ISBN : 81 - 87053 - 73-1
Remaining Life Assessment of Aged Components in Thermal Power Plants and Petrochemical Industries, Vol. 2
Eds. A. K. Ray, S. Chaudhuri, N. G. Goswami and R. N. Ghosh
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Residual life estimation of high temperature tubings based on oxide scale thickness measurement

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Abstract : *Super heater and Reheater tubes of fossil boilers, wherein creep is the major damage mechanism, are required to be assessed periodically (after one lakh hours) for remaining life. For remaining life estimation of these tubes, knowledge of the operating tube metal temperature forms a very valuable input. Unfortunately, this information is hard to get, since measurement of tube temperature directly or indirectly through the measurement of steam temperature, are carried out only infrequently due to various technical and economic considerations. It is more convenient to estimate the operating tube metal temperature in service by examination of tube samples for thickness of steam side oxide scale, hardness and deterioration of microstructure. Since the changes in these parameters are functions of time and temperature their current* *values may be used to estimate average tube thermal history for a given operating time. This paper deals with relatively accurate estimation of tube metal temperature using three approaches viz. (i) Microstructural evolution (ii) Steam side oxide scale thickness built up and (iii) Hardness degradation. One time estimate of temperature and stress values have been extrapolated back to the initial conditions using linear growth of steam side scale thickness and fire side wastage of the tube. Total service life has been discretized at a smaller interval to increase the accuracy of estimation. Typical results on remaining life calculation based on above modification have been described.*

Keywords : Residual life estimation; Microstructural evolution; Hardness degradation; Oxide scale thickness; Stress rupture failure; Thermal power plant.

INTRODUCTION

Stress rupture failure of super heater / reheater tubes is the major cause of forced outages of boilers in a thermal Power plant[1]. In the past due to absence of any accurate methodology for predicting the remaining life of these tubes, utilities were forced to choose between premature replacement of these tubes and excessive outages. Until a few years ago, the methods that were employed for making tube replacement decisions were based upon calculations involving operating history, failure frequency or destructive testing of the tubes. However, all these methods suffer from major limitations.

The calculation techniques involve estimating the creep life consumed, based upon an assumed history of temperature and stress operating on the tubes. However, the actual operating histories are often variable and undocumented. In fact, even for a constant and known boiler operating history, the tube metal temperature and stresses increase in service due to oxide scale build-up on the steam side and thickness reduction on the fireside. Moreover, tube failures are, often caused by localized conditions resulting from variations in the temperature distribution in the tube bank, a factor not easily accounted for in the calculations. Hence, there is a need for estimating the tube metal temperature more accurately.

The assessment method based on failure frequency has a limitation that it can be applied for only similar materials of similar history with identical failure mechanisms. However, such a documentation of failures is generally non-existent.

Destructive testing may be done by removing samples, followed by accelerated creep rupture testing of the samples. The limitation in this method is that accelerated creep rupture tests do not take into account the increase in tube-metal temperature and stress that occur in service, and can therefore, lead to non-conservative prediction of the remaining life. Choice of the appropriate stress and temperature for the accelerated tests is clouded in uncertainly for the same reason. Since the method is destructive and involves expensive testing, the number of samples that can be evaluated is necessarily limited, and the information obtained is also consequentially limited to the sampling locations. Possible errors in sample location selecction can also lead to totally inappropriate tube replacement decisions.

During the last few years[2,3] number of techniques based upon the deteriorating parameters of these tubes have been used to estimate the residual life. Fig 1 depicts all the currently available techniques for assessing the remaining life of SH/RH tubes. Even with this wide array of techniques, no single technique is either applicable under all circumstances or accurate on a stand-alone basis. What is needed is an approach that combines historical information, calculations

