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Modeling and Finite Element Method Analysis of Fatigue Failure of 8.72Cr-0.9Mo Steel Boiler Heat Tube

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ABSTRACT
In power plant heat tube is the main component where the water is changed to high-pressure steam, it operates under corrosive and high temperature environment. Corrosive environment and cyclic temperature fluctuation cause fatigue on boiler heater tube, and which degrade life of the component. This paper presents corrosion rate by volumetric pit growth, crack initiation and crack propagation of boiler heat tube for power plant under cyclic thermal load. 8.72Cr-0.9Mo steel is one of the steel type which mostly used nowadays as boiler heat tube. Volumetric pit growth rate approach used for crack initiation and energy release rate approach (J-integral) used to find crack propagation phenomenon. Temperature is taken in the interval of 25°C-500°C, and it has a significant effect on rate of chemical reaction (corrosion rate) and material properties. The results show 906Mpa and 895Mpa thermal stress induced at crack tip at 500°C from analytical and FEM respectively. And also energy release rate results are 33.4J/mm^2 and 35.43N/mm^2 from analytical and FEM respectively. From the result, material reach fatigue limit in the range of low cycle fatigue having the value less than 10^4 cycles. The existence of corrosion reduces crack initiation cycles since crack initiation is speed up by the presence of corrosion.

Keywords-- Corrosion pit, Crack initiation, Crack propagation, Strain energy density, Strain energy release rate

INTRODUCTION

Failure is a problem that society has faced for as long as there have been man-made structures. The engineering communities have responded to prevent failure occurring. Fatigue has discovered in 1800s when several components like bridge and rail way components are cracking [1]. In 20 century, many revolutionary design philosophies, inspection techniques and practices, material development and material processing and controls have redefined the criteria for failure. During the past four decades, an extensive research of fracture mechanics has greatly enhanced the understanding of structural failure [1].

Fatigue is the failure of material caused by cyclic loading. It is the most common source of behind failures of mechanical and thermal loaded structures. Fatigue failure has three stages. The first stage is crack initiation stage which takes large number of cycles where microscopic crack is changed to macroscopic crack. The second is macroscopic crack grows for each cycles until it reaches a critical length (propagation stage). And the third stage is physical failure of the component and where breaking is happen. This kind of fatigue is one of the forms of environmentally induced cracking. Some of the factors that have a strong influence on corrosion fatigue are temperature, PH, pressure of the gaseous environment, and concentration of the corrosion species [2]. Many high performance structural metals operate under this deleterious environment which causes failure to the components [3].

There are many factors corrosion to occur; the factors like presence of moisture, surface irregularity, presence of oxygen and inhibitors. Temperature is a parameter which accelerates the rate of corrosion.

Since the outer surface of the tube exposed to corrosive environment, corrosion occurred or detected on the surface. The localized corrosion attack on the surface of the tube creates a pit and under cyclic thermal

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stress this pit grows to crack or initiate a crack. Thermal stress cycles happened during heating and cooling of the system. The cycle is natural in power plant since there is cyclic operation and shutdown cycles.

Figure 1: *Corrosion of boiler tube and its failure[4].*

Fossil fuel is the main source of heat energy in power plant industries. There are two types of mechanisms used to convert water into steam during power generation. These are water-tube boiler and fire-tube boiler mechanism. Fire tube boiler or heat tube is focus of this study. The above Fig. 1 shows the corrosion of boiler tube and its failure.

Factors Affecting Fatigue life

Fatigue is the weakening of the material caused by cyclic loading those results in progressive and localized structural damage and the growth of crack. Crack initiation and crack propagation are two separate or different processes driven by different phenomenon. Fatigue life can be affected by a variety of factors, such as environment, surface finish, presence of oxidizing or inert chemicals, residual stresses, stress ratio, types of load, etc.

Stress Ratio

When stress is positive or tensile stress applied on the material crack will open, leaving the fresh material in its interior exposed to corrosive and aggressive atmosphere. As a time of exposure is high, corrosion damage high at crack tip. Crack propagation have directly proportional to stress ratio. When stress ratio is increased while the stress intensity (ΔK) is held constant, the crack tip strain and strain rate are increased, thus crack propagation will increased.

Types of Load

Load type significantly affects fatigue life of the material under cyclic loading. A load might be tensile, compressive or shear and these loads are different effect on fatigue life. Tensile load is significant for mode I cracking type, but compressive load reduce the effect of cracking, even it compressive residual stress added to material to resist failure under tensile load. Shearing load is significant in mode II cracking type which occurs by shearing along the plane.

Fracture Toughness

Fracture toughness is an implication of the amount of stress required to propagate an existing pit. The fracture toughness of a metal depends on factors like:

1. Metal composition
2. Metal temperature

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3. Extent of deformation to the crystal structure
4. Metal grain size
5. Metal crystalline form

Basic Assumptions

Operational boiler tubes may be considered as thin-walled cylindrical tube which subjected to thermal stress and corrosion media. To avoid complexity in engineering, different assumption should be taken. The following assumption is taken throughout the document:

1. The material is homogeneous and isotropic
2. Material properties is temperature-dependent
3. Corrosion cause pitting which later changed to crack
4. Radial stress is assumed to be zero since the wall thickness is small when compared to diameter of tube
5. Circumferential (hoop) stress and longitudinal (axial) stress is used throughout analysis
6. Plastic deformation at crack tip
7. Plane-strain analysis
8. There is no creep-fatigue since creep is activated at half the melting point of the metals

Temperature-Dependent Material Properties

Mechanical characteristics of most materials are greatly influenced by the operating temperature. Young's modulus is temperature-dependent parameter or a material property which changes with temperature is shown in Fig. 2.

$$\frac{E(T)}{E(20)}=1.0+\frac{T}{2000\ln\left(\frac{T}{1100}\right)} \quad \text{for } 20^{o}\leq T\leq 600^{o} \qquad (1)$$

