Investigating the Effects of Yttrium Additions on the Tensile and Creep Properties of Modified Eurofer97

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Abstract. Reduced-activation ferritic martensitic (RAFM) steels are candidate structural materials for future fusion reactor applications due to their high-temperature strength and reduced-activation characteristics. This study examines the effect of yttrium additions on the tensile and creep behaviour of a modified Eurofer97 steel. Results show a modest improvement in the tensile strength at 650 °C, but a loss in creep life relative to conventional Eurofer97. The unintentional presence of δ-ferrite is associated with degrading the creep properties, highlighting the importance of microstructural control. The results offer valuable insight into yttrium-containing RAFM steels, informing further optimisation of processing routes for fusion applications.

Introduction

Reduced activation ferritic–martensitic steels are among the leading candidate structural materials for future fusion reactor applications due to their favourable combination of high-temperature strength, swelling resistance, and reduced long-term activation compared with conventional structural steels. Among these alloys, Eurofer97 has been widely studied as a reference material since it offers a balance of mechanical performance and compositional control suitable for fusion-relevant environments. However, further improvements in high-temperature strength and creep resistance remain necessary to support the demanding operating conditions expected in advanced fusion systems. One approach to improving the high-temperature performance of ferritic–martensitic steels is by introducing alloying elements such as yttrium. Yttrium additions enhance radiation resistance and may positively influence mechanical behaviour through the generation of fine stable oxide particles dispersed through the martensitic matrix, which can refine the microstructure and act as barriers to dislocations. These effects have the potential to alter tensile strength, creep strength, and rupture behaviour. In the present work, an yttrium-containing variant of modified Eurofer97 was evaluated under tensile and creep loading conditions. The aim of this study is therefore to compare the mechanical behaviour of the yttrium-modified Eurofer97 to the base material [1,2].

Material and Method

Material. Table 1 contains the alloy composition for the modified Eurofer97, along with the unmodified base compositions for reference. The alloy was vacuum induction melt (VIM) cast into a 50 kg ingot and hot rolled. Solution annealing was carried out at 1150 °C for 45 minutes, followed by austenitisation at 950 °C for 20 minutes and water quenching. Tempering was performed at 750 °C for 90 minutes, followed by air cooling.

Alloy	C	Mn	Cr	V	Ta	W	Ti	Y
Eurofer97	0.09-0.12	0.20-0.60	8.50-9.50	0.15-0.25	0.10-0.14	1.00-1.20	<0.02	-
Modified Eurofer97+ Y	0.089	0.065	8.873	0.011	0.049	2.458	0.108	0.035

Table 1: Composition, in [wt%], of the Eurofer97 and the Modified Eurofer97 with yttrium addition.

Mechanical Testing. Tensile and creep specimens were machined from a 14 mm thick plate along the rolling direction, having a parallel length of 27.5 mm and gauge diameter of 4 mm. Tensile testing was carried out at room temperature and 650 °C, with three repeats per condition, on an Instron 1361 Electric Screw Testing Machine at a strain rate of 0.00025 s^{-1}. Displacement was initially tracked using a mechanical extensometer under strain control, before transitioning to crosshead position control once yield was surpassed. The tests were carried out in accordance with BS EN ISO 6892-1:2019 (RT) and BS EN ISO 6892-2:2018 (650 °C). Creep testing was conducted on the Mayes Lever Arm Rig at 650 °C using an applied stress of 90 MPa, with two repeats. The creep tests complied with BS EN ISO 204:2023 and ASTM E139-24.

Microstructural Analysis. Optical microscopy was used to capture the fracture surface. Scanning electron microscopy (SEM) was used to assess the fracture surface of the creep specimens. Electron back scatter diffraction (EBSD) maps were recorded on the threaded section and the longitudinal cross-section of the specimen.

