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Low Cycle Fatigue Life Prediction

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Abstract: *Low Cycle Fatigue (LCF) is one of the dominant failure modes in high temperature structural components. Extensive research on the behavior of various metals under LCF condition has been carried out from the last 50 years. The major concern was to develop the theory to predict the fatigue life of different materials under different loading and environmental conditions. The present study is an attempt to summarize some of the recent work done to predict the life for different material and at different working conditions. The life prediction is done by simulation of specimens made of the material under study. A notch is introduced in the specimen to resemble a stress concentration created on the actual component due to the presence of notch, weld, defect etc. The study is divided into four categories; Life prediction using plain specimens at room temperature, plain specimens at high temperature, notched specimen at room temperature and notched specimen at high temperature. From the present study it can be concluded that basically there are three ways by which the Low cycle fatigue life of a component made of a particular material can be predicted at the design stage. These are Experimentation, Numerical methods and Finite Element simulation. A suitable method has also been suggested.*

Keywords: *Low Cycle Fatigue, Nuclear structural materials, notch specimen*

1. Introduction

Fatigue life is the life of a structure when subjected to repetitive load. It accounts for 90% of service failures where the component fails at values below yield stress. 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 also increases. After a certain number of cycles, the crack will cause the component to fail [1]. Fatigue analysis helps in predicting life of the component in design phase itself. Static or dynamic analysis can tell us about stress, displacement, acceleration but not about the life of the component.

2. Low Cycle Fatigue

Components when subjected to relatively high stress, fails at low numbers of cycles and the component is subject to low cycle fatigue (LCF) as shown in figure 1. The structural components used at high temperature shows LCF failure as a predominant failure mode. Low-cycle fatigue conditions are created when the repeated stresses are of thermal origin. Since thermal stresses arise from the thermal expansion of the material, it is easy to see that in this case fatigue results from cyclic strain rather than from cyclic stress.

Most components may appear to have nominally cyclic elastic stresses, but stress concentrations present in the component result in local cyclic plastic strain. The local strains approach was developed in the late 1950s uses the local strain as the governing fatigue parameter (the local strain–life method) [1] and has been shown to be more effective in predicting the fatigue life of a component. It is based on the assumption that the life spent on crack nucleation and small crack growth of a notched 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.

Extensive research has been carried out to study the behavior of various metals under LCF condition in the last 50 years. The objective behind this was to develop a suitable theory to predict the fatigue life of different materials under different loading and environmental conditions. For this various test were conducted on heat treated specimens made of different material at room and high temperatures by individual researchers. The present study is an attempt to summarize some of the recent work done to predict the life for different material and at different conditions. As per the study, the life prediction of a particular material has been done initially by testing plain specimens under cyclic loading conditions. But later as mentioned earlier it was seen that the 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. These different studies carried out by using specimens of different materials at room temperature and high temperature are discussed below in four categories:

1. Plain specimens at room temperature.
2. Plain specimens at high temperature.
3. Notched specimen at room temperature
4. Notched specimens testing procedures.

