Study of Low Cycle Fatigue Behavior of Nickel Base Super Alloy for High Temperature Thermal Power Plant Applications

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ABSTRACT

Low cycle fatigue (LCF) evaluation and analysis of a candidate material CCA617, a Ni-base superalloy, applicable to a high efficiency coal fired boiler super heater and re-heater tube sections was carried out in this present study. This study is useful for design of components. LCF tests have been performed in full reversal, axial mode with total strain control at strain ranges of 0.5 %, 0.8 %, 1.2 % and 2.0 % for each temperature and at the following temperatures: 650°C, 700°C, 750°C and 800°C. The results show a decrease in fatigue life with increase in strain range and temperature. A consistent cyclic hardening behavior and serrated flow of maximum peak stress were observed. Serrated flow indicates dynamic strain aging (DSA) behavior in CCA617. Constants of Coffin-Manson relationship were estimated at each temperature and are reported in this work. Fractured surfaces after LCF testing have been analyzed under Field Emission Scanning Electron Microscope (FESEM) for understanding crack origin location and propagation mechanisms. The LCF properties evaluated for CCA617 is useful for high temperature thermal power plant boiler applications.

Key Words: Low cycle fatigue; Cyclic hardening; Dynamic Strain Aging (DSA); Serrated flow; Transgranular fracture

INTRODUCTION

An advanced coal fired thermal power plant system is the need of the time to support growing power requirement and to reduce the challenge of global warming. It is becoming a big challenge to satisfy both lesser CO_2 emissions as well as demand for power requirements through conventional thermal power plant. The above difficulty could be minimized to the significant level, by increasing efficiency of thermal power plant. Lower emissions can be made possible by having a high-efficiency coal fired power plant, operating at steam parameters higher than those existing today. It is estimated that efficiency under high temperature (> 700°C) and steam pressure (>300 bar) conditions will improve from 35 % to 46 % [1]. Higher efficiency of power plant necessitates the development of higher creep and fatigue resistant materials for experiencing high temperatures. CCA617 is one such material suggested for this purpose [1]. This work elaborates low cycle fatigue (LCF) behavior of CCA617 which is essential for boiler tubes design for high temperature applications. Hence, this study was taken up.

2.0 EXPERIMENTATION WORK

The material selected for the study is CCA617 in hot-rolled and solution annealed plate form. Chemical composition of the alloy selected for this study is mentioned in the Table1. Samples for tensile test were prepared with gauge length five times the diameter as per the standard ASTM E8M [2]. The tensile tests were conducted using INSTRON 8803 500kN UTM machine. Tensile test results obtained from CCA617 are given in Table 2.

LCF test samples were prepared as per the standard ASTM E606 [3] with test diameter 5.0 mm having parallel length 15 mm and gauge length 12.5 mm as shown in the Fig.1 (a). LCF tests were performed in a 250 kN MTS servo hydraulic system equipped with an electrical resistance furnace under total axial strain controlled and full reversal (strain ratio, $R_{\varepsilon} = -1$) conditions. The temperature was maintained within ± 2°C over the entire gauge length of each LCF test sample. These tests were conducted at the following strain amplitudes: ±0.25 %, ±0.40 %, ±0.50 % & ±1.00 % at temperatures 650, 700, 750 and 800°C each. In accordance with ASTM E 606 [3], LCF tests were conducted at 0.1 Hz frequency, with triangular strain ramp. The test set up is shown in Fig.1(b). 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 number of cycles corresponding to a drop of 20 % from the half-life stress was defined as the fatigue life[4, 5]. Ramberg-Osgood relationship of stress-plastic strain was used to evaluate the work hardening of the alloy. Portevin Le-Chatelier effect was analyzed to understand the dynamic strain aging (DSA) and cyclic hardening ratio was evaluated to know the degree of hardening of the alloy. Constants of Coffin-Manson equation of fatigue strain-life approach were evaluated at all the temperatures of testing. Fractography was carried out subsequent to testing of LCF samples using Field Emission Scanning Electron Microscopy (FESEM) for understanding location of crack origin and nature of crack propagation.

