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# Effect of Stress Concentration in Low Cycle Fatigue Life Prediction at High Temperature

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*Abstract:* **Low Cycle Fatigue (LCF) is one of the dominant failure modes in high temperature structural components. LCF behavior of notched specimens and un-notched specimens made of 316(L)N was investigated. Test were conducted on un-notched specimens and notched specimens with circular notch with varying diameter at high temperature in order to study the effect of notch at high temperature on estimation of fatigue life of 316(L) N. The results were also compared with the simulated results. The fatigue life at high temperature decreased with the increase in notch severities.**

## 1. INTRODUCTION

Fatigue is a localized damage process of a component produced by cyclic loading. It is the result of the cumulative process consisting of crack initiation, propagation, and final fracture of a component. Localized plastic deformation occurs at stress concentrated area during cyclic loading. A permanent damage to the component is induced and a crack is developed due to plastic deformation. With the increasing number of loading cycles, the length of the crack increases and after a certain number of cycles, the crack will cause the component to fail [1]. Life prediction using notched specimens gives a better prediction of the fatigue life of the component. Incorporating a notch in the specimen geometry leads to multiaxial loading which is similar to the condition created by notches, welds, or other stress concentrations present in the component.

Material used for the investigation is 316(L)N stainless steel. Type 316L(N) stainless steel is currently the favored structural material for several high temperature components in the primary side of liquid metal cooled fast breeder reactors ( LMFBRs). In LMFBRs, the components are often subjected to repeated cyclic thermal stresses as a result of temperature gradients which occur during start-ups and shut downs or during power transients. Therefore low cycle fatigue (LCF) represents a predominant failure mode, requiring significant consideration in the design and life analysis of LMFBR components. A sharp change in geometry of the components or applied loading conditions may lead to multi-axial state of stress in the component. In order to understand the behavior of material under multi – axial loading, either tests have to be conducted on multi axial testing systems or a notch can be incorporated to introduce the multi axiality on un-notched specimen. The state of stress can be varied by changing the notch root radius.

316L(N) is a low carbon, nitrogen-enhanced version of type 316 molybdenum-bearing austenitic stainless steel. The type 316 alloys are more resistant to general corrosion and pitting corrosion than the conventional chromium-nickel austenitic stainless steels such as type 304. They also offer higher creep, stress-rupture and tensile strength at elevated temperature. The nitrogen in type 316L(N) adds additional resistance to sensitization in some circumstances and also provides some solid solution hardening, raising its minimum specified yield strength compared to type 316L stainless steel. Life prediction of 316L(N) at high temperature with un-notched and notch specimens and the dependency of the fatigue life on temperature and notch radius was studied.

There exists extensive literature on LCF behavior of 316 LN SS considering metallurgical aspect of the steels [2-5], little exist on effect of multiaxial state of stress on LCF behavior of these steels [6]. Situation becomes more complicated when there is sharp change in geometry of the components or applied loading conditions, the state-of-stress and strain change to multiaxial conditions. The stress concentration due to sharp change in geometry may result in localized cyclic plastic strain. The local strain approach proposed by Neuber [7] uses the local strain as the governing fatigue parameter and is found to be very effective in predicting the fatigue life of a component.

The local strain–life method used is based on the assumption that the life spent on crack nucleation and small crack growth of a component can be approximated by a smooth laboratory specimen under the same cyclic deformation at the crack initiation site. By using this concept it is possible to determine the fatigue life at a point in a cyclically loaded component if the relationship between the localized strain in the specimen and fatigue life is known. This strain–life relationship is typically represented as a curve of strain versus fatigue life and is generated by conducting strain-controlled axial fatigue tests on smooth, polished specimens of the material. Strain-controlled axial fatigue testing is recommended because the material at stress concentrations and notches in a component may be under cyclic plastic deformation even when the bulk of the component behaves elastically during cyclic loading. It permits detailed consideration of cyclic loading situations where local plasticity is involved.

The strain life relationship referred for un-notched and notched specimens LCF life prediction is the Manson-Coffin-Basquin equation, which is as follows:

$$\varepsilon_t = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^c$$

where:

$\varepsilon_t$ - total true strain

$E$ - modulus of Elasticity

$N_f$ - number of cycles to failure

$\sigma_f$' -regression intercept called the fatigue strength coefficient

$b$ - regression slope called the fatigue strength exponent

$\varepsilon_f$' -regression intercept called the fatigue ductility coefficient

$c$ - regression slope called the fatigue ductility exponent

Apart from finding out the fatigue life for un-notched and notched specimens by conducting tests at high temperature, the fatigue life was also found using simulation with the help of e-fatigue. The objectives of this study are i) experimental evaluation of effect of temperature on fatigue life prediction ii) evaluate the effect of varying notch radius which is a measure of stress concentration and iii) comparing the results with simulated values.

