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Effect of W and Ta on creep–fatigue interaction behavior of reduced activation ferritic–martensitic (RAFM) steels

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HIGHLIGHTS

- SR correlated with deformation under CFI in RAFM steels.
- Stress relaxation directly related to plastic strain accumulated, inversely to CFI life.
- Optimum combination of W and Ta best for CFI life.
- RAFM steels demonstrated compressive dwell sensitivity.
- SR tends toward constant value at long hold.

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ABSTRACT

The aim of this work is to understand the effect of varying tungsten and tantalum contents on creep–fatigue interaction (CFI) behavior of reduced activation ferritic–martensitic (RAFM) steels. Increase in W improved CFI life. Effect of changing Ta and W upon the resultant CFI life seems to be interrelated and an optimum combination of both W and Ta works out to be the best for CFI life. Stress relaxation obtained during application of hold can be a useful parameter to relate deformation and damage in the RAFM steels.

1. Introduction

Reduced activation ferritic–martensitic (RAFM) steel is a candidate structural material for test blanket module (TBM) in fusion reactors [1]. Because of the proposed pulsed nature of operation (compared to steady state operation), structural materials of in-vessel plasma facing components are subjected to low cycle fatigue and creep–fatigue interaction (CFI) conditions [2,3]. It is known that during the dwell time (no fusion power), the thermal energy storage system should supply thermal energy to the power cycle. Hence fusion core temperature will follow the storage temperature during this period. At the start of the burn phase, fusion core components see a large temperature change which could result in large strains. Creep at sustained high temperature and stress under such service conditions necessitates hold-time experiments corresponding to pulse lengths more than 8 h. Ideally creep–fatigue interaction experiments should be carried out at lower strain amplitudes and long hold periods that will be much closer to the service conditions. However, it is understood that whereas long hold periods and small strain ranges favor creep dominated failures, short hold periods and intermediate strain ranges favor creep–fatigue interaction failures. Therefore taking into consideration the aforesaid and the time constraints to carry out long term laboratory experiments at low strain amplitudes, CFI tests can be performed at intermediate strain amplitude to understand the trend of the material behavior.

Ferritic–martensitic steels, with chromium content ranging between 9 and 12%, is introduced in fusion reactor material programs as they have better creep resistance and excellent thermal

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Table 1
Chemical compositions (wt.%) of the RAFM steels.

Alloy designation	1.4W–0.14Ta	1.4W–0.06Ta	2W–0.06Ta	1W–0.14Ta
Elements	Initial heat treatment			
	1253 K for 30 min + 1033 K for 90 min	1253 K for 30 min + 1036 K for 90 min	1253 K for 30 min + 1036 K for 90 min	1253 K for 30 min + 1036 K for 90 min
Cr	9.04	9.03	8.99	9.13
C	0.08	0.126	0.12	0.12
Mn	0.55	0.56	0.65	0.57
V	0.22	0.24	0.24	0.22
W	1.4	1.39	2.06	0.94
Ta	0.14	0.06	0.06	0.13
N	0.0226	0.0297	0.0297	0.033
O	0.0057	0.0016	0.0016	0.0041
P	0.002	<0.002	<0.002	<0.002
S	0.002	<0.001	<0.001	0.0015
B	0.0005	<0.0005	<0.0005	0.0005
Ti	<0.005	<0.005	<0.005	<0.005
Nb	0.001	<0.001	<0.001	<0.001
Mo	0.001	<0.002	<0.002	<0.002
Ni	0.005	<0.005	<0.005	<0.005
Cu	0.001	<0.002	<0.002	<0.002
Al	0.004	<0.005	<0.005	<0.005
Si	0.09	<0.05	<0.05	<0.05
Co	0.004	<0.005	<0.005	<0.005
As + Sn + Sb + Zr	<0.03	<0.03	<0.03	<0.03
Fe	Bal	Bal	Bal	Bal