Table 1: Chemical composition of CCA617 plate (in wt.%)

		Ni	Cr	Co	Mo	Fe	Mn	Al	C	Cu	Si	S	Ti	P	B	N
ASTM	Min.	Bal.	21	11	8	-	-	0.8	0.05	-	-	-	0.3	-	0.002	-
	Max.		23	13	10	1.5	0.3	1.3	0.08	0.05	0.3	0.008	0.5	0.012	0.005	0.05
Actual		Bal.	21.4	11.2	8.6	1.4	0.1	1.1	0.06	0.02	0.2	0.002	0.4	0.001	0.005	0.012

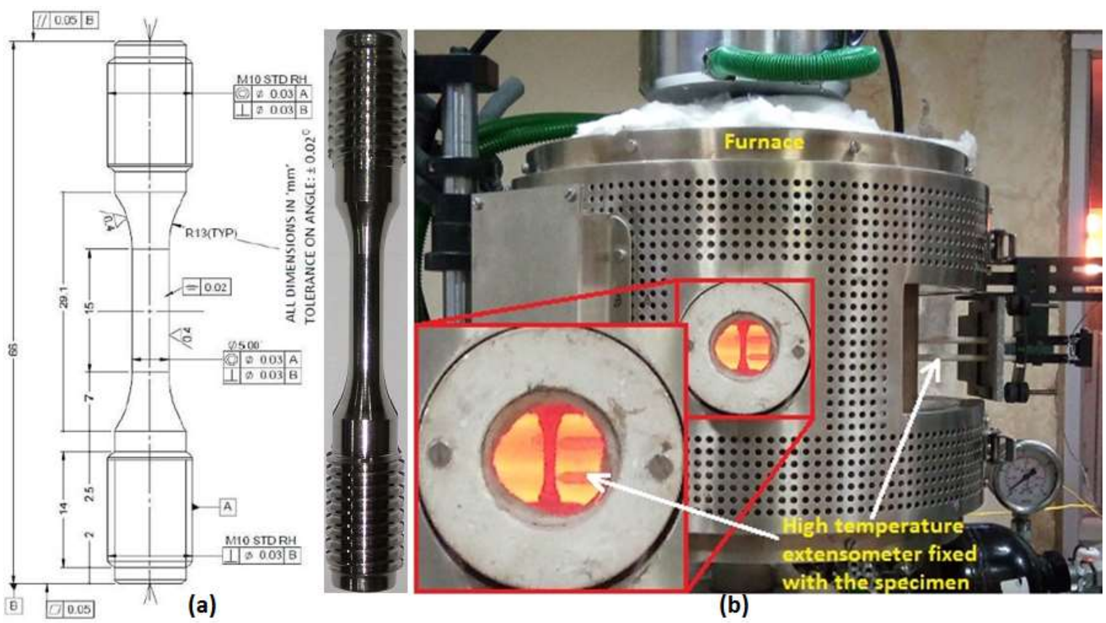

Fig.1. a) LCF Specimen; b) High temperature LCF testing in 250 kN servo hydraulic MTS machine

Table 2: Tensile properties of CCA617 super alloy

Temperature, Deg. C	0.2 % Yield Strength (σ_{YS}), MPa	Tensile Strength (σ_{TS}), MPa
650	241.43	652.39
700	236.30	627.72
750	245.94	612.34
800	213.26	573.73

3.0 RESULTS AND DISCUSSION

LCF tests were carried out and the results (stress range vs. fraction of fatigue life to failure) were presented in Fig. 2. It can be seen that the alloy exhibited cyclic hardening in all LCF tests upto a certain life fraction. Also, rate of increase of hardening is rapid initially and remains near constant till higher fraction of fatigue life.