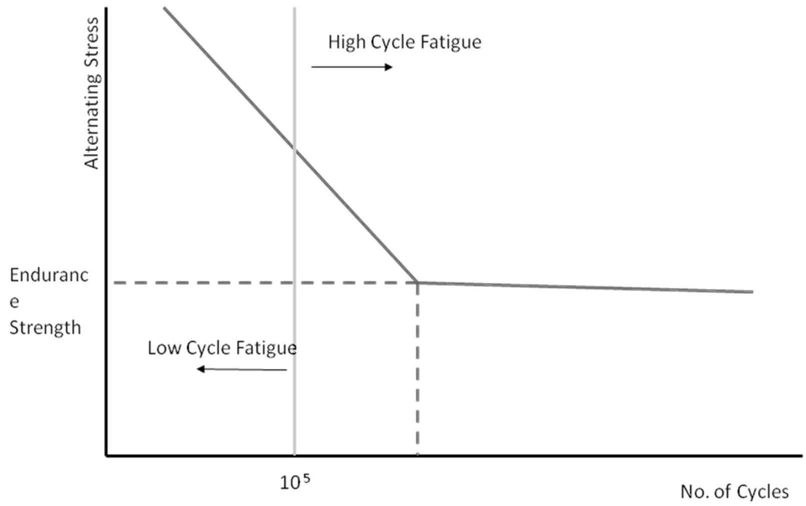


Fig1. *Low and High cycle Fatigue*

2.1 Plain Specimen at Room Temperature

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). 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 room temperature was carried out by Roy and others [2] and the elasto-plastic behavior of the material under cyclic loading for different strain amplitude was studied. The dependency of peak tensile stress on number of cycles and strain amplitude is depicted in Fig. 2.