Results and Discussion

Fig. 1a) and b) show the alloy exhibited a 0.6-2.9 % reduction in tensile strength at room temperature, but a 15.0-21.2 % improvement at 650 °C [2]. As shown in Fig. 1c), the alloy experienced a rupture time 29 % below the design target of 550 hours as reported in literature [1]. Fig. 2a) depicts a ductile fracture characterised by a dimpled morphology, where the reduction in area is 95 %. Fig. 2b) displays islands of δ-ferrite scattered throughout the lath structured martensitic matrix in the threaded section, introducing an additional microstructural feature likely to influence the mechanical properties [3]. Fig. 2c) highlights a ~0.5 mm crack propagating along complex yttrium oxides in the longitudinal cross-section near the fracture surface, which can be indicative of a crack initiation site. Contrary to δ-ferrite having a negative influence on the tensile strength [3], yttrium oxides may have provided a modest compensatory strengthening effect, potentially through improved fine particle stability or reducing thermally activated recovery processes. The slow cooling rate inherent to the VIM casting process facilitates the growth of δ-ferrite, an intrinsically softer phase devoid of the fine precipitates and subgrain structure responsible for creep resistance in the martensitic matrix; it consequently deforms preferentially under sustained loading and accelerates the overall softening of the alloy [3]. Furthermore, the ferrite-martensite interfaces act as preferential sites for void nucleation and crack initiation [3], which may explain the damage observed in Fig. 2c).

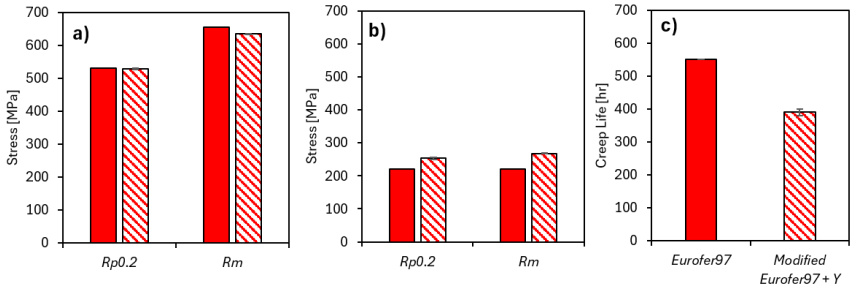

Fig. 1 : Bar charts of the mechanical properties [1,2]: a) 0.2% yield strength ($Rp_{0.2}$) and tensile strength (Rm) at room temperature; b) 0.2% proof strength ($Rp_{0.2}$) and tensile strength (Rm) at 650 °C; and c) creep life at 650 °C with an applied load of 90MPa. In each figure, Eurofer97 is solid red and modified Eurofer97 + Y is hatched.

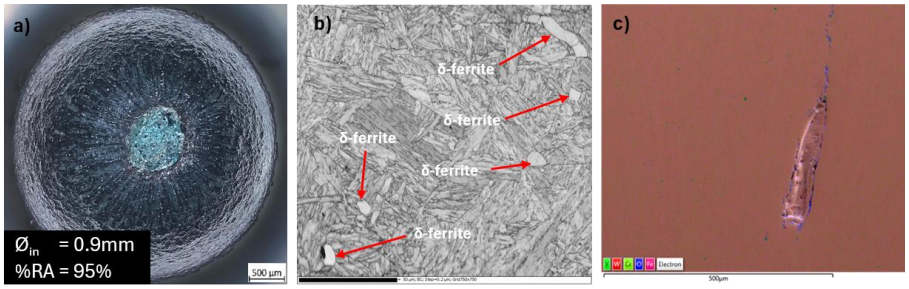

Fig. 2 : Maps of the failed creep specimen: a) optical image of the fracture surface; b) EBSD band-contrast map of the threaded section, acquired using a 0.2 µm step size; and c) EDS map of a crack along the longitudinal cross-section.

Conclusion

Although the material did not show the anticipated improvement in creep life, the benefits of yttrium were made apparent in the elevated temperature tensile strength, which offset the detrimental influence of the δ-ferrite. Controlling the cooling rate in VIM casting, by reducing the cast size, will subsequently inhibit the formation of δ-ferrite, which is crucial for revealing the expected enhancement in the creep strength of the RAFM steel.

References

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