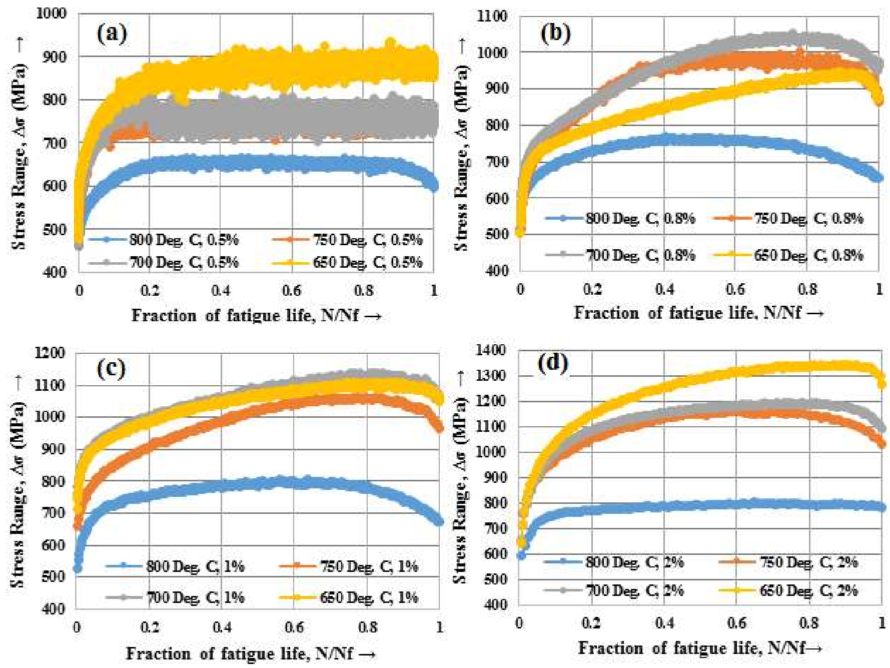

Fig.2. The normalized fatigue stress-range curves at temperatures 650, 700, 750, 800ºC of CCA617 tested at constant strain ranges of (a) 0.5 %, (b) 0.8 %, (c) 1 %, (d) 2 %

The fraction of life at which the stress range falls down rapidly can be presumed to be crack initiation and thereafter the remaining fraction of life can be attributed to crack propagation [6].

Half-life cyclic stress amplitude vs. plastic strain amplitude data at 650ºC, 700ºC, 750ºC and 800ºC is given in Fig. 3. In each graph, increase in plastic strain amplitude led to the increase in stress amplitude value upto a certain life fraction. This behavior is consistent with the empirical rule which states that when $\sigma_{TS}/\sigma_{YS} \geq 1.4$, metallic material shows a cyclic hardening [7]. The ratio, σ_{TS}/σ_{YS} for CCA617 varies from 2.49 to 2.70 at the four test temperatures and are consistent with the phenomenon. The cyclic hardening behavior can better be understood with help of Ramberg-Osgood relationship of stress amplitude-plastic strain amplitude equation (1).

$$\frac{\Delta\sigma}{2} = K'\left(\frac{\Delta\varepsilon_p}{2}\right)^{n'} \quad (1)$$

where $\Delta\sigma$, $\Delta\varepsilon_p$, K' and n' are the stress range, plastic strain range, cyclic strength coefficient and cyclic strain hardening exponent, respectively. The material constants K' and n' evaluated in present study as shown in the Fig.3. The figure shows that with increase in the plastic strain amplitude, cyclic half-life stress amplitude increases at each temperature.

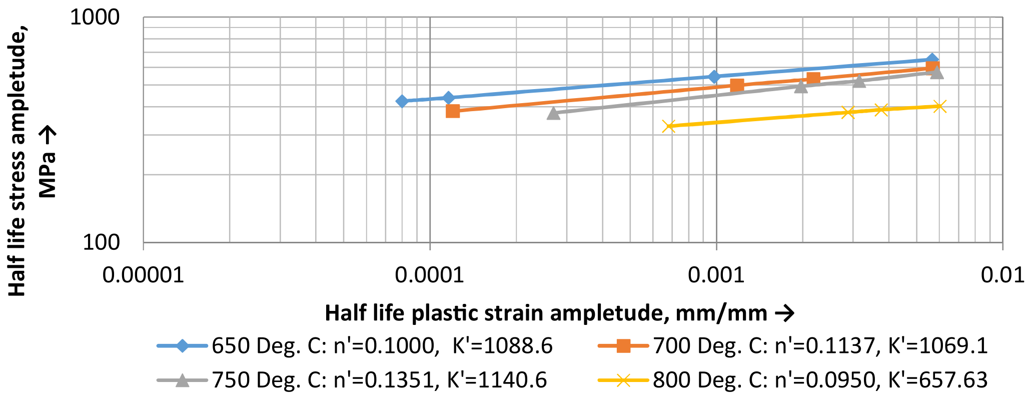

Fig.3. Half-life stress amplitude-plastic strain amplitude curves of CCA617 at four temperatures

As per the Portevin Le-Chatelier effect, if there is serration in the plastic flow of stresses, it is dynamic strain aging (DSA) of the material under fatigue testing. In this study, a fluctuation in tension-compression stresses is always observed at all the four test temperatures. This phenomenon happens due to locking-unlocking interactions of moving atoms [6]. In Fig.4. , it can be seen that, there is serrated flow during the cyclic hardening which confirms DSA mechanism operating in CCA617.