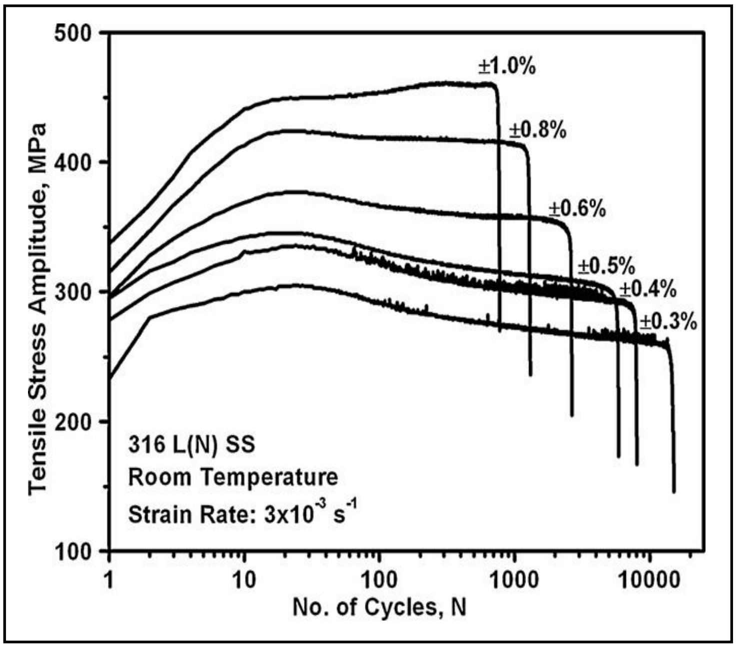


Fig2. *Cyclic stress response curve of 316L(N) SS.*

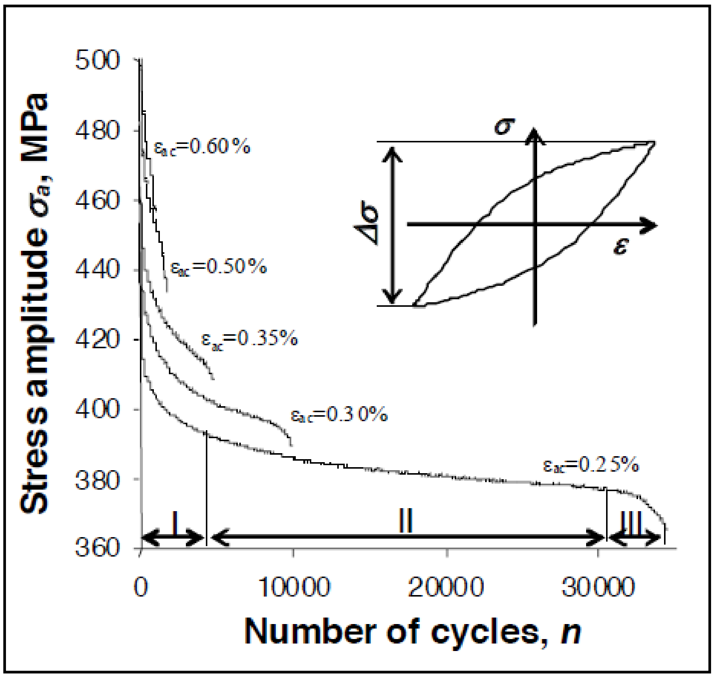


Fig3. *Cyclic Stress Response at different strain amplitude*

The material behavior was predicted using strain energy based model and also by FE analysis of LCF behavior using ABAQUS finite element software. Initial cyclic stress response from simulation and predicted cyclic hysteresis loops showed good correlation with the experimental results. The material showed masing behavior at lower amplitudes and non masing behavior at higher stain amplitudes. It also showed initial hardening for a few cycles followed by prolonged softening, saturation and final failure. Apart from 316L(N), P92 is newly developed ferritic heat resistant steel based on P91 steel, which has prestige creep fracture strength by replacing Mo with definite W, and adding V, Nb, N, B trace elements. As compared to P91 steel, P92 steel has 25%-30% higher creep strength. Modified 9Cr-1Mo steel is being used extensively as structural material for steam generator components of liquid metal cooled fast breeder reactor and fossil fired power plants.

The selection of this material is primarily based on a good combination of mechanical properties, high thermal conductivity, low thermal expansion coefficient and good resistance to stress corrosion cracking in water-steam and sodium environment systems compared to austenitic stainless steels. A further improvement of the thermal efficiency of modern steam turbines can be achieved by increasing the steam operating temperature. It has been found that the substitution of W for Mo enhances the high temperature tensile strength, fracture toughness and creep strength. This had led to the development of P92 Steel.

A study [3] carried out on P91 and P92 steels was an attempt to present the characteristics of the low-cycle life of steels P91 and P92 for a permanent strain range and graded loads. Plain fatigue specimens at room temperature were tested for fully reversed and graded load condition for varying strain amplitudes. The results showed cyclic softening behavior of the material.

In another work [4] carried on G91, fatigue life of the material was found out using similar procedures. Fig. 3 shows changes in the cyclic stress response for five strain levels assumed in the research. The saturation stress at which the change in hysteresis loops stabilizes, giving a state of saturation, was determined for different strain amplitude.

2.2 Plain Specimen at High Temperature

Whenever the component is operating at high temperature levels, it is subjected to high thermal stress leading to LCF failure. Therefore life prediction of material with specimens subjected to high temperature is important as their will be difference in the life of a component working at room temperature and high temperature. Such testing were carried out on different materials by different researchers

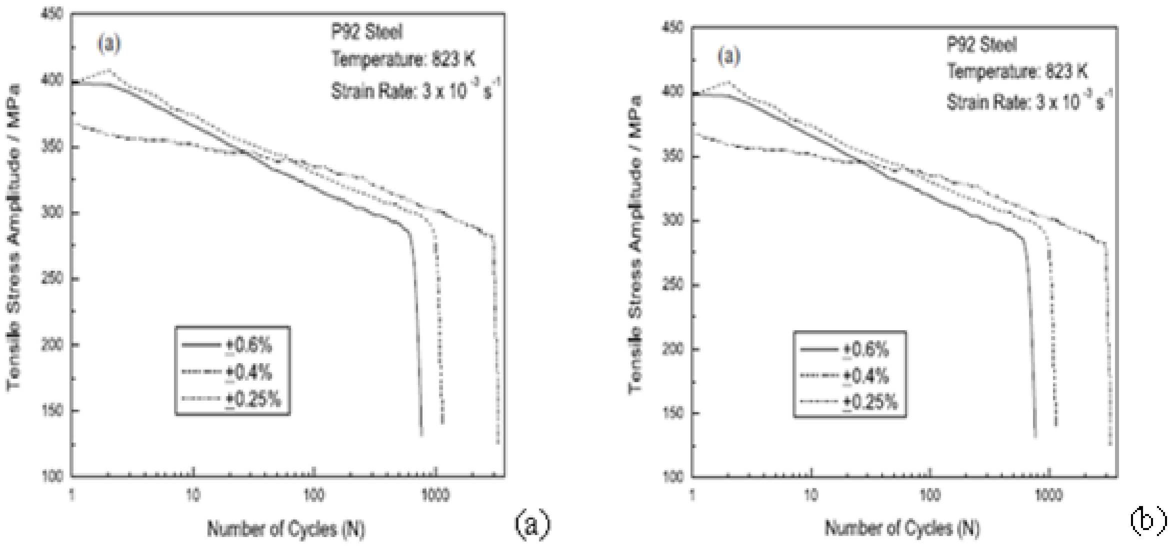
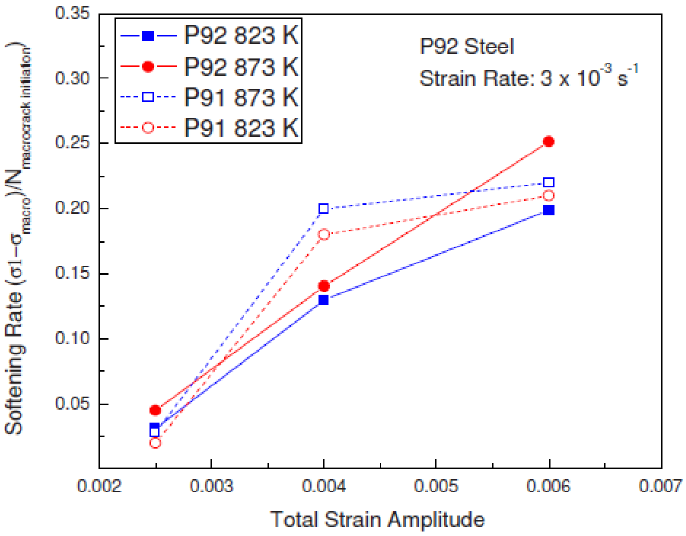


