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Assessment And Comparison of Thermal fatigue Failure For BS 3059 Boiler Tube By Using Coffin-Manson Equation

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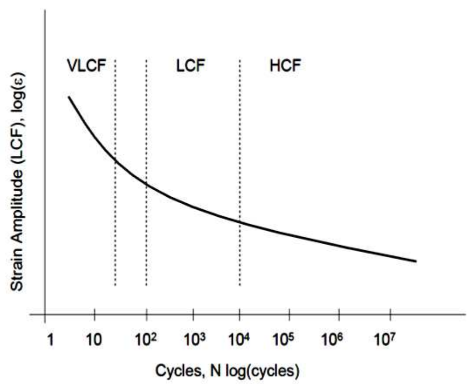
Abstract
This research highlights on the assessment of thermal fatigue failure for BS 3059/1087 Part 1 ERW 320 boiler tube using experimental procedure by using of smithy furnace and comparing with Coffin-Manson equation. Boiler tubes are highly affected by operating conditions like, high temperature and high pressure. So it needs periodic checking for the purpose of safety and health assessment of the plant. So using given technique we can identify the degradation of tubes at microstructure level and prediction life of the tube, So that one can conclude the current situation of the component and give respective judgment.

Keywords—BS 3059 tube, Smithy furnace, Metallurgical Microscope, Universal Testing Machine, Thermocouple.

Introduction
Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points, and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. Fatigue has been divided into three regimes, which depend on the number of cycles to failure as shown in graph-1. The number of cycles where transition from HCF to LCF behavior occurs varies by material.
One source suggests that high cycle fatigue is for cycles to failure greater than 105, and low-cycle fatigue is for cycles between 102 and 104. This source also advises that the phenomena of low-cycle fatigue changes below 20 cycles, and has termed this range very low-cycle fatigue (VLCF).



Graph-1.Graphical depiction of the three types of fatigue.

High cycle fatigue is defined by elastic stress governing the life, and low-cycle fatigue is defined where yielding effects (plasticity) govern the behavior. Lemaitre describes high cycle fatigue having stress amplitudes less than yield, and low cycle fatigue as having stress amplitudes between yield and ultimate strength. Stress controlled experiments are used to characterize HCF life, whereas strain-controlled testing is used to characterize LCF life [1].

Engineers and mathematicians have quantified metal fatigue with the use of sample testing. By testing small coupons of a given material, according to American Society of Testing Materials (ASTM) methods, engineers predicted the average life a material would have at a given stress or strain level. The results were typically depicted in the form of stress–cycles to failure or strain–cycles to failure. Traditionally, samples were tested with constant amplitude loadings. The heart of this analysis was the following relationship between stress and strain:

$\sigma_{stress} = E\,\varepsilon_{elastic}$………(1)

This equation describes the interaction between stresses applied to a material and the percent deformation due to those stresses (strain). The two are related by the elastic properties of the material, the Modulus of Elasticity (E). Upon loading, the material's deformation is resisted by the modulus of elasticity. Once the load is no longer applied, the material "snaps" back to its original size with no permanent deformation. When a material is never stressed to the point at which it permanently deforms, the material is said to be undergoing elastic strains. When this type of behavior is applied to alternating or cyclic stresses, it is describe as High Cycle Fatigue, since the material life-times associated with non-deforming load levels are much higher than materials subjected to loadings where there is permanent deformation. High Cycle Fatigue (HCF) is thus usually tested with constant amplitude load test. When the material does fail, the determination of the level of strain is a simple transformation:

$\varepsilon_{elastic} = \boldsymbol{\sigma}_{applied} \div \boldsymbol{E}$…….(2)

During testing, this equation is used to evaluate the strain at failure based on an established constant amplitude load level. At each failure, the number of cycles to failure (2Nf) is recorded. (A cycle is counted as, zero stress, to maximum compressive stress, to maximum tensile stress, and then back to zero load.) After many samples have been tested at different load levels the failure points are plotted on log-log paper, and predictions can be made about the life of the material based on a given stress level applied. The life is determined from the following equation:

$$\frac{\Delta\sigma}{2} = \boldsymbol{\sigma'}_f \times 2N_f^{\,b} \quad \text{………(3)}$$

$$\frac{\Delta\sigma}{2} = \text{stress amplitude}$$

$\boldsymbol{\sigma'}_f$ = fatigue strength coefficient

b= fatigue strength exponent

$2N_f$ = cycles to failure

In log space, a lined describes the trend of the data points. The fatigue strength coefficient is the Y intercept and the fatigue strength exponent is the slope of the line. During HCF the elastic strain equals the total strain. If materials are subjected to larger loads, when deformation takes place, it includes two effects, elastic and plastic. With a large enough load applied, a material will not "snap" back into shape after the load is released. Instead there will be some amount of permanent deformation. The relationship between strains is given as:

