Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Mechanical Sciences 48 (2006) 160–175

International Journal of MECHANICAL SCIENCES

www.elsevier.com/locate/ijmecsci

High-temperature low cycle fatigue, creep–fatigue and thermomechanical fatigue of steels and their welds

S.L. Mannan*, M. Valsan

Metallurgy and Materials Group, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, Tamil Nadu, India

Received 25 February 2005
Available online 12 October 2005

Abstract

High-temperature low cycle fatigue (LCF) is influenced by various time-dependent processes such as creep, oxidation, phase transformations and dynamic strain ageing (DSA) depending on test conditions of strain rate and temperature. In this paper, the detrimental effects of DSA and oxidation in high-temperature LCF are discussed with reference to extensive studies on 316L(N) stainless steel and modified 9Cr–1Mo steel. DSA has been found to enhance the stress response and reduce ductility. It localizes fatigue deformation, enhances fatigue cracking and reduces fatigue life. High-temperature oxidation accelerates transgranular and intergranular fatigue cracking in modified 9Cr–1Mo steel and during long hold time tests in austenitic stainless steel. In welds, microstructural features such as presence of course grains in the HAZ and formation of brittle phases due to transformation of δ ferrite during testing influence crack initiation and propagation and fatigue life. Thermomechanical fatigue (TMF) studies are suggested as more closer to the actual service conditions. In 316L(N) stainless steel, TMF lives under out-of-phase cycling are found to be lower than those under in-phase conditions in the low-temperature regimes, while the converse holds good when the upper temperature encompassed the creep-dominant regime.

Keywords: Low cycle fatigue; Thermomechanical fatigue; 316L(N) steel; Modified 9Cr–1Mo steel; Welds

1. Introduction

Low cycle fatigue (LCF) is an important consideration in the design of high-temperature systems subjected to thermal transients. The systems that experience thermal transients include aircraft gas turbines, nuclear reactor vessels, heat exchangers, steam turbines and other power plant components. LCF resulting from thermal transients occurs essentially under strain controlled conditions, since the surface region is constrained by the bulk of the component. In thick components the major compressive strain is introduced by the thermal transient during start up, with additional compressive and or tensile strains during load cycling and shut down. On-load periods at elevated temperatures in between transients introduce time-dependent effects. Temperature time transients which could be experienced by components in a fast reactor are the result of reactor trip (down shock) or secondary circuit failure (up shock) [1].

Thermo mechanical fatigue (TMF) with simultaneous mechanical and thermal cycling is more close to service situations. Traditionally, isothermal LCF tests have been used to assess the performance of materials subjected to thermal transients. Thus, the component behaviour is studied using mechanical strain cycling under isothermal testing conditions. The slow start up/shut down cycle is replaced by a symmetrical and continuous fatigue cycle of equal strain rates in tension and compression with a hold period at constant peak strain to simulate the on-load period.

At high temperatures the fatigue deformation and life are influenced by several time-dependent mechanisms such as dynamic strain ageing (DSA), oxidation, creep and phase transformations. These damage processes, which are strong functions of temperature and strain rate, are

---

*Corresponding author. Metallurgy and Materials Group, IGCAR, Kalpakkam 603 102, Tamil Nadu, India. Tel.: +91 4114 280 222; fax: +91 4114 280 081.

E-mail address: mannan@igcar.ernet.in (S.L. Mannan).

0020-7403/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmecsci.2005.08.004

illustrated with examples from extensive studies conducted on 316L(N) stainless steel and their welds and modified 9Cr–1Mo ferritic steel [2–12] which are the currently favoured structural materials for the primary and secondary sides respectively of the liquid metal-cooled fast reactor.

In this paper, high-temperature fatigue and creep–fatigue properties of 316L(N) stainless steel, its welds and modified 9Cr–1Mo steel are discussed. This is followed by a brief discussion of TMF properties of 316L(N) steel.

1.1. 316L(N) stainless steel and welds

Nitrogen modified 316L(N) austenitic stainless steel is used in nuclear power plants for the construction of reactor vessel, piping and heat exchangers. This alloy has emerged as a viable alternative to AISI 316 and its modified grades, with enhanced high-temperature mechanical properties and lesser susceptibility to sensitization and associated intergranular corrosion. Evaluation of elevated temperature LCF behaviour of 316L(N) stainless steel has received much attention in the recent years [2,13–19]. In these studies, nitrogen addition has been reported to be beneficial, and the LCF life has been found to improve at both ambient temperature and 873 K.