Fig4(a). *Cyclic Stress Response of P92 Steel at 823 K and* **(b)** *Strain – Life plots for P92 Steel*

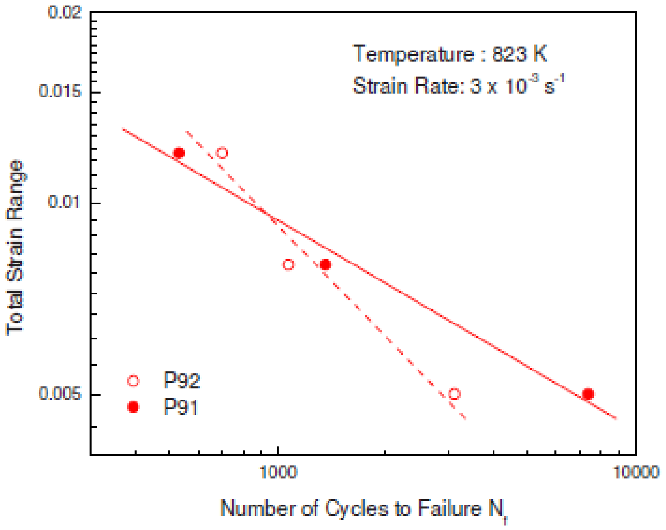
P92 steel exhibited continuous softening before the final load drop that occurred due to the propagation of macro fatigue cracks when subjected to cyclic loading at high temperature [5]. The Cyclic Stress Response of P92 Steel at 823 K and variation of elastic strain amplitude with number of reversals to failure is depicted in Fig 4 (a) and (b) respectively. The softening rate was more for the tests conducted at higher strain amplitudes compared to that of lower strain amplitudes. The study proved that fatigue life decreased with increasing temperature and strain amplitude.

In a comparative study carried out [6] for P91 and P92 in order to study the behavior of the two metals at high temperature it was found that both the steels exhibited a softening behavior before the final drop occurred due to crack propagation.

The strain controlled fatigue tests were performed at a temperature of 823 – 873K at a constant strain rate. The results showed that in general P92 exhibits a lower stress response as compared to P91 but at lower strain amplitudes it showed a higher stress response than P91. Also the softening rate of P92 was found to increase with increasing strain amplitude and the fatigue life exhibited a mixed behavior i.e. higher at higher strain amplitudes and lower at lower strain amplitude as compared to P91. Figure 5 (a) shows the softening rate and figure 5 (b) the strain life plots for both the materials.