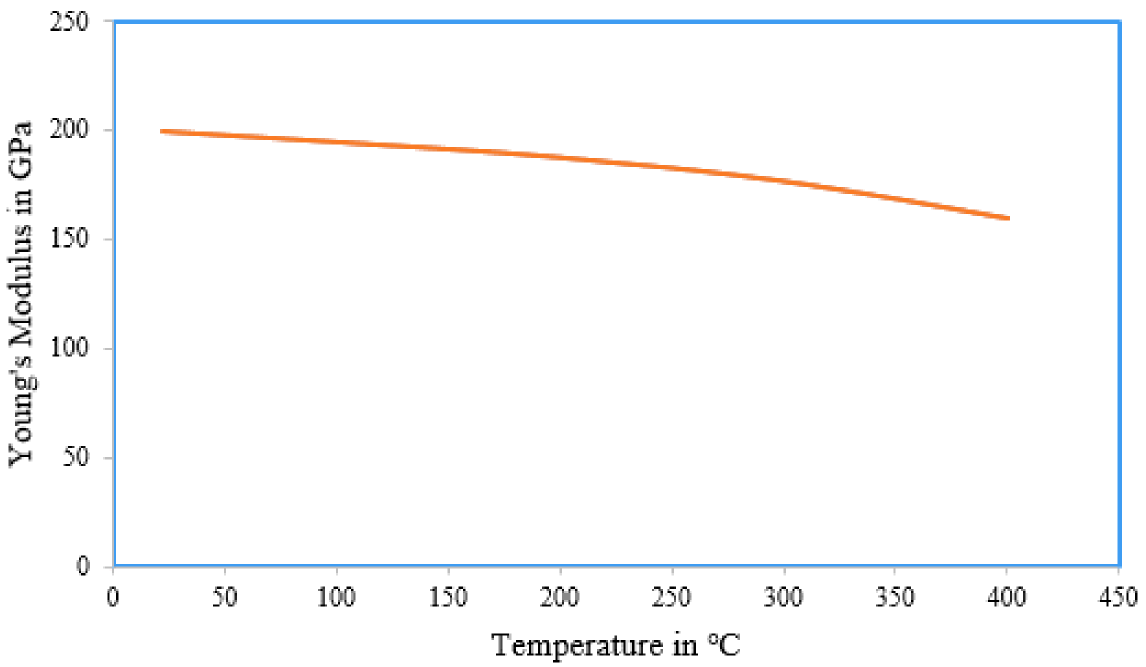

Figure 2: *Young's modulus response to change in temperature.*

Thermal Stress (Circumferential and Longitudinal Stress)

The stress-induced when the boiler tube is subjected thermal load. The stress during heating and cooling in both axial and circumferential stress will be equal and calculated as follow:

$$\sigma_a=\sigma_\theta=\pm\frac{\alpha E(T_o-T_i)}{2(1-v)} \qquad (2)$$

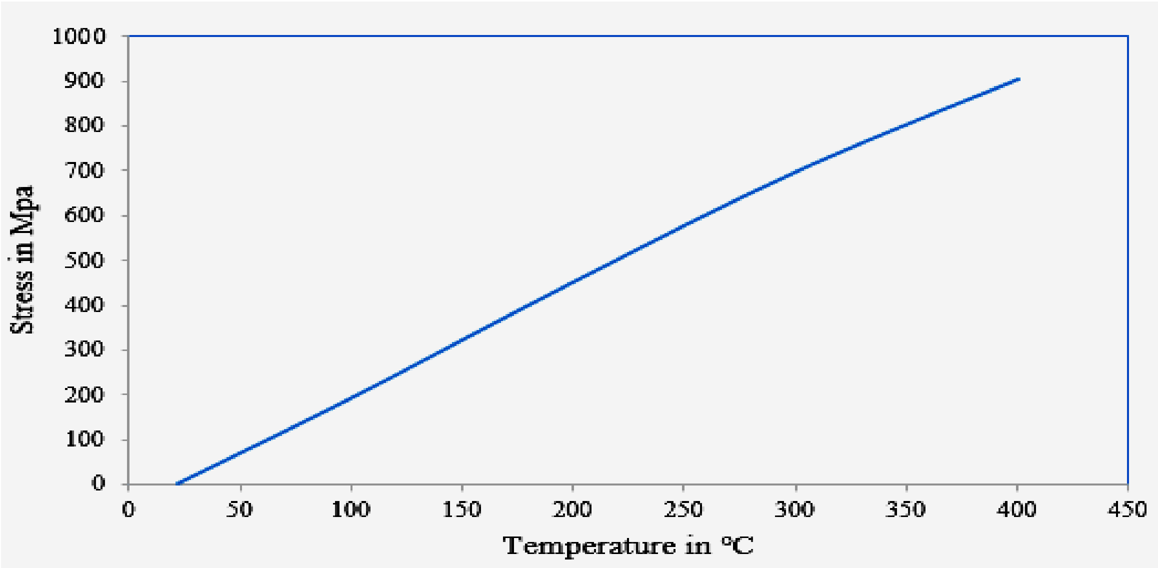

Figure 3: *Response of stress to temperature change*

Where σ_a is axial/longitudinal stress, σ_θ is circumferential stress, E is young's modulus of material, v is poison's ratio and α thermal expansion coefficient. The above graph (Fig. 3) shows the response of stress to temperature changes.

Temperature distribution through thickness

Since there is a temperature gradient across the thickness of the tube, when inner surface of the tube heated it expands but the outer part of tube resist this expansion.

$$T = T_i + \frac{(T_o+T_i)}{\ln\left(R_o/R_i\right)} \ln(R/R_i) \tag{3}$$

Where R_o is the outer radius, R_i is the inner radius, T_o is the outside temperature and T_i is the inside temperature. However, temperature change is insignificant when the thickness of the wall is very small.

Thermal Strain

Temperature change can also cause strain. In anisotropic material, the thermally induced extension strains are equal in all directions, and there are no shear strains.

$$\varepsilon_\theta = \frac{1}{E}[\sigma_\theta - v(\sigma_r+\sigma_a)] + \alpha\Delta T \tag{4}$$

$$\varepsilon_a = \frac{1}{E}[\sigma_a - v(\sigma_r+\sigma_\theta)] + \alpha\Delta T \tag{5}$$

Where ε_θ is circumferential strain, ε_a is axial/longitudinal strain and σ_r is radial stress. Radial stress is assumed to be zero since tube has small wall thickness. So, radial strain becomes zero.

LOW CYCLIC FATIGUE

In S-N curve (Fig. 4) the region can be divided into three regions. In region I, about 10^4-10^5 cycles, the material is stressed in the vicinity or beyond the yield stress. In this region material deforms plastically and the plastic strain dominates the fatigue life and it described as low cycle fatigue region.