$\varepsilon_{total} = \varepsilon_{elastic} + \varepsilon_{plastic}$………..(4)

When permanent deformations occur, the Stress-Life Methods can no longer be used to analyze the strain at failure. Strain-Life Methods must be used. It was realized that a similar log-linear transformation could be applied to plastic strain.

$$\frac{\Delta\varepsilon\, plastic}{2} = \varepsilon'_f \times 2N_f^{\,c} \quad \text{……..(5)}$$

$$\frac{\Delta\varepsilon\, plastic}{2} = \text{plastic strain amplitude}$$

ε'_f = fatigue ductility coefficient

c= fatigue ductility exponent

As with the Stress-life equation, the fatigue ductility coefficient represents the Y intercept and the fatigue ductility exponent represents the slope of the log-linear line. If the Stress-life equation is converted to strain amplitude the following equation is derived:

$$\frac{\Delta\varepsilon\, plastic}{2} = \frac{\boldsymbol{\sigma'}f}{\boldsymbol{E}} \times 2N_f^{\,b} \quad \text{……… (6)}$$

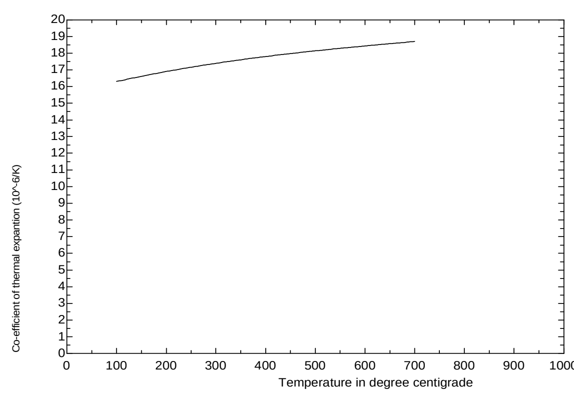
Since it has been previously determined that total strain is the combination of elastic and plastic strain, the two previous equations are combined to yield the Strain-life equation, also known as the Coffin-Manson equation:

$$\frac{\Delta\varepsilon total}{2} = \frac{\boldsymbol{\sigma'}f}{\boldsymbol{E}} \times (2N_f)^{b} + \varepsilon'_f \times (2N_f)^{c} \quad \text{…….. (7) [2].}$$

I. Experimental procedure

a. Experimental procedure for Coffin-Manson equation

Here σ'f and b are fatigue strength coefficient and fatigue strength exponent, respectively, and the ε'_f and c correspond to fatigue ductility coefficient and fatigue ductility exponent, respectively. N_f denotes number of cycles to failure. From the above equation (7), the number of cycles tend to failure are calculated. The temperature dependent material properties such as coefficient of linear expansion (α), modulus of elasticity and linear strain are shown in graph (2, 3 &4) respectively refereed from. Tensile specimens are prepared to conduct high temperature tensile test as shown in Figure 16. This test was carried out to find the fracture stress and fracture strain at 700°C and the obtained stress- displacement graph is shown in Figure.



Graph.2.temperature v/s co-efficient of thermal expansion

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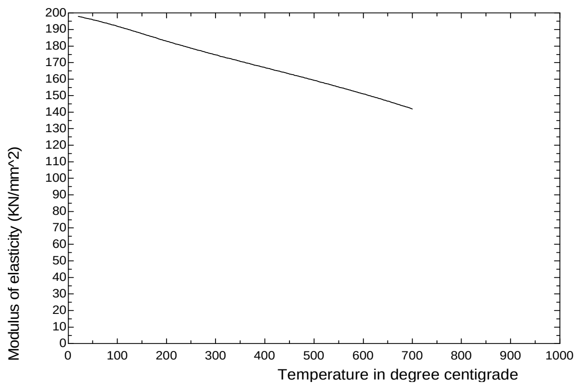
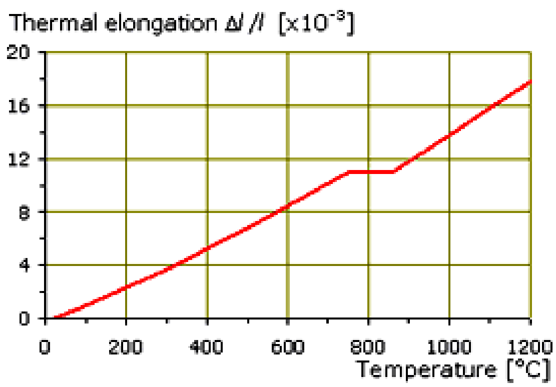


Graph.3. temperature v/s modulus of elasticity
Graph-3&4 collect data from SMST (Salzgitter Mannesmann stainless tubes) catalogs of tubes.