a) *Cyclic softening rate as a function of total strain amplitude and temperature*



b) *Strain – life plots for P91 and P92 steels.*

Fig5. *Comparisons of P91 and P92 LCF behaviors*

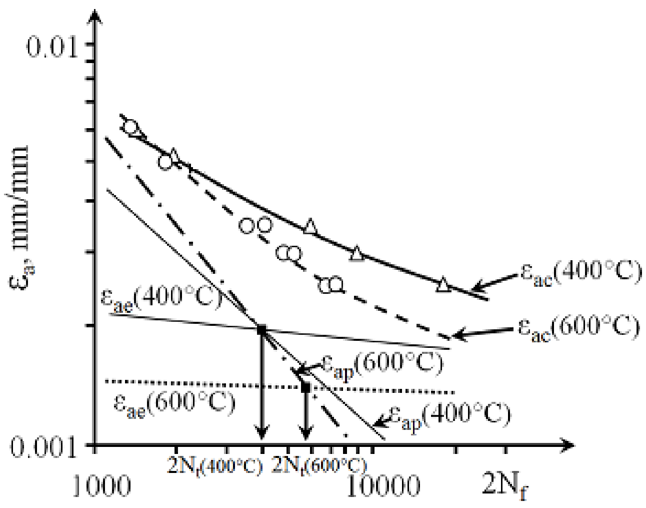


Fig6. *Low cycle fatigue life of GP91 cast steel at 400 and 600oC temperature*

In a work carried out to investigate the properties of GP91 at elevated temperatures [7] fatigue tests were conducted at five levels of strain amplitudes and at a temperature of 400, 550 and 600° C. All tests showed strong cyclic softening without stabilization period of loop parameters. It was also concluded that the fatigue lifetime as shown in figure 6 decreased as the temperature increased and the effect of temperature was more pronounced at low strain amplitudes.

2.3 Notched Specimen at Room Temperature

As mentioned earlier the life prediction using specimens with notch leads to more accurate life prediction when applied to practical problems. A notch in the geometry leads to stress concentration which can be effectively obtained by finite element simulation of the component under cyclic loading. Life prediction of a particular material by Finite Element simulation can be easily done by the advanced engineering software available. The simulation can be done for varying stress and strain amplitudes and the hysteresis as well as the E-N curve can be plotted along with the stress and strain distribution contour plot of the model. This is also possible for different loading condition. The basic requirement is a geometrical, mathematical and a material model for the respective material. The material model consists of the values of various material parameters and constants involved in the mathematical model used for the simulation. These values are obtained from the experimental results.

In a recent study [8] it was concluded that if the correct values of actual maximum strain are compared with the fatigue life, the same relationship will be obtained for the same material for any geometry. Also not only this, the total strain-life curve generated from fatigue test of round specimen can also be used for the prediction of life for notched specimens based on actual strain developed at notch tip. In this study the local stress strain at the notch was obtained from the FE results based on Armstrong-Frederick kinematic hardening model and cyclic hardening material model.