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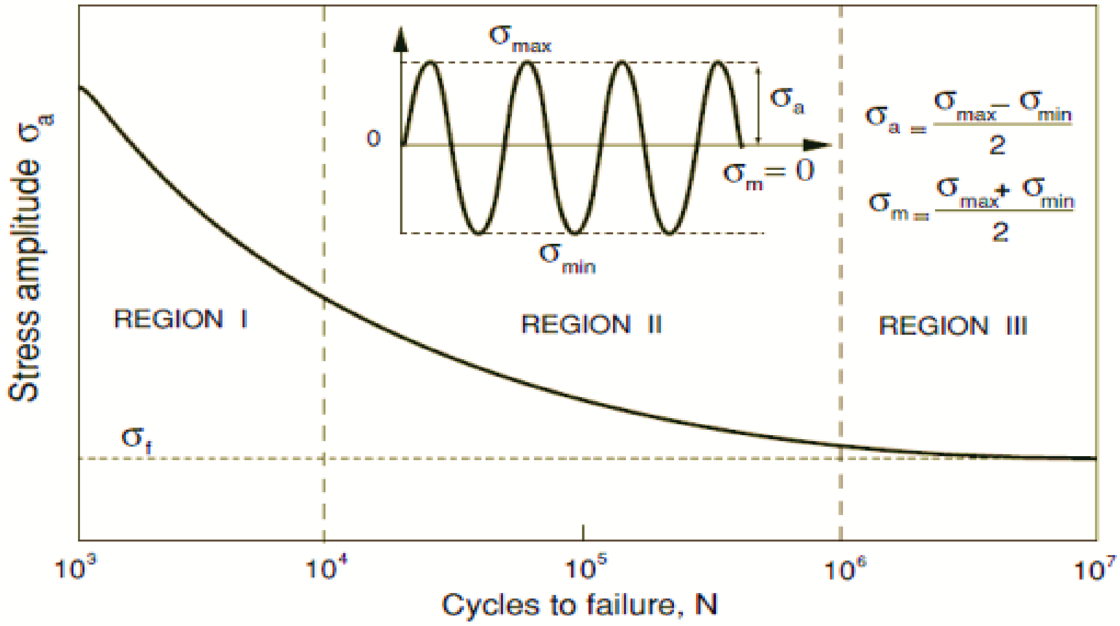

Figure 4: *A schematic of typical S-N curve showing the stress amplitude versus cycles to failure[5].*

Paris and Erdogan have been proposed the expression which govern fatigue crack propagation rate. However, this expression is limited elastic strain range fatigue (region III) which does not describe plastic strain range or region I.

But, it can be extended fracture mechanics concepts from linear-elastic to behavior to elastic-plastic behavior by using J-integral approach.

Modes of Failure

There are three cracking modes in fracture mechanics and they are linearly independent. These modes are categorized as Mode I, II, or III as shown in below Fig. 5.

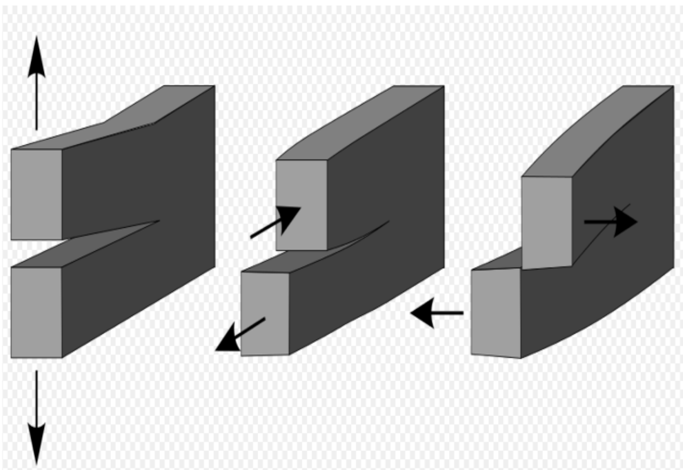

Figure 5: *Opening or mode I (left), sliding or mode II (middle) and tearing or mode III (right).*

Crack Initiation

There different types of reasons to initiate crack. Factors like porous during manufacturing, corrosion pitting, flaw happen under operation and other factors. Cracks start at the surface of the material where the highest stress is normally found. SCC frequently initiates at pre-existing or corrosion-induced surface features or pits formed during exposure to service environment. In boiler tube the rust $Fe_2O_3.xH_2O$ (iron oxide) which is transported to another surface of the tube is eroded by pressured water inside the system.

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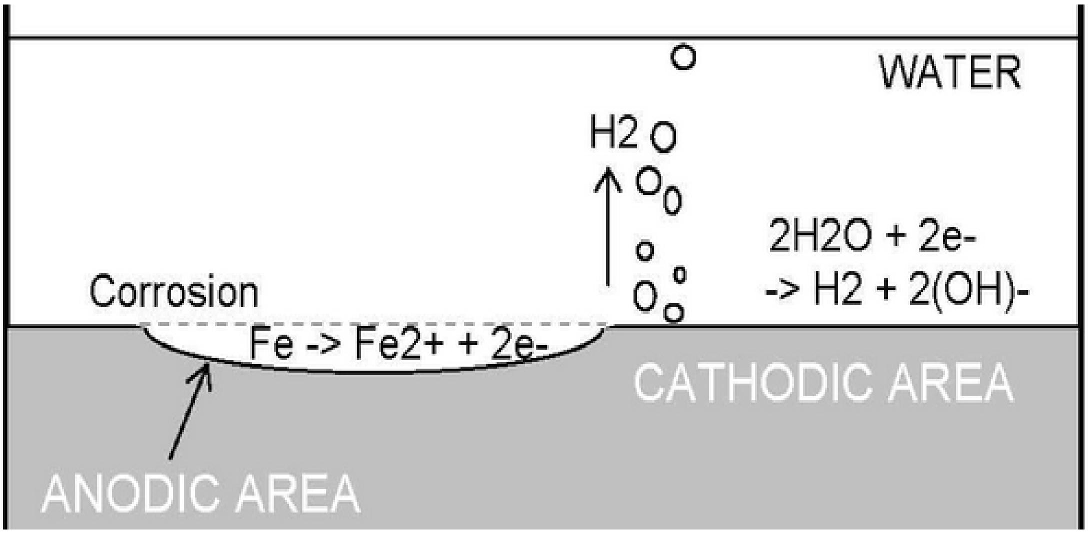

Figure 6: *Anodic and cathodic reaction of the metal under corrosion [6].*

The speed is depends on environmental condition and types of metal. The parameters, which affect the corrosion rates, are generally: solution chemistry, metallurgical and mechanical presence of stress as shown in Fig. 6.

An increase in temperature will generally increase the rate of corrosion. A rule of thumb is that temperature increases of 10^{o}C will double the corrosion rate. Thus, corrosion rate can be described using Arrhenius equation.

$$CR = A\exp^{-Ea/RT} \qquad (6)$$

Corrosion pitting is characterized by the formation of small cavities (pits) in the metal. Pitting is often difficult to detect and monitor. Pitting is the main types of destructive form of corrosion that affect boiler heat tubes as shown in Fig.7.

