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Low cycle fatigue design data for India-specific reduced activation ferritic-martensitic (IN-RAFM) steel

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HIGHLIGHTS

- Generation of first set of experimental data related to LCF performance of the commercial heat of IN-RAFM steel.
- Analysis of cyclic behavior from the perspective of both design and material characteristics.
- Various correction factors to account for various plastic strain accumulations, change in Poisson's ratio and asymmetry of loadings.
- Low cycle fatigue design parameters and correction factor values were comparable with P91 steel as reported in RCC-MR design code.

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ABSTRACT

The objective of the present paper is to provide first hand experimental data and analysis on the low cycle fatigue (LCF) performance of a commercial heat of Indian reduced activation ferritic-martensitic (IN-RAFM) steel. Since this material is not yet codified in RCC-MR, cyclic properties were generated for the design of the structural material of the Test Blanket Modules (TBM) made of RAFM steel. Hence, as a part of the material development program, LCF experiments were conducted on IN-RAFM steel obtained in the normalized and tempered condition. Total axial strain controlled experiments were performed in air by employing strain amplitudes ranging from ±0.25 to ±1.0% and at temperatures of 300, 673, 723, 823, and 873 K and a nominal strain rate, $3 \times 10^{-3}\,s^{-1}$. In the present work, various cyclic parameters that are useful for the design oriented fatigue analysis are derived as per the systematic procedure given in the RCC-MR design code. The physical significance of each design parameter such as elasto-plastic corrections based on Neuber analysis has been explained and correlated with the material behavior such as the cyclic softening nature of the RAFM steel.

1. Introduction

The activities on materials development focus on structural materials for tritium breeding blanket concepts developed for a demonstration (DEMO) fusion reactor and that is to be tested as Test Blanket Module (TBM) as part of the ITER mission [1]. There are technological challenges for the design and development of TBM for fusion power systems because of the complex cyclic loading and high-energy neutron irradiation. Hence the mission of the TBM materials program is characterization of relevant materials properties under service conditions in order to establish design allowable limits. Since 573–823 K is the operational temperature window, the mechanical properties need to be generated in the temperature range that includes this. It is known that ferritic/martensitic steels, with chromium contents ranging between 9 and 12%, has been introduced into fusion material program due to their better creep resistance and excellent heat transfer characteristics and good resistance to radiation damage induced by 14 MeV neutrons, compared to austenitic stainless steels [2]. While the use of ferritic-martensitic steels becomes conventional in the nuclear industry, the fusion environment in ITER poses new challenges for the structural materials [3,4]. Recent developments in the fusion materials program are focused on adjusting the chemical composition to achieve low activation after irradiation as well as on the reduction of the shift of the ductile–brittle transition temperature after irradiation. Hence, elements with a long radioactive decay time such as molybdenum and niobium are to be replaced with elements such as tungsten and tantalum with relatively faster decay time. International efforts to develop reduced activation ferritic–martensitic (RAFM) steel have focused on varying tungsten in the range 1–2 wt.% and tantalum in the range 0.02–0.18 wt.% [5–7]. With Europe, Japan, Russia, China and the USA, India is

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one of the partners in the material properties database generation for the development of conceptual design of TBM. In this regard, Indira Gandhi Centre for Atomic Research, Kalpakkam has initiated a three-phase program to develop India-specific reduced activation ferritic-martensitic (IN-RAFM) steel; (1) production of RAFM steel in par with the chemical composition and mechanical properties of Eurofer 97. (2) Optimization of chemical composition for arriving at the chemical composition of IN-RAFM steel: Four different heats with varying tungsten and tantalum contents ranging from 1 to 2 wt.% and 0.06 to 0.14 wt.% respectively were tested. Based on the optimum mechanical properties arrived at, the tungsten and tantalum levels of IN-RAFM was selected at 1.4 wt.% W–0.06 wt.% Ta [8,9]. (3) Production of commercial heat of IN-RAFM steel: on the basis of the chemical composition so optimized, production of commercial heat of large ingot size steel was realized. Hence as a part of the material qualification program, mechanical properties that also include low cycle fatigue properties evaluation, are being carried out on the commercial heat.

Due to the 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 [10,11]. Therefore, fatigue and creep–fatigue interaction properties become important basic inputs for the designers. Up to now, published data on the fatigue properties of structural material for fusion power systems is relatively limited [4]. Most of the works discuss either the material behavior with the underlying deformation micromechanics or only the design aspects of a component. Additionally, RCC-MR [12] does not detail on the physical significance of various design parameters used that may vary depending upon the material and its microstructural state. Hence, it will be more useful to bridge the gap between the materials behavior and the design aspects. The focus of the present paper is on generation of first set of experimental data related to LCF performance of the commercial heat of IN-RAFM steel and an analysis of the cyclic behavior from the perspective of both design and material characteristics. Various correction factors to account for various plastic strain accumulations, change in Poisson's ratio and asymmetry of loadings have been discussed.