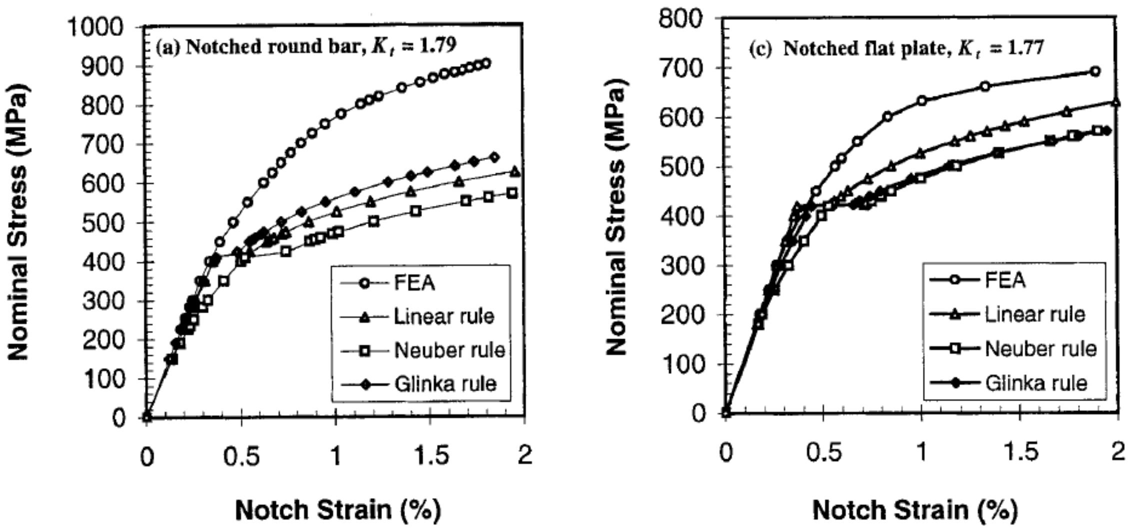


Fig7. *Notch root strains from finite element analysis, the linear rule, the Neuber rule and the Glinka rule under monotonic tensile loading*

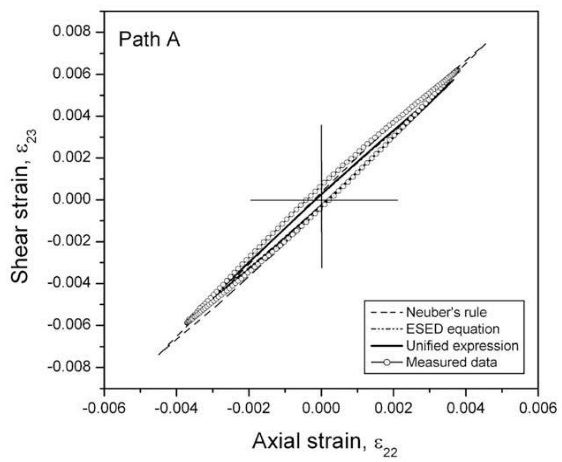


Fig8. *Notch-tip elastic–plastic shear vs. axial strain for proportional cyclic load path A*

Zeng [9] compared the elasto-plastic stress strain behavior at notch roots obtained by using linear rule, Neuber’s rule and Equivalent Strain Energy Density method (Glinka rule) with the experimental and finite element results as shown in Fig. 7 for notch round bar and notched flat plate. The notched round bar and notched flat plate represented plane strain and plane stress condition respectively. The results were obtained for different notch geometries and under monotonic and cyclic loadings. From the results it was clear that Neuber's rule works best when local region is in a state of plane stress and Glinka's rule for plane strain condition. Also the notch tip stress distribution does not exhibit any strong dependence on the global geometry. Thus a simplified analytical method [10] was developed to approximate the actual elastic–plastic notch-tip material behavior. This unified expression provides a more logical approximate approach for estimating the notch stress and strain responses of components subjected to multiaxial cyclic loading histories for local strain approach fatigue crack initiation life prediction. This gave a more accurate prediction than the most frequently used Neuber rule and the Equivalent Strain Energy Density (ESED) method. Fig. 8 show the comparisons of the calculated values of the axial versus shear notch-tip strains according to the unified expression, Neuber's rule and the ESED method, respectively, with the measured data for biaxial proportional cyclic loading path A. In the case of elastic–plastic deformation [11], Neuber's rule inevitably overestimated the actual stress and strain at the notch tip, while the equivalent strain energy density (ESED) method underestimated the actual notch-tip stress and strain.

2.4 Notched specimen at High Temperature

In the life prediction study of SAE 1040 [12] under multiaxial fatigue condition, experiments were conducted under combined bending and torsional cyclic loading on a modified Rotating Bending Machine using notched specimen. It was concluded that under multi axial fatigue loading equivalent strain on the critical plane based on Lohr-Ellipson approach yielded a closer match of the predicted life with experimentally observed life. A unified, viscoplasticity model [13], which includes combined isotropic softening and kinematic hardening with a viscoplastic flow rule for time-dependent effects, was used to model the thermal mechanical fatigue behaviour of the steels. The prediction of the model was further improved by including the linear and nonlinear isotropic hardening in order to obtain better stress-strain behaviour in the stabilization period. The developed viscoplasticity model was subsequently used in the finite element simulations using the ABAQUS software. The focus of the simulation was to validate the performance of the model under various types of loading. Simulation results were compared with the isothermal test data with different strain ranges and also the anisothermal cyclic testing data, for both in-phase and out-of-phase loadings. The simulation results showed a good comparison to the experimental data. The model's performance under 3-dimensional stress conditions was investigated by testing and simulating the P91 steel using a notched specimen under stress-controlled conditions. The cyclic notched bar tests on P91 steel were performed using a fully reversed load-controlled condition in order to verify the capability of the material model under multiaxial conditions. The stress value was chosen in order to produce a similar strain range effect, on the notch section, as that in the isothermal strain-controlled tests on a P91 solid specimen at 600°C.