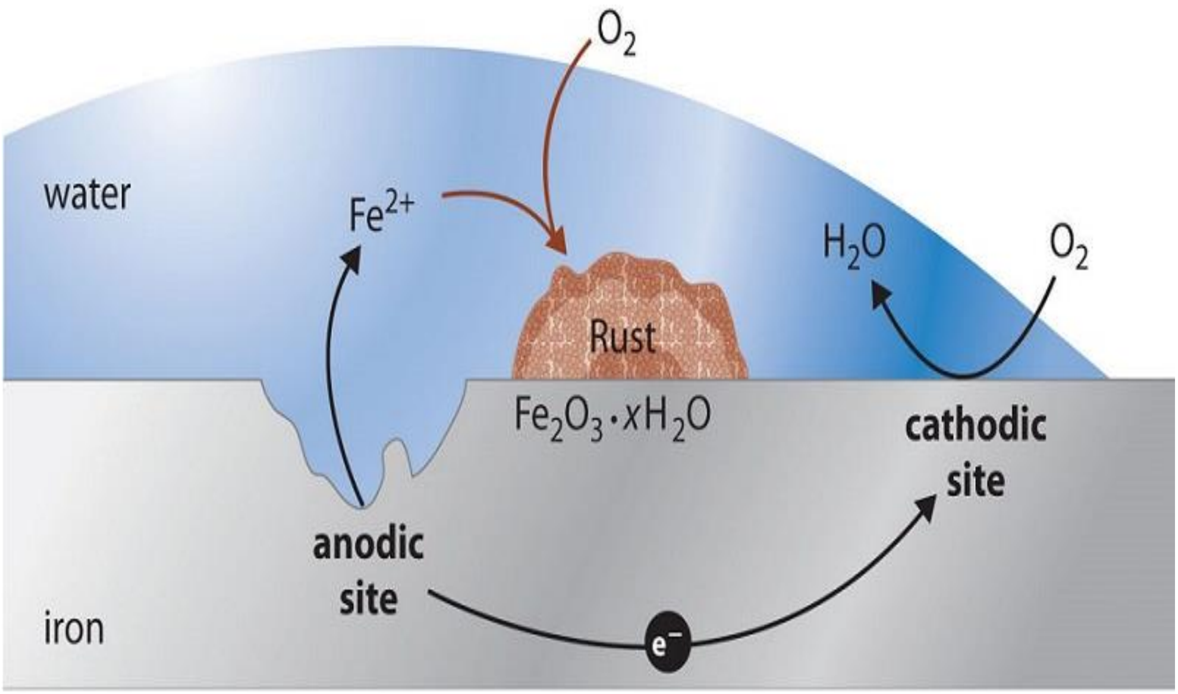

Figure 7: *Pit formation [6].*

Corrosion induces the pit on the surface of tube and which is later changed to small crack by the action of cyclic stresses.

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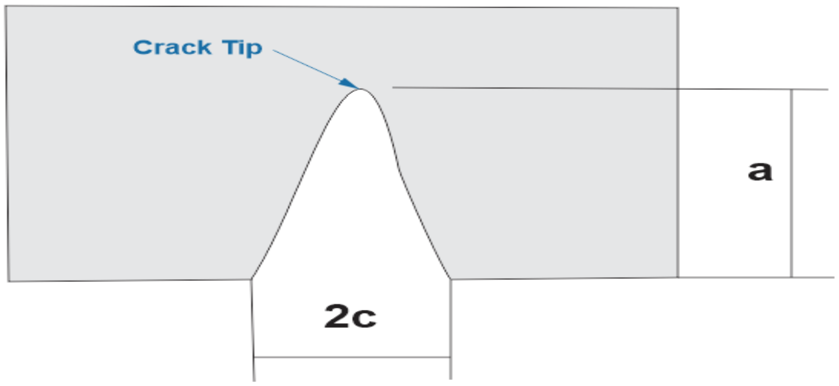

Figure 8: *Elliptical pit opening and its depth or length.*

Kondo has proposed that experimentally, opening radius of corrosion pit (c) can be described using the equations below considering pit as semi-ellipsoidal, the volume of this pattern can be calculated:

$$V=\frac{2}{3}\pi c^2 a \qquad (7)$$

According to Faraday's law pit grow at a constant volumetric growth rate

$$\frac{dV}{dt}=C_p=\frac{MI_P^o}{nF\rho}\exp\left(-\frac{\Delta H}{RT}\right) \qquad (8)$$

The number of cycles to initiate the crack will be

Crack Propagation

During crack propagation stage, crack generally accelerates and takes shorter period of time than initiation stage. Crack growth can cause catastrophic sudden failure especially under a risky operation. It is depends on several factors, such as bulk material properties, body geometry, crack geometry, loading distribution, loading rate, loading magnitude, environmental conditions, and microstructure.

Prediction of Strain based fatigue life using Manson and Coffin Equation

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.

Cyclic fatigue ductility exponent and cyclic fatigue ductility coefficient are a parameters used find fatigue life in LCF. These parameters are temperature-dependent properties of the material as shown in Fig. 9.

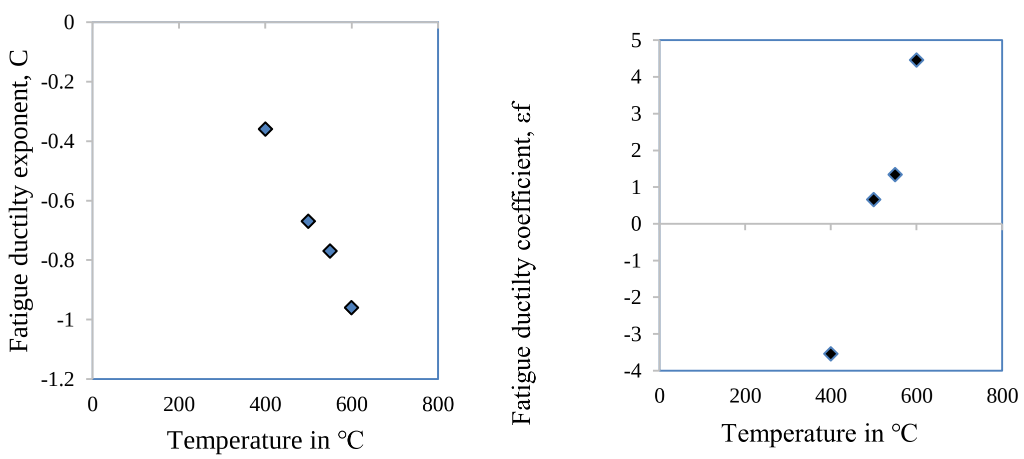

Figure 9: *Fatigue ductility exponent, C and fatigue ductility coefficient, εf.*

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For low cycle fatigue in plastic range, the number of cycle to failure can be calculated by Coffin and Manson relation.

$$N_{f,LCF}=\frac{1}{2}\left(\frac{\Delta\varepsilon_P}{2\varepsilon_f'}\right)^{1/C} \quad (10)$$

Where $\Delta\varepsilon_P$ plastic strain amplitude, $\varepsilon_{f'}$ fatigue ductility coefficient and c is the fatigue ductility exponent.

