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A review of low-cycle fatigue of Alloy 617 for use in VHTR components: Experimental outlook

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Abstract. The effect of strain range and temperature on the low-cycle fatigue behaviour and microstructure change during cyclic deformation of Alloy 617 for use in very high temperature gas-cooled reactor components were studied at elevated temperature starting from ambient condition. Increasing the strain range and the temperature was noticed to reduce the fatigue resistance of nickel-based Alloy 617 due to facilitating the transformation behavior of the carbides in the grain interior, precipitates along the grain boundary, and oxidation behavior inducing surface connected precipitates cracking. Initial hardening behavior was observed at room temperature condition during cyclic due to the pile-up dislocation of micro-precipitates. The grain size was also taking a role due to the formation of an obstacle in the matrix. In the high temperature regime, the alloy 617 was found to soften for its entire life due to the fast recovery deformation, proved by its higher plasticity compared with lower temperature. The deformation behavior also showing high environmentally assisted damage. Oxidation behavior was found to become the primary crack initiation, resulting in early intergranular surface cracking.

1 Introduction

Low-cycle fatigue (LCF) is an important design consideration in structural components operating at high temperatures. Repetition (cyclic) of thermal stresses are generated as a result of temperature gradients which release on heating and cooling during start-up, shut-down and thermal transient conditions. LCF resulting from startups and shut-downs occurs under essentially strain-controlled conditions, since the surface region is constrained by the bulk of the component. For example, a large steam turbine component may be undergoing power under peak-load conditions during its operation. Under these circumstances, the component must quickly respond from its stand-by state, and severe thermal stresses may result from the thermal transients induced by the start-up. In the other case of aircraft gas turbines, the normal operation of an engine on airlines is one implicating start and stop operation.

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In this study, the authors are focusing in the nuclear field area, such nuclear components are subjected to cyclic thermal transient and mechanical stress due to the high pressure and temperature of the coolant or of the fuel [1-2]. Therefore, nuclear plant life extension therefore remains a challenge for the material scientists and low emission as well as better performance remain as a worldwide issue. The Next Generation Nuclear Plant (NGNP) being developed in the US and Republic of Korea is a Very High Temperature Nuclear Reactor (VHTR) with helium as the primary coolant. In the VHTR, some of the major components such as the reactor internals, reactor pressure vessel, piping, hot gas ducts (HGD), and intermediate heat exchangers (IHX) are key components, with helium as a primary and secondary coolant. The VHTR may merge diversities of this baseline design to allow eventual operation at gas outlet temperatures up to 950℃. Alloy 617, a Nickel-base superalloy, is a primary candidate material for a VHTR because of its excellent thermal stability for components of power generating plants with high temperature environment [3]. The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) allows use of Alloy 617 for construction of non-nuclear pressure vessels, however, Alloy 617 is now being developed for use in VHTR plant. From these understanding, it is clear that the problem of high-temperature LCF involves a broad cross section of our advanced technology and that a deeper study of proper application is essential. These considerations can be used to determine material resistance against the cyclic loading to ensure the reliability of material structures.

This work deals with a series of LCF tests on Alloy 617, investigating for a fully reversed strain-controlled (strain ratio, $R\varepsilon$ = -1) regarding to different applied total strain ranges, i.e., 0.6, 0.9, 1.2, and 1.5% at elevated temperatures, room temperature, 900, 950℃ in an open air environment. The main aim is to study the basic characteristic of low-cycle fatigue properties during temperature change. Cyclic deformation phenomena such as hardening/softening behavior, cyclic stress-strain curves, and fatigue life dependent in a representation of a plastic deformation and ductility resistance to failure were obtained.

2 Experimental sections

2.1 As-received materials

A commercial grade Alloy 617 is approved for non-nuclear construction in the ASME Code. Thus the composition (wt%) of the Alloy 617 used for material chosen in this study is 53.11Ni, 22.2Cr, 12.3Co, 9.5Mo, 1.06Al, 0.08C, 0.949Fe, 0.4Ti, 0.084Si, 0.029Mn, 0.027Cu, 0.003P, <0.002S, and <0.002B. Fig. 1 shows the microstructure of as-received Alloy 617. The average grain size of the alloy is approximately 100 μm for coarser grain and 30 μm for finer grain. Intergranular carbides are present in banded regions aligned with the rolling direction.