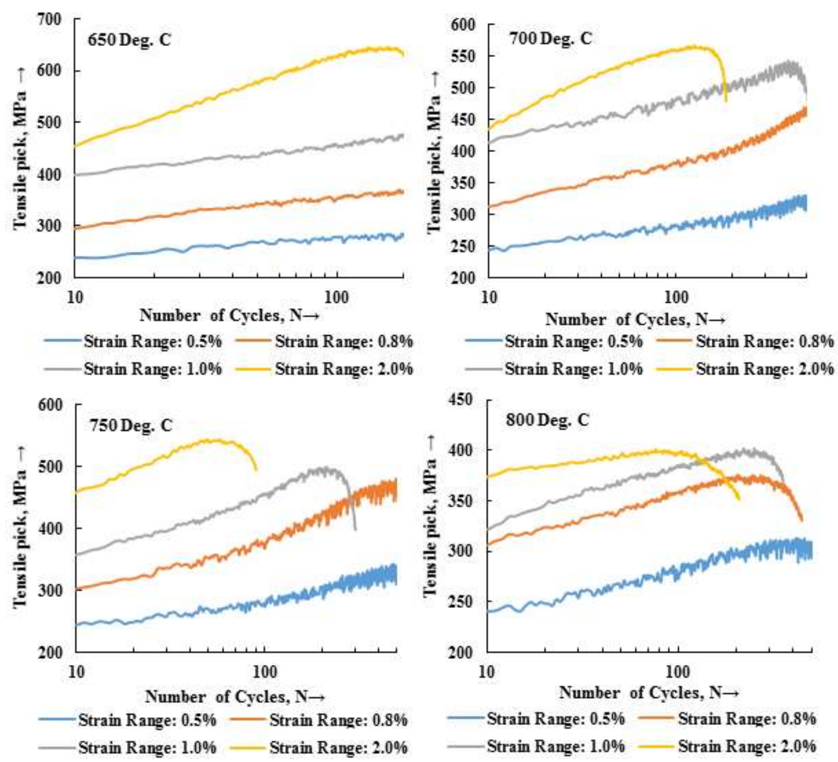

Fig.4. Tensile peak stress curves of CCA617 with their serrated flow at strain amplitude 0.25 %, 0.40 %, 0.50 % and 1.00 % and at temperatures 650°C, 700°C, 750°C and 800°C each

As per the literature, DSA happens in the temperature range from 650°C to 900°C [8]. J. D. Hong et al suggested that the degree of DSA might increase the cyclic hardening and it could be evaluated by analyzing the ratio of cyclic hardening [9]. Fig.5 shows the graphs of the ratio of maximum stress amplitude to the stress amplitude of the first cycle at the four temperatures. This ratio is known as cyclic hardening ratio, degree of DSA [9]. In all cases, the degree of DSA varies from 1.344 to 2.214. This shows a cyclic hardening of CCA617 during LCF tests for the strain range 0.5%, 0.8%, 1.0% and 2.0% at temperatures 650°C, 700°C, 750°C and 800°C each.

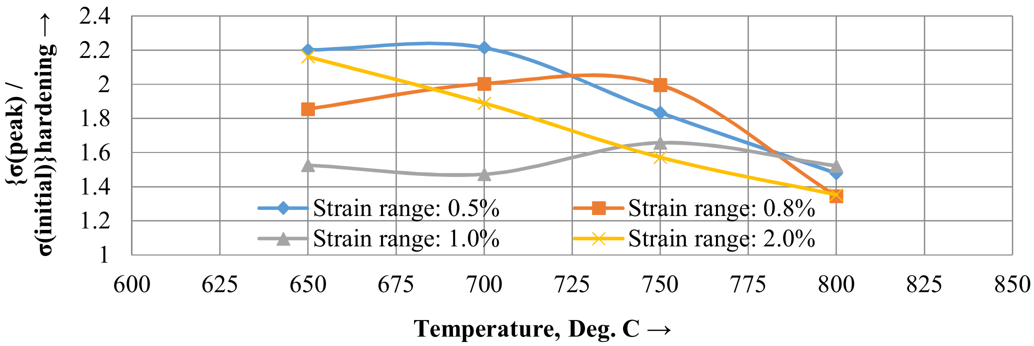

Fig.5. Cyclic stress amplitude ratio of CCA617 at temperatures 650ºC, 700ºC, 750ºC and 800ºC as a magnitude of hardening of CCA617 for the LCF test at the strain range: 0.5%, 0.8%, 1.0% and 2.0%