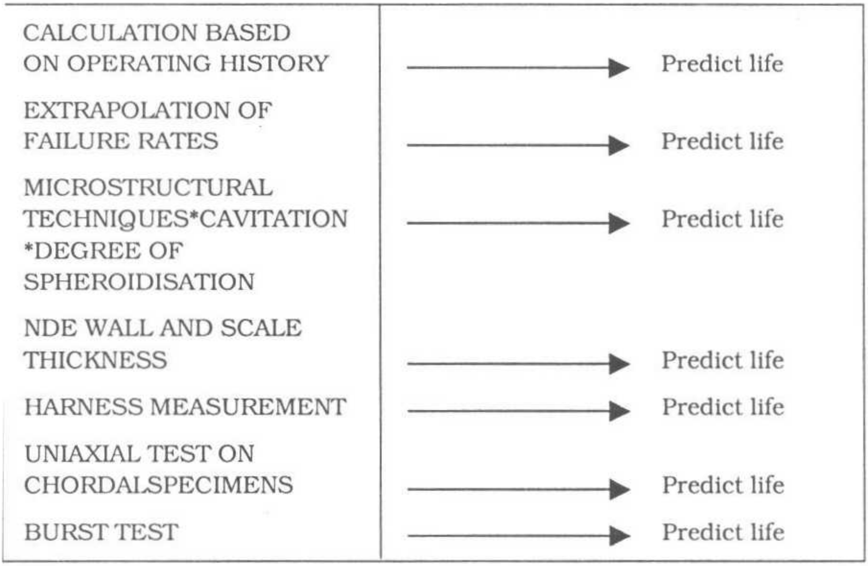

Fig. 1 : Various Techniques available for life prediction of super heater and reheater tubes

based on operating parameters & non-destructive evaluation in an interactive and complimentary fashion so that maximum amount of information can be gained in a cost effective way.

Present paper, therefore, discusses three approaches for relatively accurate estimation of the tube metal temperature namely :

i) Steam side oxide scale thickness measurements
ii) Microstructural evolution
iii) Hardness degradation.

The steam side oxide scale thickness can be measured on sample tubes cut from critical locations or non-destructively by special equipment based on ultrasonics. As a second approach, the microstructural features such as spheroidisation and dispersion of carbide phase in the tube samples can be used to estimate the tube metal temperatures. An estimate of tube metal temperature could also be made on the basis of measurement of hardness degradation after certain hours of operation. Wall thickness measurement of tubes is also carried out to obtain the current operating stress value of the tubes. One time estimate of temperature (using above methodologies) and stress values have been extrapolated back to the initial conditions using linear growth of steam side scale thickness and fireside wastage of the tube. Total service life has been discretized at a smaller interval to increase the accuracy of estimation. Typical results relating to remaining life estimation based on above modification have also been presented.

ESTIMATION OF TUBE METAL TEMPERATURE USING VARIOUS DEGRADED PARAMETERS

A number of methodologies are available for life estimation of SH/RH tubes of boiler. All these methods are based on the determination of average metal temperatures of in-service tubes by measuring the degraded properties of these tubes. The estimated temperatures are then used with standard stress rupture data to calculate the remaining life. These methods for estimation of metal temperature are described below.

Steam side oxide layer growth

The temperature of the tubes operating in creep regions increased during its life time because the build up of steam side oxide insulates the tube metal from the flow of cooling steam. As the tube metal temperature increases, rate of internal scale formation also increases. As the scale thickness increases, so does the metal temperature and the cycle continues progressively, becoming higher and higher each year. Therefore, a method which takes into account the continuous increase in metal temperature as a result of oxide layer built up is necessary in order to estimate the remaining life of high temperature tubings operating in creep region.

One of the earlier attempts to describe steam side oxide scale growth in low alloy ferritic steel (1 to 3% Cr) as a function of time and temperature is carried out by Rehn etal [4]. Their results showed a linear variation of logarithmic oxide scale thickness and penetration depth (metal lost of oxidation) with Larson-Miller parameters as :

$$\log_{10}X = 7.1438 + 2.1761 \text{ X}10^{-4}T\,(20 + \log_{10}t) \qquad \ldots (1)$$

Where,

X = steam side oxide scale thickness in mils (10^{-4} inch)

T = mean operating or aging temperature in ^{O}R (^{O}F + 460), and

t = service time in hours.

Although this co-relation has been proposed for low alloy ferritic steel, data of the higher alloy of 9Cr-1Mo steel also showed agreement to some extent to the above correlation[5].

Patterson et. al.[6] has developed a co-relation between steam side oxide scale thickness and operating temperature of the form.

$$\log_{10}X = C_1T + C_2T + C_3T\log_{10}t \qquad \ldots (2)$$

Where 'X' is the scale thickness expressed in mils and 'T' is mean operating temperature in rankings and

C1 = – 6.839869

C2 = 0.003860

C2 = 0.000283

This co-relation also gives prediction similar to as expressed by Rehn et.al[4] over the normal temperature range of interest.

Having known the equivalent temperature of operation of tubes with the help of above correlations of scale growth with Larson-

Miller Parameter (LMP) , the next step is to find out the representatives stress of tubes under the given operating conditions. Commonly used equations for calculating the representative tube stresses for this purpose are:

(i) Maximum elastic Hoop stress

(ii) Minimum diameter stress and

(iii) Tresca reference stress.