The cylindrical LCF specimens with 6.0 mm in diameter in the reduced section with a parallel length of 18 mm and gauge length of 12 mm were made from alloy plate. The long axis of the specimen aligned with the rolling direction. Low stress grinding was performed during the final machining to avoid notches for the LCF test.

2.2 Low-cycle fatigue test

A closed loop 100kN servo hydraulic testing machine was used and equipped with a tube furnace for heating the specimens of Alloy 617 in dry air, therefore the temperature was remained within ± 2°C of the nominal temperature. We performed a fully reversed (strain ratio, $R\varepsilon$ = -1) axial strain controlled LCF tests for Alloy 617 regarding to four different total strain ranges, i.e., 0.6, 0.9, 1.2, and 1.5%. A triangular waveform and constant strain rate of 10^{-3}/s was applied. The failure criteria was defined as the number of cycles which means a 20% reduction in the stress ratio (peak tensile-compressive stress ratio). Microstructures were observed by optical microscopy (OM) and scanning electron microscopy (SEM) equipped with an energy-dispersive X-ray spectroscopy (EDS).

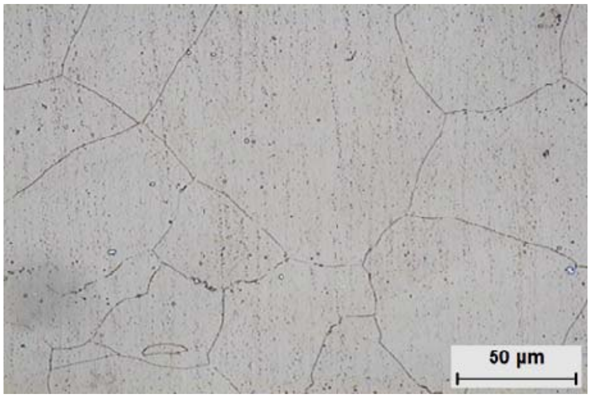


Fig. 1. Metallography of carbides and grain structure in the as-received Alloy 617.

3 Results and Discussions

3.1. Low-cycle fatigue results

LCF testing was completed in air at elevated temperatures to provide a baseline of understanding in cyclic deformation behavior. Table 1 shows the test results in term of strain range and temperature. Four different applied strain ranges were shown from 0.6% - 1.5% total strain. The number of cycles to failure, elastic and plastic strain at a half-life cycle are also listed in Table 1.

Table 1. LCF test results of Alloy 617 at elevated temperatures.

Temperature	Total strain range (%)	Cycles to failure (cycles)	Plastic strain range at half-life (%)	Stress range at half-life (MPa)
Room temperature	0.6	42360	0.078	474.2
	0.9	13042	0.205	505.5
	1.2	3410	0.321	552.4
	1.5	1409	0.435	583.0
900°C	0.6	1179	0.176	193.5
	0.9	913	0.323	188.0
	1.2	487	0.470	186.2
	1.5	405	0.625	181.2
950°C	0.9	823	0.343	148.9
	1.2	481	0.480	139.9
	1.5	392	0.641	136.6

The stress amplitude response curves at four total strain ranges as a function of number of cycles to failure are illustrated in Fig. 2 under continuous cyclic loading. The cyclic stress response at room temperature exhibited a cyclic softening regime for the major portion of the life after a brief period of initial hardening. The short period of cyclic initial hardening was observed about 2–200 cycles and remained softening phase until failure. Almost all of the stress amplitude paths of Alloy 617 at high temperature ranges exhibit a cyclic softening region for the major portion of the life. At the end of the test, the stress amplitude was decreased rapidly as a formation of macro-crack initiation or just prior to failure. Peak tensile and compressive stresses as a function of cycle reached a stable value within less than 20 cycles.