J-Integral Approach for Large Plastic Strain

Crack extension occurs when material at the crack tip exceeds its fracture strain due to continued strain cycling. Fatigue crack growth rate (FCGR) can be expressed by elastic-plastic components of ΔJ integral by power law. J-integral is the rate at which energy is transformed as a material undergoes fracture and has units of energy-per-unit area.

$$\frac{da}{dN}=C(\Delta K)^m \quad (11)$$

Where C_f *and* m_f are a material constant and it is assumed that R= 0 and J-integral range ΔJ_{el} is calculated if only mode I is considered.

$$\Delta J_{el}=\frac{K_{max}^{2}}{E^*} \quad (12)$$

$$E^*=\frac{E}{1-v^2} \quad (13)$$

$$\Delta J_{ep}=f_{ep} x\Delta J_{el} \quad (14)$$

$$f_{ep}=\frac{\sigma_{ref}^{3}}{2\sigma_y^{2}E\varepsilon_{ref}}+\frac{E\varepsilon_{ref}}{\sigma_{ref}} \quad (15)$$

$\boldsymbol{\sigma_{ref}}$ is the reference stress calculated at the maximum load of the cycle. Here the J-integral is in plastic range, so that cyclic J-integral equal to elastoplastic cyclic J-integral. $C_f=3.05x10^{-5}$ and $m_f=1.31$ for specific material used for this study.

FINITE ELEMENT METHOD SIMULATION

Finite element method is the most widely used method to solve problems in engineering and mathematics fields. It is a numerical technique used to perform finite element analysis of any given physical phenomenon and gives us solution in the forms different outputs which is easy to understand by the experts or readers.

The ABAQUS/CAE is FEA product suite offers powerful and complete solutions for both routine and sophisticated engineering problems covering a vast spectrum of engineering applications as shown in Fig. 11. Fig. 12 and Fig. 13 show the stress distribution around crack tip and under thermal stress respectively. Plastic strain energy density is shown in Fig. 14.