Graph.4. temperature v/s thermal elongation
Table collect Professor Colin Bailey, University of Manchester

Fig.1 Parent tube BS-3059 before hot tensile test.

From figure, the linear thermal expansion corresponding to 700°C is $18.7x10^{-6}$ K and the difference in temperature is 700°C (ΔT).

Hot tensile test perform at 700°C to achieve this temperature after 3 hour of heating and soaking time after 20 minute.

After performing of hot tensile test below result table achieved of tube material, and figure of test tube see below the table.

Sr. No.	Descriptions	
1	Outer diameter	64 mm
2	Thickness	3.40 mm
3	Dia-width	12.40 mm
4	Cross sectional area	42.16 mm^2
5	Yield load	11560 N
6	Yield strength (min)	274.1 MPa
7	Ultimate load	17370 N
8	Tensile strength (min)	411.9 MPa
9	Gauge length	35 mm
10	Final length	48.70 mm
11	Elongation % on gauge length 5.65 $\sqrt{A}$	39.14 mm

Table-I test achieve data of boiler tube at 700°C

Fig.2 hot tensile test specimen

Figure of hot tensile test of tube at 700° C (a) figure of test tube breaking before separation and (b) figure of test tube breaking with separation.

$\Delta\varepsilon = \alpha\ \Delta T = 13.09x10^{-2}$

Using the above equation, the linear strain is found to be $13.09x10^{-2}$. The true fracture stress (σ'f) and true fracture strain (ε'_f) are found to be 411.9 (N/mm^2) and 0.37 respectively. From Figure, the modulus of elasticity (E) for 700°C is $1.42x10^5$ MPa. The fatigue strength exponent and fatigue ductility exponent are -0.12 and -0.7 taken from George E. Dieter. All the above values are substituted in equation and it is identified that after 224 cycles failure will occur.

b. Experimental set up procedure

The same effect achieve at the tube peripheral surface we can use smithy furnace, in this procedure tube specimen prepare and close both ends with the help of arc welding because to prevent elongation of the tube. After that all process completed tube ready to use in smithy furnace.

Fig.3 boiler tube heating in smithy furnace

The boiler bube of which is prepare for experimental procedure that is put in the furnace. Before the heating of the tube the furnace prepare with the wooden peacies and kerosine spraying in the fornace after that starting of the firing. After proper firing of the furnace blower start to supling of the air with proper velocity and supply more and monre coal for firing. The boiler tube heating temperature up to 700˚C and to check the temperature with the help of thermocouple at every cycle of heating. For reaching this temperature 20 to 25 minutes taken.

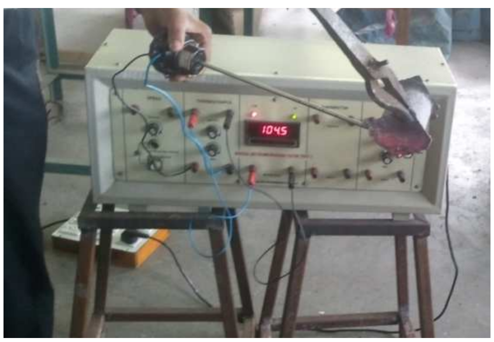


Fig.4 Themocouple

There are three tubes use to performing thermal fatigue failure at the diferent range of the cycle and comparing the thermal fatigue at microstructure, hardness. Above two parameter use and conclude results.

Fig.5 Quanching process

For the cooling of the tubes water tub used in which water filling up to ¾ portion of the tub. After the heating of the tubes and temperature reach at 700˚ C, tubes quanching in the water tub and the drop the temperature up to the room temperature. To reduce the temperature 7 to 10 minutes required. After every cycle water change in the tub.

Results and disscusion

Performing of the hot tensile test on the tube and result obtain from it that data applide in the equation no.7 and solving that we can find the 224 cycles for the failure.

Fig.6 Tube after 200 thermal fatigue cycles.