2. Experimental

Commercial heat of Indian RAFM steel was produced by M/s. MIDHANI Limited, Hyderabad, India. The chemical composition of the steel is provided in Table 1. The steel has been produced by proper selection of pure raw materials, employing vacuum induction melting and vacuum arc re-melting routes and by exercising stringent control over the thermo-mechanical processing parameters such as forging, rolling and heat treatments. The steel was subjected to normalizing (1250 K for 30 min) and tempering (1033 K for 90 min) heat treatments. Low cycle fatigue experiments were conducted in air, under fully reversed, total axial strain control mode in accordance with ASTM specification E606 [13] in a closed loop servo hydraulic testing system equipped with a resistance heating furnace. The experiments were conducted at strain amplitudes ranging from ±0.25 to ±1.0% and temperatures 300, 673, 723, 823 and 873 K at a nominal strain rate of $3 \times 10^{-3}\,\mathrm{s}^{-1}$ using a triangular wave form. The temperature variation along the gauge length of the specimen was controlled within ±2 K. In each test condition, at least two specimens were tested and the average value was reported. 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 fatigue life [14].

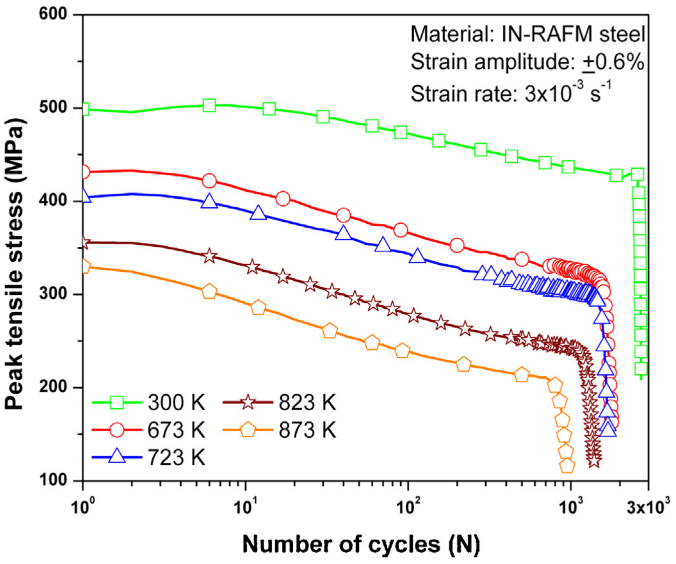

Fig. 1. Cyclic stress response of IN-RAFM steel tested at various temperatures and at a constant strain amplitude (±0.6%).

3. Results and discussion

3.1. Initial microstructure and cyclic stress response

Like any ferritic martensitic steel, IN-RAFM steel has a complex microstructure consisting of prior austenite grains, packets, blocks, martensitic laths and sub-grains and $M_{23}C_6$ carbides along the boundaries and MX precipitates in the intralath regions [15]. This microstructure which is expected to be stable under unstressed (only aging) or monotonic loading condition, gets severely altered during cyclic loading condition that affects the cyclic stress response (CSR). Under all the test conditions, the IN-RAFM steels show cyclic softening from first cycle onwards (Fig. 1). The rate of softening is very rapid for the first few initial cycles followed by a more gradual decrease in the peak tensile stress until there is a sharp decrease in the stress due to the initiation of a macrocrack, that leads to final failure. The cyclic softening is due to the decrease in the initially present high dislocation density due to interactions among mobile dislocations, and between mobile dislocations with lath boundary dislocations and coarsening of the strengthening carbides [16,17]. At higher temperatures, thermally activated dislocation motion (climb/cross-slip) accelerates the annihilation mechanism and coarsening of the substructure [18–20], hence causing a higher amount of overall cyclic softening. Apart from this, the deleterious effect of surface oxidation in ferritic martensitic steels in causing fatigue life reduction at elevated temperatures is also reported [16–18].

3.2. Coffin–Manson plot and cyclic stress–strain parameters

LCF properties of IN-RAFM steel is provided in Table 2. Plot of stress range (obtained from half life hysteresis loop) versus plastic strain range (%) for different temperatures is depicted in Fig. 2. The cyclically stabilized or half life stress–strain curve is represented by the well-known power law relationship. Cyclic curve coefficients k′ and n′ are calculated using the following equation:

$$\Delta\sigma = k'(\Delta\varepsilon_{\mathrm{p}})^{n'} \tag{1}$$

where $\Delta\sigma$ and $\Delta\varepsilon_{\mathrm{p}}$ are the stress and plastic strain ranges obtained from the stable hysteresis loops. The values of cyclic fatigue strength coefficient k' and strain hardening exponent n' were calculated from Eq. (1) and the values are given in Table 2. The