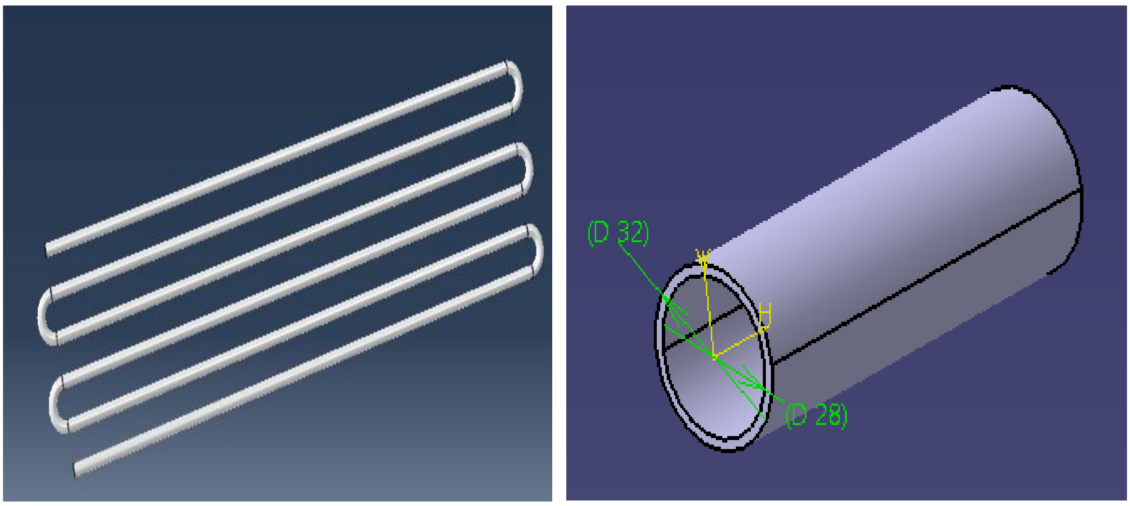

Figure 11: *Abaqus model of boiler heater tube.*

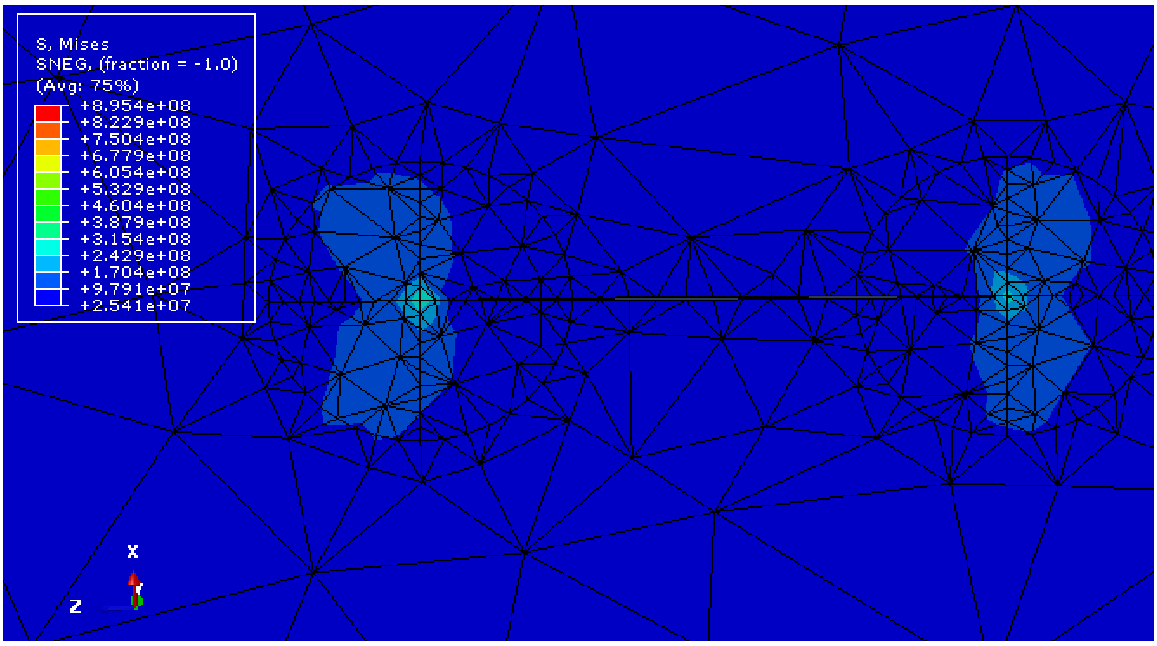

Figure 12: *Stress distribution around crack tip (Von-Mises stress).*

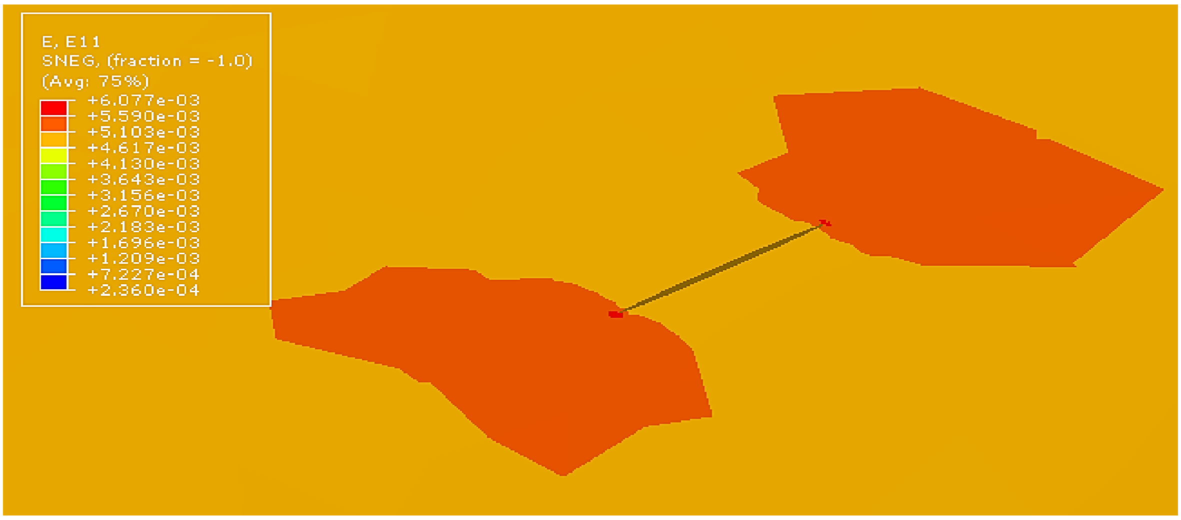

Figure 13: *Strain at the crack tip under thermal stress.*

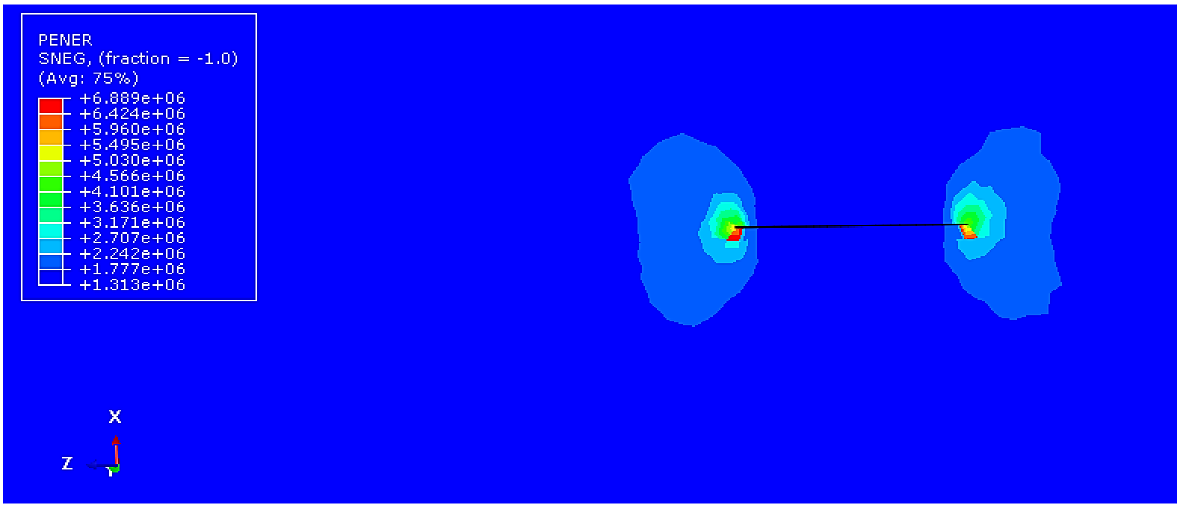

Figure 14: *Plastic strain energy density (PENER).*

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RESULT AND DISCUSSION

Whenever the material is a under a load, it will respond to the applied load, this applied load develop stress on the material and it might deform elastically or plastically. Nowadays 8.72Cr-0.9Mo steel mostly used material in power generating power plants and reactors.

The result shows in Fig. 15 change in temperature has great influence on rate of corrosion. It influences the rate of corrosion by increasing kinetic energy at molecular level. This facilitates the collision between participles which can alter the reaction rate. Especially, above 250º there is a significant change in volumetric pit growth rate.

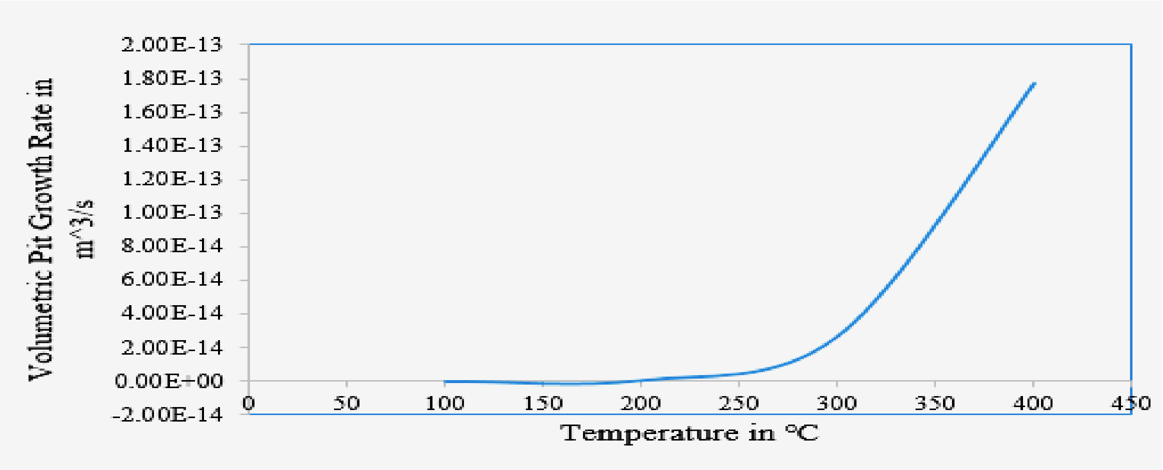

Figure 15: *Volumetric pit growth rate response to temperature change.*

Pit to crack transition happen when pit reach critical value a_{cr} and transition depends on different factors like volumetric pit growth rate, stress intensity factor, and cyclic stress. Volumetric pit growth rate is the main factor that affect this transition since the pit is initiated by the corrosion. A large volumetric pit growth rate reduce the cyclic life to initiate crack initiation and vice versa.

The comparison between other literature (experimental data) and analytical have a good agreement. Analytical result found taking the temperature of the surface of part 500°C and calculating the strain amplitude. Using Manson-Coffin expression the number of reversal to failure is calculated. The result from this expression has good approximation with other literature data.