3. MATHEMATICAL MODELS

In all the literature cited above the strain life relationship referred for plain 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: ε_t = Total true strain

E = Modulus of Elasticity

σ'_f = regression intercept called the fatigue strength coefficient

N_f = number of cycles to failure

b = regression slope called the fatigue strength exponent

ε'_f = regression intercept called the fatigue ductility coefficient

The widely used approaches to notched fatigue behavior are generally known as the local stress–strain approaches. These approaches are based on relating the crack initiation life at the notch root to the crack initiation life of smooth laboratory specimens. The study of notch behavior by using the local approach usually includes two steps. The first step is to estimate the local damage using a parameter such as stress, strain or plastic energy density at the notch root. The second step is to predict crack nucleation life based on uniaxial smooth specimen tests, where it is assumed that smooth and notched specimens experience the same number of cycles to failure if they have the same local damage values. Therefore, predicting the local stress– strain behaviour is essential to the understanding of notch fatigue behaviour and of fatigue life prediction. The commonly used notch stress and strain models are the linear rule, Neuber's rule and Glinka's rule. A review of these models was done by Zeng [9] in his study of Elasto-Plastic stress and strain behavior at notch roots under monotonic and cyclic loadings. A unified expression of elastic–plastic notch stress–strain calculation in bodies subjected to multiaxial cyclic loading was proposed by Duyi et al. [10]. It is formed on the basis of the thermodynamic analysis of the notch-tip material element during cyclic plastic deformation and under an assumption of so-called localized plasticity. The expression is as follows:

$$\Delta\sigma_{ij}^{e}\Delta\varepsilon_{ij}^{e} = \Delta\sigma_{ij}^{U}\Delta\varepsilon_{ij}^{U} + C_q \Delta W_p (\Delta\sigma_{ij}^{U}, \Delta\varepsilon_{ij}^{U})$$

where - Cq ($0 \le Cq \le 1$) denotes the ''energy dissipation coefficient''

- the second right hand term represents the heat energy dissipated during cyclic plastic deformation &

- the superscript U denotes the elastic–plastic notch-tip components as estimated by the proposed expression

In the proposed theory the thermodynamic analysis exhibited the fact that when a notched body is subjected to cyclic external forces, resulting in the localized plastic deformation in the notch-tip region, only a small part of the deformation work, namely the stored energy, contributes to the notch-tip stresses and strains through cyclic strain hardening. Most of the plastic deformation work is dissipated in the form of the heat that does not influence the notch-tip stress and strain states. The new unified expression was developed considering an energy dissipation coefficient whose value is 0 for Neuber's rule and 1 for ESED method. Therefore Neuber's rule and ESED method formed the upper and the lower bound limits of the notch - tip stress and strain estimation. The above expression was experimentally verified and compared with Neuber's rule and ESED method under both proportional and non proportional loading paths.

4. CONCLUSION

From the above study it can be concluded that basically there are three ways by which the Low cycle fatigue life of a component made of a particular material can be predicted at the design stage. These are

1. Experimental results obtained by conducting cyclic test on specimens made of the same material under different strain amplitudes and loading condition.
2. Numerical methods which involves a mathematical model describing the behavior of the material. But in order to obtain the results using numerical simulation the values of the material properties and constant involved are required. These are obtained either from the standard data available for the existing material or have to be obtained by testing the material in laboratory if the material is new.
3. Finite Element simulation using available softwares which also requires material properties for carrying out the analysis.

