germany); in the framework of this programme, extensive research is currently in progress for the development and full qualification of the European reference 9Cr RAFM steel, designated EUROFER. This paper focuses on the work being performed within the EFDA Technology Workprogram

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TTMS-001 task "*Irradiation Performance of EUROFER*", aimed at defining the post-irradiation mechanical and microstructural characteristics of the material, through irradiations, post-irradiation examinations (PIEs) and theoretical studies. An overview of the progress made will be given, as well as an anticipation of future research activities.

Keywords: Reduced activation ferritic/martensitic steels; EUROFER; Irradiation; Post-irradiation examination; Theoretical study

1. Introduction

Ferritic/Martensitic steels, with Chromium contents ranging between 9 and 12%, were introduced into fusion material programmes about 30 years ago, when it became evident from research in fast reactor programmes that they possessed better swelling resistance and excellent thermal properties with respect to austenitic stainless steels [1]. Indeed, the choice of possible structural materials for the first wall or the blanket structure of the reactor was limited, since the operating conditions envisage both elevated temperatures (in the range 500–700 °C) and a flux of high-energy neutrons.

In the course of the 80s, attention was redirected towards so-called "low activation" structural materials, which during irradiation would either not activate or give rise to induced radioactivity rapidly decaying to allow safe operation or at least hands-on reactor maintenance [2,3]. However, truly low activation materials were not feasible and "reduced activation" material were proposed instead, whose chemical composition would carefully exclude all elements which could transmute by interaction with high-energy neutrons into long-life radioactive elements; low enough radioactivity levels should be achieved in about 100 years, as compared to several thousands for conventional structural steels [4].

Reduced activation ferritic/martensitic (RAFM) steels are presently considered as primary structural materials for a demonstration fusion plant (DEMO). Although service conditions are not yet fully established in terms of temperatures, stresses or environment, simplified studies are available investigating different concepts [5]. As far as temperatures are concerned, designers push for elevated temperatures in order to increase efficiency; considering stresses in the order of 50 MPa, the upper operating temperature for RAFM steels would be similar to that of conventional power plants when creep is a limiting factor, that is approximately 550–600 °C. Depending on the type of coolant, oxidation or liquid-metal corrosion and/or embrittlement could promote a reduction of the service temperature [6,7]. Predictably, irradiation effects are of highest concern amongst environmental conditions in a fusion reactor.

High-energy (14 MeV) neutrons cause damage in a material by generating He and H via transmutation and by displacing atoms from their lattice positions, thereby forming various types of defects, such as vacancies and interstitials. Such "displacement damage", measured in terms of displacement per atom (dpa), affects mechanical properties and changes the microstructure by agglomerating vacancies and interstitials into voids and dislocation loops that cause swelling up to 500 °C [8,9]. Effects on mechanical properties consist in hardening (increase in mechanical strength) and embrittlement (decrease in toughness). The effects of irradiation on the mechanical properties depend on irradiation temperature; for irradiations above 400 °C, properties are generally unchanged [10], although the occurrence of radiation-enhanced softening has been reported [11]. Changes in mechanical properties tend to saturate with increasing fluence; for some RAFM steels, saturation has been observed around 10 dpa [11].

The European Fusion Long Term Programme is carried out under the coordination of the European Fusion Development Agreement (EFDA) Close Support Unit located in Garching, Germany [12]. Within the area "Materials Development", first priority is given to timely supply a structural material for breeding blankets inserted in DEMO. As these have to be tested in ITER, this material has consequently to be fully qualified also to the needs of Test Blanket Modules (TBMs). The EU reference material is a 9Cr RAFM steel, called EUROFER, which exhibits a tempered martensitic microstructure and presently allows operation up to 550 °C [13,14].

Since, as detailed above, one of the main issues of RAFM steels is the effect of irradiation at temperatures lower than about 400 °C, European institutes have devoted considerable efforts and budget to the characterization of post-irradiation mechanical