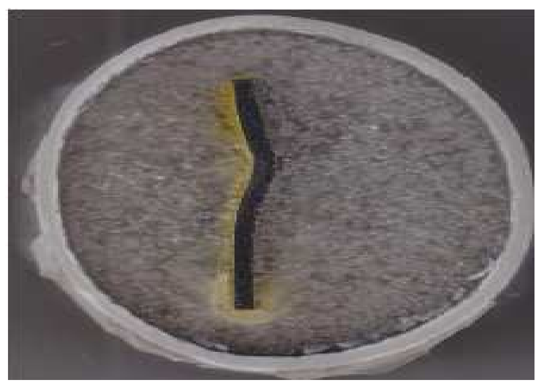


Fig. 7 after 200 thermal cycles performed material of tube at internal side magnification of 100 X

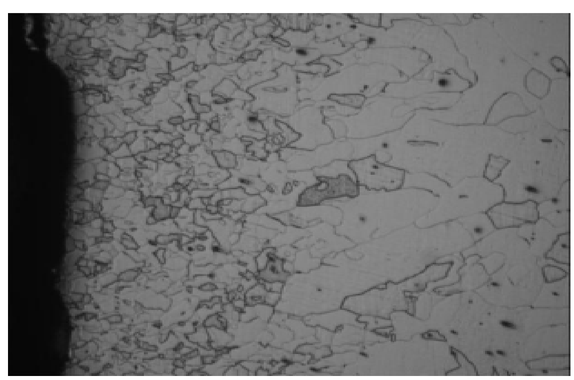


Fig.8 after 200 thermal cycles performed material of tube at internal side magnification of 100 X

Internal edge microstructure after 200 thermal fatigue cycles at portion away from damage having essentially coarse-grained ferritic structure.

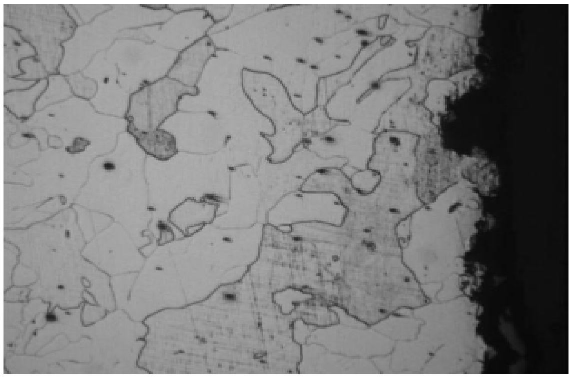


Fig.9 after 200 thermal cycles performed material of tube at external side magnification of 100 X

External edge microstructure after 200 thermal fatigue cycle at portion away from damage having essentially fine & coarse-grained ferritic structure. Corrosion damage is observed at the edge.

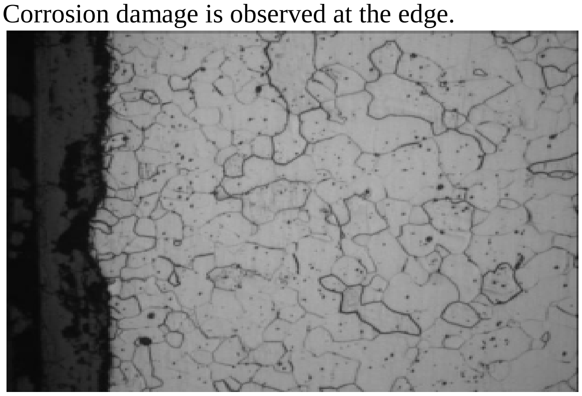


Fig.10 after 200 thermal cycles material of tube at external side magnification of 400 X

External edge of tube after 200 thermal fatigue cycle microstructure having essentially fine & coarse-grained ferritic structure. Presence of oxide scale is observed at the edge.
Microstructure having essentially coarse-grained ferritic structure. Present of oxide scale is observed at edge.

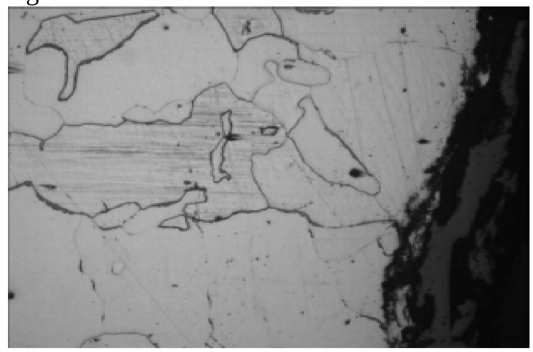


Fig.11 after 200 thermal cycles material of tube at internal side magnification of 400 X

Internal edge of tube after 200 thermal fatigue cycles.

Conclusion

The boiler tube of BS-3059 ERW320 having thermal fatigue life at $700^{\circ}C$ by solving of the Coffin-Manson equation is 224 thermal fatigue cycles.

At experimental setup the tube failure at the 200 thermal fatigue cycles and the variation of the Coffin-Manson equation and the experimental set up is 10%.

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