Lazzarin, et al and Sumel et al [10, 11] have studied LCF behavior of metals at higher temperature and found the plastic deformation as the key phenomenon in this process. Total strain can be analyzed in terms of plastic strain and elastic strain and the relation between total strain and life, i.e., number of LCF cycles to failure can be well established by Coffin-Manson power function as per the equation 2 [4].

$$\Delta\varepsilon_t = A\,(N_f\,)^{-a} + B(N_f\,)^{-b} \quad \text{………………………………………..} \ (2)$$

Where, $\Delta\varepsilon_t$ is total strain range, N_f is the number of cycles to failure and A, a, B & b are constants. 'Total strain range' consists of a plastic strain component, $A\,(N_f\,)^{-a}$ and an elastic strain component, $B(N_f\,)^{-b}$ as given in equation (2). Fig.6 shows a plot of total strain range and the number of cycles to failure of CCA617 at temperatures 650ºC, 700ºC, 750ºC and 800ºC. The curves are plotted based on equation (2) wherein least squares best fit method is followed. All the constants determined as per the Coffin-Manson equation are indicated in Table 3. Fig.6 shows an increase in life of CCA617 with decrease in strain range. At lower temperature, fatigue life is more for any selected 'total strain range' as compared to higher temperatures. At higher 'total strain range, plastic strain component is dominant whereas at lower 'total strain range', elastic component is dominant at each temperature. In between, there is a transition zone where elastic and plastic strain influence is equal and matrix deforms in both ways equally. As per the previous work [4, 12], the constant "-a" typically varies from -0.5 to -1.0. In this study, the constant '-a' was evaluated from -0.771 to -0.862 and values are within the range.

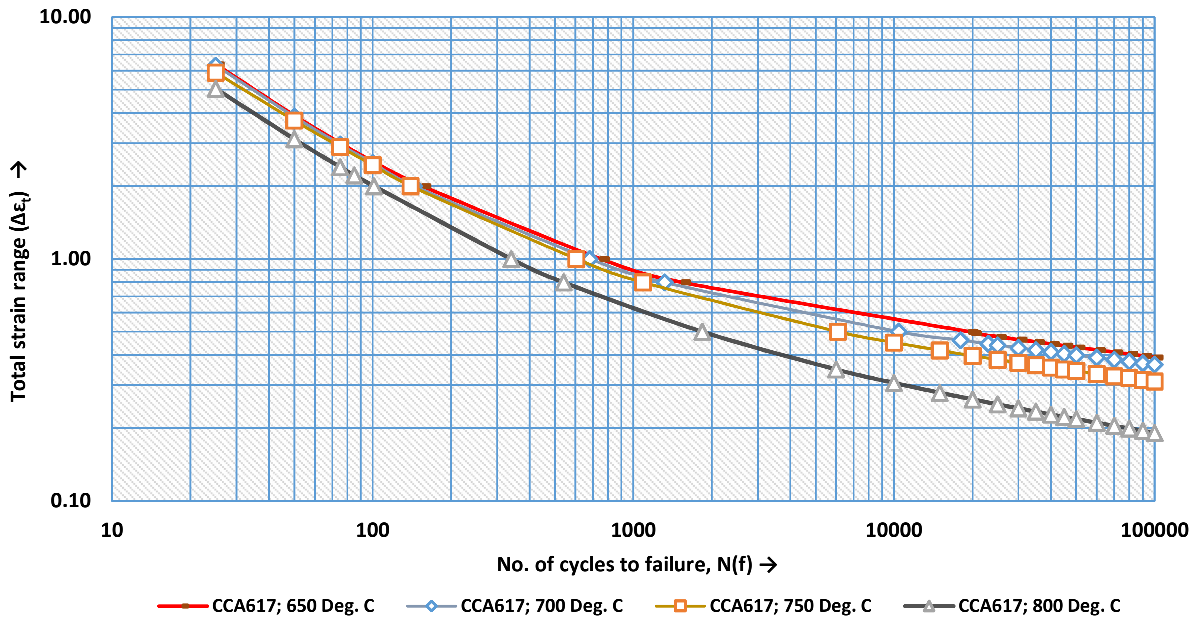

Fig.6. Total strain range-number of cycles to failure curves for CCA617 Super Alloy