## 2. EXPERIMENTAL PROGRAM

Un-notched specimen and circumferentially notch round specimens were used. The notch specimens used were with a notch radius 5 mm and 2.5 mm. The specimen geometry for un-notched and notched samples with 5mm and 2.5 mm notch radius are shown in Fig. 1(a), (b) and (c) respectively. The diameter at the notch root is same for both notch radii and is 7.07 mm. The stress concentration factors $K_t$ for all the three type of specimens used for simulation are un-notched specimen $K_t$ = 1, notched specimen with 5mm notch radius $K_t$ = 1.34 and notch specimen with 2.5 mm notch radius $K_t$ = 1.6. The tests were strain controlled cyclic fatigue test with R ratio -1, strain range as ±0.6% constant strain rate of $3 \times 10^{-3}$ $s^{-1}$ and at 823K temperature.

Blanks of 316(L)N were subjected to a solution annealing treatment at 1373 K for 1 hr followed by water quenching before specimen fabrication. The chemical composition of steel is (in wt %): C: 0.03, Cr: 17.5, Ni: 12.1, Mo: 2.53, N: 0.14, Mn: 1.74, S: 0.0041, P: 0.017, Fe: balance. The un-notched and notched specimens with 25 mm gauge length and 10 mm gauge diameter machined from the heat-treated blanks.

All the tests were carried out in air under fully reversed, total axial strain control mode employing a symmetrical triangular strain–time waveform. The temperature was controlled by a cascade controller which maintains the temperature of the specimen at 823K by means of a thermocouple attached to the specimen inside the furnace. Table 1 summarizes the fatigue test condition with the corresponding experimental life and life calculation by simulation.

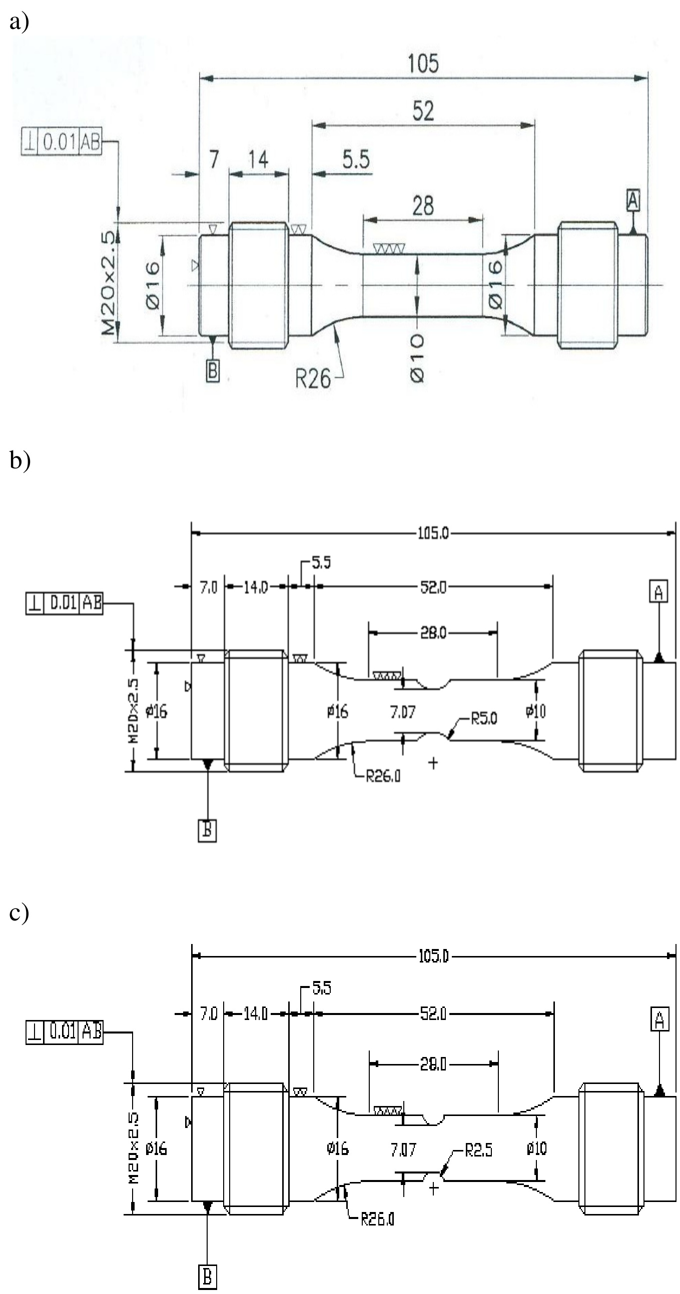


**Fig. 1 Specimen configuration and dimension a) Un-notched specimen b) notched specimen with notch radius 5 mm c) Notched specimen with notch radius 2. 5 mm.**