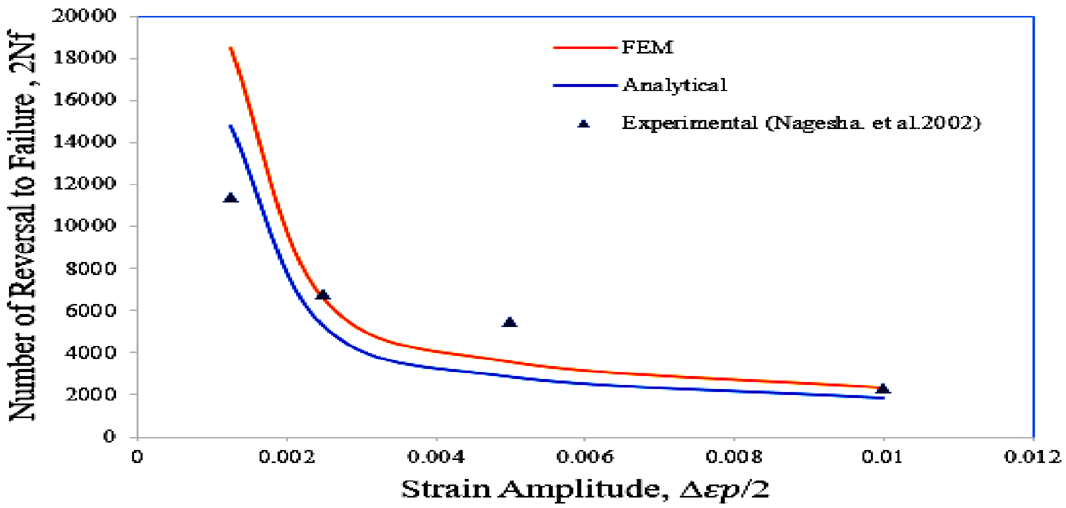

Figure 16: *Comparison between analytical, FEM and other literature (experimental result) using strain amplitude versus number of reversal to failure at 500ºC (773K).*

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From the result, it is observed that at large strain amplitude has low fatigue life as shown in Fig.16. The result computed by taking fatigue ductility coefficient $\varepsilon_f' = 0.66$ and fatigue ductility exponent C = -0.67 at 500℃ or 773k from experimental data.

Corrosion pit reduce the fatigue life with a significant value. In Manson-Coffin expression the fatigue life depends on the fatigue ductility exponent and fatigue ductility coefficient. The presence of pit and high temperature increase these values. The smaller the value of fatigue ductility coefficient and fatigue ductility exponent, large number of fatigue life and vice versa. The graph below (Fig. 17) shows the comparison between the fatigue life of boiler heat tube with corrosion pit and without corrosion pit. The result indicates there is a large difference between the two. However, the results have close result to each other for large cyclic strain amplitude.

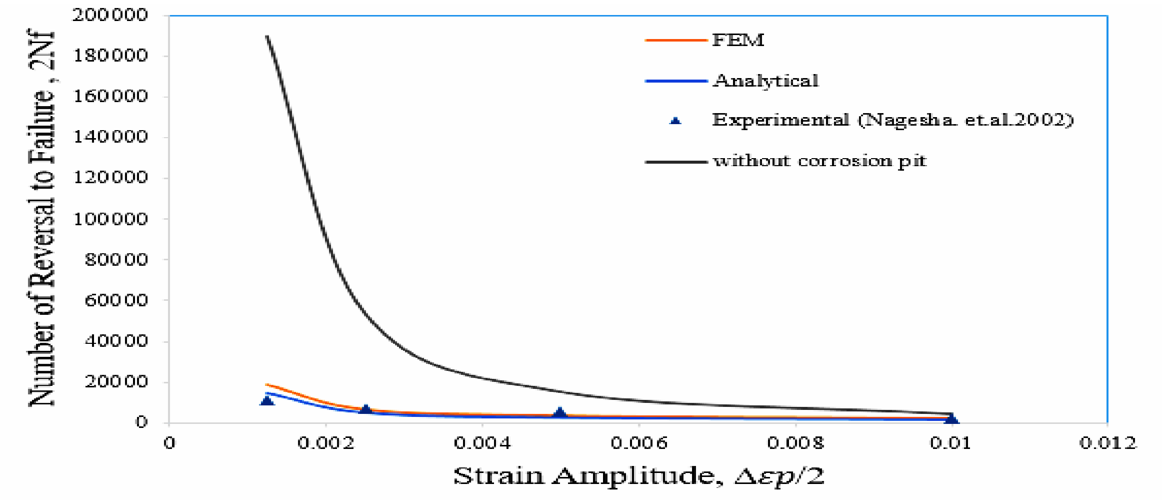

Figure 17: *Comparison between fatigue with corrosion pit and without corrosion pit.*

The result shows J-integral and crack growth rate have a direct proportionality. The graph below (Fig. 18) compares analytical result which is calculated, finite element and experimental data taken from the literature [7, 8]. Analytical model have very nice agreement with experimental data. From the graph, it is clearly observed that large crack growth rate means it release large energy during plastically deformation of crack tip.

The cyclic J-integral (ΔJ) finite element method (FEM) is estimated to 35.43N/mm or 35.43J/mm^2 at 500℃ and from analytical approach is calculated to 33.4N/mm at the thermal load.

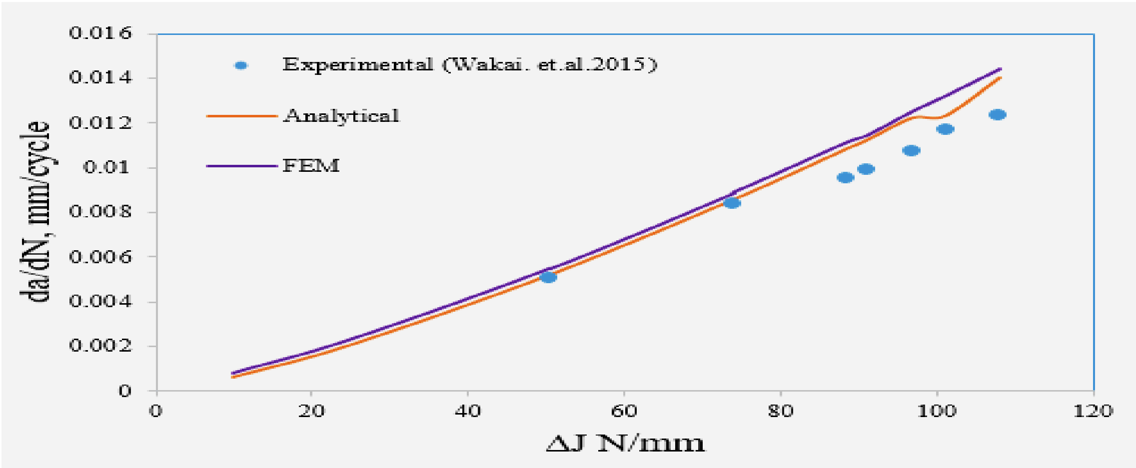

Figure 18: *Comparison of analytical, FEM and other literature (experimental data) of crack growth rate versus cyclic J-integral.*

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The result shows, fatigue condition is within range of the low cycle fatigue (below 10^5 cycles). Crack propagation (crack size versus number of cycles) found very close value with experimental result. This graph (Fig. 19) shows the comparison of analytical, FEM and experimental data (other literature). The results have good agreement to each other with small deviation in acceptable range.