Among all these criteria maximum elastic Hoop stress criteria gives the most conservative value and hence is very widely used. This is represented by the following equation.

Maximum Elastic Hoop Stress $(\sigma) = P(b^2 + a^2)/(b^2 - a^2)$ ... (3)

Where P = working pressure (N/mm^2)
b = outer radius (mm)
a = inner radius (mm)

Once equivalent temperature of operation of tube (T_s) is known, representative stress (σs) of tube is known , time to rupture (t_r) of the tube is determined either from the proposed relationship between LMP and the rupture stress of the tube or with the help of following type of equations :

$$P = T_s(20 + \log_{10} t_r)$$
$$= A(\log_{10} \sigma s)^2 + B(\log 10\ \sigma s) + C \quad \text{... (4)}$$

where P is the Larson-Miller Parameter and A,B and C are constants. Hence knowing the value of tr (time to rupture) and t (service time in hours), expended life fraction of the tube at the equivalent temperature of operation (T_s) can easily be calculated and thus remaining life of tube is predicted.

The various oxide scale thickness-temperature correlations described above have all been developed from data on aging times representing a small fraction of service life, so their applicability to general long term service is yet unproven. The database used in deriving the various correlations are different and hence lead to large variations in estimated temperatures. Therefore, preference for a particular co-relation must at this time be considered subjective.

In spite of these limitations, the oxide scale thickness measurement has become a standard tool in life prediction of high temperature tubings. For a boiler tube operating at high temperature an estimate of steam side oxide scale thickness with L-M parameter is first established. The equivalent temperature of operation of tube is thus estimated from the practical data of oxide layer thickness and the duration of service exposure. Knowing the value of equivalent temperature and the applied stress, the t_r (time to rupture) is estimated based upon the proposed relationship between L-M parameter and the rupture stress for that steel. From the knowledge of expended life, the remaining life is thus predicted. Therefore, once L-M parameter relationships for steam side oxide scale growth kinetics and rupture stress for the particular steel are established, the method is the most simple approach for remnant life prediction.

Alternatively, to increase the accuracy of prediction, current effective temperature of the tube is determined from the proposed relationship of oxide scale thickness and Larson-Miller parameter. The tube dimensions are used to calculate the effective current stress using maximum elastic hoop stress criteria or Tresca reference stress criteria. The temperature and stress values are then extrapolated back to the initial conditions assuming linear growth of oxide scale and fireside corrosion. The service life up to present time is divided into three months intervals. For each interval, the oxide scale thickness and reduced wall thickness are estimated using linear kinetics of scale growth and hot corrosion. The life fraction expended at each three months interval is computed from the temperature increase caused by steam side oxide scale, the hoop stress and the stress rupture curve at each calculated temperature. These life fractions are summed to evaluate the expended life up to present time and their subtraction from unity determines the remaining life fractions of the tubes. When the total expended life fractions comes to a value of unity, the end of the life is deemed to have reached.

Microstructural evolution (spheroidisation)

For carbon and low alloy ferritic steels that undergo spheroidisation alongwith carbide precipitation and growth processes during elevated temperature service, detailed microstructural studies may independently support the service temperature estimates based open operating records. There are basically six stages of spehroidisation of carbides have been identified as written below :

A. Ferrite and fine pearlite (Microstructure of New tube)

B. First stage of carbide spheroidisation usually accompanied by precipitation at the grain boundary.

C. Intermediate stages : Appreciable spheroidisation of pearlite but some carbides plate still evident.

D. Spheroidisation is virtually complete but the carbides are still grouped in original pearlitic pattern.

E. Spheroidisation is complete and carbides are dispersed living little trace of original pearlitic pattern.

F. There is a marked increase in the size of some of the carbide particles, partly due to coalescence.

These stages of microstructural evolution in low alloy ferritic steel has been conveniently used by state electricity commission of Victoria in Austarlia to know the equivalent temperature of operation (T_s) of the tubes. Following equation is used to know the value of 'T_s'

$$P = \log t - C/T_s \qquad \dots (5)$$

Where,

P = constant values assigned to different stages of spheroidisation as for :

Stage A : -12.17

Stage B : -11.95

Stage C : -11.69

Stage D : -11.56

Stage E : -11.32

Stage F : -10.71

t = time elapsed in hours

C = 12370, and

T_s = equivalent temperature of operation (°K)

Microstructures obtained after certain hours of operation (t) could be compared with various stages of spheroidisation and assigned a value of 'P' to know the equivalent temperature of operation of the tube. Once temperature of operation is known, with known operating stress value the time of rupture (t_r) of the tube is calculated and thus remaining lie is estimated.