and nuclear properties compared to austenitic stainless steels [4]. Recent work in the fusion material development program includes adjustment of the chemical composition of the RAFM steel to achieve low activation after irradiation as well as on the reduction in the shift of the ductile–brittle transition temperature after irradiation. Efforts are made internationally to develop RAFM steel with varying tungsten in the range 1–2 wt.% and tantalum in the range 0.02–0.18 wt.% [5–7]. A three-phase development programme has also been initiated to develop India-specific RAFM steel as one of the potential structural materials for lead–lithium ceramic breeder (LLCB) test blanket module to be tested in ITER, France [8]. RAFM steel such as EUROFER97, is a modified composition of conventional ferritic–martensitic 8–12% CrMoVNb steels (modified 9Cr–1Mo steel) developed by substituting elements like molybdenum and niobium with tungsten and tantalum respectively, which have the same metallurgical functions as alloying elements and achieve fast radioactive decay properties. The chromium content is around 9 wt.% to warrant a full martensitic structure at room temperature on normalizing. The manganese concentration is high (0.5%) to avoid the formation of delta ferrite. Tungsten addition increases creep rupture strength but also increases ductile to brittle transition temperature (DBTT) [9]. Ta restricts the grain growth during normalization and is strong carbide former. Tantalum in the RAFM steel plays a vital role in lowering DBTT through its effect on prior austenitic grain refinement [10]. Higher tantalum and tungsten content decreases the weldability [11]. As a part of the materials development plan, four different RAFM steels with varying W and Ta contents were taken to study the CFI behavior of these RAFM steels. To the best of the authors' knowledge, effect of varying W and Ta on CFI behavior has not been systematically studied so far. Hence, the objective of the present study is to understand the effect of these elements on the CFI behavior of RAFM steels.

2. Experimental

2.1. Material, low cycle fatigue and creep–fatigue interaction

The indigenous RAFM steels used for the present investigation were produced by selection of proper raw materials and by employing vacuum induction melting and vacuum arc refining routes with strict control over the thermo mechanical processing parameters during forging, rolling and heat treatments. The chemical composition along with the heat treatment schedule followed for the four RAFM steels is given in Table 1. Blanks of 22 mm × 22 mm × 110 mm were cut for machining of standard low cycle fatigue (LCF) specimens with 25 mm length and uniform gauge section of 10 mm diameter. The orientation of the LCF specimen was along the rolling direction of the plates. The CFI experiments were conducted in air at 823 K, under fully reversed, total axial strain control mode in accordance with ASTM specification E606 [12] in a closed loop servo hydraulic testing system equipped with a resistance heating furnace. The temperature variation along the gauge length of the specimen did not exceed ±2 K. Creep–fatigue interaction (CFI) tests were conducted at a constant strain rate of $3 \times 10^{-3}\ s^{-1}$ and at total strain amplitude of ±0.6% by introducing hold periods of 10 and 30 min at peak tension or in peak compression. Peak tensile stress at the half-life (i.e. at half of the number of cycles to failure) was taken as saturation or half-life stress and the cycle number corresponding to a drop of 20% from the half-life stress was defined as the CFI life.

3. Results and discussion

3.1. Initial microstructure

The initial microstructure of RAFM steels with varying chemical compositions in the normalized and tempered condition is shown in Fig. 1. The microstructure is quite complex consisting of several boundaries pinned by numerous precipitates. These white precipitates are identified as Cr and W rich $M_{23}C_6$ carbides. TEM studies also confirmed formation of coarse Cr and W rich $M_{23}C_6$ carbides at the boundaries and finely distributed MX type precipitates in the intralath regions. The complex microstructure of 9Cr ferritic steels has been reported to consist of prior austenite grains, packets, blocks, martensitic laths and subgrains [13] and $M_{23}C_6$ carbides along the boundaries and MX precipitates in the intralath regions. In the present study, it is found that a change in chemical composition significantly influences the initial precipitate distribution;