Table 3: Values of constants and exponents evaluated as per Coffin-Manson equation for CCA617 Superalloy

Temperature (°C)	, % A	a	B	b
650	84.287	0.862	1.6941	0.128
700	78.500	0.834	1.3712	0.116
750	60.588	0.771	1.2353	0.122
800	57.519	0.805	1.2698	0.167

After fatigue testing of CCA617, fracture samples of 650°C temperature and 0.8 % and 1.0 % strain range test conditions were analyzed and fractographs are shown in the Fig.7. In these two test samples, the fractographs at early crack propagation areas (adjacent to crack initiation locations) shown in Fig.7.(a, c) indicate a trans-granular-fracture with fine striations and center regions shown in Fig.7.(b, d) show a trans-granular fracture with coarse striation.

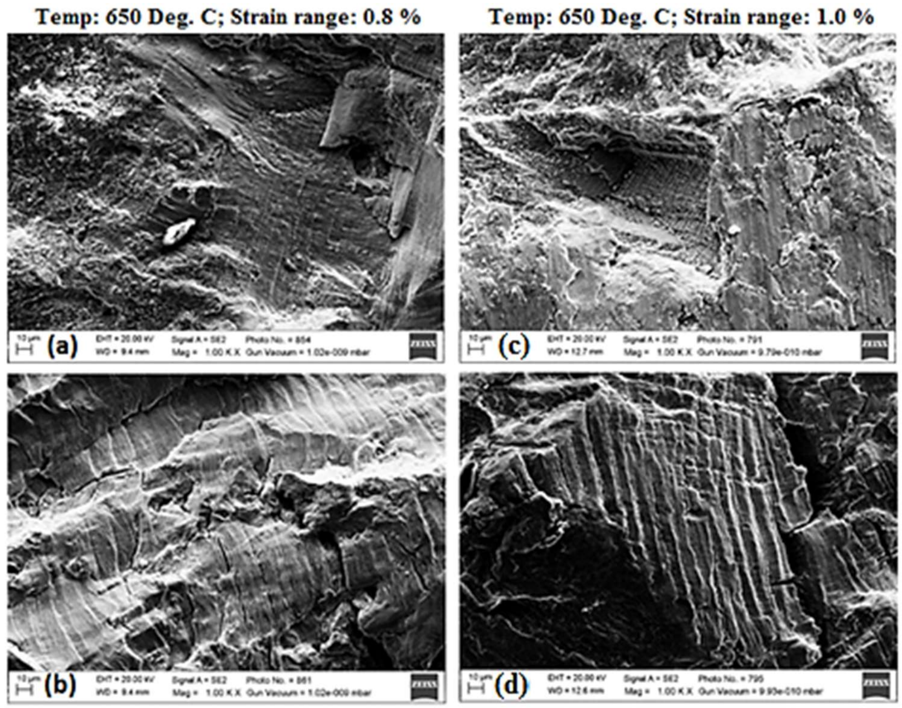

Fig. 7. SEM micrographs of CCA617 Superalloy LCF fractured samples: (a) fractograph at early crack propagation region; Strain range: 0.8% (b) fractograph at center region, Strain range: 0.8% (c) fractographs at early crack propagation region, Strain range: 1.0 % (d) fractograph at center region, Strain range: 1.0%

4. CONCLUSION

The following are the conclusions from present work:

1. From the Ramberg-Osgood relationship of stress-plastic strain evaluation it can be inferred that degree of strain hardening of CCA617 increases with increase in plastic strain amplitude. Constants of Ramberg-Osgood relation for CCA617 were obtained and reported in this study.

2. CCA617 exhibits a DSA hardening mechanism in the all LCF test conditions at the test temperatures, 650ºC, 700ºC, 750ºC and 800ºC. This is the reason for cyclic hardening which was observed upto a certain fraction of life

3. As per the strain-range vs. life curves, the increase of strain range and temperature resulted in a reduction of fatigue life. Constants of Coffin Manson relation for CCA617 were estimated and reported in this study.

4. CCA617 exhibits a purely trans-granular crack initiation and its propagation at 650ºC. The early crack propagations show trans-granular fracture with fine striation. Central crack propagations are purely trans-granular with coarse striation.

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