Welds are the weak links in structures. Most of the service failures are found to occur either in the HAZ or in the weld metal, which are more frequently associated with the presence of defects or microstructural inhomogeneities compared to the base metal. In austenitic stainless steel welds, the δ ferrite introduced to reduce their tendency to hot cracking and micro fissuring, transforms to a hard and brittle phase known as σ phase, when these materials are exposed to elevated temperatures (773–1173 K) for extended periods of time, leading to low ductility creep ruptures when sufficiently high stresses are applied at elevated temperatures.

The allowable number of fatigue cycles in welds is one-half the value permitted for parent material as per the ASME Boiler and Pressure Vessel Code [20] and a factor of 1.25 on fatigue strain is applied as per the RCC-MR design code [21].

1.2. Modified 9Cr–1Mo steel

Modified 9Cr–1Mo ferritic steel (with alloying additions of niobium and vanadium and controlled amount of nitrogen) is extensively used as a structural material at elevated temperatures up to 873 K in fossil-fired power plants, petrochemical industries and as a material for tubing in the reheater and superheater portions and as thick-section tube sheet material in the steam generators of liquid metal cooled fast breeder reactor [22]. High thermal conductivity and low thermal expansion coefficient coupled with enhanced resistance to stress corrosion cracking in steam–water systems are important considerations in the selection of this steel for these applications. The material also possesses better monotonic tensile and creep strengths at elevated temperatures compared with the plain 9Cr–1Mo steel. The alloy also exhibits good weldability and microstructural stability over very long periods of exposure to high-temperature service conditions.

The addition of Nb improves the properties by promoting nucleation of finely distributed $M_{23}C_6$ carbides and by aiding grain size refinement, whereas V enters the carbide particles and retards their growth. It must be mentioned that in this alloy, strength in normalized and tempered condition is derived from carbides like NbC, VC and $M_{23}C_6$ on sub-boundaries and from the tempered martensitic laths with high dislocation densities. In addition, V and Nb could also form fine precipitates of nitrides/carbonitrides within the ferrite matrix contributing to further strengthening [23–26]. Mo is a solid solution strengthener and is considered a retardant for dislocation recovery/recrystallization [27].

LCF behaviour of modified 9Cr–1Mo ferritic steel has been reported earlier under normalized and tempered [25,28–32,9,11] and thermally aged conditions [27,33,34]. Further, detailed investigations have been carried out to evaluate the creep–fatigue interaction behaviour of the alloy [27,28,33–36]. Ebi and McEvily [25] showed that the hot forged alloy exhibits inferior fatigue properties at 811 K as compared to the fine-grained, hot-rolled material. It was concluded that the coarse grain size adversely affects the fatigue crack initiation stage but had little effect on the crack propagation. Prolonged ageing of the alloy at elevated temperatures prior to testing was found to reduce the LCF and creep–fatigue interaction lives [27,34]. Ageing resulted in the formation of Laves phase with associated reduction in the toughness and LCF life of the alloy [27,34]. Studies on the influence of strain hold position on the creep–fatigue life indicated that the hold in compression peak strain was more deleterious than that in tension. This was attributed to the detrimental effect of oxide behaviour in compression hold [36]. Life was observed to decrease with increase in the dwell time up to 1 h under tension hold beyond which there was an apparent saturation [27]. During long time creep tests, carbide coarsening and coalescence at grain boundaries were found to introduce intergranular damage in the alloy [37].

2. Experimental

The 316L(N) base metal in the mill-annealed condition was solution treated at 1373 K for 1 h, followed by water quenching prior to machining the LCF specimens. Weld metal specimens were machined from weld pads prepared by shielded metal arc welding process using 316 and 316(N) electrodes. X-ray radiography was used for assessing the soundness of the welds followed by δ ferrite measurements using a magne-gauge. Modified 9Cr–1Mo steel was obtained in the form of hot-forged rods of 70 mm diameter. The normalizing treatment of this steel was carried out at 1313 K for 1 h plus air cooling and tempering was done at