3.2. Fracture behaviour

Fig. 3 shows microstructure evolution of LCF fracture behaviour under wide range of temperatures. At room temperature crack initiation and propagation occurred in transgranular nature (Fig. 3a). With the help of the cross section of OM photograph, the fatigue crack propagation site was essentially characterized by typical fatigue striations which were perpendicular to the fatigue loading direction. Fig. 3b and 3c showing crack initiation and propagation behavior was similar to that exhibited at 900°C and 950°C that is the transition from intergranular oxide cracking to a mixed mode transgranular propagation occurred at a slightly greater depth from the surface. This is confirmed in [7] when over exposed to high temperature applications, metal alloys are oxidized, which formed precipitates and cavities. Surface brittle oxides were found in outside layer of specimen and became potential sites for crack initiation where cyclic strain was localized and generated a critical zone of fatigue failure.

Fatigue damage process of the propagation mode is identified by the result of the slip band. Slip character is described as a measure of the degree to which dislocations tend to disperse during plastic deformation [8]. Therefore, it can be drawn that at high temperature process, fatigue damage is more obvious due to the presence of more parallel slip band.

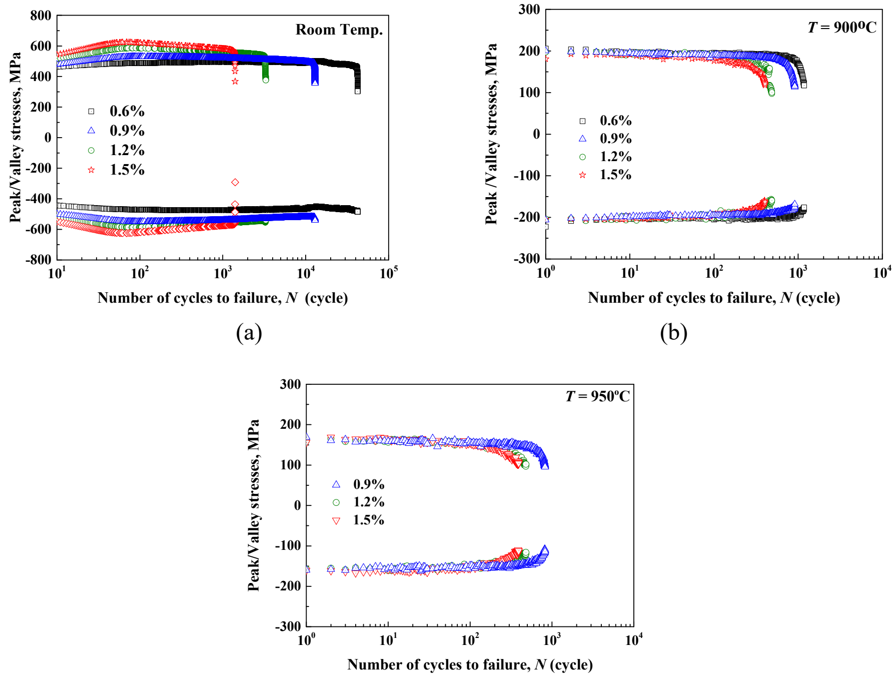
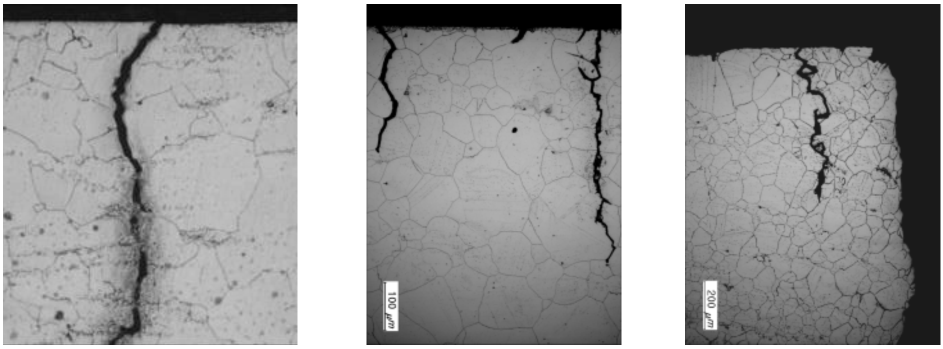


Fig. 2. Peak and tensile compressive stresses response as a function of the number of cycles of Alloy 617 at elevated temperatures: (a) Room temperature; (b) 900°C; and (c) 950°C.