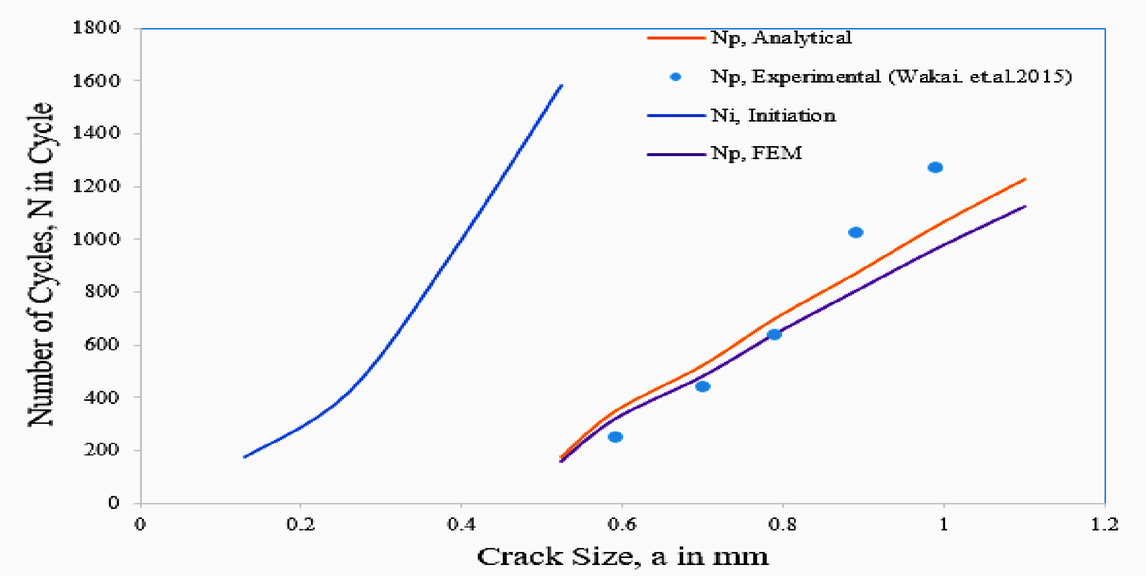

Figure 19: *Comparison between analytical, FEM and other literature (experimental data), crack initiation and crack propagation results.*

The total life the tube is the summation of number of cycles to take crack initiation N_{in} and number cycles takes during propagation stage N_p.

CONCLUSION

This study addressed a fatigue phenomenon of 8.72Cr-0.9Mo steel boiler tube under cyclic thermal loading and corrosion pitting. Analytical and finite element method (FEM) are two methods, and strain-based approach (i.e. low cycle fatigue), used during analysis. Corrosion rate in pit growth rate up to crack initiation and crack propagation were the main concern of this study.

The crack initiated by pit growth on the surface of the boiler. Pit growth rate can be influenced by temperature on surface of the tube. Temperature is most influencing factor. It also affects the material properties, like young's modulus, tensile strength, fracture toughness, and other mechanical properties which reduce the fatigue strength of the boiler. The overall changes in material have a negative effect on fatigue life of the component. That means it significantly affect fatigue life.

Crack propagation rate was estimated using energy release rate in both analytical and finite element approaches. Cyclic J-integral (energy release rate) method with Paris law was used and the result have good approximation with other literature (experimental data). As energy release rate increase, crack propagation rate increases. In normal fatigue analysis of the material, crack initiation takes longer time than crack propagation stage. However, here due to presence of corrosion crack initiation takes almost equal life cycles when compared to crack propagation stage in this study.

REFERENCES

1. Katarina M. Dragi S & Ivana V (2016). Determination of Fracture Mechanics Parameters Structural Components with Surface Crack Under Thermomechanical Loads. *Scientific Technical Review*, 66(3), pp.27-33, Available at: http://www.vti.mod.gov.rs/ntp/rad2016/3-2016/4/4.pdf.

e-ISSN: 2582-5747
Volume-6, Issue-1 (January-April, 2021)

2. Miguel L. & Infante B. Béjar M (2012). Corrosion-fatigue testing on steel grades with different heat and surface treatments used in rock-drilling applications. *DEGREE PROJECT IN MATERIALS SCIENCE AND ENGINEERING, Available at: https://www.diva-portal.org/smash/get/diva2:1040935/FULLTEXT01.pdf.*
3. Gangloff P (1995). Environmental cracking-corrosion fatigue. ASTM manual series mnl. pp. 253-271, Available at: https://www.astm.org/DIGITAL_LIBRARY/MNL/PAGES/MNL11032M.htm.
4. Ahmad J, Purbolaksono J & Beng LC (2010). Thermal fatigue and corrosion fatigue in heat recovery area wall side tubes. *Engineering Failure Analysis*, 17(1), pp. 334-43. DOI: https://doi.org/10.1016/j.engfailanal.2009.06.014
5. Agrawal R, Uddanwadiker R & Padole P (2014). Low cycle fatigue life prediction. International Journal of Emerging Engineering Research and Technology, 2(4), pp. 5-15. Available at: http://www.ijeert.org/pdf/v2-i4/2.pdf
6. Wang W & Hsu T (1994). Fatigue crack growth rate of metal by plastic energy damage accumulation theory. *Journal of engineering mechanics*, 120(4), pp. 776-95. Available at: https://ascelibrary.org/toc/jenmdt/120/4
7. Nagesha A, Valsan M, Kannan R, Rao B & Mannan SL (2002). Influence of temperature on the low cycle fatigue behavior of a modified 9Cr-1Mo ferritic steel. *International Journal of Fatigue*. 24(12), pp. 1285-1289, DOI: https://doi.org/10.1016/S0142-1123(02)00035-X
8. Wakai T, Inoue O, Ando M & Kobayashi S (2015). Thermal fatigue crack growth tests and analyses of thick wall cylinder made of mod. 9Cr–1Mo steel. *Nuclear Engineering and Design*. 295, pp. 797-803. Available at: https://doi.org/10.1016/j.nucengdes.2015.07.034