Interparticle spacing of carbides

It has been observed that in low alloy ferritic steels various phases of carbides precipitate and their coalescence take place as a result of increase in time and temperature. As a result inter-particle spacing of these carbides are taken as one parameter to know the equivalent temperature of operation of these tubings. For 1Cr-1/2Mo steel this correlation is as follows :

$$\frac{dx^3}{dt} = 1.33\, x\, 10^{-26}\ \exp(0.0534T) \quad \ldots (6)$$

Where,

x = Interparticle spacing between carbides in (micron)

t = time in hours

T = equivalent temperature of operation in degree Kelvin.

By measuring x at two different time intervals, could be evaluated and using above equation value of 'T` (equivalent temperature of operation) can be obtained. Once 'T' is known the same general method as described earlier can be utilized to know the value of remnant life of tubes.

Hardness decline

The hardness of low alloy steel changes with service exposure in a time and temperature dependent manner. Thus any measure of change in hardness during service may be used to estimate the equivalent temperature of operation for the component. This approach however is particularly suitable when hardness changes in service occur primarily as a result of carbide precipitation and growth. Needless to mention, the effect of strain induced softening is neglected in this kind of assessment.

The tempering responses of steels at typical service temperature, as evidenced by hardness changes influenced by time (t) and temperature (T) of exposure, often are described by Larson-Millar parameter 'P'. Typical correlations between hardness and Larson- Miller parameter for aging for 1.25Cr-

0.5Mo, 2.25cr-1Mo and 9Cr-1 Mo steels (in the LMP range of 34,000 to 40,000) are as follows[2,7] :

VHN = 595-0.012P (for 1 Cr-0.5 Mo steel) ... (7)
VHN =960-0.02 P (for 2.25 Cr-1 Mo steel) ... (8)
VHN =933-0.018P (for 9 Cr-1 Mo steel) ... (9)

If the service exposure, duration and current hardness are known, above equations can be used to estimate the equivalent temperature of operation of the tube. With known operating stress value, the time of rupture (t_r) is calculated from the relationship of L-M parameter and rupture stress. Since the expended life is known, the remnant life is also calculated.

A common problem in using this approach is that the initial hardness of the material is often unknown and assumptions have to be made based on typical values obtained on similar material. If initial hardness value is known, tube metal temperature could be calculated for every assumed shorter interval of time from the beginning of service iteratively. And knowing the stress value at each interval, life fraction expended at each interval could be known. They are then summed up to known the total life fraction expended till the present time.

RESULTS AND DISCUSSION

Steam side oxide scale thickness of final super heater tubes of 30 MW boiler was carried out along with dimensional measurement in order to evaluate the remaining life. Relevant data is given below :

Component	: Final super heater tube
Material	: SA213-T22
Steam outlet temperature	: 485 degree C
Working Pressure of steam	: 62 Kg per sq. Cm

Original tube thickness : 4.5 mm
Reduced tube thickness : 3.5 mm
Measured outer diameter : 44.5 mm
Hours of operation : 1,82,142 Hours
Measured value of scale thickness : 0.35mm (14mils)

IBR and Maximum elastic hoop stress criteria have been used to calculate the value of representative stress, which turned out to be 39.38 N per sq.mm and 39.64N per sq.mm respectively. One time estimate of temperature and equivalent stress resulted that 66 percent of tube life has been exhausted. In contrary when total time has been divided into four equal intervals each of about 45,000 hours of duration and life fraction exhausted at each intervals is determined using current value of temperature and stress, it has been found that only 32 percent of life is exhausted till the present time. It clearly indicated that a result obtained as a result of direct assessment is highly conservative in comparison to segment wise assessment. In this case, the remaining life obtained as a result of segment wise assessment is almost double than that of direct assessment.

CONCLUSIONS

Various methodologies for residual life assessment of tubes based on some typical parameters are complimentary to each other and should be used in combination to obtain a realistic value. Life assessment studies require knowledge of damage mechanisms, critically of different locations, extent of current damage and methods of ensure the detection of worst defects. It is concluded that accuracy of prediction could be enhanced by referring the methodologies based on physical principles of processes involved for deterioration of components. In the present case of scale thickness measurement direct assessment gives a very conservative value of remaining life of tube in comparison to segment wise estimation. Segment wise assessment estimated the remaining life to be doubled than the direct assessment.

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