**Table 1. Summary of fatigue test condition and experimental and simulated life**

| Specimen | Notch Radius | Kt | % Strain | Experimental Life | Simulated Life |
|---|---|---|---|---|---|
| Un-notched | - | 1 | ±0.6 | 1438 | 1592 |
| Notched | 5 mm | 1.34 | ±0.6 | 327 | 382 |
| Notched | 2.5mm | 1.6 | ±0.4 | 705 | 653 |
| Notched | 2.5mm | 1.6 | ±0.6 | 211 | 165 |
| Notched | 2.5mm | 1.6 | ±0.8 | 95 | 65 |

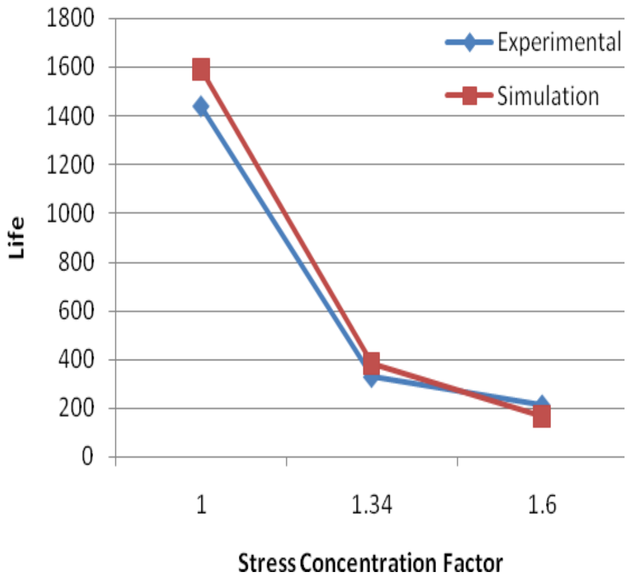


**Fig. 2 Life versus Stress Concentration Factor**

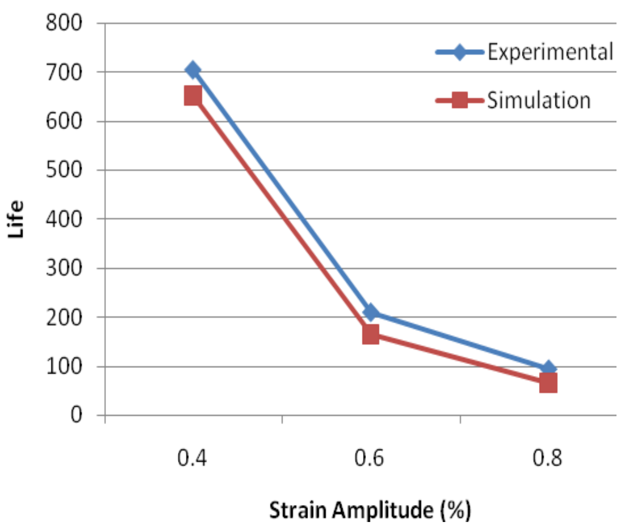


**Fig 3. Life versus Strain amplitude for notched specimens**

**Fig. 4 Fractured Specimen**

## 3. ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS

Fig 2 shows the variation in experimental life of the specimens at various stress concentration factor for ±0.6% strain amplitudes. Life calculated by simulation is also shown in the same figure in order compare the life obtained by both the methods. Fig 3 shows the variation in experimental life of notched specimens (R 2.5 mm) at various strain amplitudes. Fig 4 shows a specimen after fracture.

The results indicate that the notch has very significant effect on fatigue life. This is because notches give rise to stress concentrations which in turn decrease the fatigue life of the specimen. Therefore the life should be estimated by conducting test on notch specimens were a sharp change in geometry lead to multi-axial state of stress which are similar to that created by small cracks, flaws etc. in the actual component. There is also decrease in fatigue life with increase in stress concentration factor which is due to the decrease in notch radius.

The results also shows that the life obtained by simulation agrees reasonably well with that obtained experimentally. The simulated life was calculated by the Manson-Coffin-Basquin equation and using high temperature material properties. The effect of the stress concentration factors was incorporated in the fatigue life calculation.

The fatigue life of un-notched specimen at high temperature was also found to be approximately 50% less than that estimated at room temperature at same strain amplitude [5]. Some variation is definitely due to the change in composition of the steel but the major reason for the decrease in life at high temperature is due to the phenomena of dynamic strain ageing [3]. The life of the component first increases due to rise in temperature. For 316(L)N this takes place till 573K temperature but beyond this there is decreases in the life of the components at temperature range 573K to 873K. At higher temperatures oxidation also contributes in decreasing the life of the component.

## 4. CONCLUSIONS

Based on the experimental data presented and the analysis performed, the following conclusions can be drawn:

1. The fatigue life of the component decreases due to the presence of notch which creates similar multi-axial state of stress as created by small cracks, flaws etc. present in the actual component.
2. Life prediction using notch specimens should be used to predict the life of component.
3. Life of the component decreases with increase in stress concentration factor.
4. Life of the component at high temperature (823K) is less than that at room temperature.
5. Life estimation by simulation agrees reasonably with the experimental values which can be used to predict the life of the component if material properties are known.

## 5. ACKNOWLEDGEMENTS

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