Experimental measurements and numerical simulations are often too expensive and time-consuming especially when components are subjected to long arbitrary multiaxial cyclic loading histories in service. Therefore finite element analysis predictions have been widely used by researchers for evaluating the different models used for life prediction.

Table1. *Life prediction using Plain Specimen*

Sr. No	Specimen used for Analysis	Temp	Material	Model	Loading condition	Strain Range (%), Gauge Dia. (mm)	FEA Done	Researcher
1	Plain	RT	316L(N)	Strain energy based	R = -1 (Fully Reversed)	0.3 – 1.0 10 mm	Yes	Roy, 2012
2	Plain	RT	P91 & P92	Smith, Hirschberg and Manson's dependence	R = -1 (Fully Reversed) & Graded loads	0.6 – 1.2 12 mm	No	Junak, 2011
3	Plain	RT	GP91	Coffin-Manson-Basquin Equation	R = -1 (Fully Reversed)	0.25 – 0.6 8 mm	No	Golanski, 2011
4	Plain	HT 550°C & 600°C	P92	Coffin-Manson Equation	R = -1 (Fully Reversed)	0.25 – 0.6 10.0 mm	No	Kannan, 2010
5	Plain	HT 823 & 873 K	P91 & P92	-	R = -1 (Fully Reversed)	0.25 - 0.6.	No	Kannan, 2013
6	Plain	HT 400, 550 and 600oC	GP91	Coffin-Manson Equation	R = -1 (Fully Reversed)	0.25 - 0.6 8 mm	No	Mroziński, 2013

(RT – Room Temperature, HT – High Temperature)

Table2. *Life prediction using Notched Specimen*

Sr. No	Specimen used for Analysis	Temp	Material	Model	Loading	Notch Radius	FEA Done	Researcher
1	Plain & Notched specimen	RT	SS316	Strain Life Approach	Cyclic Loading	3 mm for notch angle 30°, 45° and 60°	Yes	Joadder, 2011
2	Notched round bar and notched flat plate	RT	MA Steel	Linear, Neuber and Glinka rule	Monotonic and Cyclic Loadings	Round bar - 0.529 & 1.588 Flat plate – 2.778 & 9.128	Yes	Zeng, 2001
3	Notched Specimen	RT	S460N	Unified Expression	Non Proportional Cyclic loads	1.4 mm	Yes	Duyi, 2008
4	Plain & Notched specimen	HT 400, 500 and 600˚C	P91-92	Unified viscoplasticity model	Fully-reversed, (In-phase and out-of-phase)	2 mm	Yes	Hyde, 2012

On the basis of the present survey done it can be concluded that FE simulation can be effectively used for life predictions of different material once the material properties are known. So the best procedure for predicting low cycle fatigue life of the component would be:

1. Testing plain specimens in laboratory in order to obtain the material properties
2. Incorporating a perfect mathematical model considering the kinematic and isotropic hardening and softening behavior of material and the temperature effect in FE simulation.

3. Predicting the localized stress strain values by performing fatigue test on notched specimen using FE simulation.
4. Predicting the life of the component using the localized stress strain values using mathematical model incorporated in FE simulation.

Apart from the above conclusions the material behavior the two important structural material used for nuclear components are as follows:

1. 316L(N)
   a. Initial hardening for a few cycles followed by prolonged softening, saturation and final failure.
   b. Masing behavior at lower amplitudes and non masing behavior at higher stain amplitudes
2. P91 & P92
   a. Cyclic softening behavior
   b. For test of P92 at high temperature, the softening rate was more for the tests conducted at higher strain amplitudes compared to that of lower strain amplitudes and fatigue life decreased with increasing temperature and strain amplitude.
   c. In general P92 exhibits a lower stress response as compared to P91 but at lower strain amplitudes it showed a higher stress response than P91.
   d. The softening rate of P92 was found to increase with increasing strain amplitude and the fatigue life exhibited a mixed behavior as compared to P91.

The different studies carried out by the researchers with the model and geometry of the specimens used are presented in a tabular form in Table 1 and Table 2 for plain and notched specimen respectively. Further studies in developing the FE simulation technique are under progress in order to incorporate various theories developed [14] to predict the life of material under low cycle fatigue.

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