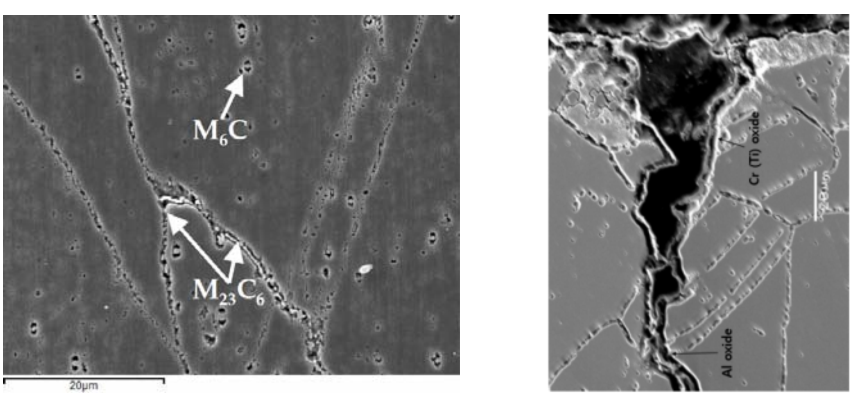
(a) (b) (c)

Fig. 3. Micrographs illustrating failure mechanism of Alloy 617 at elevated temperatures: (a) Room temperature; (b) 900°C; and (c) 950°C. The stress axis is from left to right in the plane of the page.

3.3. Discussion

Failure mechanism at room temperature occurred in nature way of cyclic slip. The slip band from fatigue mechanism that contain extrusions and intrusions leads to the production of point defects that will develop into micro-cracks within the grain in gauge section, finally, at the critical stage, coalescence of the micro-cracks again develops into the macro-crack that the stress rapidly drops until failure.

The high temperature condition has been well known to induce the heavily damaged by environment. Fig. 4 shows EDX spectroscopy results, the primary carbides of Ti-rich M_6C, with large precipitations, were formed in the body of the grain structure and the carbides of Mo, Cr-rich $M_{23}C_6$ were developed mainly on the grain boundary. These precipitates (especially Mo, Cr-rich $M_{23}C_6$) were diffused with oxygen ions simultaneously and adapted with metal ions to create a protective oxide layer, namely Cr_2O_3. These brittle cracks on the surface-connected grain boundary were found to generate crack nucleation and accelerate the propagation rate, which the dislocation movement become easier around the grain boundary. This phenomenon at high temperature was also known to reduce the applied stress during cyclic loading, otherwise the plastic strain accumulation was continuously increasing.



(a) (b)

Fig. 4. Typical SEM images of Alloy 617 at high temperature environment illustrating:
(a) Precipitates formed in the grain interior and its boundary; and (b) Surface brittle Cr-oxides cracks.

4 Conclusion remarks

Low-cycle fatigue behaviours were investigated by LCF tests with different temperature at room temperature, 900, and 950°C and strain ranges at 0.6-1.5%. The cyclic stress response at room temperature exhibited a cyclic softening regime for the major portion of the fatigue life after a brief period of initial hardening. The short period of cyclic initial hardening was observed about 2–200 cycles (pile-up dislocation across the slip barrier) and remained softening phase until failure. Meanwhile, at high temperature the softening phase governed the major mechanism due to the recovery of precipitates during fatigue. It was observed that the reduction in LCF resistance with increasing temperature yields partly from homogenization of slip mechanism during fatigue and simultaneous increase in plastic deformation generated and partly from the intergranular crack initiation obtaining from oxidation of surface connected grain boundaries and environmentally assisted mixed mode propagation.

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